

The Beringian Ancestry of *Phenacomys* (Rodentia: Cricetidae) and the Beginning of the Modern Arctic Ocean Borderland Biota

By CHARLES A. REPENNING, ELISABETH M. BROUWERS,
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The Beringian Ancestry of *Phenacomys* (Rodentia: Cricetidae) and the Beginning of the Modern Arctic Ocean Borderland Biota

By Charles A. Repenning, Elisabeth M. Brouwers, L. David Carter, Louie Marincovich, Jr., and Thomas A. Ager

Abstract

The living North American heather vole, genus *Phenacomys*, is one of the few living microtine rodent genera whose ancestry has not been traced back to the Miocene. A recently discovered fossil *Phenacomys* from the late Pliocene part of the Gubik Formation along Fish Creek, northern Alaska, clearly resembles the extinct Asiatic genus *Cromeromys*, a progressive offshoot of the extinct Holarctic genus *Mimomys*, suggesting the probable ancestry.

Marine ostracodes from the base of the Fish Creek section record a much warmer Arctic Ocean than do those found high in the section with the fossil *Phenacomys*. Both mollusks and mammals in the fauna with *Phenacomys* indicate that this ocean was not perennially frozen during deposition of the upper part of the section. Pollen in the Fish Creek section records a transition from shrub tundra with nearby conifer forests in the lower part to herbaceous tundra with the mollusks and mammals of the Fish Creek Fauna.

Correlation, by means of rodent evolution and magnetic patterns, with a similar floral transition in northeastern Siberia and with the oxygen isotope record of the northern oceans indicates that the floral change probably represents the first development of widespread, low-elevation tundra in the Arctic Ocean Borderland and indicates an age of 2.4 Ma for the Fish Creek Fauna in the upper part of the section.

The Fish Creek Fauna lived during the time span that includes the beginning of the first significant accumulation of continental ice in the Northern Hemisphere, according to oceanic and North American terrestrial records. The older parts of the Fish Creek section record part of the climatic deterioration that led to this first glaciation. This climatic history integrates the known late Pliocene history of climatic change in the Arctic Ocean and its borderland.

INTRODUCTION

Fish Creek drains into the Arctic Ocean at Harrison Bay to the west side of the Colville River delta. The fossil locality of this report is about 15 miles (24 km)¹ south

¹Distances are given in miles (the common United States unit), but conversion to kilometers is given to accord with metric measurements of the report.

of the Arctic Ocean at lat 70°16' N., long 152°01' W. It is the most northerly pre-Pleistocene microtine rodent fauna known (figs. 1, 2) and one of very few Tertiary mammalian faunas from Beringia, that part of northeastern Siberia and northwestern North America on either side of the Bering Strait that shares great faunal and floral similarity.

The Gubik Formation exposed at the Fish Creek locality is of Pliocene age and consists of 10–12 m of marine and estuarine sediments that have been described as consisting of two units (Carter and others, 1986): a basal unit about 4 m thick composed of distinctly to indistinctly bedded dark-gray silt containing scattered granules of chert and quartz, sparse sand interbeds with sand-filled burrows, and a few mollusk shells; and an upper unit composed of fossiliferous brown to gray sand, pebbly sand, and silt that is predominantly trough cross-bedded but includes evenly bedded zones that are relatively thin and discontinuous.

The character of the cross-strata in the upper unit was interpreted by Carter and Galloway (1985) to indicate deposition in a tidal channel. A strong dominant current is indicated by sets of large-scale cross-strata as thick as 4 m, which have consistent foreset dips to the north-northeast. A nearly opposed subordinant current is indicated by ripple stratification that has built up the dip of the large-scale foreset beds, and by sets of medium-scale cross-strata that contain molluscan and mammalian fossils of the Fish Creek Fauna.

Lithologic changes for the part of the exposure where most of the samples discussed here were collected are shown in figure 3, in which the median gray sand unit and the upper silt represent the tidal channel deposits of Carter and Galloway (1985). These marine deposits are overlain by alluvial and eolian sands. One sample from the lowest part of the section is normally magnetized; the remainder of the section is reversely magnetized (V. Pease, written commun., 1985; Carter and others, 1986).

A few ostracodes markedly different from those in the upper part of the 5-m medial gray sand unit occur at the base of the lower silt and clay unit. These ostracodes

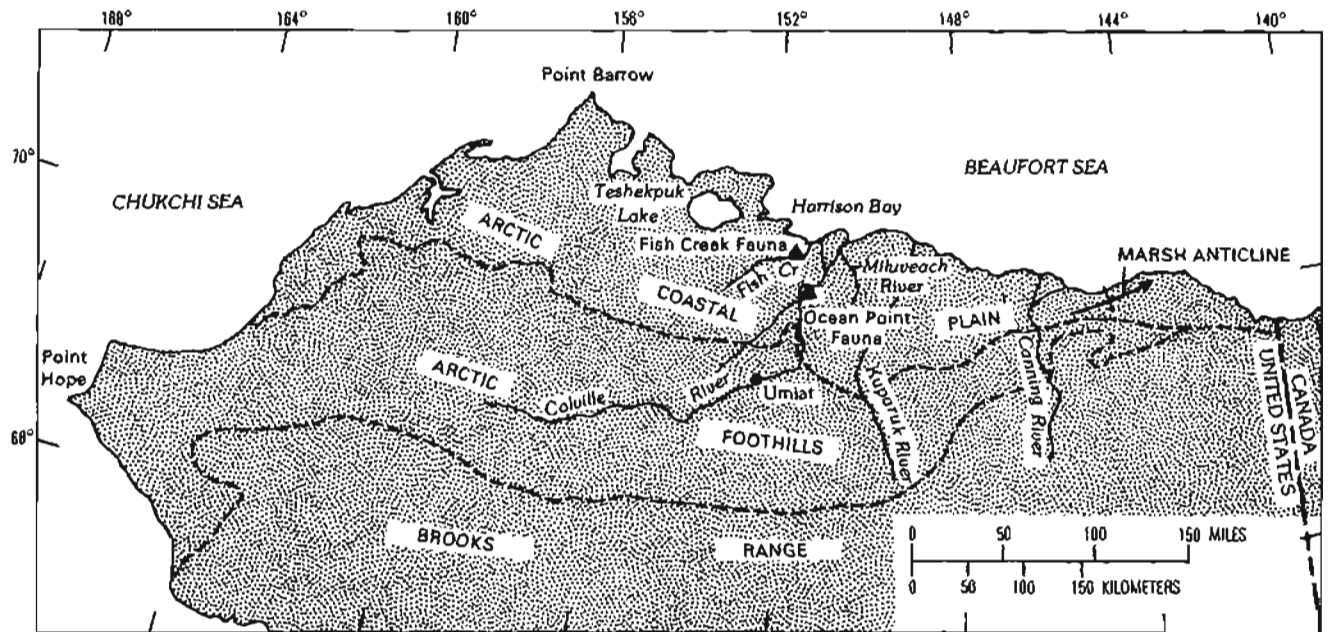


Figure 1. Location of places and features in northern Alaska mentioned in the text. Dashed line, general physiographic boundary. Anticline symbol shows strike, dip, and plunge.

are excluded from the formal Fish Creek Fauna because they are thought to be substantially older. Ostracodes of the Fish Creek Fauna are abundant and diverse 1.5 m above the base of the medial sand unit and in two mollusk-rich beds at the top of this unit. Mollusks occur throughout the section, but are most abundant only in a distinct, organic-rich shell bed in the upper 1.5 m of the medial sand unit. Palynomorphs occur 3 m above the base of the section and with the ostracodes of the upper part of the medial sand unit, about 7.5 m above the base of the exposures. These are the only samples of pollen not flooded with reworked Cretaceous pollen and that are believed to reflect the vegetation at the time of deposition. Large, shallow-water benthic foraminifers (*Elphidiella groenlandica* and *Cyclogyra involvens*, fide K. McDougall, oral commun., 1984) are common in the upper part of the medial sand unit; fossil bone, primarily microtine rodent remains, is common in the mollusk-bearing bed of the medial sand unit, about 9 m above the base of the exposure.

The exposures along Fish Creek have been discussed by Carter and others (1979), who proposed a middle Pleistocene age based on very limited data. Carter and Galloway (1985) preferred a late Pliocene age based partially on data reported more fully herein. The locality is the type section of the Fishcreekian transgression as used by Brouwers and others (1984) and dated as 1.2 Ma, and as named by Carter and Brigham-Grette (in press).

Microtine rodent teeth were first discovered in 1983 in washed mollusk samples, along with small water-rounded fragments of other mammals. The microtine teeth are generally not abraded, and many are perfectly

preserved, with no rounding of their delicate features. One last upper molar of a microtine bears a fragment of its maxillary still adhering to one side of the roots, a situation hardly plausible if the fossils had been reworked from older unconsolidated deposits. The microtine teeth represent two species, a primitive lemming and a new and primitive species of the heather vole *Phenacomys*. Further collecting at Fish Creek in 1984 yielded only a few additional teeth.

All mammalian specimen numbers from the Fish Creek Fauna are from the catalog of the National Museum of Natural History, Smithsonian Institution, and are prefixed by the abbreviation USNM. University of Alaska specimens from the Cape Deceit Fauna of the Seward Peninsula (fig. 2), described by Guthrie and Matthews (1972), are prefixed by the abbreviation UA.

Acknowledgments

Charles L. Powell (USGS, Menlo Park) first found fossil bone and teeth while picking fossil mollusks from samples collected at Fish Creek, reflecting an interdisciplinary interest not often found in paleontology. Mary L. McGann, Ginger Vagenas, and Katherine B. Lormand (USGS, Menlo Park) spent long weeks in further picking of the samples for microtine teeth. Katherine M. Reed (Geological Survey of Washington, Seattle) and John Galloway (USGS, Menlo Park) returned to the Fish Creek locality with Carter in 1984 and screened for additional rodent teeth. Joseph E. Hazel, Léo Laporte, and J. Platt Bradbury reviewed earlier versions of the manuscript and offered helpful suggestions.

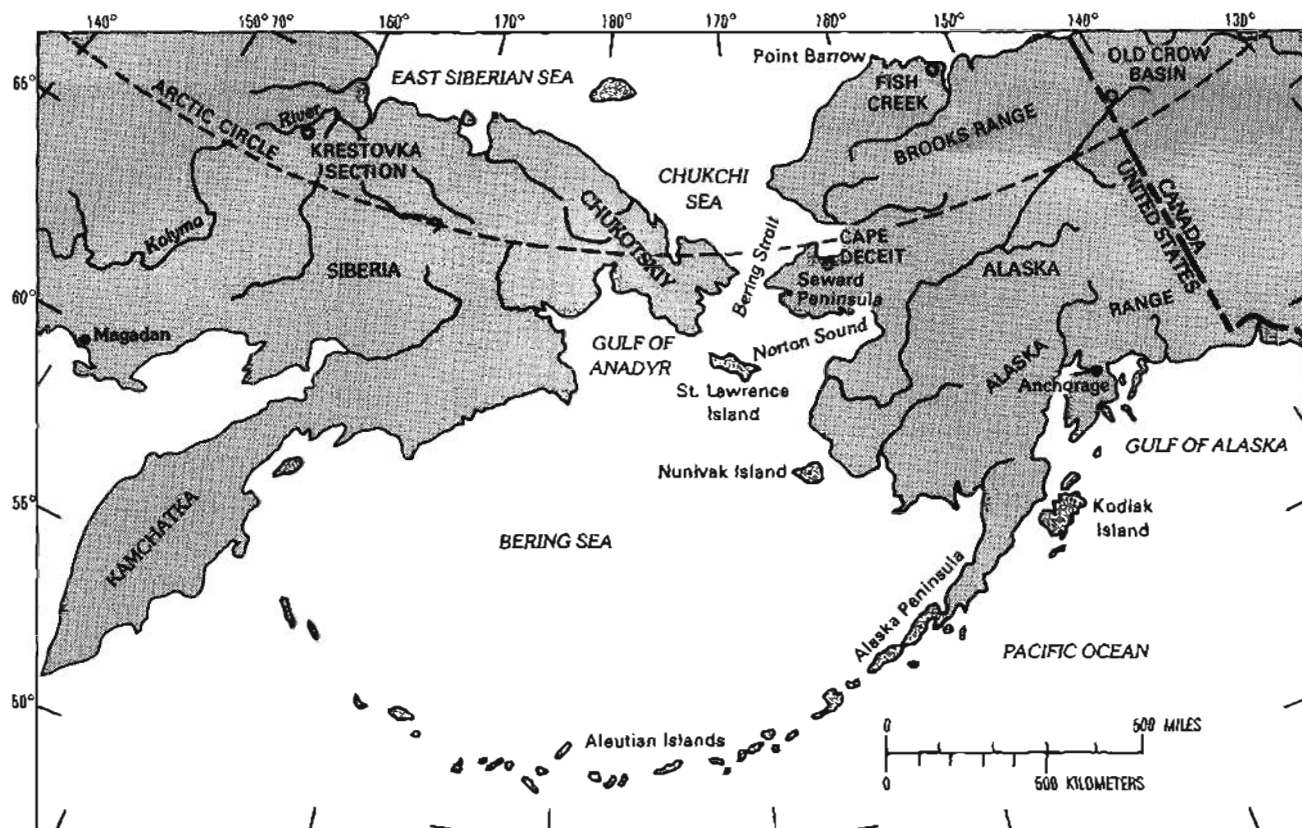


Figure 2. Beringia, showing places mentioned in text, including the pre-Pleistocene microtine faunas discussed: Krestovka Section in Yakutsk, northeastern Siberia; Cape Deceit Fauna of Seward Peninsula, Alaska; Fish Creek Fauna of the North Slope, Alaska; and faunas of Old Crow Basin of Yukon Territory, Canada. Old Crow Basin contains microtine rodents of Pliocene age, but age relationships are unknown and localities are not further discussed.

MAMMALS OF THE FISH CREEK FAUNA

Nearly all identifiable mammalian fossils are from a 5.0- to 7.6-cm-thick interval within the most conspicuous mollusk-bearing bed, which is 15–23 cm below the upper contact of the medial gray sand. This part of the Fish Creek section is shown (fig. 3) above the large-scale crossbedded deposits that are believed to be of tidal-channel origin, but it is actually interbedded with them along strike, and the entire unit is composed of lenses and lenticular beds of the two lithologies. The mammal-bearing deposits are characterized by medium-scale crossbedding. Organic detritus is common in these parts of the cross-stratified medial gray sand, particularly in the mollusk-rich zones, and includes fragments of wood, one specimen of which has been identified as *Larix* (larch) (Carter and Galloway, 1985). Larch does not now grow north of the Brooks Range. The fauna consists of two microtines, miscellaneous fish remains, a few bird bones, the lower third premolar of the pika *Ochotona* sp. cf. *O. alpina*, two incomplete teeth of a ground squirrel that could be *Spermophilus undulatus*, and a single well-worn and abraded lower fourth premolar that resembles that of the “crab-eating” otter *Enhydrion*.

The *Enhydrion* lower fourth premolar (USNM 264293) has a root development comparable to that indicated by the alveolae of this tooth in a fossil edentulous ramus of a sea otter (USNM 264275) found in a marginal-marine unit of the Gubik Formation at Ocean Point (fig. 1), about 16 miles (25 km) to the southeast of the Fish Creek locality (Repenning, 1983a). The tooth from Fish Creek does not resemble that of the living sea otter, *Enhydra lutris*, and is more *Enhydrion*-like, and less *Enhydra*-like, than *Enhydrion? reevei* from the Norwich Crag in East Anglia (see discussion in Repenning, 1983a). The Norwich Crag also contains a microtine rodent fauna that is Villangian in age, between 1.9 and 2.6 Ma old. The youngest known unquestioned *Enhydrion* from North America is approximately 3 Ma old (Repenning, 1976). The decision as to whether these specimens from the Arctic Ocean Borderland should be considered the earliest known and most primitive *Enhydra* or a late record of *Enhydrion* awaits discovery of additional material. However, the two records of an intermediate form in marginal-marine Pliocene deposits of the Arctic Ocean, at Ocean Point and at Fish Creek, suggest that evolution of the North Pacific sea otter may have taken place in the Arctic Ocean. Further, the records enhance

the possibility of a relationship of the living sea otter to *Enhydriodon? reevei* (Newton) from the English Norwich Crag, a possibility considered less likely in earlier publications by Repenning (1976, 1983a).

The two microtine rodent species from the Fish Creek locality are represented by 19 teeth (including 9 first lower molars and 2 last upper molars) of the new species of heather vole described herein and 3 teeth (including one incomplete first lower molar) of the bog lemming identified as *Synaptomys (Pliotomys) mimomiformis* Suchov.

The first lower molar of the bog lemming is shown in figure 4; the resemblance is strong to that of the 4.5 to 4.0 Ma old *S. (P.) mimomiformis* Suchov (1976) from the western side of the southern Ural Mountains north of the Caspian Sea, and to that of the 3.7 to 2.6 Ma old *S. (P.) europaeus* Kowalski (1977), from southern Poland, which appears to be a subgeneric and probably specific synonym of *S. (P.) mimomiformis* (von Koenigswald and Martin, 1984). Zazhigin (in Sher, Virina, and Zazhigin, 1977, and also in Sher and others, 1979) reported *Synaptomys* (cf. *Pliotomys*) sp. from the Kutuyakh Beds in the Krestovka Section of the Kolyma Lowlands (fig. 2). The Kutuyakh Beds are between 3.4 and 2.4 Ma old (Repenning, 1984). The resemblance of the Fish Creek lemming is less close to *Synaptomys (Pliotomys) rinkerii* Hibbard from Blancan V faunas of the Great Plains of North America (between 2.6 and 1.9 Ma old) because the anterobuccal reentrant of the first lower molar, which is on the anteroconid complex of this tooth, is much less developed. Emargination of this reentrant increases in younger forms to the extreme condition found in living *Synaptomys (Synaptomys) cooperi* Baird. Von Koenigswald and Martin (1984) reported that the primitive "Schmelzmuster," or enamel structure, persists in *Synaptomys* at least to the *S. rinkerii* stage. *Synaptomys* now lives only in North America.

