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PLIOCENE PALEOECOLOGIC RECONSTRUCTIONS BASED ON OSTRACODE ASSEMBLAGES FROM THE SAGAVANIRKTOK AND GUBIK FORMATIONS, ALASKAN NORTH SLOPE

by

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ABSTRACT

Shallow-marine ostracode assemblages from late Pliocene sediments of the upper part of the Sagavanirktok Formation and lower part of the Gubik Formation record the last series of warm periods that occurred before the onset of significant cooling of the Arctic Ocean, which ultimately led to Northern Hemisphere continental glaciation. The informally named Colvillian and Bigbendian transgressions represent the oldest deposits of the Gubik Formation and are dated, based on various lines of evidence, between 2.48 and 3 Ma. Ostracode faunas from the lower part of the Gubik Formation indicate a cold temperate to subfrigid marine climate with summer bottom temperatures 3-5°C warmer than today. Deposits of the upper part of the Sagavanirktok Formation at Barter Island and Manning Point are older than Colvillian sediments, but are believed to be late Pliocene in age and contain an ostracode fauna with many species in common with the lower Gubik assemblages. The Sagavanirktok ostracode faunas indicate a cold temperate to subfrigid marine climate, with summer bottom temperatures 3-5°C warmer than today.

The opening of Bering Strait between 3 and 4 Ma altered Arctic Ocean assemblage composition as Pacific species migrated into the Arctic and North Atlantic Oceans. The admixture of evolutionarily distinct faunas from the two oceans identifies Colvillian (and younger) faunas and the first appearance of these mixed faunas provides a convenient reference horizon in the Alaskan fossil record. The marine climatic deterioration that followed the Bigbendian appears to have been generally abrupt and is documented by biotic turnover, with large numbers of species extinctions and first appearances of new species. The change in species composition can be correlated with the cooling of the Arctic Ocean during

the Pliocene.

INTRODUCTION

Pliocene marine sediments throughout the Northern Hemisphere provide evidence of oceanographic and climatic changes that impacted the Arctic Basin, including (1) changes in North Atlantic circulation between 3-5 Ma caused by the final closure of the Isthmus of Panama and the consequent strengthening of the Gulf Stream (Keigwin, 1978; Jones and Hasson, 1985), (2) the opening of Bering Strait between 3 and 4 Ma (Gladenkov, 1981; Einarsson and Albertsson, 1988; Gladenkov and others, 1991), allowing the first exchange of Pacific faunas and water masses since the late Cretaceous (Marincovich and others, 1990), (3) progressive cooling of the Arctic Ocean beginning about 4 Ma (Herman and Hopkins, 1980; Clark, 1990), and (4) the first significant development at about 2.4 Ma of greatly increased ice rafting and iceberg delivery to lower latitudes of the North Atlantic (Shackleton and others, 1984; Raymo and others, 1989; Jansen and Sjoholm, 1991).

The effects of these climatic and oceanographic changes can be seen in Arctic Ocean shallow-water faunas and include the first appearance of North Pacific forms in the Arctic and North Atlantic beginning about 3 Ma (Durham and MacNeil, 1967; Gladenkov, 1981; Gladenkov and others, 1980; Fyles and others, 1991) and the first development of endemic Arctic taxa representative of frigid and subfrigid marine climates between 2.7-2.4 Ma (Repenning and others, 1987), including forms tolerant of sea ice conditions.

Sediments representing the upper part of the Sagavanirktok Formation and the lower part of the Gubik Formation are believed to represent a Pliocene shallow marine record of the climatic and oceanographic changes that occurred at high northern latitudes. This paper examines a distinctive assemblage of ostracode species from sedimentary rocks of the uppermost Sagavanirktok Formation at Manning Point and Barter Island and from the lower Gubik Formation, both of which crop out on the eastern coastal plain of the Alaskan North Slope, with the goals of reconstructing paleoenvironments and estimating bottom water temperatures.

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GEOLOGIC SETTING

Tertiary rocks range northward from the Brooks Range to the Arctic Ocean (Figure 1), extending into the continental shelf beneath the Beaufort Sea (Grantz and others, 1982, 1990). Bedrock exposures of pre-Quaternary sediments are sparse in the foothills and coastal plain of the North Slope, with a few exceptions where streams have eroded the tundra cover and exposed older sediments. In northeastern Alaska, post-Cretaceous sediments have been placed into the Tertiary Sagavanirktok Formation (Detterman and others, 1975; Figure 1) and the Pliocene-Quaternary Gubik Formation (Dinter and others, 1990).

Figure 1 shows the location of the streams and coastal bluffs on the central and eastern coastal plain of the Alaskan North Slope where fossiliferous shallow-marine strata of the Sagavanirktok Formation and the basal Gubik Formation studied here have been collected.

Sagavanirktok Formation

The Sagavanirktok Formation includes three members (Detterman and others, 1975): (a) the Sagwon Member (oldest), whose type section is at Sagwon (Figure 2) , (b) the Franklin Bluffs Member, whose type section is at Franklin Bluffs, and (c) the Nuwok Member (youngest), whose type section is on

Carter Creek. The Sagwon and Franklin Bluffs Members are nonmarine Paleogene deposits (Ager and others, 1985; J.A. Barron, written communication, 1976); the Nuwok Member represents the only marine sediments in the Sagavanirktok Formation.

Manning Point and Barter Island, situated along the Beaufort Sea coast (Figure 2) are two localities with sediments that have been referred to the Nuwok Member (Brouwers and Marincovich, 1988; Marincovich and others, 1990), but are probably best considered as unnamed deposits of the Sagavanirktok Formation. At Manning Point, a coastal bluff of massive mudstone crops out along the northeast side of the island. A distinctive horizon containing concretions, concentrations of broken shells of the mollusk *Thyasira alaskana*, and large crystals of glendonite occurs stratigraphically in the middle of the exposure. Microscopic glendonite crystals are found in the mudstones stratigraphically above the distinctive horizon at Manning Point as well as in mudstones on the north side of Barter Island, where the concretion-mollusk horizon does not occur.

Gubik Formation

The Pliocene and Quaternary Gubik Formation consists of interfingering marine and nonmarine clastic sediments that were deposited during a series of sea-level transgressions and regressions across the broad, low-gradient coastal plain of Alaska. Marine subunits of the Gubik Formation representing sea-level highstands are recognized and distinguished on the basis of unconformities, faunal suites, distinctive sedimentary facies, and amino acid stratigraphy (Dinter and others, 1990). At least six and possibly seven or eight late Cenozoic marine transgressions are represented by deposits of the Gubik Formation on the coastal plain. The six that are presently defined are informally named, from oldest to youngest, the Colvillian, Bigbendian, Fishcreekian, Wainwrightian, Pelukian, and Simpsonian transgressions (Carter and others, 1986a). Colvillian, Bigbendian, and Fishcreekian deposits are of Pliocene age (Carter and Galloway, 1985; Carter and others, 1986a; Repenning and others, 1987; Nelson and Carter, 1991; Carter and Hillhouse, 1991); the Wainwrightian, Pelukian, and Simpsonian deposits are of Pleistocene age (Carter and others, 1986a).