Genus *Phenacomys* Merriam

Type Species.—*Phenacomys intermedius* Merriam, the heather vole of North America.

Range.—Now living in Canada and in the Canadian and Hudsonian life zones of the United States and known as a fossil in faunas of northeastern Siberia and northwestern North America that are herein recognized to be as old as 2.5 Ma. *Phenacomys* is not known in the conterminous United States until approximately 800,000 years ago and apparently was more or less confined to Beringia, the areas of Asia and North America near Bering Strait (fig. 2), prior to that time. However, recent evidence from Walter W. Dalquest (written commun., 1985) suggests, indirectly, that some undated fossil records in the United States may be twice that old. The

lack of a similar southward dispersal in Asia possibly is related to the much less extensive development of continental ice in Eurasia 800,000 years ago (Repenning, 1984).

Diagnosis.—*Phenacomys* is an arvicoline microtine rodent² with rooted, hypsodont cheek teeth having no cementum deposited in the reentrant angles; the commissures of the posterior loop and three basic triangles of the first lower molar (Repenning, 1983c) have a strong tendency toward a position buccal to the sagittal midline of this tooth; the anteroconid complex of the first lower molar has from two poorly pinched-off accessory triangles to four well-separated accessory triangles, varying with wear and with stage of evolution; the variability in configuration of the cap of the anteroconid complex is remarkably great with both wear and stage of evolution; the anteroconid complex never contains an enamel islet, although a "Mimomys Kante" is present in older forms; dentine tracts increase in height with evolution; and the last upper molar has two buccal and two lingual well-formed reentrants in all stages of evolution with no islet preserved in the posterior loop.

Discussion.—Johnson (1973) has suggested that the living *Phenacomys longicaudus* is sufficiently distinct from *Phenacomys intermedius* to warrant designation as *Arborimys longicaudus*. This question has not been further considered in the present study, and the three living species, *P. intermedius*, *P. longicaudus*, and *P. albipes* (also included in *Arborimys* by Maser and others, 1981), are retained in *Phenacomys* without opinion.

Only two pre-Pleistocene records of *Phenacomys* have been published, one in Alaska and one in Siberia. The Siberian fossil has been compared with the Alaskan extinct species *Phenacomys deeringensis* (Guthrie and Matthews, 1971) and this form of *Phenacomys* is considered to be more primitive; very low dentine tracts were noted (Sher, Gitterman, and others, 1977). *Phenacomys deeringensis* from the Cape Deceit Fauna of the Seward Peninsula, Alaska, was described as *Pliomys*, but Chaléne (1975) placed it in *Phenacomys* because of the characters of the first lower molar and the non-*Pliomys* enamel pattern of the last upper molar. The great variation, with wear, of the configuration of the enamel pattern on the anteroconid complex is particularly vexing in the identification of *Phenacomys deeringensis* (fig. 5); this is a character of the generic lineage, but is especially evident in more primitive species.

Phenacomys deeringensis is the only previously

²What are commonly called microtine, or arvicoline, rodents of the Subfamily Arvicolinae have five separate origins in the low-crowned cricetid rodents and the subfamily is polyphyletic. The Subfamily Arvicolinae is here restricted to those microtines (a descriptive term) that derive from the genus *Mimomys*.

named extinct species of the genus.³ At any stage in tooth wear, the variations of the enamel pattern on the occlusal surface of the first lower molar of *Phenacomys deeringensis* are essentially identical to variations found in specimens of living *Phenacomys intermedius*. However, similar patterns appear in earlier stages of wear in *P. deeringensis* because the reentrant angles on the anteroconid complex responsible for these variations in enamel pattern persist relatively shorter distances down the sides of the tooth and thus are lost with relatively less wear. The root-ward extent of these reentrants also varies individually. Dentine tract development and the basic structure of the last upper molar are essentially the same in the two species. *Phenacomys deeringensis* is large, however, and the length of the first lower molar⁴ averages about 3 mm compared to about 2.5 mm in *P. intermedius*.

The Cape Deceit Fauna (fig. 2), from which *Phenacomys deeringensis* was described, also is the type fauna of the most primitive known collared lemming, *Predicrostonyx hopkinsi*, and of a very primitive form of the *Microtus* lineage which seems best assigned to *Lastopodomys deceitensis* (Guthrie and Matthews) (see fig. 2e in Repenning, 1983c). This member of the *Microtus* lineage is not greatly modernized from *Lasiopodomys prebraebranti* Erbaeva (1976) (sometimes assigned to *Allophaiomys*, the ancestral genus) from central Siberia (see Repenning, 1983b). The oldest record of the *Microtus* lineage in the Krestovka Section of northeast Siberia, also described as archaic (Sher and others, 1979) and close to the "*Arvicola-Allophaiomys* group" (Vangengeim and Sher, 1970), is immediately below the Reunion Subchron (about 2.1 Ma according to a recent reevaluation of the data) (Repenning, 1984). The lineage is clearly of Asian origin and there is no basis for assuming an older age at Cape Deceit. As both Cape Deceit and the Krestovka Section are in the Beringian Faunal Province and share many faunal similarities, it is possible that the Cape Deceit Fauna and the first appearance of *Microtus* in the Krestovka Section are coeval. *Microtus* first appeared in temperate North America and Europe about 200,000 years later than the first appearance in the Arctic.

Tundra flora is indicated by pollen and insects from the deposits containing the Cape Deceit Fauna, which overlie strata whose pollen indicates a regional tree line very near to the locality (Matthews, 1974). The deposits underlying the Cape Deceit Fauna contain evidence of

alternating tundra and forest or forest-tundra. The tundra in which the Cape Deceit Fauna lived is believed to have been influenced by local permafrost and to represent a climate colder than at present (Matthews, 1974, table 6-Cape Deceit Formation, Unit 2).

The above-mentioned microtine rodents indicate a Blancan V age for the Cape Deceit Fauna, between 2.0

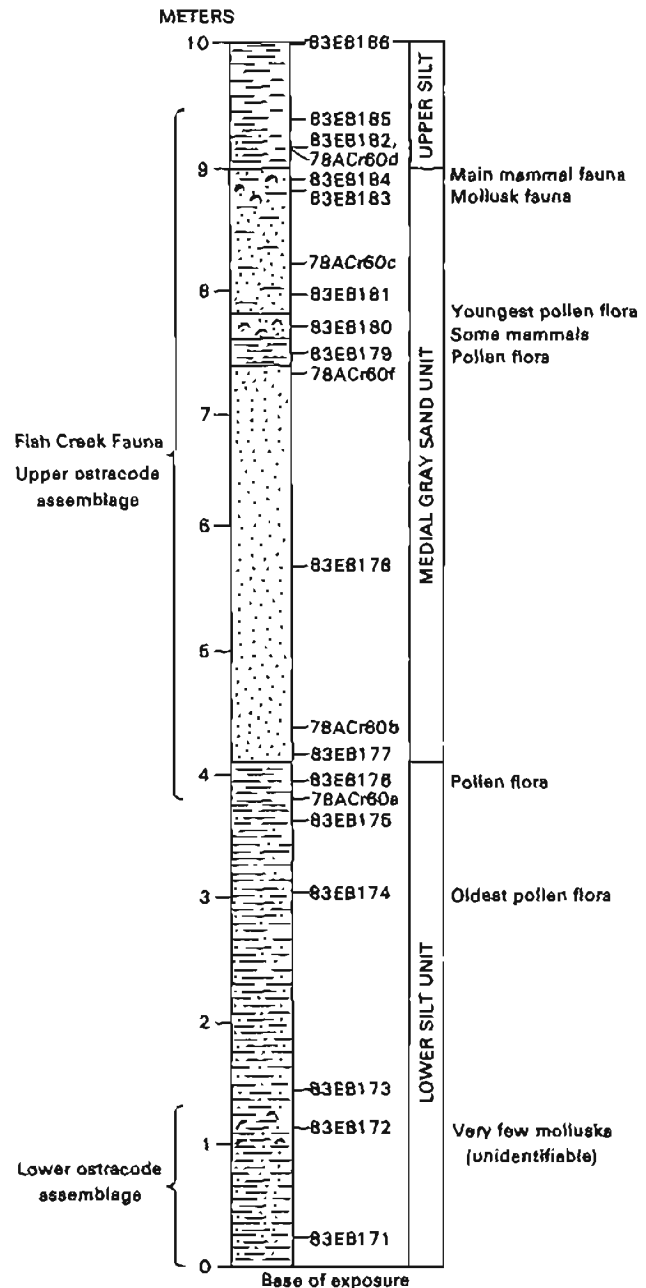


Figure 3. Stratigraphic section of marine and marginal marine sediments of the Gubik Formation at Fish Creek, showing stratigraphic position of microfossil samples, Fish Creek Fauna, and ostracode assemblages. EB, samples collected by Elisabeth Brouwers; ACr, samples collected by L. David Carter.

³As has been noted by others including Chaline (1975), the extinct North American Pliocene genus *Pliophenacomys* is unrelated to the *Phenacomys* lineage and is not an arvicoline microtine; that is, it does not derive from the genus *Mimomys*.

⁴Guthrie and Matthews (1972) indicated a size range of about 3.3-4.7 mm, but there appears to have been a 1-mm error in lettering of their figure 8. Presently available specimens (four first lower molars) show a range between 2.7 and 3.1 mm.

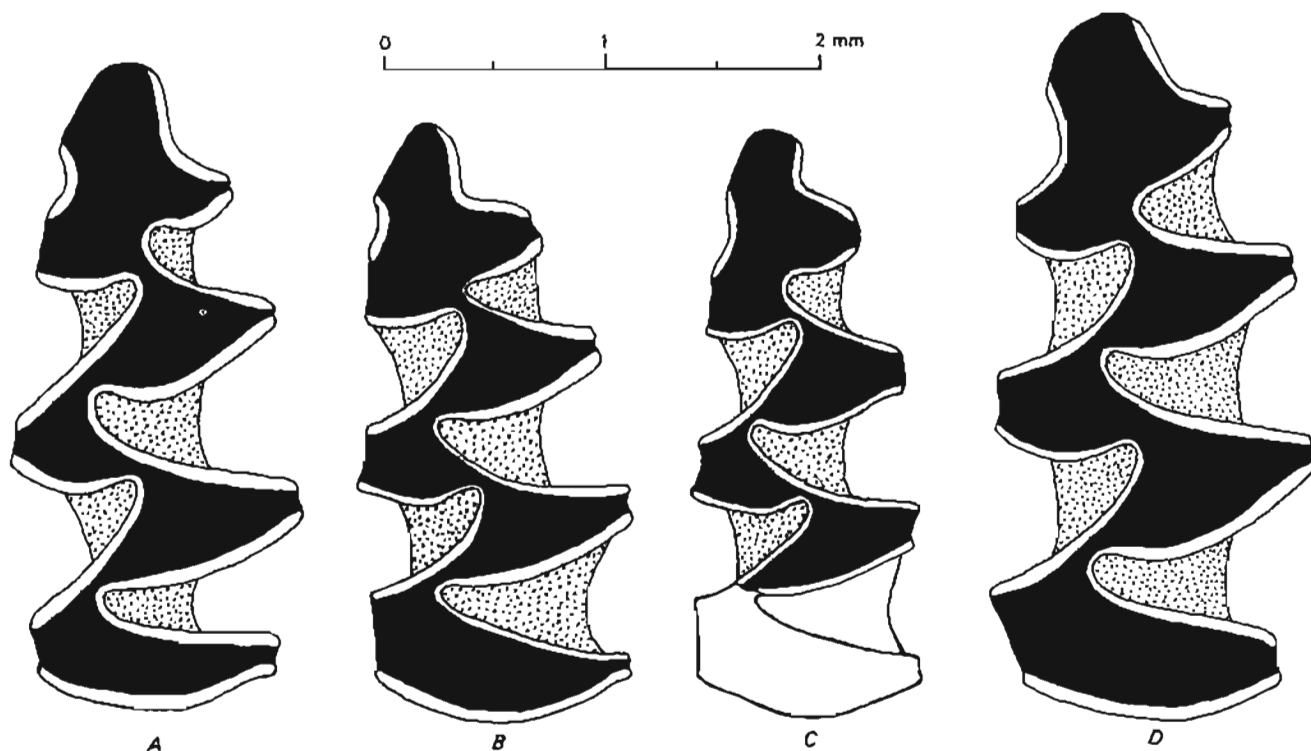


Figure 4. First lower left molars of species of *Synaptomys* (*Pliotomys*). Note differences in development of the left upper (anterobuccal) syncline or reentrant; size is variable although *S. (P.) rinker* averages largest. A, Molar of *S. (Pliotomys) mimomiformis* Suchov from the Simbugino Fauna near Ufa, Bashkir A.S.S.R., Moldavian mammal age, between 4.5 and 4.0 Ma. Redrawn from Suchov (1976). B, Molar of *S. (P.) europaeus* Kowalski from the Rebelice Krolewskie I Fauna, Poland, Rebelice mammal age, between 3.7 and 2.6 Ma. Redrawn from Kowalski (1977). C, Molar of *Synaptomys (Pliotomys) mimomiformis* from the Fish Creek Fauna near Point Barrow, Alaska (USNM 264294). D, Molar of *S. (Pliotomys) rinker* Hibbard from the White Rock Fauna near Republic, Kansas, Blancan V mammal age, between 2.6 and 1.9 Ma. Redrawn from Eshelman (1975).

and 2.6 Ma old. None of these microtines are known in Holarctica before this time, and by the end of Blancan V time fully developed *Microtus* species lived both in temperate North America and in Europe, and *Predicrostonyx* had evolved into the modern genus *Dicrostonyx* in the Old World. Given these time constraints, the presence of *Lasiopodomys deceitensis* is compelling evidence for inferring an age no older than 2.1 Ma (age of first *Microtus* in the Krestovka Section) for the Cape Deceit Fauna. The primitive collared lemming makes it difficult to assign a younger age to the Cape Deceit Fauna. The climatic history of Holarctica is in complete agreement with this interpretation (Repenning, 1984), and it seems most probable that the Cape Deceit Fauna is about 2.1 Ma old, although paleomagnetic support is not available.

Zazhigin (in Sher, Gitterman, and others, 1977) has reported *Phenacomys* sp. from the Krestovka River 4 km upstream from the main exposure (fig. 2). This occurrence is not assignable with certainty to the Kutuyakh Beds of the Kolyma Lowlands (Zazhigin in Sher and others, 1979), which are between 3.4 and 2.4 Ma old. This Siberian record has not been described or illustrated,

although Zazhigin noted that it was smaller than *P. deeringsensis* and had very low dentine tracts. The new species of *Phenacomys* here described is markedly more primitive than *Phenacomys deeringsensis*.

***Phenacomys gryci* Repenning, n. sp.**

Figures 6 and 7

Type Specimen.—USNM 264295, a left lower first molar with moderate wear (fig. 6B).

Etymology.—The species is named in honor of George Gryc, who has devoted four decades of his life to the geology and paleontology of northern Alaska. The species name is pronounced “gritchi.”

Type Locality.—Fish Creek Fauna near Harrison Bay, Alaska. Gubik Formation of Pliocene to Holocene age.

Diagnosis.—A species of *Phenacomys* with only two accessory triangles in the anteroconid complex of the first lower molar, the lingual one broadly confluent with the highly variable anteroconid cap and the buccal one preserving a “*Mimomys* Kante” on the occlusal pattern

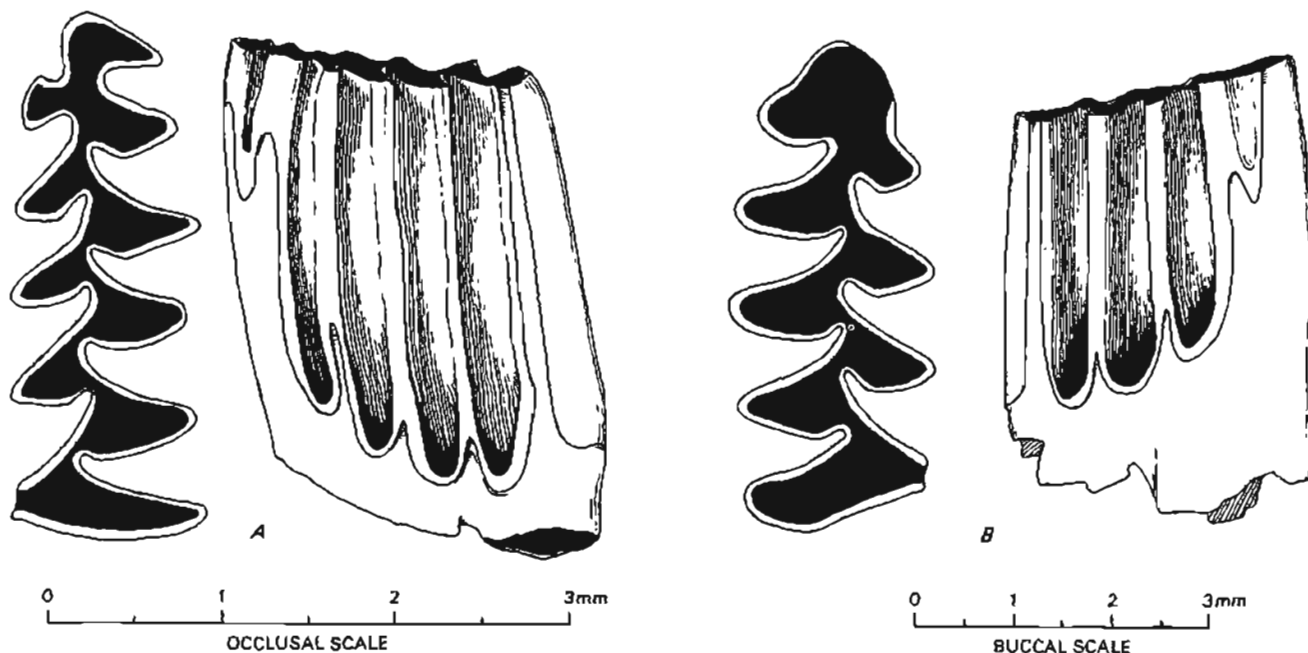


Figure 5. First lower molars of *Phenacomys deeringensis* from the Cape Deceit Fauna, Seward Peninsula, Alaska, showing variability of occlusal pattern with wear. *A*, UA 768, a little-worn left molar. *B*, UA 777, a moderately worn right molar. Individual variability occurs mainly in depth of wear required to reach a particular occlusal pattern. Note higher dentine tracts, greater occlusal pattern complexity with very little wear, and greater hypsodonty in comparison with *Phenacomys gryci* (fig. 6). Enamel pattern is essentially identical to that of living *Phenacomys intermedius* but tooth size is significantly greater and the pattern of little-worn teeth is modified with significantly less wear. The Cape Deceit Fauna is about 2.1 Ma old. Buccal views shown at a different scale than are occlusal views.

in all but the least worn specimens (fig. 6); dentine tracts very short. Anteroposterior length of the first lower molars between 2.5 and 2.8 mm.

Discussion.—This species is strikingly more primitive than *Phenacomys deeringensis* in having only two accessory triangles in the anteroconid complex in all stages of wear, in retention of the “*Mimomys Kante*” in nearly all stages of wear except in nearly unworn first lower molars, and in having very low dentine tracts. In these respects, *Phenacomys gryci* broadens the diagnosis of the genus to that given above. The teeth are lower crowned and smaller than in *P. deeringensis*, being about the size as in living *Phenacomys intermedius*.

The “*Mimomys Kante*” is a relict of a structure of the anteroconid complex in primitive *Mimomys* species; it is preserved in most advanced species and derived lineages on the first accessory triangle on the buccal side of the anteroconid complex of the first lower molar. The “*Mimomys Kante*” is universally present in *Phenacomys gryci*, noted on only one specimen of *Phenacomys deeringensis*, and has not been observed in fossil or living *Phenacomys intermedius* or *P. longicaudus*.

The anteroconid complex of living *Phenacomys intermedius* has four accessory triangles with about half or less wear and *Phenacomys deeringensis* has four accessory triangles with about one third or less wear, but only two

accessory triangles are present in the anteroconid complex of *Phenacomys gryci* in the least worn (essentially unworn) first lower molars available for examination. Except in an essentially unworn condition (fig. 7), the anteroconid complex of *Cromeromys* has no accessory triangles clearly separated from the rest of the complex. The lesser dentine-tract height in *P. gryci* is obvious. However, the buccal location of the commissures between the posterior loop and the three basic triangles is clearly evident in the first lower molars (fig. 6) and the last upper molars (fig. 7) of all species of *Phenacomys*, unlike the basic pattern of *Cromeromys* (fig. 7). These trends suggest that the ancestry of *Phenacomys* lies in an unknown earlier form of the extinct Siberian genus *Cromeromys*.

Genus *Cromeromys* Zazhigin

Type Species.—*Cromeromys irtyshensis* Zazhigin (1980). *Cromeromys* was discussed earlier in several reports by Zazhigin and by Gromov and Polyakov (1977).

Range.—*Cromeromys* has been found in faunas ranging from Siberian Beringia to Kazakh S.S.R. The generic name is based upon *Mimomys intermedius* Newton (= *Mimomys savini* Hinton) from the Cromerian of England, and the genus thus has a wide distribution

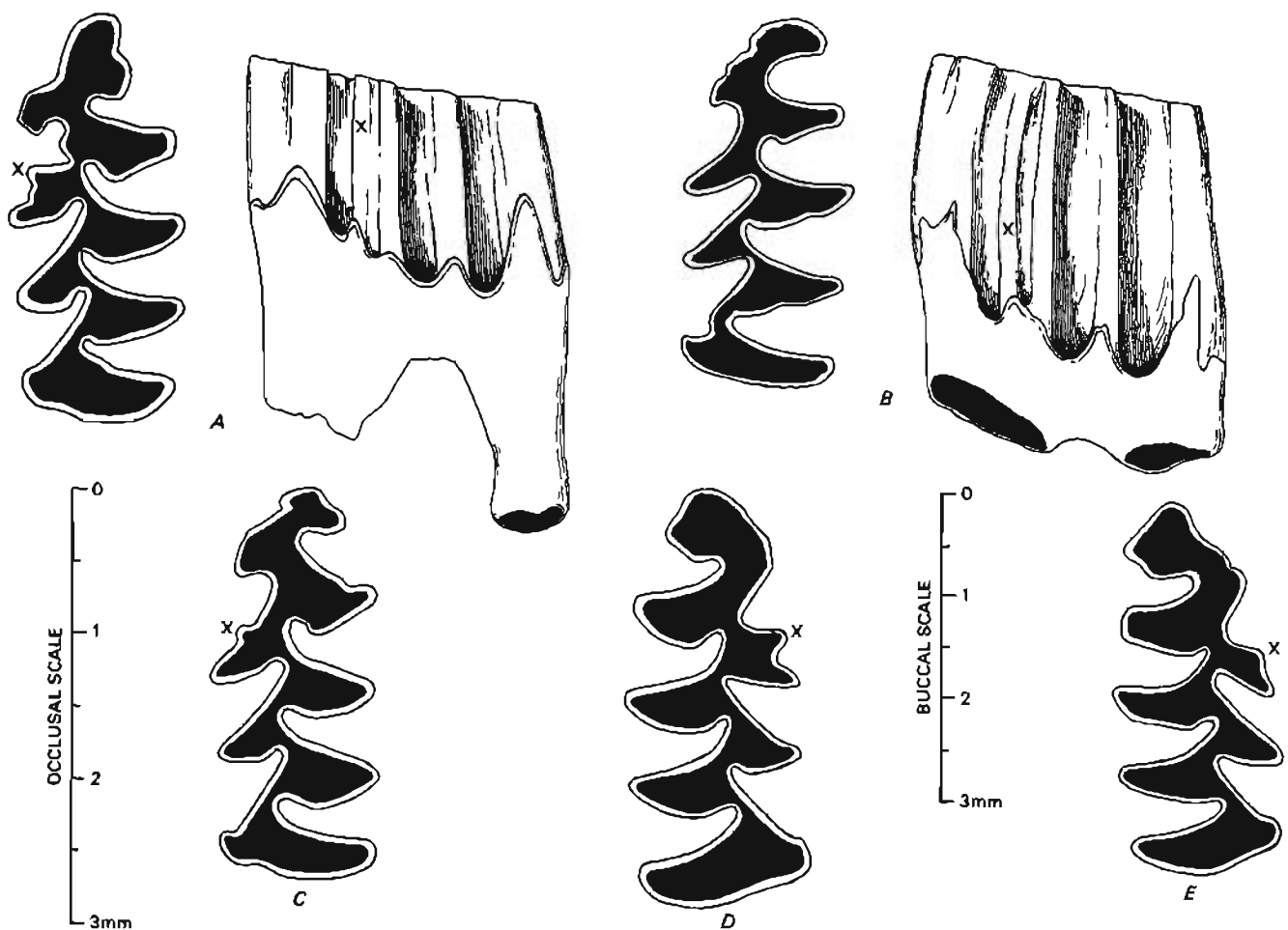


Figure 6. First lower molars of *Phenacomys gryci* from the Fish Creek Fauna showing individual variability and variability with wear of the occlusal pattern. In relative order of increasing wear, specimens rank B, C, A, D, and E. Note strong tendency for elongation of lingual alternating triangles, and low dentine tracts on buccal side of teeth. A, Occlusal and buccal aspects of USNM 264296. B, Occlusal and buccal aspects of the type specimen, USNM 264295. C-E, Occlusal aspects of USNM 264297, 264298, and 264299, respectively. Buccal views shown at a different scale than occlusal views. "*Mimomys Kante*" located by X.

in Europe, although it is not generally recognized by European workers.

Diagnosis.—*Cromeromys* is an arvicoline microtine rodent distinguished from other lineages of *Mimomys*, from which it is obviously derived, by the early loss of an enamel islet in the anteroconid complex of the first lower molar; by the loss of a similar islet in the last upper molar, which instead has two well-developed reentrants on both buccal and lingual sides; by the early development of cementum deposited in the reentrant angles of the cheek teeth; by the retention of the "*Mimomys Kante*"; and by the lack of development of any clearly pinched-off accessory triangles on the anteroconid complex. In addition, the last upper molars do not have a posteriorly elongate posterior loop with or without an enamel islet. Many of these characters are found in other lineages derived from or included in the genus *Mimomys*, but these other lineages differ in that these characters develop at

a much later date than in *Cromeromys*. Thus, *Cromeromys* is a lineage that developed all of these relatively advanced features at an earlier period in history than did those lineages retained in the genus *Mimomys*; the consistency of these progressive features demonstrates a clear-cut divergence of this genus from the main evolutionary line of *Mimomys*. The commissures of the posterior loop and the three basic triangles of the first lower molar and the last upper molar are located along the sagittal midline of these teeth, and the anteroconid complex includes no well-separated accessory triangles, in contrast with *Phenacomys*.

Discussion.—Interestingly, these precocious features in *Cromeromys* (except the development of cementum) also characterize many North American species of the genus *Mimomys* and, until recently, have been the reason for not recognizing *Mimomys* in North America; the genera *Cosomys*, *Ophiomys*, and *Ogmodontomys* have

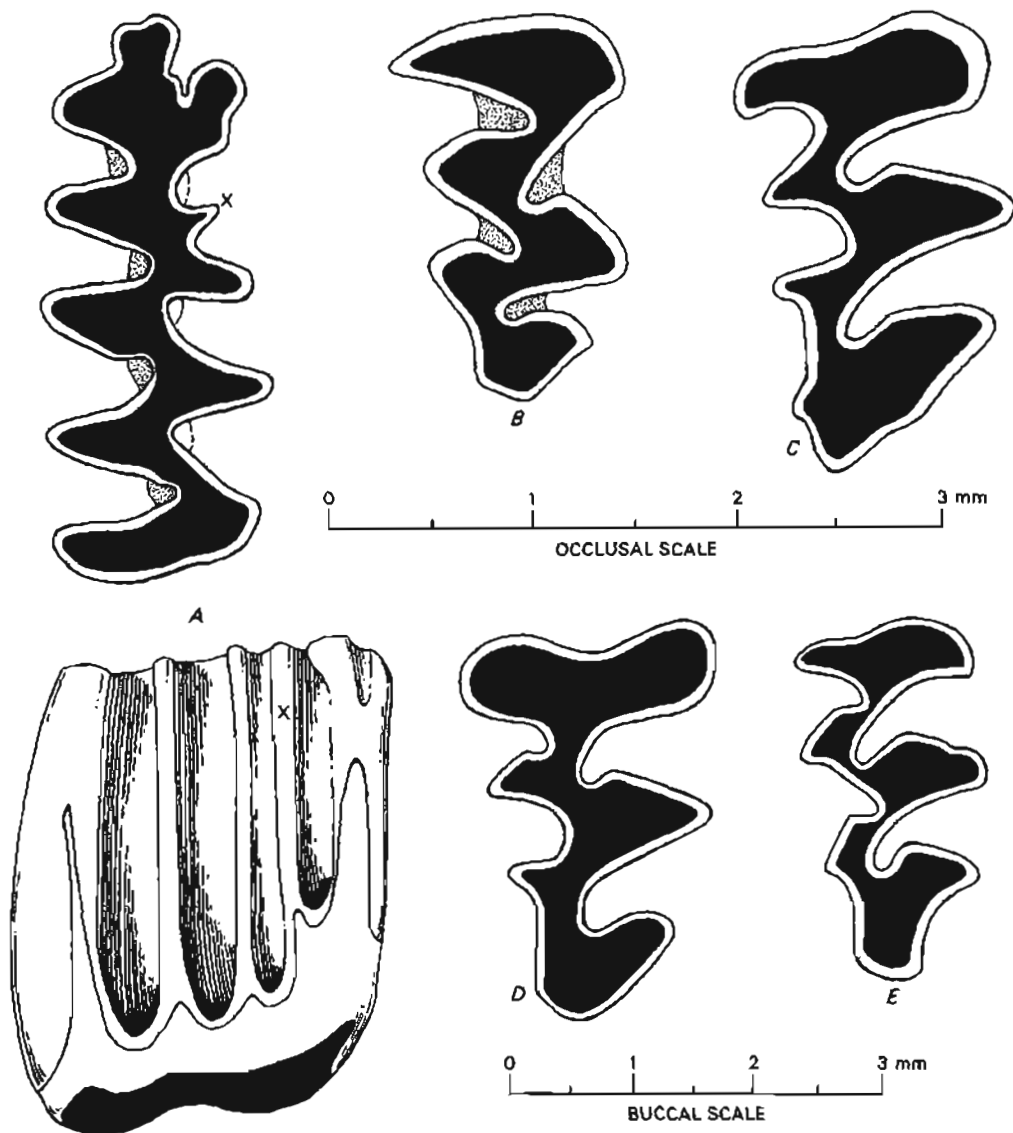


Figure 7. Cheek teeth of *Cromeromys* and *Phenacomys*. A, Little-worn right first lower molar of *Cromeromys* ex gr. *intermedius* from the Beteke Fauna southwest of Petropavlovsk, Kazakh S.S.R., in occlusal and buccal aspects; between 3.7 and 4.2 Ma old. B-E, Right last upper molars. B, *Cromeromys* sp. from the Kartashovo Fauna along the Irtysh River northeast of Omsk, U.S.S.R.; Beteke age. C, *Phenacomys gryci* from the Fish Creek Fauna (USNM 264300). D, *Phenacomys deer-ingensis* from the Cape Deceit Fauna, Seward Peninsula, Alaska; 2.1 Ma old. E, *Phenacomys intermedius* from Glacier National Park, Montana; modern. A and B redrawn from Zazhigin (1980) and D, from Guthrie and Matthews (1971); their scale is only approximate. Note that earliest known representatives of *Cromeromys* already possess some cementum in reentrant angles and that dentine tract development is greater than in *Phenacomys gryci* (fig. 6). "Mimomys Kante" of *Cromeromys* located by X.

been used instead. However, the earliest forms of *Mimomys* in North America [*M. (Ophiomys) mcknighti* (Gustafson) and *M. (Cosomys) sawrockensis* (Hibbard)] do have the enamel islets and a *Mimomys*-like last upper molar. These features were lost early in the North American history of the genus, and they cannot be derived

from the Eurasian genus *Cromeromys*. *Cromeromys* conceivably derives from the North American *Mimomys* lineage.

Except for the central commissures between the dentine fields, the lack of accessory triangles in the anteroconid complex, and the presence of cementum only

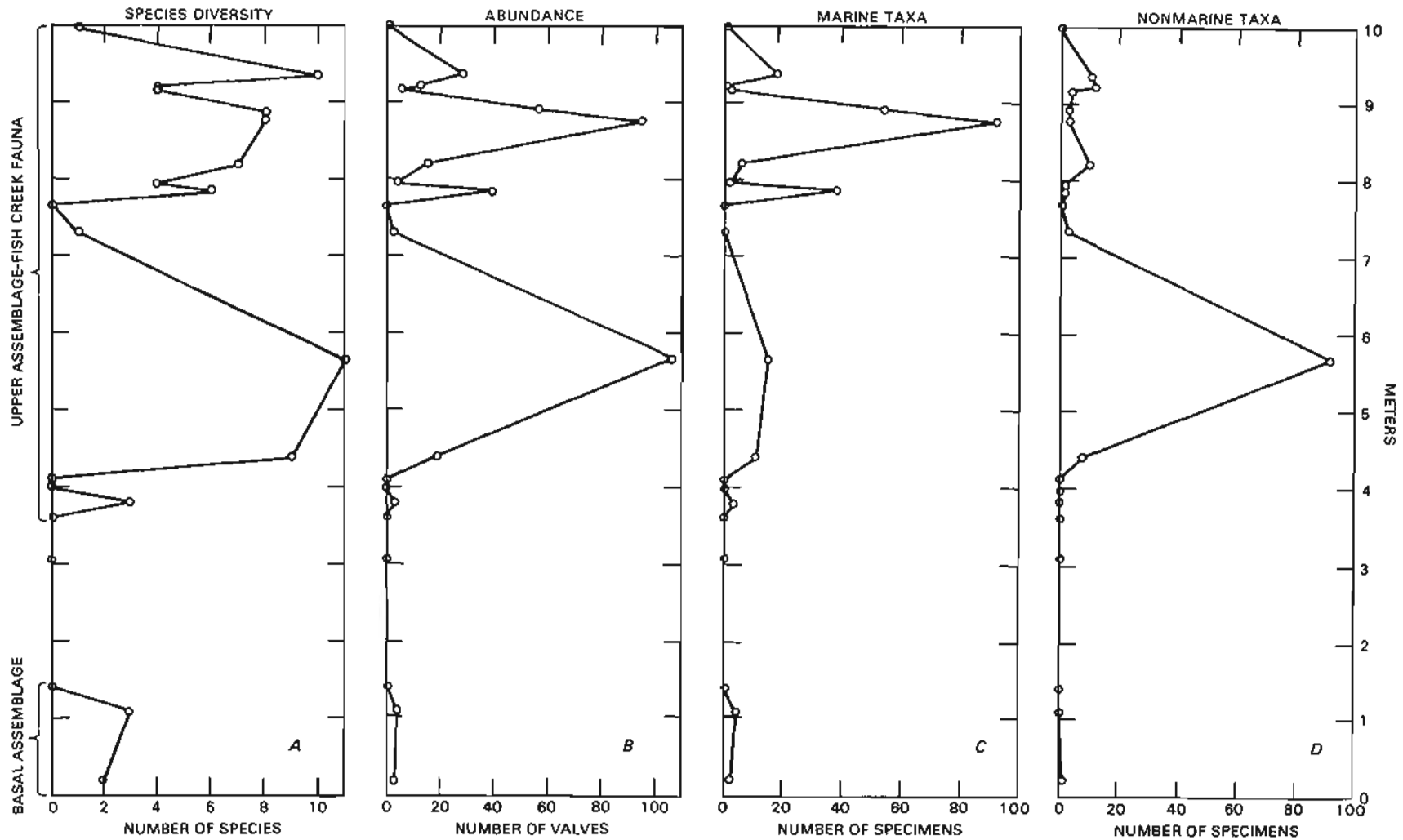


Figure 8. Plot of ostracode abundance and species diversity in the Fish Creek section. *A*, Species diversity. *B*, Total abundance of specimens, shown in number of valves; adults and juveniles have been combined. *C*, Abundance of specimens of marine taxa, shown in number of valves. *D*, Abundance of specimens of non-marine taxa, shown in number of valves.

in *Cromeromys*, the genus would conform to the diagnosis of *Phenacomys* given here. The first two are primitive characters, suggesting that *Cromeromys* was ancestral to *Phenacomys*. The presence of cementum in *Cromeromys*, although rudimentary in the earliest known form (fig. 7), suggests that the divergence of *Phenacomys* (which lacks cementum) from *Cromeromys* took place earlier than the oldest known record of *Cromeromys*, between 3.7 and 4.2 Ma old. In addition, *Phenacomys gryci* has less progressive dentine tract development than the earliest known *Cromeromys* (figs. 6, 7), further suggesting a branching of *Phenacomys* from *Cromeromys* at an early date.