Colvillian deposits--

The oldest marine deposits of the Gubik Formation that have been recognized on the Arctic Coastal Plain were deposited during the Colvillian transgression (Carter and others, 1986a), which is named for marine deposits exposed in bluffs along the lower Colville River and its tributaries. Colvillian deposits unconformably overlie Cretaceous or lower Tertiary strata throughout the extent of exposure, except in the Marsh Creek region. In the "type" area along the Colville River, where the event was first recognized, Colvillian deposits are locally overlain by 1.0 to 1.5 m of Bigbendian deposits and elsewhere by 11 to 12 m of Quaternary fluvial and eolian sediments (Dinter and others, 1990).

The Colvillian transgression is the first sea-level highstand after the opening of Bering Strait (Carter and others, 1986a), and it is readily distinguished from older Pliocene faunas by the mixture of Pacific and Atlantic faunas. The presence of Pacific-derived taxa thus indicates an age that post-dates the opening of Bering Strait at about 3 Ma (Hopkins, 1967; Gladenkov, 1981; Einarsson and Albertsson, 1988). 3 Ma is a minimum date for the immigration of Pacific-derived taxa, and the date is based on the age of a lava interbedded with sediments containing the first occurrence of Pacific mollusks in Iceland (Gladenkov, 1981); the earliest Pacific immigrants could be as old as 4 Ma (Gladenkov and others, 1991). A minimum age for the Colvillian is provided by the next younger sea-level event, the Bigbendian transgression, dated at 2.48 Ma (Carter and Hillhouse, 1991).

Strontium isotope analyses of marine mollusk shells indicate a minimum age of 1.6 Ma and a maximum age of 4.5 Ma for Colvillian sediments (Kaufman and others, 1990). Brigham-Grette and Carter (1992) estimate the age of the Colvillian transgression as between 2.48 and 2.7 Ma, based on amino acid epimerization rates.

In this paper, the Colvillian transgression is considered to be younger than the opening of Bering Strait and therefore no older than 3 Ma, and older than the Bigbendian transgression and therefore no younger than 2.48 Ma.

Bigbendian deposits--

The Bigbendian transgression is the second oldest sea-level highstand after the opening of Bering Strait (Carter and others, 1986a, 1986b; Carter and Hillhouse, 1991). The Bigbendian transgression is named for marine deposits exposed in bluffs along the big bend of the Colville River near Ocean Point that extend from near the Big Bend benchmark upstream for about 10 km (Brigham-Grette and Carter, in press). Bigbendian deposits unconformably overlie Cretaceous or older Tertiary strata in most places, and overlie a few meters of Colvillian strata in some places (Carter and Hillhouse, 1991). Based on amino acid racemization ratios, Bigbendian deposits also occur in the basal sediments at Fish Creek and along the Miluveach River (Carter and Hillhouse, 1991; Figure 1).

Strontium isotope analyses of marine mollusks indicate a minimum age of 1.9 Ma for Bigbendian deposits (Kaufman and others, 1990). Based on determinations of normal magnetic polarity for Bigbendian sediment and climatic arguments, Carter and Galloway (1985) suggested that the Bigbendian transgression was older than 2.48 Ma.

More recent measurements by Carter and Hillhouse (1992) identified a change from normal to reversed magnetic polarity reversal within Bigbendian sediments, and they noted that stratigraphic evidence and ground temperature history based on amino acid ratios suggest that the polarity reversal represents the Gauss-Matuyama boundary (2.48 Ma). They note that the minimum age for the Bigbendian transgression is constrained by the overlying Fishcreekian transgression, which is dated between 2.14 and 2.48 Ma. Brigham-Grette and Carter (1992) noted that the large difference in amino acid ratios between Colvillian and Bigbendian mollusks may indicate an age difference of as much as 1 m.y. if ground temperatures were as low as those at present. However, if permafrost was absent, then this amount of epimerization could have been accomplished in less than 100,000 years.

In this paper, the Bigbendian transgressionis considered to be younger than the Colvillian transgression and older than or equal to 2.48 Ma.

OSTRACODE ASSEMBLAGES

Qualitative observations of the ostracode assemblages from the Gubik and Sagavanirktok Formations indicate that the samples can be sorted into two groups: one group with Pacific- (indicated by an asterisk in Table 2) and Atlantic-derived taxa (samples from the Gubik, including 81-ACr-6a, 83-EB-187, 83-EB-188, 85-ACr-120, 82-ACr-229, 82-ACr-23, 84-EB-51, 84-EB-54, 84-EB-60, 84-EB-62, 83-ACr-56, 80-AHp-85d, 90-ACr-17a5, 90-ACr-19c1) and one group with Atlantic-derived taxa only (samples from the Sagavanirktok, including 87-ACr-10, 80-AHp-92, 83-EB-68, 83-EB-70, 83-EB-71, 83-EB-86, 83-EB-87, 83-EB-88).

The principal ostracode assemblage examined in this paper is from the lower part of the Gubik Formation. This assemblage was originally described as comprising a distinctive warm water fauna (Repenning and others, 1987; Marincovich and others, 1990) and was believed to represent deposition during the Colvillian transgression. Based on subsequent determinations of amino acid racemization ratios, some deposits previously ascribed to the Colvillian transgression are now thought to have been deposited during the Bigbendian transgression (L.D. Carter, written communication, 1991). Localities in northeast Alaska that contain sediments and ostracode assemblages deposited during the Colvillian and Bigbendian transgressions are shown in Figure 2, and include two main regions: (1) the area around the Colville River, including exposures along the Colville and Kikiakrorak Rivers, the Miluveach River, Fish Creek, and the Kogru River, and (2) the north flank of the Marsh Creek anticline, including exposures along the Katakturuk River, Carter Creek, the Hulahula River, Barter Island, Manning Point, and Pokok Lagoon.

The twenty three samples analyzed in this study contain 61 ostracode species. The assemblage was analyzed using several multivariate statistical procedures to test the empirical observations and to identify additional patterns. Dissimilarity coefficients were employed to semi-quantitatively measure differences between samples. Three coefficients were used: the unweighted Manhattan metric, the equal weight squared standardized Euclidean distance, and the signal to noise squared chord distance. The Manhattan metric coefficient is most influenced by common species, the Euclidean distance coefficient up-weights less common species, and the chord distance coefficient is influenced by less common species, but to a lesser extent than equal weight coefficients (Overpeck and others, 1985). The chord distance coefficient generated a dendrogram that illustrated the most meaningful relationships between samples (Figure 4).

A principal components analysis (PCA) was run to illustrate variance between samples by means of points on axes (eigenvalues). Patterns in the data are represented as clusters of samples, where smaller distances between samples indicate greater commonality of species (Hazel, 1977). The data set analyzed by PCA was plotted on the first three axes, which represent eighty-two percent of the variance. Figures 5 and 6 illustrate plots of the first versus second axes and first versus third axes, respectively.

The multivariate statistical methods employed did not differentiate the samples into distinct groups or clusters, which highlights the similar species composition of the samples. The qualitative differences noted above could not be duplicated using a variey of quanitative techniques.

The dendrogram generated by the dissimilarity coefficient clustered the Barter Island and Manning Point samples into two groups (Figure 4), but the clusters are not effectively sorted from the Gubik samples. The principal components analysis grouped most of the samples into one cluster; a few samples, such as 83-EB-187, plotted far away from the main cluster, but this due to the numerical dominance of one or two species. The pre-Colvillian, Colvillian, and Bigbendian samples cannot be differentiated quantitatively. The overall comparable species composition of the samples is believed to be related due to similar ecological conditions, especially the marine climate, during the late Pliocene.

Ostracode Assemblage of the Sagavanirktok Formation

Samples from unnamed deposits of the Sagavanirktok Formation at Manning Point (83-EB-86, 83-EB-87, 83-EB-88) and Barter Island (83-EB-68, 83-EB-70, 83-EB-71) contain an ostracode assemblage of Arctic affinity that is different from the Nuwok assemblage of the type locality at Carter Creek. The samples from Manning Point and Barter Island included in this study are believed to represent sediments intermediate in age between the uppermost Nuwok at the type locality and the oldest recognized Gubik Formation. Samples shown in figure 3 that are not discussed here are believed to be older and correlate with the Nuwok at the type locality (Brouwers and Marincovich, 1988). The Barter Island-Manning Point assemblage shows similarities both to the faunas of the Colvillian transgression of the Gubik Formation farther west and to the ostracode assemblage of the Nuwok Member at Carter Creek. The most diagnostic indicator of age is the absence of Pacific-derived ostracode genera such as *Palmenella, Robertsonites, Finmarchinella*, and *Cythere*, which suggests a minimum age of > 3 Ma for the pre-Colvillian samples.

Ostracode Assemblage of the Gubik Formation

Ostracode assemblages occurring in the Gubik sediments can be separated into two distinct groups that differ based mostly on water depth and to a lesser extent on paleotemperature. A group of taxa characteristic of shallow water environments occurs at the type area of the Colvillian, and a group of taxa typical of deeper water environments occurs in a number of localities that are north (more seaward) of the type area.

Deep water fauna: The deep water assemblage (deeper inner shelf to middle shelf water depths) has the most diverse fauna, consisting of 50 species (Table 1). The assemblage is remarkably uniform in composition, even among localities that are widely separated geographically. Similar species associations (dominated by *Acanthocythereis dunelmensis, Cytheropteron arcuatum, Elofsonella concinna, Heterocyprideis sorbyana, Krithe glacialis, Palmenella limicola, Paracyprideis pseudopunctillata, Pterygocythereis vannieuwenhuisei, Rabilimis paramirabilis, Robertsonites tuberculatus, Sarsicytheridea macrolaminata*, and *Sarsicytheridea punctillata*) characterize the localities.

The deeper water assemblage contains a fairly high percentage of large-sized, heavy-shelled hemicytherids and trachyleberids; both adults and juveniles are present, but specimens are predominantly adults. The assemblage nearly always includes cytherideids such as *Heterocyprideis, Paracyprideis*, and *Sarsicytheridea*, which imply inner to middle shelf water depths. The presence of a diverse group of *Cytheropteron* species (13 species total in the Colvillian and Bigbendian deposits) is indicative of either a muddy bottom, generally found in more offshore environments or of bottom water temperatures warmer than arctic conditions. High species diversity of *Cytheropteron* today is a measure of cold temperate to subfrigid marine climates (Whatley and Masson, 1979; Brouwers, 1983).

Based on knowledge of the extant species and inferences for the extinct species, the deeper water assemblage indicates a stable paleoenvironment with little fluctuation of the physical-chemical environment, conditions typical of deeper inner shelf to middle shelf water depths. Water temperatures were characteristic of the northern cold temperate to subfrigid marine climatic zones (typified today by the Nova Scotian and Labradorian biogeographic provinces; Hazel, 1970).

Shallow water fauna: The shallow water assemblage occurs only at the proposed type area of the Colvillian transgression (Carter, written communication, 1990), and to date is represented by three samples (90-ACr-17a5, 90-ACr-19a1, 90-ACr-19c1) from two localities (Figure 2). The assemblage shows a lower species diversity than the deeper water assemblage, consisting of 16 taxa (Tables 1, 2). The shallow water assemblage is overwhelmingly dominated by *Hemicythere villosa*, whose presence in Colvillian deposits marks the oldest known occurrence of the species in the Arctic. The other dominant species in the assemblage are *Howeina sp., Rabilimis paramirabilis, Sarsicytheridea bradii* and *Sarsicytheridea macrolaminata.*

The type area is located landward of the "deeper water assemblage" localities, and the profound difference in species composition reflects differences in water depth and probably bottom water temperature. Elofson (1941) recorded *Hemicythere villosa* as deep as 30 m, but noted that it is a phytal species that is more common in shallow water. The other species in the assemblage are not as indicative of depth, although *Semicytherura* and *Sarsicytheridea* are more common in inner shelf environments in the Arctic.

The shallow water assemblage does not contain any nonmarine or low salinity taxa, implying that the environment was probably not strongly affected by seasonal fluctuation of the physical-chemical environment. The assemblage is a mixture of taxa restricted to frigid and subfrigid marine climates (*Cytheromorpha macchesneyi, Cytheretta teshekpukensis, Finmarchinella logani, Loxoconcha* *venepidermoidea, Rabilimis paramirabilis, Sarsicytheridea bradii, Sarsicytheridea macrolaminata*) and taxa that do not range farther north than subfrigid marine climates, such as *Cythere lutea, Hemicythere villosa, Howeina sp.*, and *Tetracytherura sp.*

Colvillian ostracode assemblages are dominated by Atlantic-derived genera (*Sarsicytheridea, Rabilimis, Pterygocythereis, Heterocyprideis*), but Pacific-derived genera have their first appearance in the Arctic in Colvillian sediments (eg., *Finmarchinella,.Hemicythere, Howeina, Palmenella, Robertsonites*). The Colvillian deposits mark the first record in Alaska of the faunal exchange between the Atlantic and Pacific Oceans that occurred after the opening of Bering Strait. Water temperatures were warm enough to allow many genera that were originally temperate in nature to move northward--some of these genera evolved species that now make up the distinct arctic fauna. After the Colvillian and Bigbendian transgressions, sea temperatures began to cool (Carter and others, 1986b; Repenning and others, 1987), causing most species to migrate to lower latitudes and warmer waters.

PALEOTEMPERATURE ANALYSIS

Figure 7 illustrates the temperature range of 37 extant species that occur in the Gubik and Sagavanirktok assemblages. These data are taken from a modern data set of 288 high-latitude shallow marine samples (Cronin and others, 1991) that examined the distribution of 100 ostracode species. The average summer bottom water temperature of the extant species ranges from a low of about 0^{0}C to a high of about 10.5^{0}C, with most species showing average summer bottom temperatures of $1\text{-}4^{0}$C, or as much as 4^{0}C warmer than temperatures today.