Thus, the inferred phylogeny of *Phenacomys* began with an origin, more than 4 million years ago, from a notably progressive branch of *Mimomys*, called *Cromeromys*, by development of an almost static rate of evolution of those primitive characters retained in the *Phenacomys* lineage. Living *Phenacomys* still has not developed rootless teeth or cementum; *Phenacomys gryci*, although clearly younger, has dentine tracts that approximate those of *Mimomys* of about 4 to 4.5 Ma ago, and the genus still retains today an upper last molar that is like that of *Cromeromys*. In contrast, *Phenacomys* has progressively increased the number of alternating triangles in the anteroconid complex of the first lower molar, unlike *Cromeromys* and some living descendants of *Mimomys*, as, *Arvicola*. *Arvicola* itself may have derived from *Cromeromys intermedius* (equals *Mimomys savini*) as recently as 400,000 years ago.

OSTRACODES OF THE FISH CREEK SECTION

Marine and nonmarine ostracodes from the Fish Creek sediments (pl. 1) can be divided into two distinct assemblages that differ from each other in age and in environment of deposition. A basal assemblage is present in the lowest meter of the 4-m-thick lower silt unit, and an upper assemblage (the Fish Creek Fauna) is present in the upper 0.3 m of the lower silt unit and throughout the medial sand unit and into the upper unit (figs. 3, 8; table 2). These two assemblages are separated by 2 m of the lower silt unit from which no ostracodes have been recovered.

Basal Assemblage

The basal ostracode assemblage contains three marine taxa, *Pterygocythereis* n. sp., *Loxoconcha venepidermoidea* Swain, and *Paracyprideis pseudopunctillata* Swain, and one nonmarine species, *Cytherissa lacustris* (Sars) (table 1). Specimen abundance is low (fig. 8B), consisting of two adults and four juveniles, all very well preserved; the small number of specimens indicates that reworking cannot be totally ruled out. *Pterygocythereis* n.

sp. is an unusual, highly distinctive taxon with no known occurrence in Pleistocene North Slope sediments or in modern shelf environments of the Arctic circumpolar region. The species is an extinct one that occurs only in older sediments of the Arctic Ocean. *Pterygocythereis* n. sp. has recently been identified from a small number of sites in the eastern coastal plain of Alaska. It occurs at these sites exclusively as an element of a deeper water fauna (middle to outer shelf), which is composed of taxa known previously only from the northeast Atlantic. *Pterygocythereis* n. sp. also has been found recently at several localities near Harrison Bay (fig. 9A) in a distinctive assemblage consisting of *Rabilimis paramirabilis* and a large number of extinct *Cytheropteron* and cytherideid species. *Rabilimis paramirabilis* has been identified from 18 m depth in a shothole at Fish Creek (Swain, 1963) that is geographically very close to the locality that we report on herein (fig. 9A).

Pterygocythereis n. sp. is known from deposits at least as old as the presumed middle Miocene-lower Pliocene Nuwok Member of the Sagavanirktok Formation of the Marsh anticline (Barter Island and Manning Point) to the east (fig. 1), where it recently has been found. The co-occurrence (fig. 10) of *Pterygocythereis* n. sp. with *Rabilimis paramirabilis* at localities near Fish Creek is the principal argument for an age less than 3 Ma for the basal *Pterygocythereis* assemblage at Fish Creek. *Rabilimis* is closely related to *Echinocythereis* based on valve shape, hinge type, muscle scar arrangement, and ornamentation, but *Rabilimis* is larger than any known species of *Echinocythereis*, with no intermediate forms known. *Rabilimis* is thought to have arisen from the *Echinocythereis* stock of the North Atlantic Ocean (fig. 11) in the late Pliocene (J.E. Hazel, oral commun., 1985). The oldest known *Rabilimis* species is *R. paramirabilis* (Swain, 1963), first identified from sediments in shotholes taken in the central and western Arctic Coastal Plain. Hazel (written commun., 1968) identified *R. paramirabilis* in dredge and core sediments from the Seward Peninsula (fig. 2); these sediments have been defined as Beringian by Hopkins (1967), and are between 3 Ma (opening of Bering Strait) and 2.48 Ma (Gauss-Matuyama boundary) old. Hazel (1967, p. 38) mentioned the modern occurrence of *Rabilimis paramirabilis* off Point Barrow. However, Hazel (oral and written commun., 1985) has pointed out that this occurrence was the result of a clerical error on a checklist prepared during study for the 1967 paper. *Rabilimis paramirabilis* apparently evolved in the Alaskan region, as the species has not been recorded elsewhere.

Rabilimis paramirabilis, thought to have evolved directly from *Echinocythereis*, is the ancestral species in the *Rabilimis* lineage (figs. 10, 11), and gave rise to *Rabilimis septentrionalis* and *Rabilimis mirabilis* in post-Beringian time. *Rabilimis septentrionalis* is known back to Anvilian time (about 2.2 Ma; Brouwers and others,

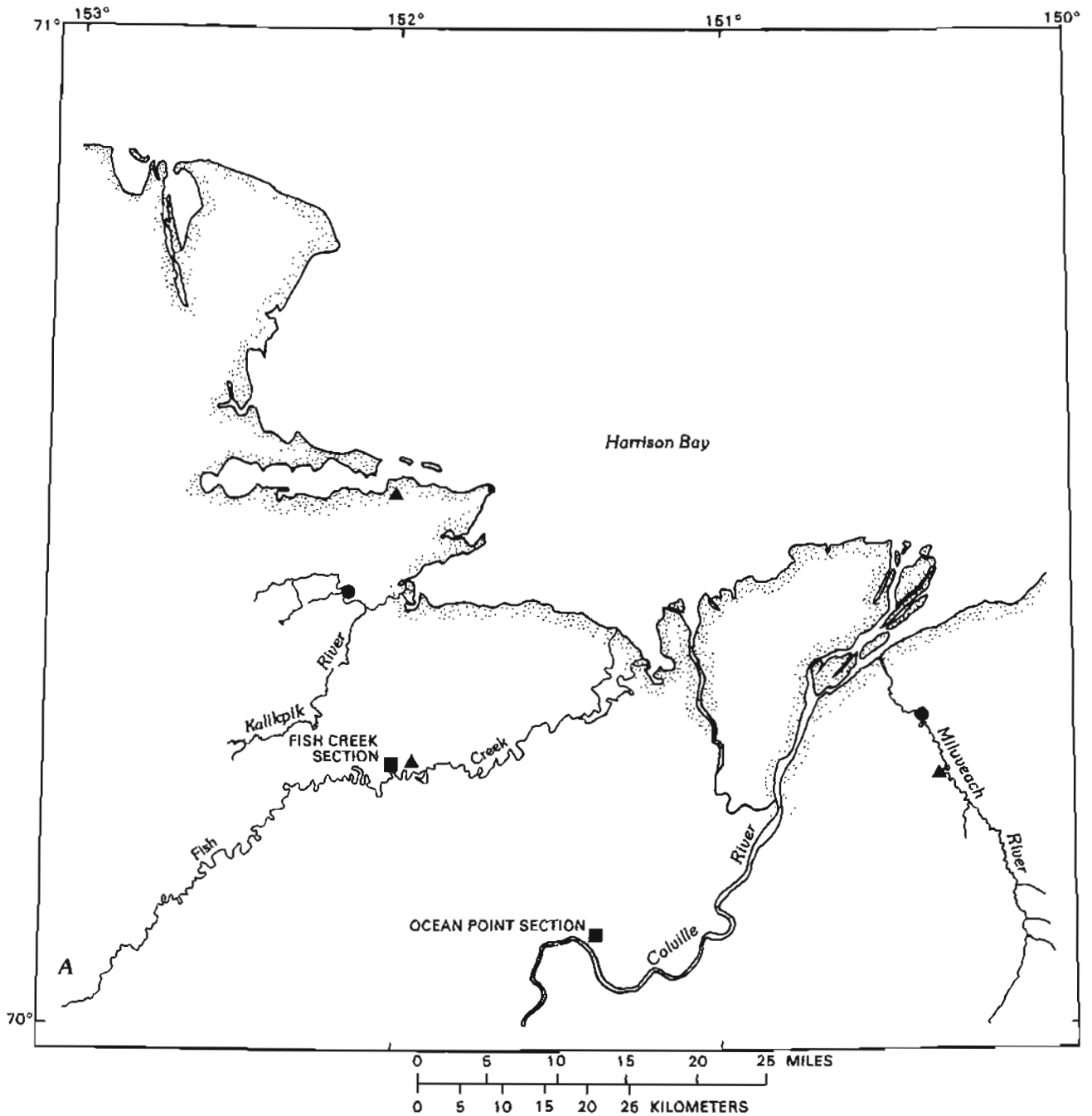
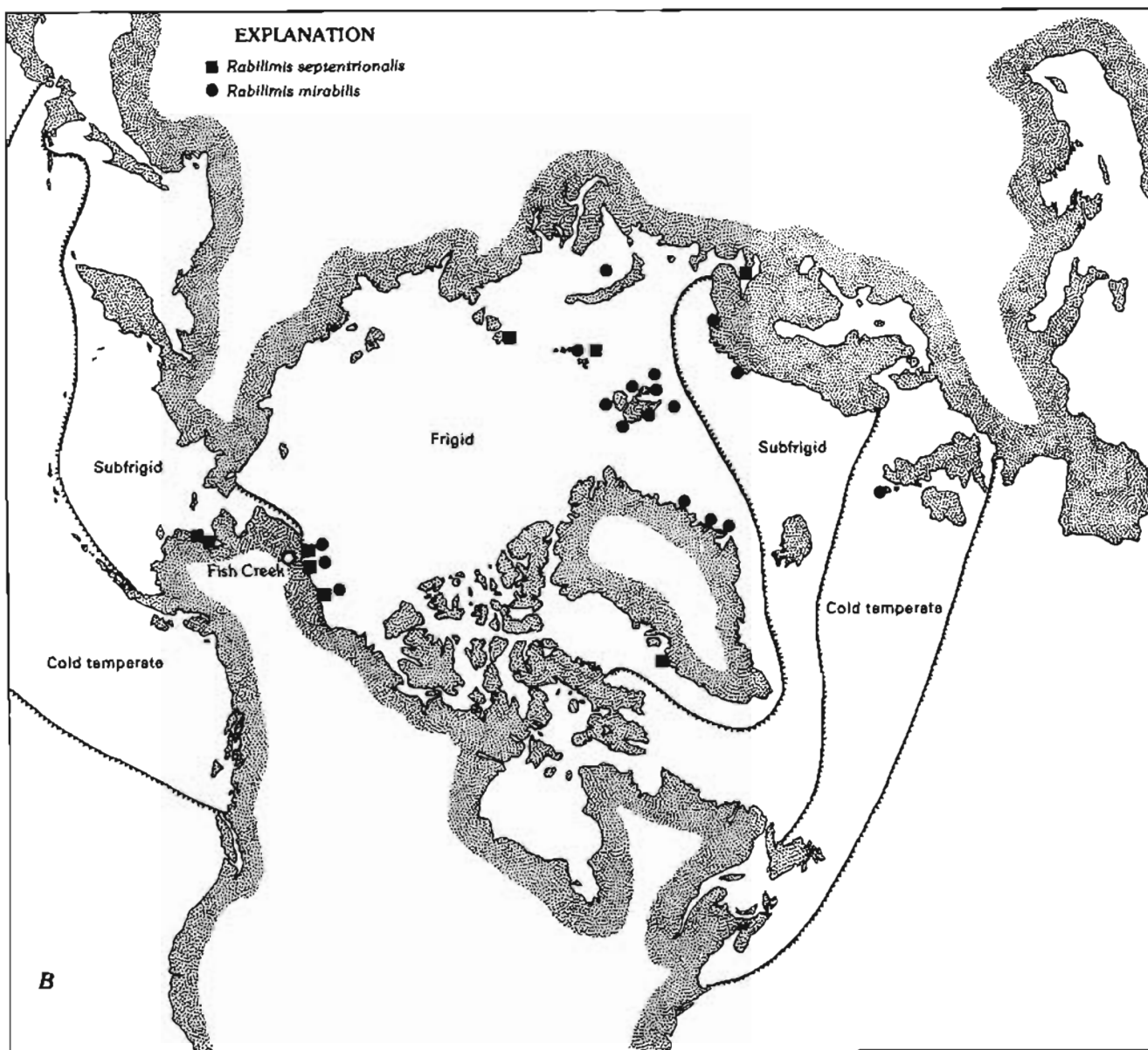


Figure 9 (above and facing page). Localities and zoogeographic distribution of *Pterygocythereis* n.sp. and *Rabilimis* species used for this study. A, Localities of Gubik Formation in vicinity of Fish Creek in which older assemblages of ostracodes have been identified. Circle, locality in which both *Pterygocythereis* n. sp. and *Rabilimis paramirabilis* were identified. Triangle, locality in which only *Rabilimis paramirabilis* was identified. Square, Fish Creek section in which only *Pterygocythereis* n. sp. was identified, and Ocean Point section. Ocean Point section contains no distinctive ostracodes; the few taxa present represent long-ranging shallow-water forms. B, Modern zoogeographic distribution of the two living *Rabilimis* species. *R. mirabilis* prefers middle to outer sublittoral water depths, and occurs in cold temperate to frigid marine climates. *R. septentrionalis* is a shallow-water form, preferring inner sublittoral environment; occurs predominantly in the frigid marine climate, although also present in subfrigid marine climate of Norton Sound. Data from Hazel (1970) and Neale and Howe (1975).



1984), being present in all the Gubik transgressive cycles except the Beringian. There is one possible exception along the Colville River south of Ocean Point at LDC locality 78 ACr 113, where several specimens of *Rabilimis septentrionalis* are found in sediments for which an older amino acid ratio has been determined. In addition, geomorphic and depositional relationships appear to indicate an older age (Carter and Brigham-Grette, in press). At present evidence is insufficient to explain the apparent discrepancy. *Rabilimis mirabilis* is known back to Kotzebuan time (possibly 240,000 years ago, Brouwers and others, 1984), occurring predominantly in upper Pleistocene sediments in Alaska. *Rabilimis mirabilis* is a deeper water form (greater than 20 m, middle to outer shelf), and most of

the onshore Gubik Formation represents shallow, inner sublittoral water depths; therefore, any earlier Pleistocene occurrences of *Rabilimis mirabilis* are likely to be preserved in offshore sediments. The modern distribution of *Rabilimis* is shown in figure 9B and that of *Echinocythereis* in figure 12A.

The most convincing argument in support of the *Rabilimis* lineage is seen in the adductor muscle scar pattern (fig. 11). Hazel (1967) demonstrated the taxonomic stability and utility of the frontal and adductor scar pattern in hemicytherid and trachyleberid ostracode genera, and showed that the pattern tends to become more complex through time within a lineage. The lineage of *Echinocythereis* - *Rabilimis paramirabilis* - *Rabilimis*

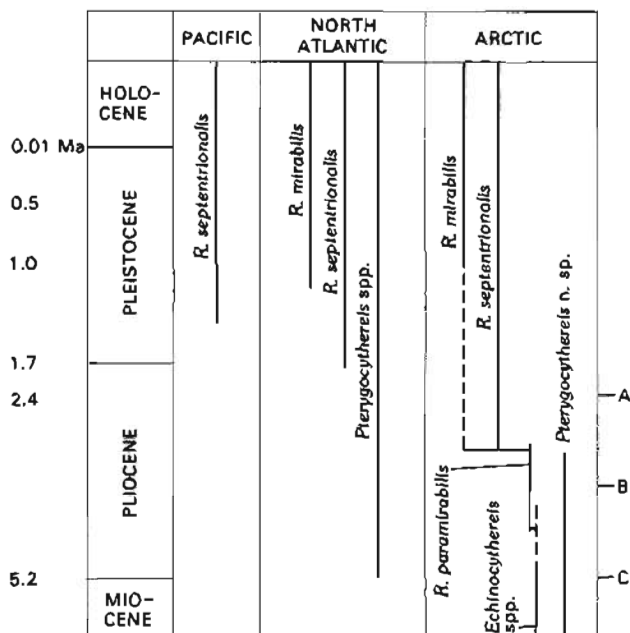


Figure 10. Stratigraphic range of the three *Rabilimis* species in Pacific (Norton Sound), North Atlantic, and Arctic Oceans. Known Neogene stratigraphic range of *Pterygocythereis* in North Atlantic and Arctic Oceans is also plotted. Dashed portion of a range, uncertainty in exact time of origin of the taxon. A Approximate position of Fish Creek Fauna (upper ostracode assemblage). B Approximate position of lower ostracode assemblage in Fish Creek section. C Approximate position of Marsh Creek anticline ostracode assemblage.

septentrionalis shows the two median adductor scars splitting from two to three to four scars, respectively. *Rabilimis mirabilis* maintains a more conservative pattern by retaining only three median scars.

The presence of *Pterygocythereis* n. sp. is also important for understanding the paleoenvironment, which indirectly provides information about the age range of the basal assemblage. *Pterygocythereis* ranges from the Paleocene through the Holocene, occurring commonly throughout the subtropical and temperate northern Atlantic Ocean and rarely in the subfrigid Norwegian Sea (fig. 12B). In the northwestern Atlantic Ocean, *Pterygocythereis* occurs in the southern part of the cold temperate zone, but apparently does not live in the northern cold-temperate or subfrigid zones of the western North Atlantic (fig. 12B). *Pterygocythereis* n. sp. is related to European forms of the genus and not to the more temperate northwest Atlantic *P. americana* - *P. inexpectata* lineage. The presence of *Pterygocythereis* suggests that warmer conditions existed during deposition of the lower Fish Creek assemblage than the modern frigid temperatures that are present today.

Upper Assemblage—The Fish Creek Fauna

The upper ostracode assemblage, part of the Fish Creek Fauna, is much more diverse and abundant than the basal assemblage (table 1; fig. 8A, B). Eleven marine species and six nonmarine species occur in the nearly 6 m that include the uppermost part of the lower silt unit, the marine/estuarine medial sand unit, and part of the upper silt unit of the Fish Creek section (fig. 3). Diversity and abundance have three distinct peaks at 5.75 m, 7.7 m, and 8.8 m above the base of the exposure (samples 84-EB-178, -180, and -183, respectively). The peak at 5.75 m contains a mixture of marine and nonmarine taxa, with the nonmarine species dominating in abundance. The sample at 5.75 m is dominated by eurytopic shallow marine to marginal marine taxa. The ostracode composition and the known modern tolerances of the individual species support the interpretation of a tidal channel setting with associated estuarine and nearshore marine deposits as suggested by the sedimentary structures. The peaks at 7.7 m and 8.8 m correspond to the two upper shell beds (fig. 3); the upper of these shell beds is the source of the microtine remains. The ostracode assemblages in the shell beds are dominantly marine (fig. 8C), consisting of well-preserved, intact valves. The shell beds are composed of concentrations of mollusks, detrital wood, and gray sand. Most of the ostracode species are represented by adults, but some juveniles are also present, suggesting a small amount of differential transport and (or) destruction of juveniles versus adults. The ostracode species composition in the shell beds suggests a nearshore, predominantly marine environment, such as a beach or bar.

The nature of the marine environment indicated by the upper assemblage (the Fish Creek Fauna) is considerably different from that of the basal assemblage. The upper assemblage taxa are indistinguishable from a modern Arctic Ocean assemblage, containing mostly extant species characteristic of frigid to subfrigid marine temperatures. *Rabilimis septentrionalis* (Brady), *Loxiconcha venepidermoidea* Swain, and *Cytheretta teshepkukensis* Swain do not live south of Norton Sound (fig. 2) today.

The age of the upper ostracode assemblage can be constrained by the presence of *R. septentrionalis*, which implies a post-Beringian age. The taxa present thus range from the late Pliocene through the Holocene.

MOLLUSKS OF THE FISH CREEK FAUNA

Late Cenozoic mollusks in the Fish Creek Fauna (table 2) show clearly that these deposits were formed after the opening of Bering Strait. All but one of the species is extant, and the sum of their modern distributions

Table 1. Ostracode species present at Fish Creek

Samples -----	Lower assemblage		Upper assemblage (Fish Creek fauna)											
	171	172	60a	60b	178	60f	180	181	60c	183	184	182	185	186
Marine taxa														
<i>Pterygocythereis</i> n. sp -----	X	X	--	--	--	--	--	--	--	--	--	--	--	--
<i>Loxococoncha venepidermoidea</i> ----	--	X	X	--	--	--	--	--	--	X	X	--	--	--
<i>Paracyprideis pseudopunctillata</i> ---	--	X	--	X	X	--	X	--	X	X	X	--	X	--
<i>Cytheromorpha macchesneyi</i> -----	--	--	X	--	--	--	--	--	--	--	--	X	--	--
<i>Cytheropteron montrosiense</i> -----	--	--	X	--	--	--	--	--	--	--	--	--	--	--
<i>Cytheretta teshekpukensis</i> -----	--	--	--	X	X	--	X	--	X	X	X	--	--	--
<i>Heterocyprideis sorbyana</i> -----	--	--	--	X	X	--	X	--	--	X	X	--	X	--
<i>Normanicythere leioderma</i> -----	--	--	--	X	--	--	--	--	--	--	--	--	--	--
<i>Rabilimis septentrionalis</i> -----	--	--	--	X	X	--	X	X	X	X	X	--	X	X
<i>Sarsicytheridea bradii</i> -----	--	--	--	X	X	--	--	--	X	--	--	--	--	--
<i>Cytheropteron pyramidale</i> -----	--	--	--	--	X	--	--	X	--	--	--	--	X	--
<i>Sarsicytheridea punctillata</i> -----	--	--	--	--	X	--	--	--	--	X	--	--	--	--
<i>Robertsonites tuberculata</i> -----	--	--	--	--	--	--	X	--	--	X	--	X	--	--
<i>Acanthocythereis dunelmensis</i> ----	--	--	--	--	--	--	--	--	--	--	--	--	X	--
Nonmarine taxa														
<i>Cytherissa lacustris</i> -----	X	--	--	X	X	X	--	X	X	X	--	X	X	--
<i>Limnocythere</i> spp -----	--	--	--	X	X	--	--	--	X	--	X	X	X	--
<i>Candona</i> spp -----	--	--	--	X	X	--	X	X	X	--	X	X	X	--
Cyprid -----	--	--	--	--	X	--	X	--	--	--	X	--	--	--

indicates a marine climate warmer than now occurs in northern Alaska. Further, the mollusks lived in shallow water, at or very close to shoreline.

Among the 43 species-level molluscan taxa present at Fish Creek (table 2), 22 (51 percent) have their earliest stratigraphic records in the Pacific, 3 (7 percent) occurred first in the Atlantic, and 18 (42 percent) have histories too poorly known to show provenance. If the Bering Strait had not yet been opened when the Fish Creek strata were laid down, half of the known molluscan fauna would be absent. Most of the Fish Creek mollusks have modern geographic ranges that extend into the Arctic Ocean. However, the bivalve *Clinocardium californiense* and the gastropods *Aforia circinata* and *Littorina squalida* now live only south of Bering Strait. In addition, the ranges of the Pacific gastropods *Admete regina*, *Liomesus ooides*, and *Neptunea beringiana* (tentatively identified here) now extend northward only to the Chukchi Sea. Because molluscan stratigraphic ranges within the Gubik Formation are not yet well documented, the molluscan fauna does not help to assign the Fish Creek deposits to a particular interval within the Gubik. The Fish Creek mollusks clearly show, however, that this fauna lived after the Late Cenozoic opening of Bering Strait that allowed Pacific species to migrate into the Arctic Ocean.

Except for the bivalve *Axinopsida orbiculata* and the extinct gastropod *Neptunea lyrata leffingwelli* (tentatively identified here), all the Fish Creek mollusks

currently range south of Bering Strait. The mollusks of the Fish Creek Fauna represent a cold-temperate to subfrigid marine climate, such as exists today in the southern Bering Sea and northern Gulf of Alaska, distinctly warmer than the modern marine climate off northern Alaska. The relatively warmer marine climate during Fish Creek time is also suggested by the presence of *Littorina squalida*, an intertidal to shallow subtidal gastropod that cannot tolerate thick accumulations of sea ice, which can occur virtually year round along the northern Alaskan coastline today. This species lives as far north as lat 65°30' N., on the western Seward Peninsula south of Bering Strait (Foster, 1981); it does so apparently by living subtidally below the relatively thin ice cover during the colder part of the year, then repopulating the intertidal zone during the warmer summer months (Joseph Rosewater, written commun., 1984). The large adult size of the Fish Creek individuals, comparable to modern *L. squalida*, suggests that they lived for several years at the Fish Creek site and did not occur there as a result of a single summer's migration. Modern littorines live for about 3 or 4 years, and it is doubtful that larger individuals could reach their full growth in a single year (Joseph Rosewater, written commun., 1984), especially in the colder northern reaches of the species' range.

The presence of abundant *L. squalida* in the Fish Creek Fauna also indicates that a shoreline was nearby, because this species lives in the intertidal and shallow

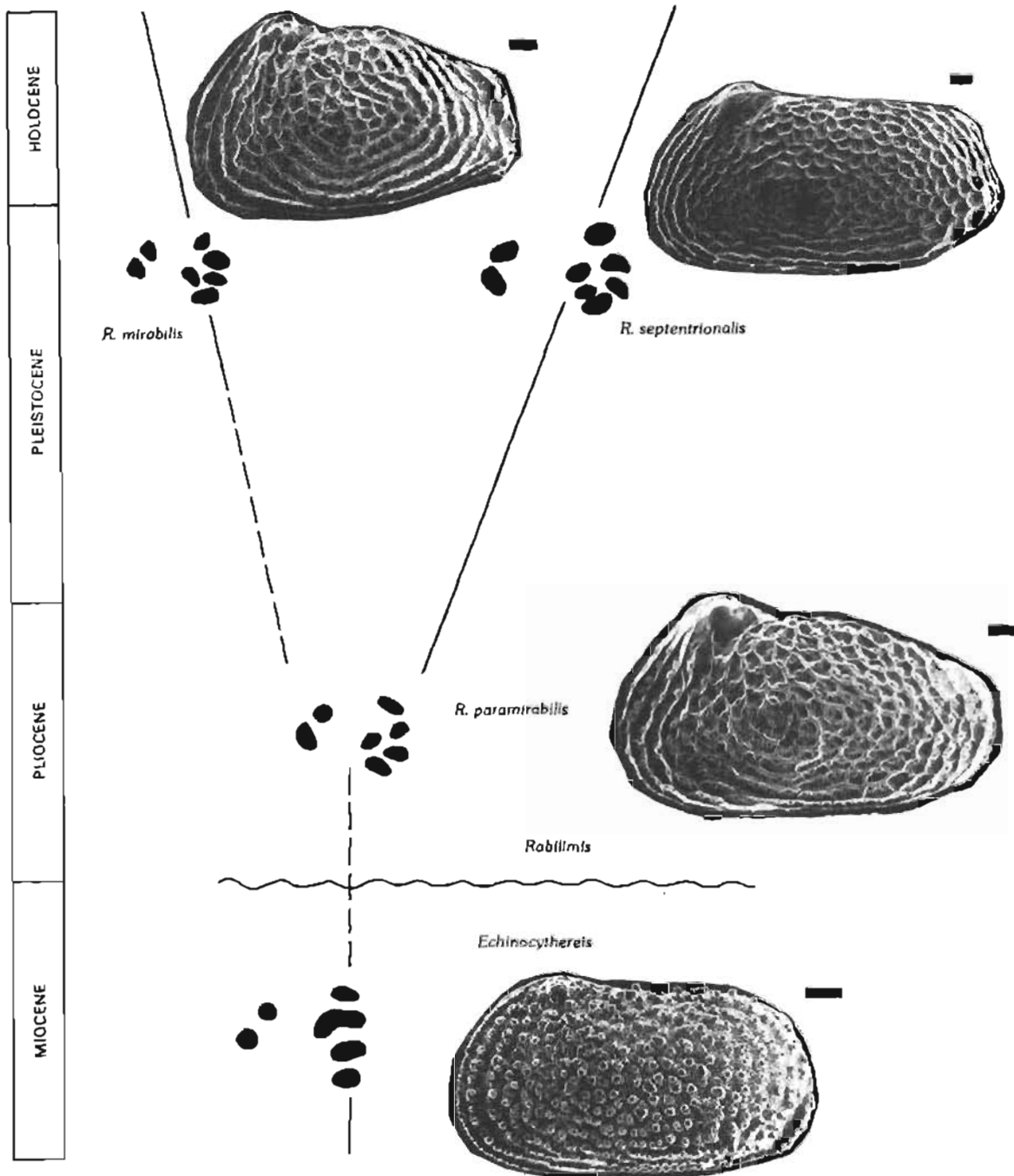


Figure 11. Sketches of adductor muscle scar pattern from right valves of *Rabilimis* and *Echinocythereis* and scanning electron micrographs illustrating lateral view of male left valves. General evolutionary trend of adductor muscle scars within ostracode lineages is for increased complexity through time (Hazel, 1967), clearly illustrated in trend of two median scars splitting from two scars in *Echinocythereis* to three scars in *Rabilimis paramirabilis*, and, finally, to four scars in *R. septentrionalis*. *R. mirabilis* is apparently more conservative, retaining three median adductor scars. Dashed lines, uncertainty in exact time of origin of taxon. Note that magnification of *Rabilimis* specimens and that of *Echinocythereis* specimen are different. *Echinocythereis* scar pattern from Hazel (1967). *Echinocythereis* specimens are from the collections of T. Cronin, USGS, Reston, Virginia. *Rabilimis* scar patterns from personal observations (EMB) and from written communication of K.G. McKenzie to J.E. Hazel (1968). Scale bar = 100 μ m.

subtidal zones. The remainder of the Fish Creek mollusks also clearly indicate a shallow marine habitat. The bivalves *Astarte borealis*, *Hiatella arctica*, *Mya truncata*, and

Serripes groenlandicus, and the gastropods *Boreotrophon pacificus* and *Plicifusus kroyeri* have their upper bathymetric limits in the intertidal zone. Further, of the 31 Fish

Table 2. Origins of Fish Creek mollusks

	Pacific	Atlantic	Unknown
Bivalves			
<i>Astarte borealis</i> (Schumacher)		X	
<i>A. esquamalti</i> (Baird)			X
<i>Axinopsida orbiculata</i> (Sars)			X
<i>Clinocardium californiense</i> (Deshayes)	X		
<i>C. ciliatum</i> (Fabricius)	X		
<i>Cyclocardia crassidens</i> (Broderip & Sowerby)			X
<i>C. crebricostata</i> (Krause)			X
<i>Cyrtodaria kurriana</i> Dunker		X	
<i>Hiatella arctica</i> (Linnaeus)			X
<i>Liocyma fluctuosa</i> (Gould)	X		
<i>Macoma</i> cf. <i>M. brota</i> Dall	X		
<i>M. balthica</i> (Linnaeus)	X		
<i>Mya truncata</i> Linnaeus	X		
<i>Nuculana radiata</i> Krause			X
<i>N.</i> cf. <i>N. minuta</i> (Fabricius)			X
<i>Serripes groenlandicus</i> (Bruguiere)	X		
<i>Yoldia myalis</i> Couthouy			X
Gastropods			
<i>Admete couthouyi</i> (Jay)	X		
<i>A. regina</i> Dall	X		
<i>Aforia circinata</i> Dall	X		
<i>Amauopsis islandica</i> (Gmelin)			X
<i>Boreotrophon clathratus</i> (Linnaeus)		X	
<i>B. pacificus</i> Dall			X
<i>B. truncatus</i> (Stroem)			X
<i>Buccinum</i> cf. <i>B. plectrum</i> Stimpson	X		
<i>B. polare</i> Gray	X		
<i>Colus pubescens</i> Verrill			X
<i>C. spitzbergensis</i> (Reeve)	X		
<i>Epitonium greenlandicum</i> (Perry)			X
<i>Liomesus ooides</i> Middendorff			X
<i>Littorina squalida</i> Broderip & Sowerby	X		
<i>Natica clausa</i> Broderip & Sowerby	X		
<i>Neptunea</i> cf. <i>N. beringiana</i> (Middendorff)	X		
<i>N.</i> cf. <i>N. lyrata leffingwelli</i> Dall	X		
<i>N. heros heros</i> (Gray)	X		
<i>Obesotoma</i> cf. <i>O. laevigata</i> (Dall)			X
<i>Oenopota</i> cf. <i>O. arctica</i> (Adams)			X
<i>Plicifusus kroyeri</i> Moeller			X
<i>Polinices pallidus</i> (Broderip & Sowerby)	X		
<i>Retusa umbilicata</i> (Montagu)			X
<i>Tachyrhynchus erosus</i> (Couthouy)	X		
<i>Trichotropis borealis</i> Sowerby	X		
<i>T. bicarinatus</i> (Sowerby)	X		

Creek mollusks with documented modern bathymetric ranges, 15 species have their shallowest occurrences in the 0-10 m range, 21 occur as shallow as the 0-20 m range, and all but two species are found in 0-50 m depths.

At Fish Creek no mollusks were seen in life orientations. All bivalves were disarticulated and most mollusks show breakage and abrasion. However, abundant

unbroken specimens of extremely delicate species such as *Axinopsida orbiculata* and *Refusa umbilicata* suggest that the post mortem transport of the mollusks was not extensive. Redeposition of the mollusks is likely to have occurred shortly after death by waves or currents, instead of by reworking of specimens preserved in an earlier Gubik transgressive deposit.