Figure 8 shows the bottom temperature of 16 extant ostracode genera that occur both in the Gubik and Sagavanirktok assemblages and in a data set compiled by Cronin and Dowsett (1990). The data in the figure are taken from a modern data set of 100 shallow marine samples from the North Atlantic (Cronin and Dowsett, 1990). The mean February (winter) bottom temperature of the genera ranges from a low of -1^{0}C to a high of about 15^{0}C, with most genera showing winter bottom temperatures of $0\text{-}5^{0}$C, or about 2^{0} to 7^{0}C warmer than temperatures today. The mean August (summer) bottom temperature of the genera ranges from a low of 0°C to a high of 20°C, with most genera showing summer bottom temperatures of 2-5°C, or about 2-5°C warmer than temperatures today.

The presence of a number of endemic arctic species such as *Cytheretta teshekpukensis, Heterocyprideis sorbyana, Paracyprideis pseudopunctillata, Sarsicytheridea bradii, Semicytherura complanata, Loxoconcha venepidermoidea*, and *Pteroloxa venepuncta*, indicate that the Arctic Ocean had undergone some cooling of bottom water temperatures by Colvillian time. However, the presence of several extralimital taxa such as *Jonesia simplex, Pterygocythereis sp.*, and *Munseyella sp.*, found today in marine climates no colder than subfrigid, indicates that water temperatures were not frigid.

Colvillian.--

Figure 7 illustrates the temperature range of 12 extant ostracode species that occur in the type Colvillian samples, with temperature data derived from the modern data set of Cronin and others (1991). The average summer bottom temperatures range from a minimum of 0°C to a maximum of 9°C, with most species indicating 1-3°C, or about 1.5° to 3.5°C warmer than today.

The plot showing the temperature ranges of eight extant genera that occur in the type Colvillian samples (Figure 8) indicates mean winter (February) sea bottom temperatures of -1°C to 13°C, with most genera indicating 0-2°C, or about 2-4°C warmer than today. The mean summer (August) sea bottom temperature ranges from 1°C to 20°C, with an average of 9°C, or about 9°C warmer than temperatures today. The average summer temperature based on the extant genera is very high, which is probably related to the fact that the genus level estimate is based on a North Atlantic sample set. The species level estimate is probably more relevant for Alaska because it uses a higher order taxonomic level and is based on a high-latitude sample set.

Pre-Colvillian of Manning Point and Barter Island

The pre-Colvillian assemblage contains many of the same species as the Gubik assemblages (Table 2), with the notable lack of Pacific-derived taxa. The extant species that occur in the Nuwok samples from Manning Point and Barter Island (eg., *Acanthocythereis dunelmensis, Cytheropteron arcuatum, C. biconvexum, C. paralatissimum, C. pseudomontrosiense, C. simplex, Heterocyprideis sorbyana, Krithe glacialis, Paracyprideis pseudopunctillata, Roundstonia globulifera, Sarsicytheridea macrolaminata, Semicytherura complanata*) are indicative of subfrigid to frigid marine climates (Hazel, 1970; Cronin and others, 1991). The pre-Colvillian ostracode fauna indicates colder water conditions than are inferred for the ostracode assemblages from the type Nuwok Member of the Sagavanirktok Formation (Fouch and others, 1990) and comparable water temperatures to those inferred for the younger Colvillian and Bigbendian assemblages of the Gubik Formation.

Twelve extant species occur in the pre-Colvillian samples, and their modern temperature range is shown in Figure 7. The average summer bottom water temperature of the extant species ranges from a minimum of $0^{\circ}C$ to a maximum of $5^{\circ}C$, with most species falling between $1\text{-}3^{\circ}C$, or $2\text{-}5^{\circ}C$ warmer than today. At the genus level, the pre-Colvillian assemblage (Figure 8) indicates mean February (winter) bottom temperatures of $-1^{\circ}C$ to $16^{\circ}C$, with an average of about $5^{\circ}C$, and mean August (summer) bottom temperatures of $0^{\circ}C$ to $20^{\circ}C$, with an average of $9^{\circ}C$.

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Figure 1.--Geologic map showing distribution of major units in northeast Alaska (adapted from Detterman and others, 1975).