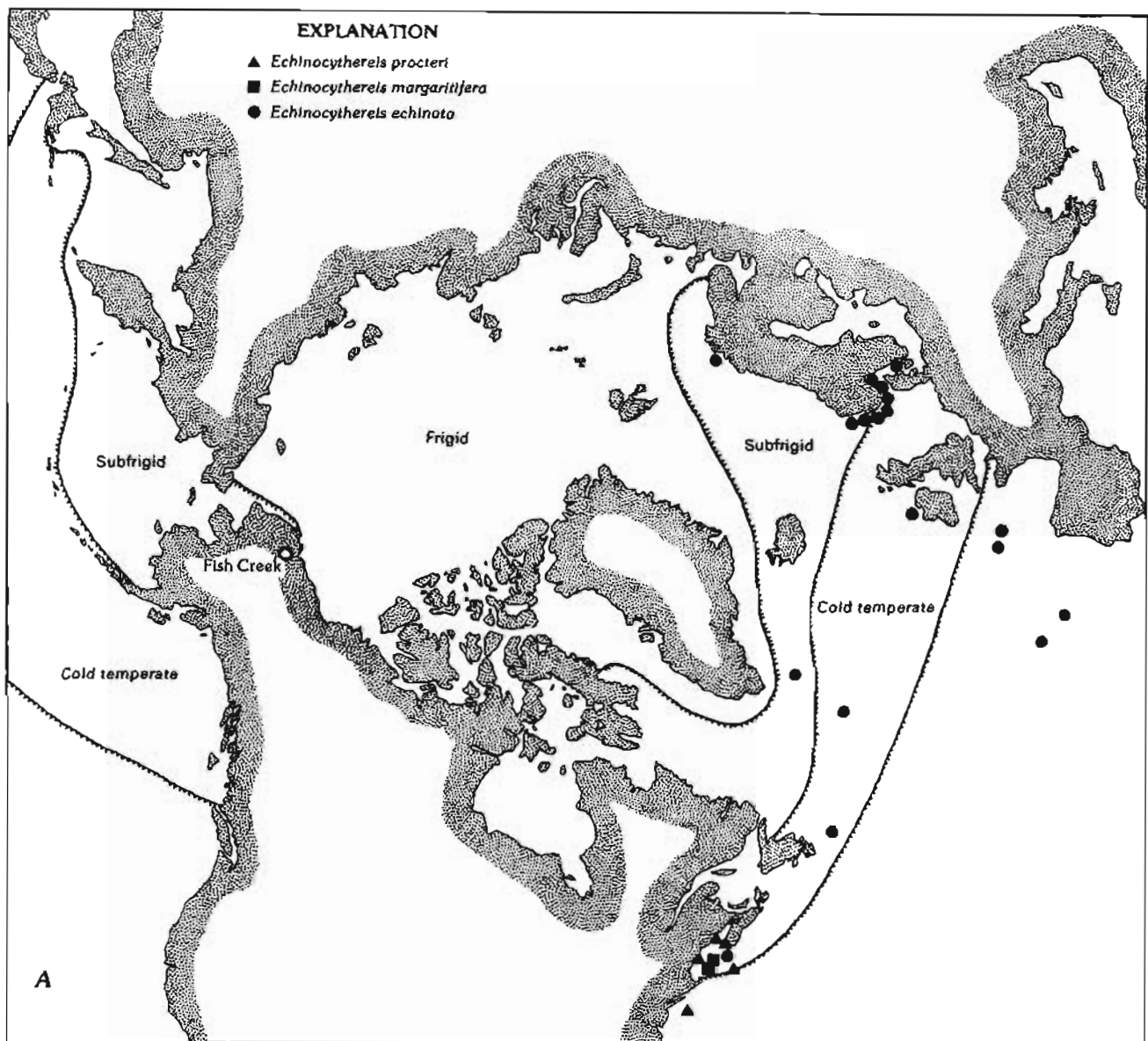
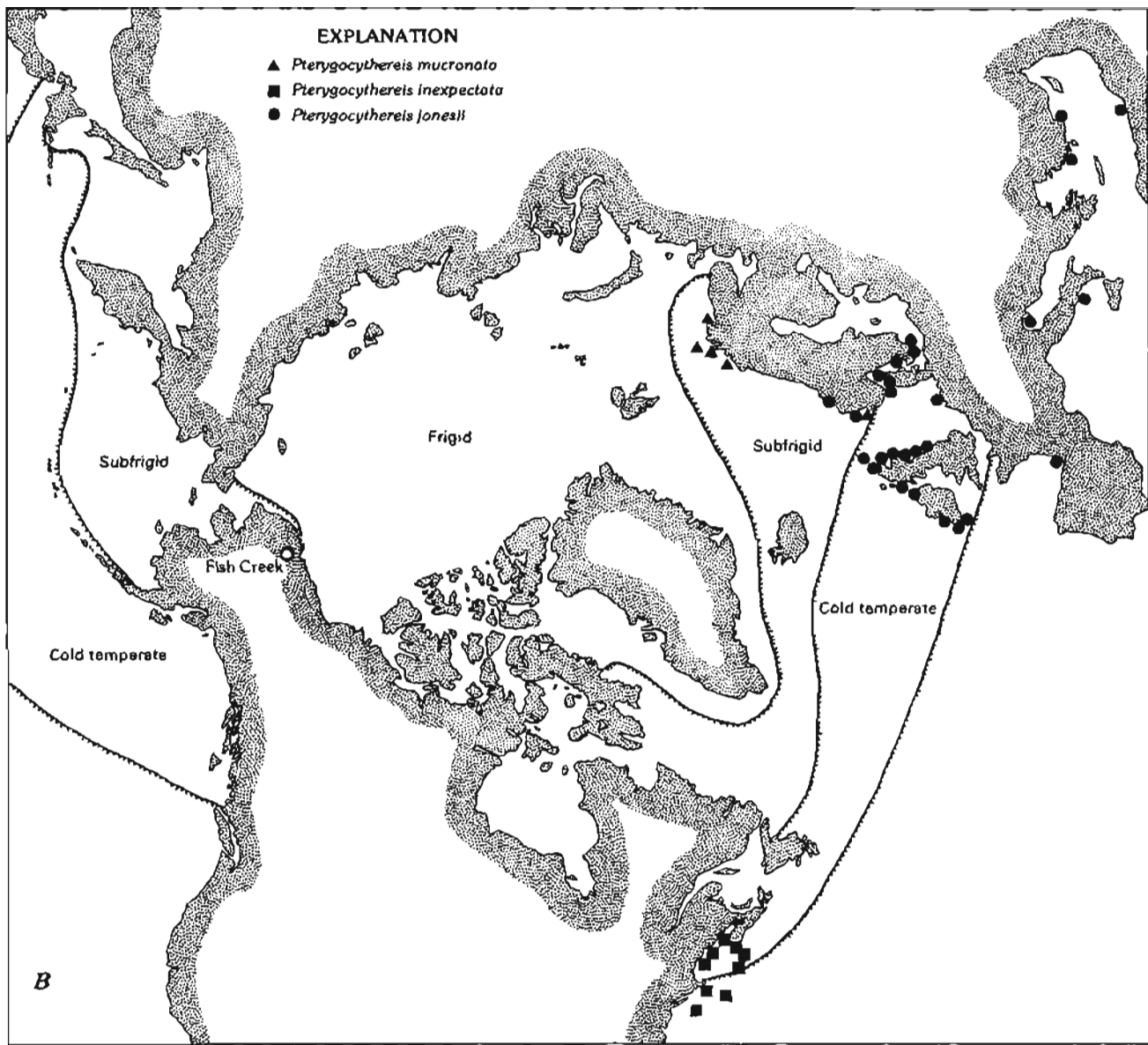


Figure 12 (above and facing page). Zoogeographic distribution of *Echinocythereis* and *Pterygocythereis* species in this study. A, Modern zoogeographic distribution of the three living *Echinocythereis* species in the North Atlantic. *Echinocythereis*, presumed ancestor of *Rabilimis*, can live only in warmer water environments than exist in the Arctic today. Data from Hazel (1970). B, Modern zoogeographic distribution of the three living *Pterygocythereis* species. These occurrences clearly illustrate that *Pterygocythereis* does not live in frigid marine climate of modern Arctic Ocean. *Pterygocythereis* n. sp. found at Fish Creek is related to *Pterygocythereis mucronata* - *P. jonesii* species complex, lacking dorsal crest of *P. inexpectata* species complex. Data from Hazel (1970) and Neale and Howe (1975).

FLORA OF THE FISH CREEK SECTION

Sixteen sediment samples collected at Fish Creek in 1983 by E.M. Brouwers for ostracode analysis were also subsampled and processed for palynological study. Ten of the samples contained pollen and spores, but only four contained palynomorphs in sufficient number to permit quantitative analysis (fig. 3). These four samples (table 3; 83-EB-174, -176, -179, -180) selected for detailed study

contained few reworked palynomorphs, whereas the remaining six contained a high proportion of reworked pollen and spores, mostly of Late Cretaceous age. None of the useful pollen samples came from the lower 3 m of the medial sand unit with bedding suggestive of tidal channels. Two samples from the upper meter of the lower silt unit (approximately 3 m above the basal ostracode assemblage) and two samples from the upper 1.5 m of the medial gray sand unit (approximately 3.5 m above the



lowest ostracodes included in the Fish Creek Fauna and 1.5 m below the principal mollusk and mammal beds) were analyzed for pollen and spore content. The results of those analyses are presented in table 3. The two samples from the lower unit have comparatively abundant pollen of *Betula* (birch), Ericaceae (for example, blueberry), and Cyperaceae (sedge). Pollen of conifers, particularly *Picea* (spruce) and *Pinus* (pine), is present in significant amounts, along with very small amounts of *Larix* (larch) and *Abies* (fir). None of these conifers now grows on the North Slope of Alaska (Viereck and Little, 1972). *Picea glauca* (white spruce) and *P. mariana* (black spruce) reach as far north as the valleys on the south flank of the Brooks Range and eastward to the Mackenzie Delta in Canada. *Larix laricina* (larch or tamarack) grows south of the Brooks Range along much of the Yukon River and some

of its tributaries. The nearest species of *Pinus* is *P. contorta* (lodgepole pine), now found in the southeastern Yukon Territory and areas to the south; in Alaska, it now lives only in the "panhandle" region to the southeast. *Pinus banksiana* (Jack pine) grows far to the southeast in Northwest Territories. *Abies* spp. grow as far north as Juneau in the Alaska "panhandle" region. The conifer assemblage from the lower unit at Fish Creek is similar to that described by Nelson (1979, 1981) and Nelson and Carter (1985) from the lower (marine) part of the Gubik Formation at Ocean Point, 16 miles (25 km) to the southeast of the Fish Creek section, on the Alaskan North Slope. Nelson compared the Ocean Point pollen flora from this lower unit with that of modern Anchorage, although some components of this pollen flora now have northern limits well to the south of that city. However,

not enough is yet known about Pliocene vegetation of the Arctic Ocean Borderland to be certain of the significance of modern analogs. Pliocene vegetation probably included at least some, and perhaps many, species that differ taxonomically and ecologically from the modern analogs.

The variety of fossil pollen from Fish Creek is sufficiently similar to that represented by pollen from surface samples in Alaska and Canada to permit some broad interpretations of paleovegetation. The two samples from the lower unit most probably represent a vegetation roughly equivalent to present-day shrub tundra ("moist tundra" of Viereck and Little, 1972, as differentiated from "wet tundra"). The significant percentages of *Betula*, Ericaceae, Cyperaceae, along with *Salix* and assorted taxa of herbaceous plants such as Caryophyllaceae, *Valeriana*, *Artemisia*, and Tubuliflorae are strongly suggestive of shrub tundra vegetation, such as that found today in the Arctic Foothills of the Brooks Range. The percentages of *Picea* and *Pinus* pollen are higher in the fossil assemblages of the lower unit at Fish Creek than in most surface pollen samples that have been reported from northern Alaska (for example, Nelson, 1979; Livingstone, 1955; Moriya, 1978), but a few surface samples have been described (Nelson, 1979) from the Arctic Coastal Plain that contain high percentages of conifer and shrub pollen, transported by wind long distances from sources to the south and southeast. That such pollen predominates in those few samples may be due to the low pollen production of local tundra vegetation that does not mask the accumulation of long-distance transported pollen. This contrasts to the situation in boreal or temperate vegetation communities where relatively high pollen production masks wind-transported pollen from distant sources. It remains unclear, however, why the percentage of conifer pollen is so highly variable in modern surface samples in northern Alaska.

The presence of *Pinus* and *Picea* pollen in the Fish Creek samples can be interpreted in two ways. The relative abundance of conifer pollen in the lower unit at Fish Creek may indicate that the northern edge of the boreal forest was farther north than at present, or it may indicate differences in prevailing wind patterns that favored long distance transport of these conifer pollen types. It is most likely that conifers, including *Picea*, *Pinus*, *Abies*, and *Larix*, grew north of their present limits, probably growing on the north side of the Brooks Range in the Arctic Foothills. Forests may have been restricted to river valleys rather than forming a continuous forest cover. However, it seems unlikely that forest vegetation existed as far north as Fish Creek at the time of deposition because the percentages of conifer pollen are more suggestive of tundra (Birks, 1973).

Pollen samples from the upper part of the medial gray, organic-rich sand unit containing the Fish Creek Fauna (table 3) also contain Cyperaceae, Gramineae,

Salix, Ericaceae, *Betula*, and most of the herbaceous taxa and spore types found in the lower unit. *Picea* and *Pinus* are present, but in significantly smaller amounts than in the lower unit. The uppermost sample (83 EB 180), a little more than 1 m below the fossil microtine bed, contains the lowest percentages of conifer pollen, as well as of pollen of *Betula*, Ericaceae, and Gramineae, and a much higher percentage of Cyperaceae pollen, suggesting herb tundra (wet tundra of Viereck and Little, 1972), rather than shrub tundra, and progressive southward retreat of conifer forests from the Arctic Foothills and shrub tundra from the Arctic Coastal Plain. Nevertheless, the climate may have been somewhat milder than that of the present day in the coastal plain or foothills, because *Nuphar* (water lily) pollen is present in the samples from the Fish Creek Fauna. *Nuphar* is not known today north of the Brooks Range (Hultén, 1968). The shift from shrub tundra vegetation to herb tundra vegetation may reflect more localized vegetation changes resulting from poor drainage. There is a trace of *Larix* pollen in sample 83 EB 180. Because *Larix* is poorly represented in most pollen records, the presence of even a small amount of *Larix* pollen suggests the possibility of some larch trees in the area. The presence of *Larix* wood in the deposits strengthens that possibility (Carter and Galloway, 1985); however, it is possible that the pollen was reworked from older deposits or transported a long distance by wind or water and that the wood is driftwood.

In sum, the pollen evidence suggests that during that part of the Pliocene represented by the Fish Creek section, tundra vegetation covered the Arctic Coastal Plain. During deposition of the lower unit, conifer forests containing spruce, pine, fir, and larch may have grown as far north as the Arctic Foothills south of Fish Creek. Shrub tundra vegetation covered the Arctic Coastal Plain near Fish Creek. Later, during deposition of the strata containing the Fish Creek Fauna, conifer forests were probably farther to the south and the vegetation of the coastal plain changed to wetland herbaceous tundra. This suggests climatic cooling and a shift to wetter habitats, possibly because of the development of permafrost, but during deposition of the Fish Creek Fauna it does not appear to have gotten as cold as it is today on the North Slope.

CORRELATION IN THE ARCTIC OCEAN BORDERLAND

Age of the Fish Creek Fauna

The evolution of the *Phenacomys* and *Synaptomys* lineages of microtine rodents, the approximate 3.0 Ma opening of the Bering Strait with introduction of mollusks of Pacific origin into the Arctic Ocean (Gladenkov, 1981),

Table 3. Pollen and spore counts of four samples from Fish Creek

Sample No. -----	Lower unit		Upper unit (Fish Creek Fauna)	
	83-EB-174	83-EB-176	83-EB-179	83-EB-180
Tree and shrub pollen (in percent)				
<i>Picea</i> (spruce) -----	8.7	6.7	2.3	1.3
<i>Pinus</i> (pine) -----	8.7	13.8	6.0	1.1
<i>Larix</i> (larch) -----	0.0	0.4	0.0	Tr. ¹
<i>Abies</i> (fir) -----	0.0	1.1	0.0	0.2
<i>Betula</i> (birch) -----	36.7	34.7	32.3	5.9
<i>Alnus</i> (alder) -----	4.2	1.5	4.7	1.6
<i>Populus</i> (poplar) -----	0.0	0.4	0.0	0.0
<i>Salix</i> (willow) -----	2.3	2.2	0.0	0.9
Ericaceae (such as blueberry) -----	13.6	18.7	11.7	5.5
Herb pollen (in percent)				
Cyperaceae (sedge) -----	15.2	10.8	20.0	72.3
Gramineae (grass) -----	4.9	2.2	14.0	7.3
<i>Artemisia</i> (wormwood) -----	0.8	1.1	0.0	0.5
Tubuliflorae (aster type) -----	2.3	3.0	2.0	0.6
Liguliflorae (dandelion type) -----	0.0	0.4	0.3	0.0
Cruciferae (mustard family) -----	0.8	0.4	0.0	0.0
Caryophyllaceae (pink family) -----	0.8	1.1	2.7	0.3
<i>Valeriana</i> -----	0.0	0.4	0.3	0.2
Aquatics (in percent)				
<i>Nuphar</i> (water lily) -----	0.0	0.0	0.3	Tr. ¹
Total pollen count -----	264	268	300	640
Spore types (in percent)				
<i>Equisetum</i> (horsetails) -----	0.0	0.0	0.0	0.3
<i>Lycopodium</i> (club moss) -----	3.1	1.4	0.6	1.8
Polypodiaceae (ferns) -----	2.8	1.9	0.3	1.0
<i>Selaginella sibirica</i> (spike moss) -----	0.0	1.1	0.0	Tr. ¹
<i>Sphagnum</i> -----	26.0	23.0	5.3	5.3
Total pollen and spore count -----	388	369	320	699
Algae types (in percent)				
<i>Pediastrum</i> -----	0.8	0.4	0.3	0.6
<i>Botryococcus</i> -----	6.8	5.6	10.7	4.1

¹Tr., trace.

the broad history of vegetational changes in the coastal regions of the Arctic Ocean, paleomagnetic patterns during the time that is indicated by the microtine evolution, and the stratigraphic framework provided by oceanic oxygen isotope records provide the constraints for an age interpretation of the Fish Creek Fauna that is very precise in comparison with what was possible less than 10 years ago. Supportive evidence derives from the ostracode fauna at Fish Creek and from temporally and climatically related biotas of the Arctic Ocean Borderland.