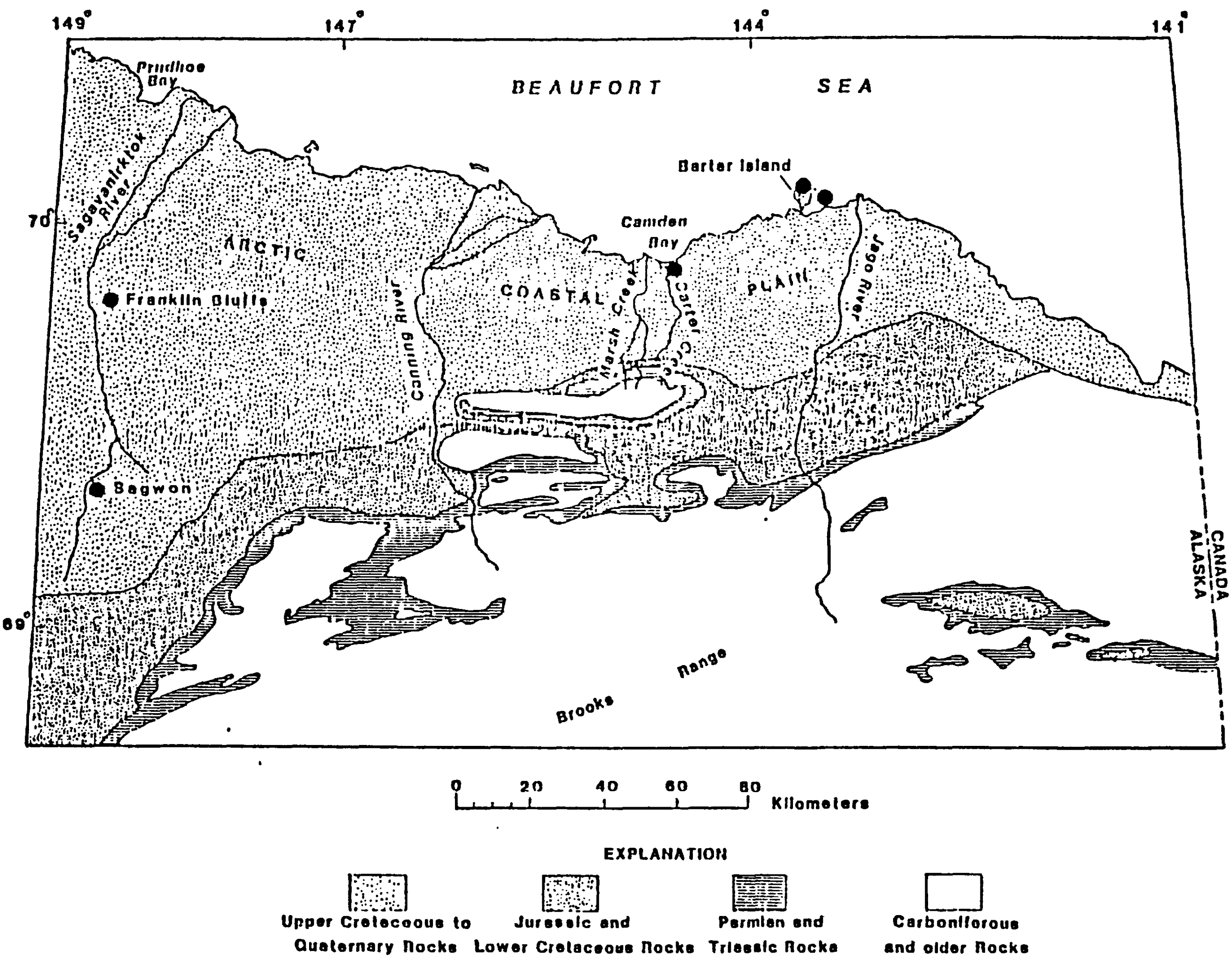

Figure 2.--Map of northeast Alaska showing localities of the upper part of the Sagavanirktok Formation and basal Gubik Formation (Colvillian and Bigbendian) discussed in this report. *1*-Miluveach River (samples 81ACr6A; 82ACr23; 83EB187, 188; 84EB51, 54, 60, 62), *2*-Fish Creek (sample 85ACr120), *3*-Kogru River (sample 85ACr229), *4*-Colville River (samples 90ACr17a5, 19a1, 19c1), *5*-North flank of Marsh anticline (sample 83ACr56), *6*-Carter Creek (sample 87ACr10), *7*-Barter Island (samples 83EB68, 70, 71), *8*-Manning Point (samples 83EB86, 87, 88), *9*-Pokok Lagoon (samples 90AHp85d, 92).

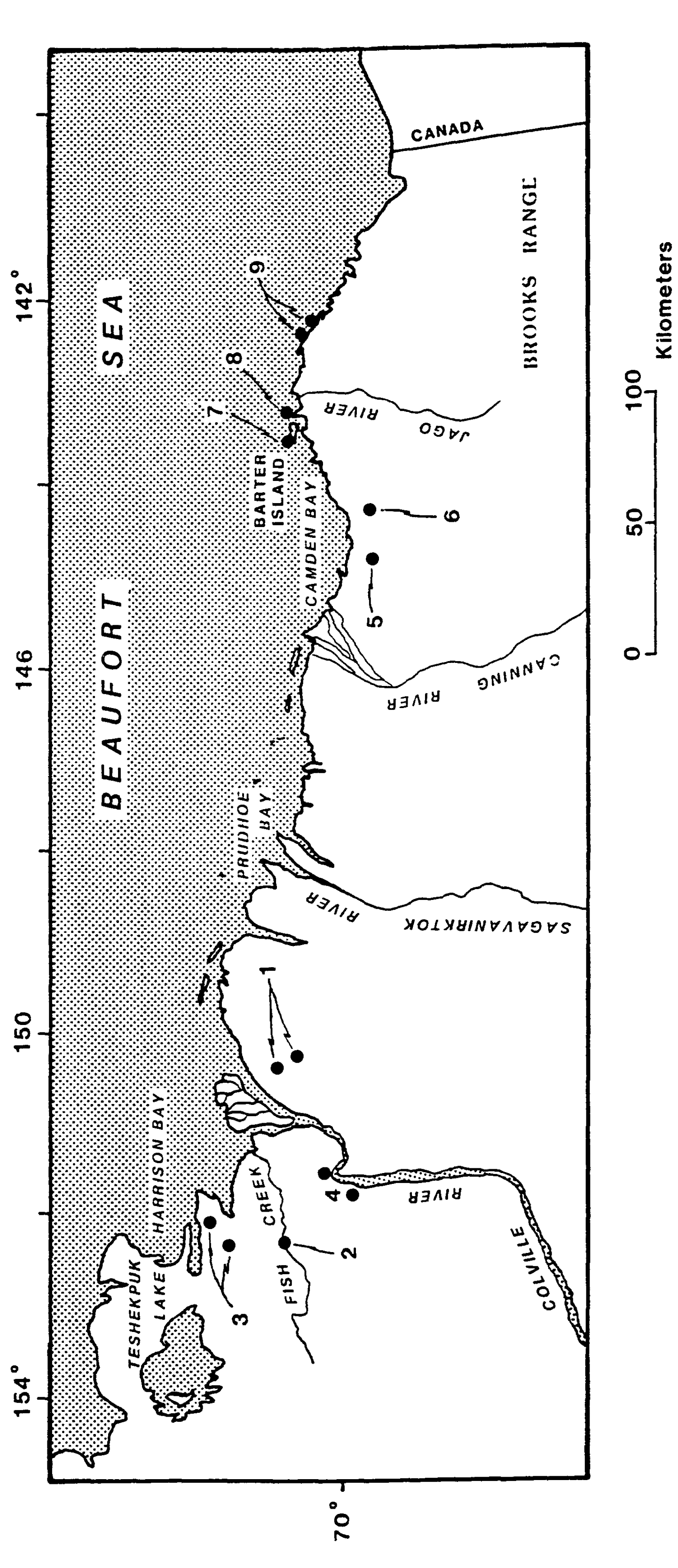
BEAUFORT SEA
CANADA
BROOKS RANGE
142°
146
150
154°
70°
BARTER ISLAND
CAMDEN BAY
JAGO RIVER
CANNING RIVER
PRUDHOE BAY
SAGAVANIRKTOK RIVER
HARRISON BAY
TESHEKPUK LAKE
FISH CREEK
COLVILLE RIVER
1
2
3
4
5
6
7
8
9
0
50
100
Kilometers

Figure 3.–Map showing location of samples collected from unnamed deposits of the Sagavanirktok Formation at Barter Island and Manning Point. Samples 83EB-68, 70, 71, 86, 87, and 88 are discussed here; samples 83EB-72, 73, 74, 75, 77, and 83 represent presumed older deposits of the Sagavanirktok Formation.

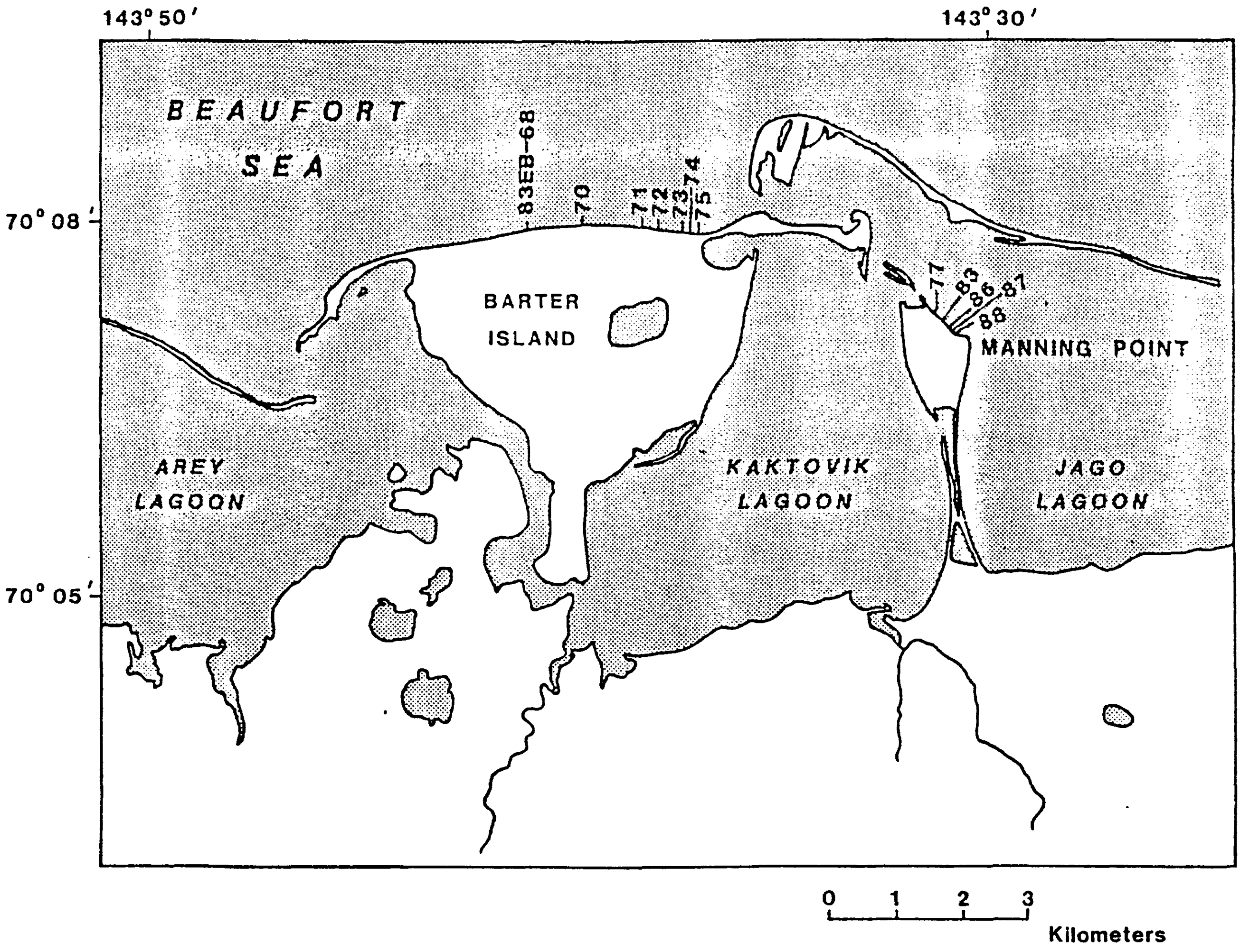

Figure 4.--Plot of the dendrogram generated by a cluster analysis using the chord distance dissimilarity coefficient. Shaded area indicates samples from Barter Island and Manning Point.

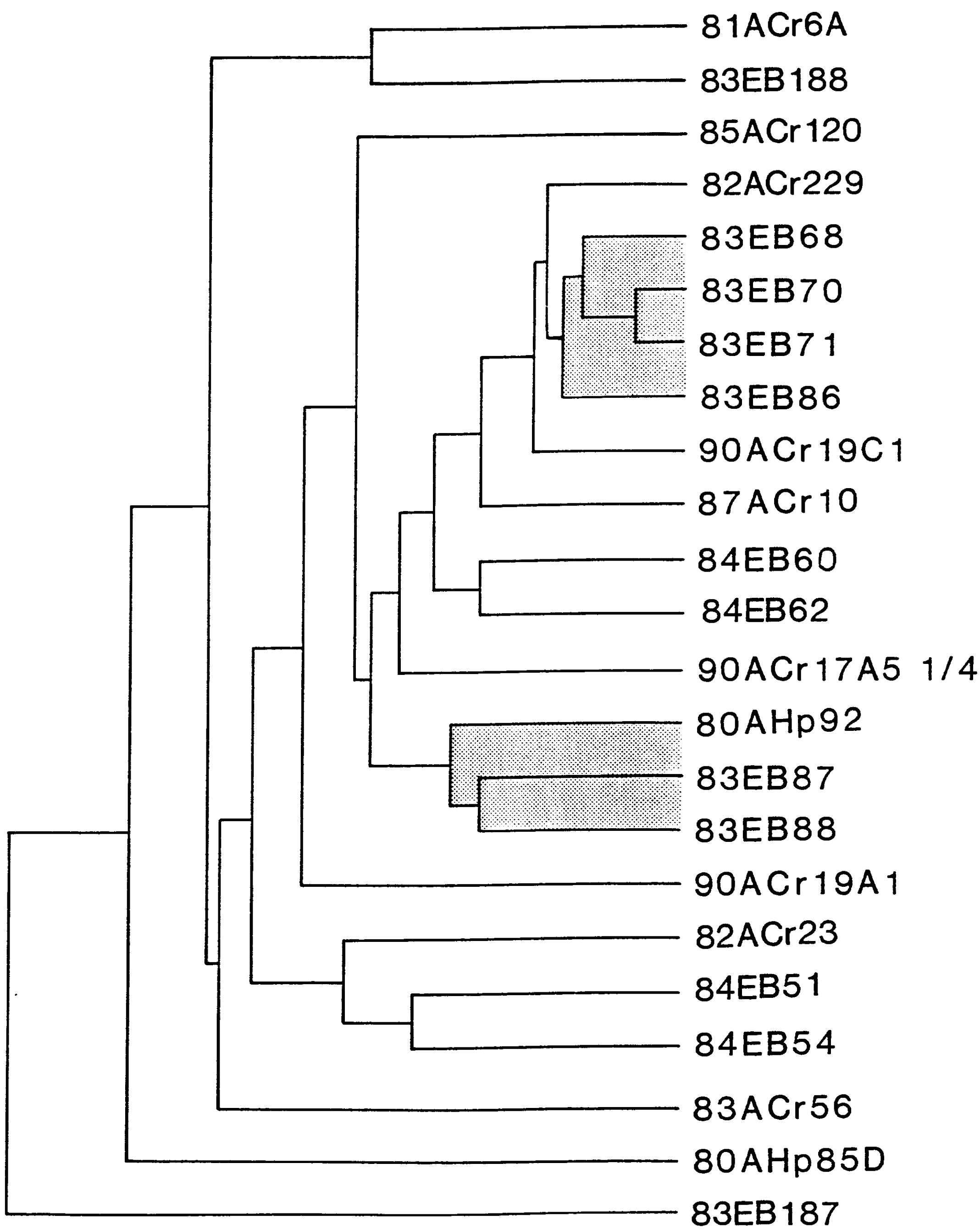

Figure 5.--Plot of the first and second principal components of the late Pliocene ostracode faunas studied.