The time of concern is the period between the opening of Bering Strait and the beginning of a Northern Hemisphere warm period, about 2.0 Ma ago. Shackleton and Opdyke (1977) reported that a progressive cooling began about 3.2 Ma ago in the record of the North Pacific Ocean, and that the first significant accumulation of continental ice in the Northern Hemisphere peaked about 2.4 Ma ago. Shackleton and others (1984) reported a similar but more detailed record from the North Atlantic. The greater detail of this core (fig. 13) suggests that

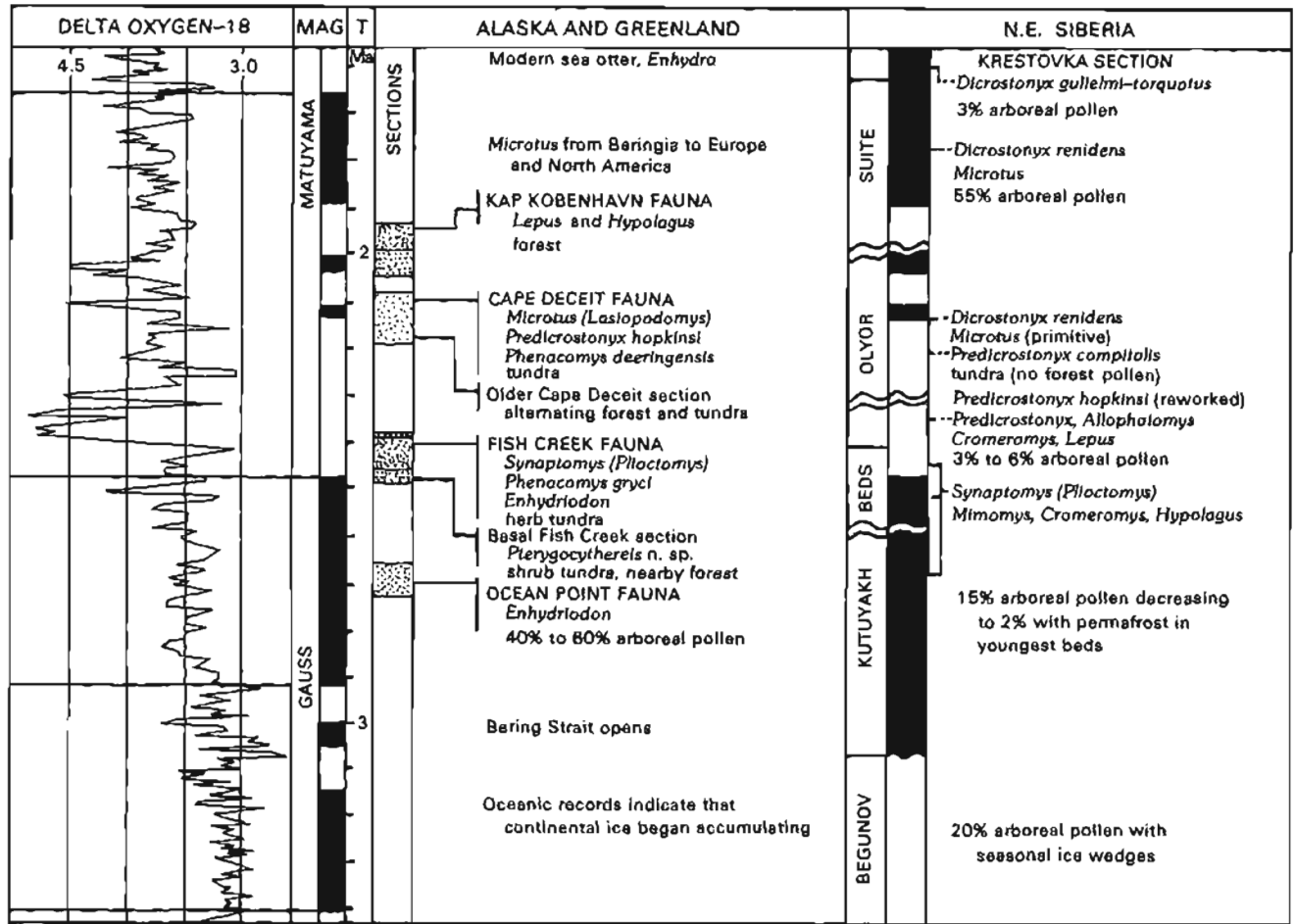


Figure 13. Correlation of faunas from Beringian Siberia and Alaska with time (T) in millions of years, paleomagnetic stratigraphy (MAG), and the oceanic record of oxygen isotope ratios from North Atlantic site 552A on the Rockall Plateau south of Iceland and west of Scotland (Shackleton and others, 1984). All isotopic data on figure from site 552A. Wavy lines in the composite Krestovka Section indicate breaks in continuity of sections described by Sher and others (1979).

this continental ice cap had two major peaks and persisted until about 2.0 Ma ago.

Species of the primitive bog lemming subgenus *Synaptomys* (*Pliotomys*) are known from southern Russia, Poland, Hungary, Mongolia, northeastern Siberia, Alaska, and the Great Plains of North America; their evolutionary history is sketched and described in figure 14. The oldest record is in the Simbugino Fauna from southern Russia that is correlated with European faunas older than 4 Ma, and comparable faunas in the United States are as old as 4.8 Ma (Fejfar and Heinrich, 1983; Repenning, 1983b); the youngest, in the Great Plains of the United States, no less than 2.0 Ma old. With the exception of those records from the Great Plains, probably all known occurrences should be assigned to *S. (P.) mimomiformis* Suchov, as there is no known way to diagnose them separately. *Synaptomys (P.) rinkerii* Hibbard and *Mictomys vetus* (Wilson) from 2.6- to 2.0-Ma-old faunas of the Great Plains and western mountain States can be distinguished from *S. (P.) mimomiformis* and from

younger species that are assigned to more advanced taxa (fig. 14).

The youngest Old World record of *Synaptomys* (fig. 13) is from the Kutuyakh Beds of the Krestovka Section in the Kolyma Lowlands, Beringian Siberia, where it occurs below and above the 2.5-Ma-old top of the Gauss Chron (Sher and others, 1979; Repenning, 1984). This is an awkwardly young record, as both the derivative forms, *S. (P.) rinkerii* from the Great Plains west to the Texas Panhandle and *Mictomys vetus*, a North American genus derived from *Synaptomys (Pliotomys)*, from west and south of the Rocky Mountains, are known from faunas slightly older than the end of the Gauss Chron. Obviously, *S. (P.) mimomiformis* persisted in the Arctic while part of its population dispersed southward in North America during the climatic deterioration, to evolve into a different species of *Synaptomys* and a different genus, *Mictomys*, by 2.6 Ma ago. *Synaptomys (Pliotomys) mimomiformis* from the Fish Creek Fauna thus suggests an age no younger than 2.4 Ma, the earliest part of the Matuyama

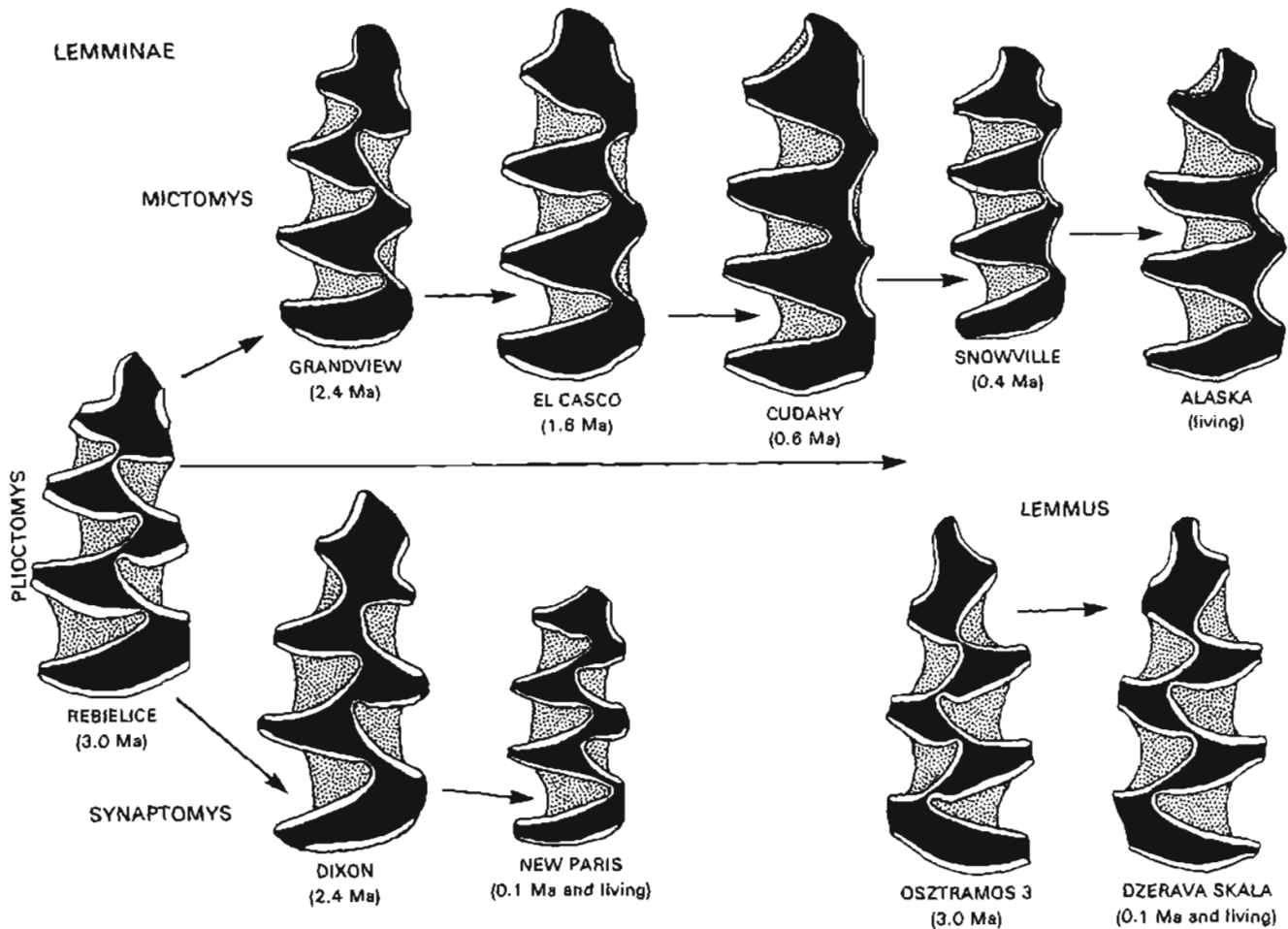


Figure 14. Outline of evolutionary history of brown and bog lemmings, Subfamily Lemminae, shown by changes in pattern of chewing surface of first lower molar. Only specimens pertinent to the present discussion are noted here. *Synaptomys* (*Pliotomys*) *mimomiformis* (labeled Rebelice, from Rebelice Fauna of Poland) has known temporal range from more than 4 Ma ago to younger than the 2.5-Ma-old Gauss/Matuyama polarity boundary in Beringian Krestkovka Section, Siberia, and Fish Creek Fauna, Alaska. *Synaptomys* (*Pliotomys*) *rinkerii* (labeled Dixon from the Dixon Fauna, Kansas) and *Mictomys vetus* (labeled Grand View from the Grand View Fauna, Idaho) have evolved out of *mimomiformis* and are known from deposits in Texas, Arizona, and Idaho older than the 2.5-Ma-old Gauss/Matuyama polarity boundary; both grade, in the fossil record, into living forms of North America; intermediate forms are shown.

Although obviously related to *Synaptomys* and *Mictomys*, the brown lemming, *Lemmus*, has its distinctive tooth structure already in the oldest known fossils (at least 2 Ma old, as shown by the specimen labeled Osztramos 3, Hungary) and has not detectably changed its tooth pattern in living species (shown by latest Pleistocene specimen from Dzerava Skala, Czechoslovakia); this genus of Lemminae is not discussed further in present report.

Chron. Its obvious relict status leaves open the possibility of a still younger age.

Phenacomys gryci from the Fish Creek Fauna is distinctly more primitive than the fossil heather vole *Phenacomys deeringensis* from the Cape Deceit Fauna (figs. 5-7). The Fish Creek Fauna might seem to be considerably older than the Cape Deceit Fauna on the basis of this markedly more primitive evolutionary stage of *Phenacomys*, and its association with a primitive species of *Synaptomys*, but it is not. The reversed polarity of the deposits containing the Fish Creek Fauna, coupled with the tundra environment of the fauna and its Pacific mollusks, indicates that it cannot be older than the

beginning of the Matuyama Chron at about 2.5 Ma ago. We are therefore forced to choose one of two interpretations: either (1) a very brief period of explosive evolution is represented by the dramatic development of *Phenacomys* between the times of Fish Creek and Cape Deceit Faunas (the morphologic difference between the two species is far greater than that between the Fish Creek species and its hypothetical *Cromeromys* ancestor (>4 Ma), and far greater than that between the Cape Deceit species and living species of *Phenacomys*), or (2) that *Phenacomys gryci*, like *Synaptomys* (*Pliotomys*) sp., was a primitive relict of the Arctic Ocean Borderland and that the advanced *P. deeringensis* evolved somewhat to the south (but not

in conterminous United States) and appeared in the Cape Deceit Fauna at the close of the first North American continental glaciation. The first choice provides no more than 200,000 years for the morphologic change; the second could provide as much as 1 million years, and seems more realistic.

The second choice suggests the possibility that the Fish Creek microtines, having lived in an arctic refugium, could be much younger in age. Although this interpretation enlarges the temporal overlap of ancestral and descendant forms of microtine rodents, that it is actually impossible is demonstrated by consideration of climatic history and geopolarity.

According to oceanic oxygen isotope records, the first North American continental glaciation appears to have terminated 2 Ma ago (fig. 13); this time of climatic warming is recognized throughout the Northern Hemisphere from the Praetiglian (cold)-Tiglian (warm) change in northwestern Europe (Zagwijn and Doppert, 1978) across Eurasia and North America to northernmost Greenland where evidence indicates that boreal forests replaced tundra along its coast close to 2 Ma ago (Funder and others, 1985). Within 100,000 years after the termination of this first continental glaciation, as calibrated by oxygen isotope records, the climatic change stimulated the most distinctive of all microtine rodent dispersal events in the Northern Hemisphere, which is dated in both Europe and North America as having been completed during the earliest part of the Olduvai Subchron, about 1.9 Ma ago (Repenning, 1983d). In the Krestovka Section of eastern Siberia, Sher and others (1979) reported a change in arboreal pollen concentration from 0 to 55 percent at the time of this climatic warming (Repenning, 1984). The Fish Creek Fauna does not record an increase of arboreal pollen, and its paleomagnetic signal cannot represent the reversed sediments overlying the 2-Ma-old termination of the normal Reunion Subchron. The next similar magnetic pattern would be the reversed polarity period following the normal Olduvai Subchron, younger than approximately 1.67 Ma; by this time the modern genus of sea otter, *Enhydra*, is known to have evolved (Repenning, 1983a).

Age of the Ocean Point Fauna

The Ocean Point Fauna of the Gubik Formation, located about 16 miles (26 km) southeast of the Fish Creek Fauna, was discussed by Repenning (1983a). It is noteworthy because it was the first evidence in recent times that parts of the formation are older than middle Pleistocene (older than 1 Ma). In the 1983 discussion Repenning concluded that the fauna was older than 1.5 Ma and younger than 3 Ma on the basis of a primitive

form of sea otter and mollusks of North Pacific origin; an approximate age of about 2 Ma was discussed. It was noted that the pollen flora associated with the marine Ocean Point Fauna indicated a nearby forest environment, according to Nelson (1981).

Since publication of the Ocean Point Fauna (Repenning, 1983a), it has become apparent that just prior to 2 Ma ago the Arctic Ocean Borderland was not forested. The magnetic polarity of the Ocean Point Fauna is normal (J.W. Hillhouse, written commun. to LDC, 1977, and Carter and others, in press), and cannot be distinguished from either modern or Gauss Chron polarity on declination; in magnetic cleaning (AC) changes in inclination were random and showed no tendency toward becoming reversed (J.W. Hillhouse, oral commun., 1985). Abundant forest pollen and normal polarity could match the Arctic Ocean Borderland history during the Olduvai Subchron, but this seems too close in time to the earliest known record of the modern sea otter, *Enhydra*. In addition, amino acid analyses of marine mollusks show clearly that the Ocean Point Fauna is older than the Fish Creek Fauna, and these data are supported by geomorphic evidence (Carter and others, 1986). Because the sediments containing the Fish Creek Fauna formed during the early part of the reversed Matuyama Chron, we conclude that the Ocean Point marine beds must have formed during some part of the normal Gauss Chron (fig. 13). The age estimate of the marine Ocean Point Fauna is consequently here revised from about 2 Ma to between 3 and 2.5 Ma, and is so recognized by Carter and others (1986).

Age of the Cape Deceit Fauna

As discussed earlier, the Cape Deceit Fauna appears to be very close to 2.1 Ma old (fig. 13). The presence in the Cape Deceit Fauna of the primitive meadow mouse *Microtus (Lasiopodomys) deceitensis* that is obviously one of the first of the *Microtus* lineage (Repenning, 1983c, fig. 2), of the ancient genus of collared lemming *Predicrostonyx*, and of pollen recording a tundra flora with a nearby forest in that part of the section underlying the fauna indicates that this age is very close to the beginning of the Reunion Normal Subchron. In the Krestovka Section, *Predicrostonyx* is present at an earlier time (possibly 200,000 years earlier) than *Microtus*, and the descendant genus *Dicrostonyx* first appears with the oldest *Microtus*-bearing fauna. This inconsistency seems reasonable in view of the Asiatic origin of *Dicrostonyx*; an interpretation on the basis of the synchronicity of *Predicrostonyx* would necessitate the assumption that the *Microtus* lineage originated in North America and dispersed to Eurasia, which is contrary to evidence. Although their history is poorly known, the presence of the giant pika, *Ochotona whartoni* (Guthrie and Matthews, 1971),

in the Cape Deceit Fauna is suggestive of a correlation with the Nihowan Fauna of China of this approximate age.

Insofar as we are aware, there is no paleomagnetic evidence from the Cape Deceit section.

Age of the Krestovka Section

The Krestovka Section at the junction of the Krestovka River with the Kolyma River of eastern Siberia (figs. 2, 13) has been the object of much study and has been described by Sher and others (1979); parts of this study have been published separately in other reports by Sher, Zazhigin, Virina, Gitterman, and others. As of the present date (1986) it is the most detailed record of late Pliocene faunal and floral history in the Arctic Ocean Borderland. Sher and others (1979, in text on p. 63) inadvertently correlated the youngest of the Kutuyakh Beds (containing their Khapry (Pliocene)-equivalent fauna) with a time younger than the Olduvai Subchron, thus making the Kutuyakh Fauna appear contemporaneous with European Biharian faunas (Pleistocene) as used by Fejfar and Heinrich (1983). In the immediately preceding sentence, however, they correctly suggested that the reversely magnetized deposits at the top of the Kutuyakh Beds (and overlying the normal deposits they next correlated with the Olduvai) represent the polarity of the early Matuyama Chron. This inconsistency, which makes faunas in the younger part of the Krestovka Section appear much younger than they can be, was corrected by Repenning (1984), and the faunal succession was correlated with Holarctic history.

Unlike the North American record in the central United States (Easterbrook and Boellstorff, 1984), there is no evidence of continental glaciation in Eurasia or in Beringia (including Fish Creek) at 2.4 Ma ago (Repenning, 1984), which is the time of the first significant peak in $\delta^{18}\text{O}$ of the North Pacific and North Atlantic. Sher and others (1979) reported the earliest evidence of permafrost at this time in the youngest part of the Kutuyakh Beds of the Krestovka Section in Beringian Siberia. This was preceded, in older beds of the Kutuyakh, by a progressive decrease in arboreal pollen for an uncalibrated period of the normal magnetism during the Gauss Chron. These deposits in the very top of the Kutuyakh Beds, recording the earliest reversed magnetism of the Matuyama Chron, appear to correlate with the Fish Creek Fauna and contain the youngest Old World records of *Synaptomys* (*Pliotomys*) *mimomiformis*, the last Beringian record of the ancestral arvicoline microtine *Mimomys*, a relatively primitive form of *Cromeromys*, and the pre-Pleistocene hare *Hypolagus* (fig. 13). A primitive species of *Phenacomys* may come from this fauna.

Higher in the reversed deposits of the earlier Matuyama Chron, the deposits are assigned to the early part of the Olyor Suite and contain *Predicrostonyx*, *Microtus*, and the modern hare *Lepus*, genera more characteristic of the Cape Deceit Fauna, as well as a more advanced species of *Cromeromys* and the earliest *Allophaiomys* and *Dicrostonyx*. The oldest deposits of the Olyor Suite contain a low percentage of arboreal pollen (suggesting correlation with the earliest part of the Cape Deceit section that contains an alternation of pollen assemblages indicative of forest and tundra), but at the horizon where *Microtus* first appears, close to the base of the Reunion Subchron, forest elements again have no representation in the pollen spectrum. This floral and faunal history of the early Olyor Suite appears to be identical with that at Cape Deceit.

In summary (fig. 13), paleomagnetism, pollen, and rapidly evolving mammals all strongly suggest that the Cape Deceit Fauna of Alaska correlates best with the faunas of the earlier Olyor Suite of the Krestovka Section at the point in time very close to the beginning of the Reunion Subchron, about 2.1 Ma ago. These data also suggest that the Fish Creek Fauna of Alaska correlates best with the latest part of the Kutuyakh Beds of the Krestovka Section at a point in time shortly following the end of the Gauss Chron, about 2.4 Ma ago. The marine part of the Gubik Formation at Ocean Point must correlate with some part of the older Kutuyakh Beds that has greater evidence of forests in the Arctic Ocean Borderland and that was deposited during the normal Gauss Chron following the opening of Bering Strait 3 Ma ago (Gladenkov, 1981). Indeed, Nelson and Carter (1985) reported that the arboreal pollen from the marine beds at Ocean Point represent as much as 40–60 percent of the Tertiary pollen present, a percentage more similar to the older Begunov Suite of the Krestovka Section, than to the Kutuyakh Beds.

Age of the Kap Kobenhavn Fauna

Funder and others (1985) have described a section in northernmost Greenland that has deeper water glaciomarine deposits in its lower part, and high-energy shoreline deposits in its upper part, indicating little or no perennial sea ice. The upper part also contains evidence of a forested coast line and is reversely magnetized, except, possibly, at the very top of the magnetic section (fig. 13). The uppermost part of the section, near the top of the paleomagnetic record, contained a few fossil bones among which was a large species of the Pliocene rabbit *Hypolagus*, of an age of 2 Ma or older in North America and Asia, and (not mentioned by Funder and others) a very large species of the modern hare *Lepus*, of an age of 2 Ma or younger in North America. Large *Lepus* and

medium-sized *Hypolagus* occur together in the Borchers Fauna of Kansas in the top of and just above the 2.0 Ma "Pearlette Ash" (variously known as the "Pearlette B," Borchers, or Huckleberry Ridge ash). In the Krestovka Section *Lepus* first appears earlier, between 2.3 and 2.4 Ma ago as the records of Sher and others (1979) are calibrated by Repenning (1984); *Hypolagus* is reported upsection from *Lepus* in the Krestovka Section as re-worked material, but is not found in fossil faunas believed to be in place.

The combination of (1) a tundra environment in northeastern Siberia and Alaska between 2.4 and 2.0 Ma ago followed by a forested Arctic Ocean Borderland in northeastern Siberia and Greenland at or shortly following 2.0 Ma ago, (2) the reversed polarity of that part of the Kap Kobenhavn section recording an open ocean, (3) the co-occurrence of well known and temporally distinct forms of rabbits, and (4) other evidence of age cited by Funder and others (1985) leaves little doubt that the Kap Kobenhavn section records the time immediately following the culmination of the first continental glaciation of North America and of the Praetiglian-Tiglian climatic stage boundary of northwestern Europe (fig. 13).

Environment of the Arctic Ocean Borderland Between 3.0 and 1.9 Ma

Oceanic records of oxygen isotopes indicate that about 3.2 Ma ago ice began to accumulate on the continents of the Northern Hemisphere (fig. 13). Although not dated, the Begunov Suite of northeastern Siberia may possibly represent such an early time and its fossil pollen suggests a forested Arctic Ocean Borderland. About 3.0 Ma ago, North Pacific mollusks reached Iceland, indicating that the Bering Strait had opened and connected the North Pacific with the Arctic Ocean. The marine beds at Ocean Point, Alaska, were deposited sometime between the opening of the strait and about 2.5 Ma ago; they indicate a forested borderland and an ice-free Arctic Ocean. The Ocean Point deposits would seem to have been deposited earlier in the 3.0 to 2.5 Ma time interval than the basal beds of the Fish Creek section because the basal Fish Creek beds, with their warm-water ostracode assemblage, appear to be about 2.5 Ma old on paleomagnetic grounds.

The Fish Creek section records a transition from shrub tundra to herb tundra through a stratigraphic sequence that is reversely magnetized, but the Arctic Ocean was not frozen at the time. The section appears to correlate with the uppermost part of the Kutuyakh Beds of northeastern Siberia which have the same magnetic pattern, the same floral pattern, and very similar mammalian species; these Kutuyakh Beds record the first permafrost and first full tundra of northeastern Siberia. The Fish

Creek Fauna, in the upper part of the Fish Creek section, indicates a cooler, but not frozen, Arctic Ocean. This fauna is believed to be 2.4 Ma old and to have been deposited during the beginning of the first North American continental glaciation, a glaciation that extended southward in North America to Iowa. Rea and Schrader (1985) discussed evidence from the North Pacific indicating that significant ice rafting began at this time. Shackleton and others (1984) indicated a similar event in the North Atlantic at the same time. Despite these indications of extensive ice accumulation, all available evidence in the Fish Creek Fauna indicates that the Arctic Ocean was not yet frozen.

Following deposition of the Fish Creek Fauna and during the first glaciation of North America, the Arctic Ocean Borderland may have alternated between supporting tundra or boreal forest during the time between 2.4 and 2.0 Ma. This span of time appears in the oceanic records as several peaks in the accumulation of continental ice and appears to be represented in the section underlying the Cape Deceit Fauna of the Seward Peninsula; it is expressed there as alternating forest and tundra pollen records. A similar record is suggested by minor increases in arboreal pollen in the basal part of the Olyor Suite of the Krestovka Section in Siberia. The Cape Deceit Fauna, in the upper part of the Seward Peninsula section, is associated with tundra and appears to correlate with faunas in the Olyor Suite having no arboreal pollen at the horizon of the Reunion Subchron, about 2.1 Ma ago. It also appears to correlate with the last peak of the first continental glaciation as indicated in the oceanic record.

The north Greenland locality at Kap Kobenhavn records evidence indicating that the Arctic Ocean was not frozen and that forests returned to its borderland about 2 Ma ago. This warm period continued (1) at least to the end of the Olduvai Subchron [Zagwijn and Doppert (1978) believed that the Tiglian warm period ended and the Eburonian cold period started at that time], or (2) to shortly following the Olduvai [Herman and Hopkins (1980) reported that ice rafting increased in the Arctic Ocean at that time, if the normal event they call the Gauss Chron is considered the Olduvai Subchron], or (3) to about 1.4 Ma when Pacific Core V28-239 shows an abrupt shortening of isotope "warm" periods.

At present, the evidence of Herman and Hopkins (1980), which suggests that the Arctic Ocean froze about 850,000 years ago (with the above-mentioned revision of magnetic correlations), appears to be the earliest evidence of a frozen Arctic Ocean. This date corresponds to the beginning of oxygen stage 22, to a major Holarctic dispersal of microtine rodents that is rather well dated in both Europe and North America, and to the first advance of the Nebraskan ice sheets southward into the midwestern United States (Easterbrook and Boellstorff, 1984).

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<i>Predicrostonyx</i>	6, 24, 25
<i>hopkinsi</i>	5
Prudhoe Bay	pl. I
<i>pseudopunctillata</i> , <i>Paracyprideis</i>	11
<i>Pterygocythereis</i>	11
<i>americana</i>	14
<i>inexpectata</i>	14
n.sp	11; pl. I
<i>pyramidale</i> , <i>Cytheropteron</i>	pl. I

R

<i>Rabilimis</i>	11
<i>mirabilis</i>	11; pl. I
<i>paramirabilis</i>	11; pl. I
<i>septentrionalis</i>	11, 14; pl. I
<i>reevei</i> , <i>Enhydriodon</i>	3
<i>regina</i> , <i>Admete</i>	15
<i>Retusa umbilicata</i>	17
Reunion Normal Subchron	24
Reunion Subchron	5, 24, 25

<i>rinker</i> , <i>Synaptomys</i>	4
(<i>Pliotomys</i>)	4, 22
<i>Robertsonites tuberculata</i>	pl. I

S

Sagavanirktok Formation, Nuwok Member	11
<i>Salix</i>	20
<i>Sarsicytheridea bradii</i>	pl. I
<i>savini</i> , <i>Mimomys</i>	7, 11
<i>sawrockensis</i> , <i>Mimomys (Cosamys)</i>	9
<i>septentrionalis</i> , <i>Rabilimis</i>	11, 14; pl. I
<i>Serripes groenlandicus</i>	16
Seward Peninsula	4, 15
Simbugino Fauna	22
<i>sorbyana</i> , <i>Heterocyprideis</i>	pl. I
<i>Spermophilus undulatus</i>	3
<i>squalida</i> , <i>Littorina</i>	15
<i>Synaptomys</i>	4, 20, 22
<i>rinker</i>	4
(<i>Pliotomys</i>)	22
<i>europaeus</i>	4
<i>mimomiformis</i>	4, 22, 25
<i>rinker</i>	4, 22
sp	4
(<i>Synaptomys cooperi</i>)	4
(<i>Synaptomys cooperi</i> , <i>Synaptomys</i>)	4

T-Z

<i>teshekpukensis</i> , <i>Cythereta</i>	14; pl. I
<i>truncata</i> , <i>Mya</i>	16
<i>tuberculata</i> , <i>Robertsonites</i>	pl. I
<i>Tubuliflorae</i>	20
<i>umbilicata</i> , <i>Retusa</i>	17
<i>undulatus</i> , <i>Spermophilus</i>	3
<i>Valeriana</i>	20
<i>venepidermoidea</i> , <i>Loxoconcha</i>	11, 14; pl. I
<i>vetus</i> , <i>Mictomys</i>	22
<i>wharioni</i> , <i>Ochatona</i>	24
Yukon River	19
Yukon Territory	19

PLATE 1

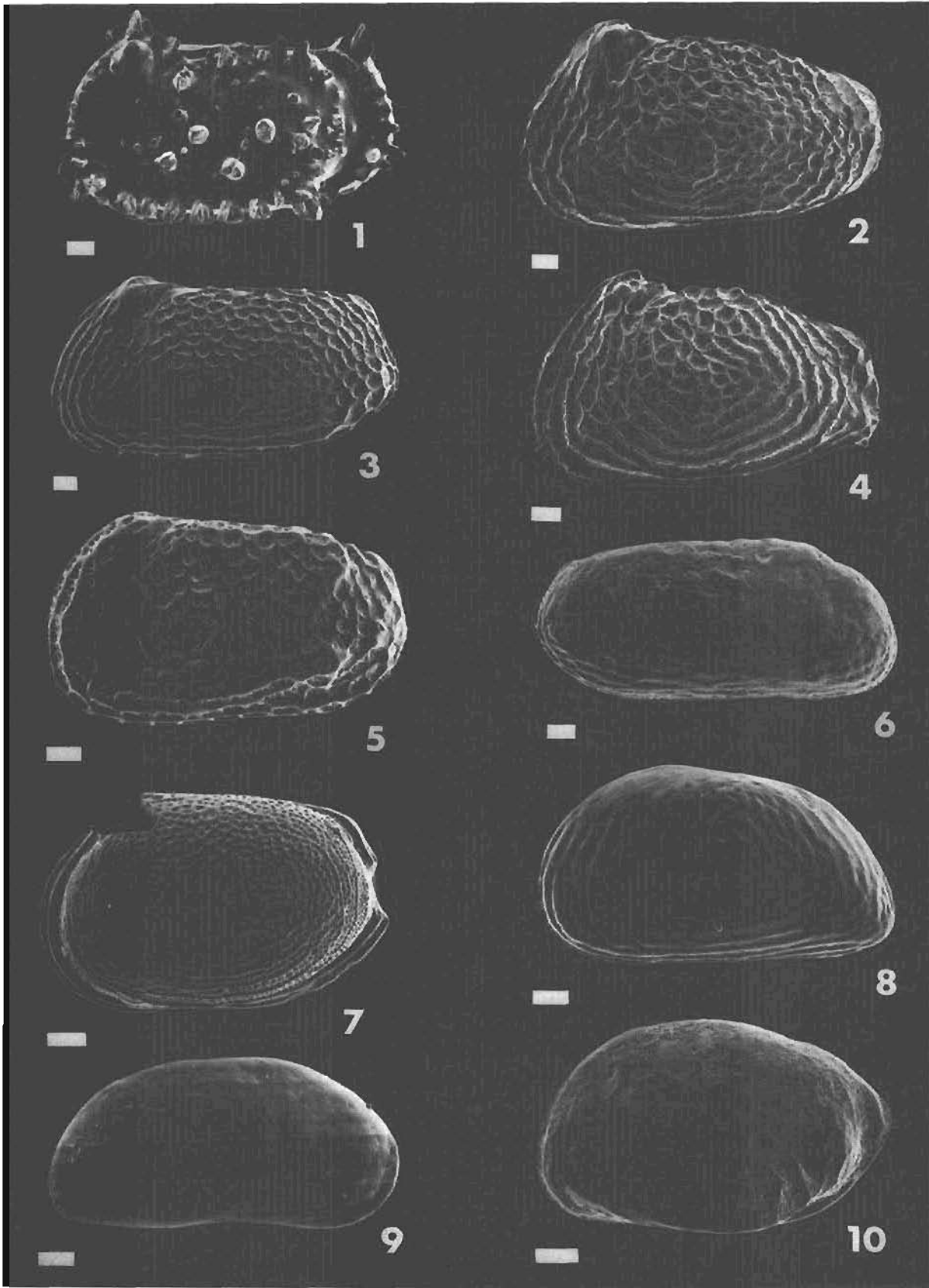
Contact photographs of the plate in this report are available,
at cost, from U.S. Geological Survey Library,
Federal Center, Denver, CO 80225

PLATE 1

(Bar scale = 100 micrometers)

Scanning electron micrographs of the diagnostic ostracode species from the Fish Creek section. Stratigraphic positions of localities are shown on figure 3 except for 83-EB-187, which is from Miluveach River, and HLA-12, which is from a borehole taken in the inner shelf off Prudhoe Bay.

- Figure
1. *Pterygocythereis* n. sp. Exterior of left valve, female. Locality 83-EB-187A.
 2. *Rabilimis paramirabilis* (Swain, 1963). Exterior of left valve, male. Locality 83-EB-187A.
 3. *Rabilimis septentrionalis* (Brady, 1866). Exterior of left valve, male. Locality 83-EB-187.
 4. *Rabilimis mirabilis* (Brady, 1868). Exterior of left valve, male. Locality HLA-12, 27.5-28.0 ft.
 5. *Robertsonites tuberculata* (Sars, 1865). Exterior of left valve, juvenile. Locality 83-EB-183.
 6. *Cytheretta teshekpukensis* Swain, 1963. Exterior of right valve, male. Locality 83-EB-183.
 7. *Loxoconcha venepidermoidea* Swain, 1963. Exterior of left valve. Locality 83-EB-183.
 8. *Heterocyprideis sorbyana* (Jones, 1856). Exterior of left valve, male. Locality 83-EB-183.
 9. *Sarsicytheridea bradii* (Norman, 1865). Exterior of right valve, male. Locality 83-EB-178.
 10. *Cytheropteron pyramidale* of Neale and Howe, 1975. Exterior of left valve. Locality 83-EB-181.



PTERYGOCYHEREIS, RABILIMIS, ROBERTSONITES, CYTHERETTA, LOXOCONCHA, HETEROCYPRIDEIS, SARSICYTHERIDEA, AND CYTHEROPTERON