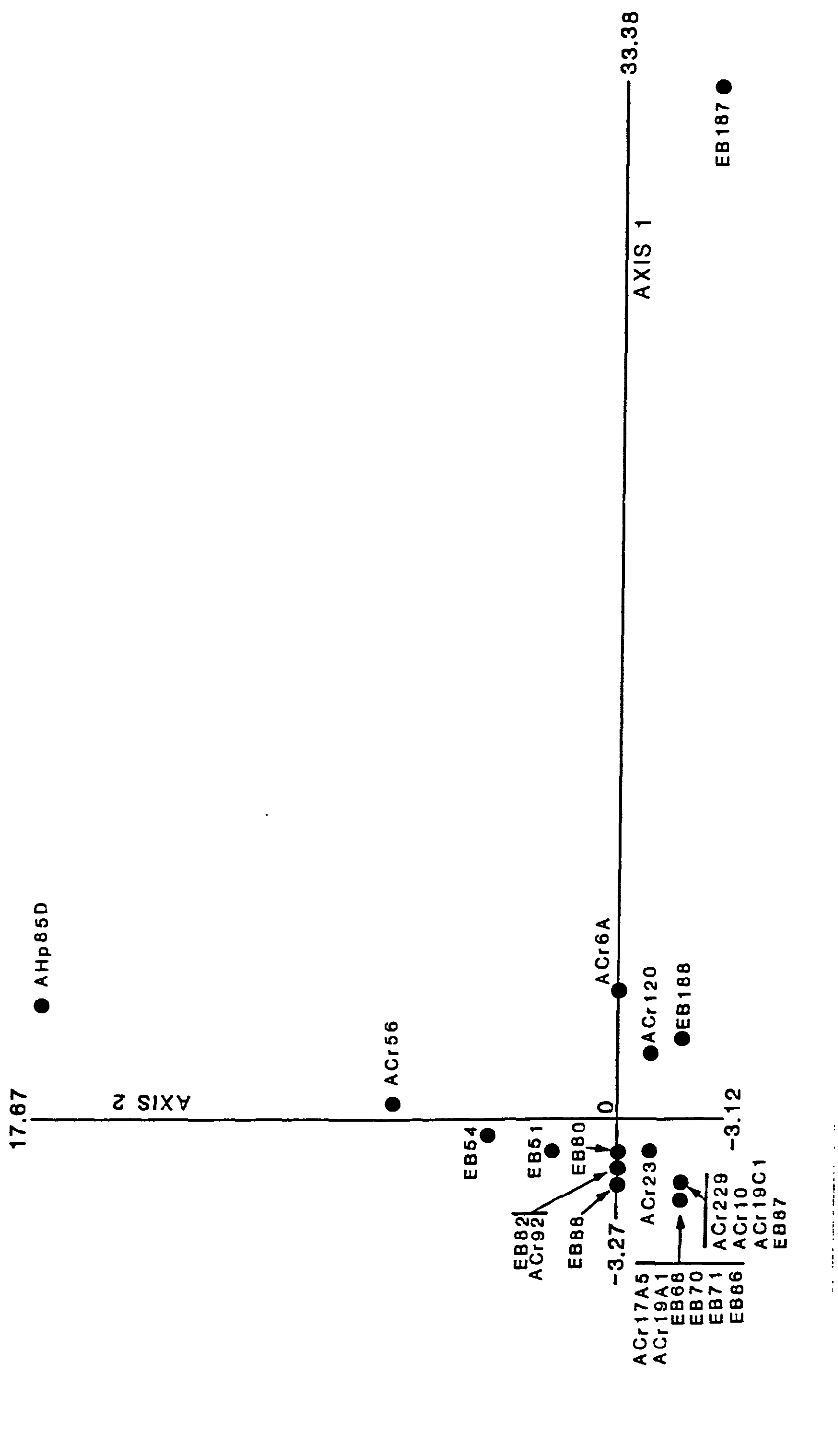

Figure 6.--Plot of the first and third principal components of the late Pliocene ostracode faunas studied.

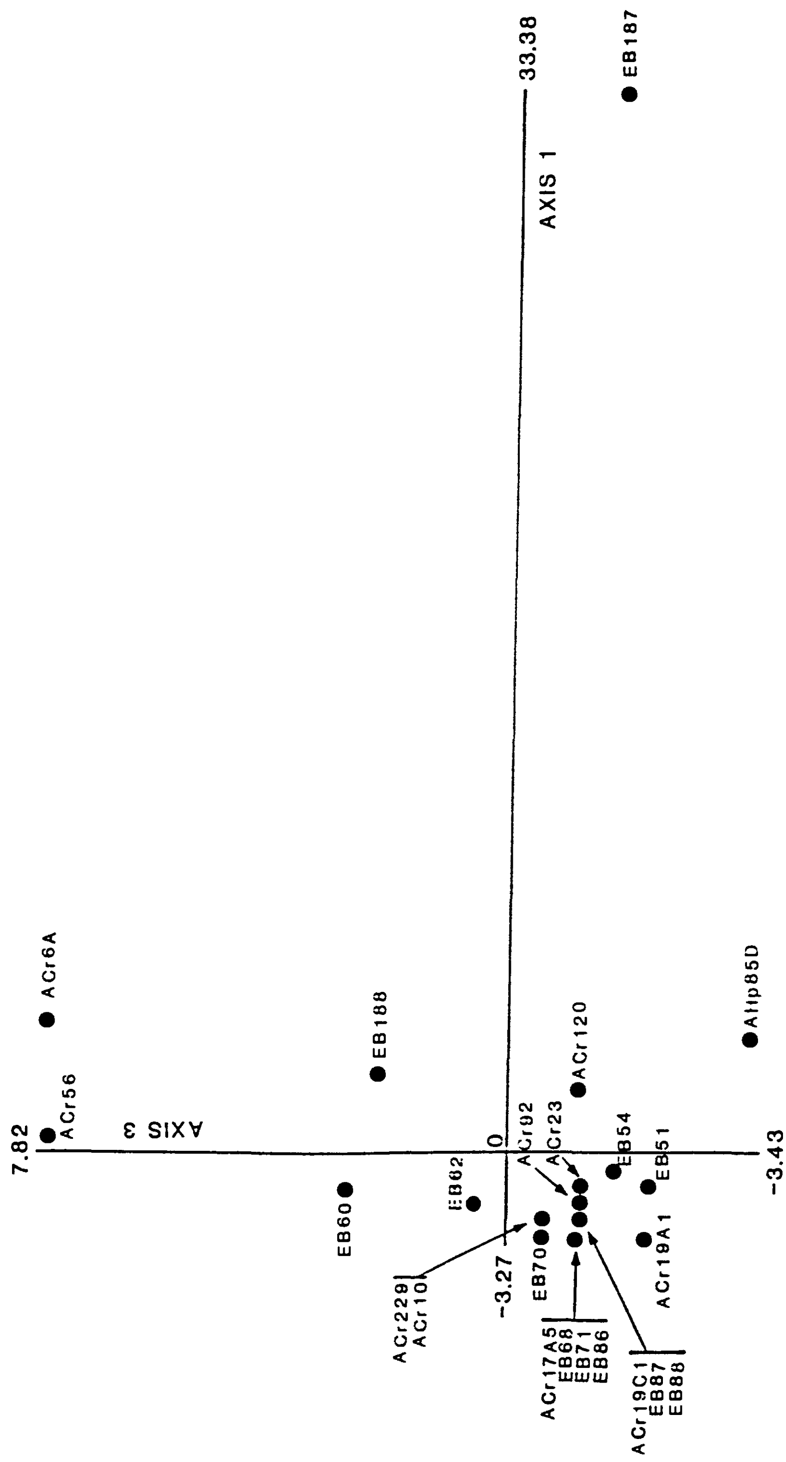

Figure 7.--Average summer and survival temperature ranges of 37 extant ostracode species occurring both in the Gubik and Nuwok samples and in the data set compiled by Cronin and others, 1991, and unpublished data. The data set consists of 100 ostracode species occurring in 288 modern samples from northern high latitude sites. Solid line represents the temperature range of a species based on the high latitude sites (some species extend further south). Average summer sea bottom temperature marked by a filled circle.

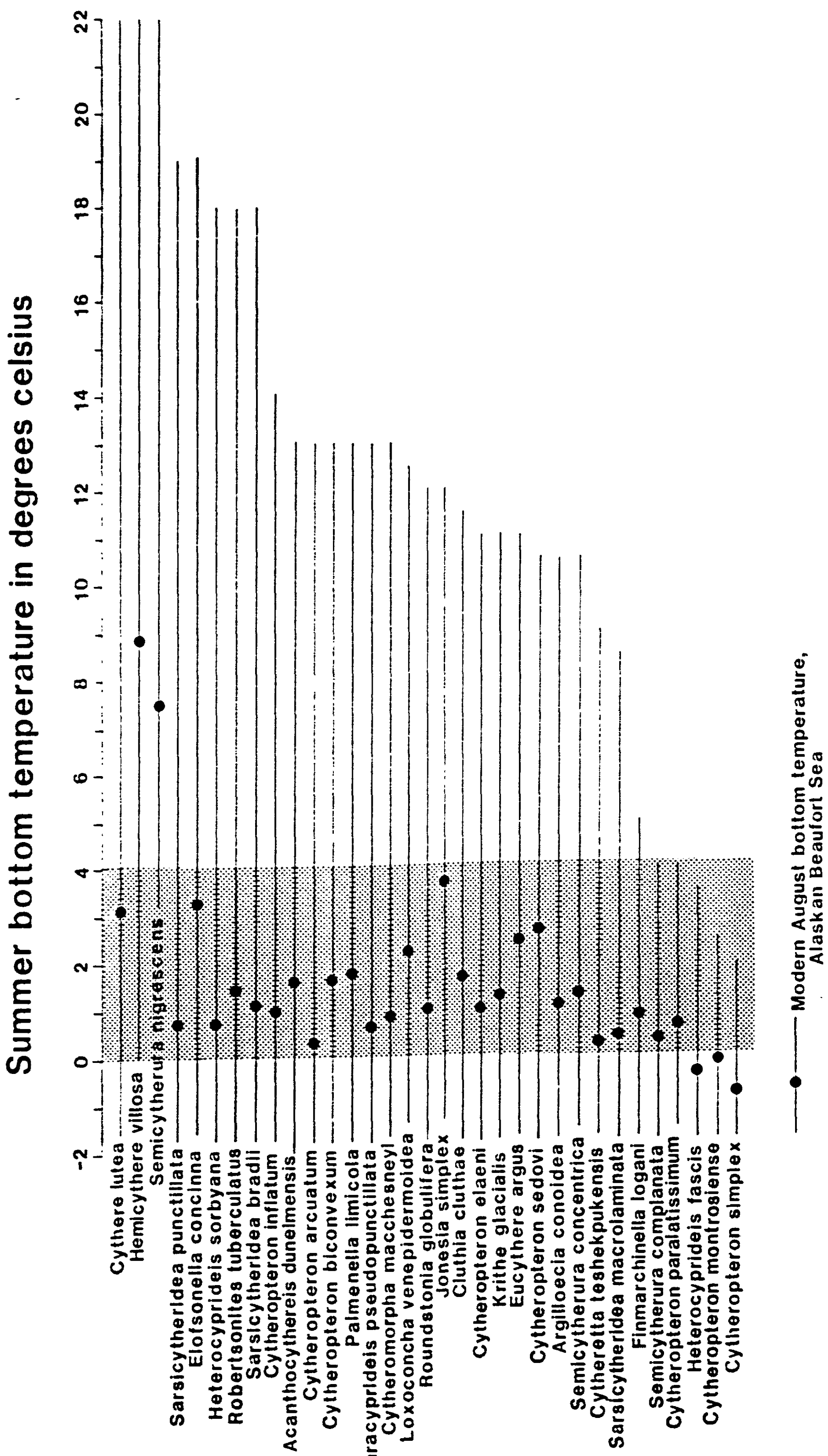
Summer bottom temperature in degrees celsius
-2
0
2
4
6
8
10
12
14
16
18
20
22
Cythere lutea
Hemicythere villosa
Semicytherura nigrescens
Sarsicytheridea punctillata
Elofsonella concinna
Heterocyprideis sorbyana
Robertsonites tuberculatus
Sarsicytheridea bradii
Cytheropteron inflatum
Acanthocythereis dunelmensis
Cytheropteron arcuatum
Cytheropteron biconvexum
Palmenella limicola
Paracyprideis pseudopunctillata
Cytheromorpha macchesneyi
Loxoconcha venepidermoidea
Roundstonia globulifera
Jonesia simplex
Cluthia cluthae
Cytheropteron elaeni
Krithe glacialis
Eucythere argus
Cytheropteron sedovi
Argilloecia conoidea
Semicytherura concentrica
Cytheretta teshekpukensis
Sarsicytheridea macrolaminata
Finmarchinella logani
Semicytherura complanata
Cytheropteron paralatissimum
Heterocyprideis fascis
Cytheropteron montrosiense
Cytheropteron simplex
Modern August bottom temperature, Alaskan Beaufort Sea

Figure 8.--Mean- and survival-temperature range, based on latitudinal distribution, for 16 extant ostracode genera occurring both in the Gubik and Nuwok and in the Cronin and Dowsett (1990) data set. Filled triangle represents mean February bottom temperature (ave FBT); filled circle represents mean August bottom temperature (ave ABT).

GENUS LEVEL TEMPERATURE RANGES

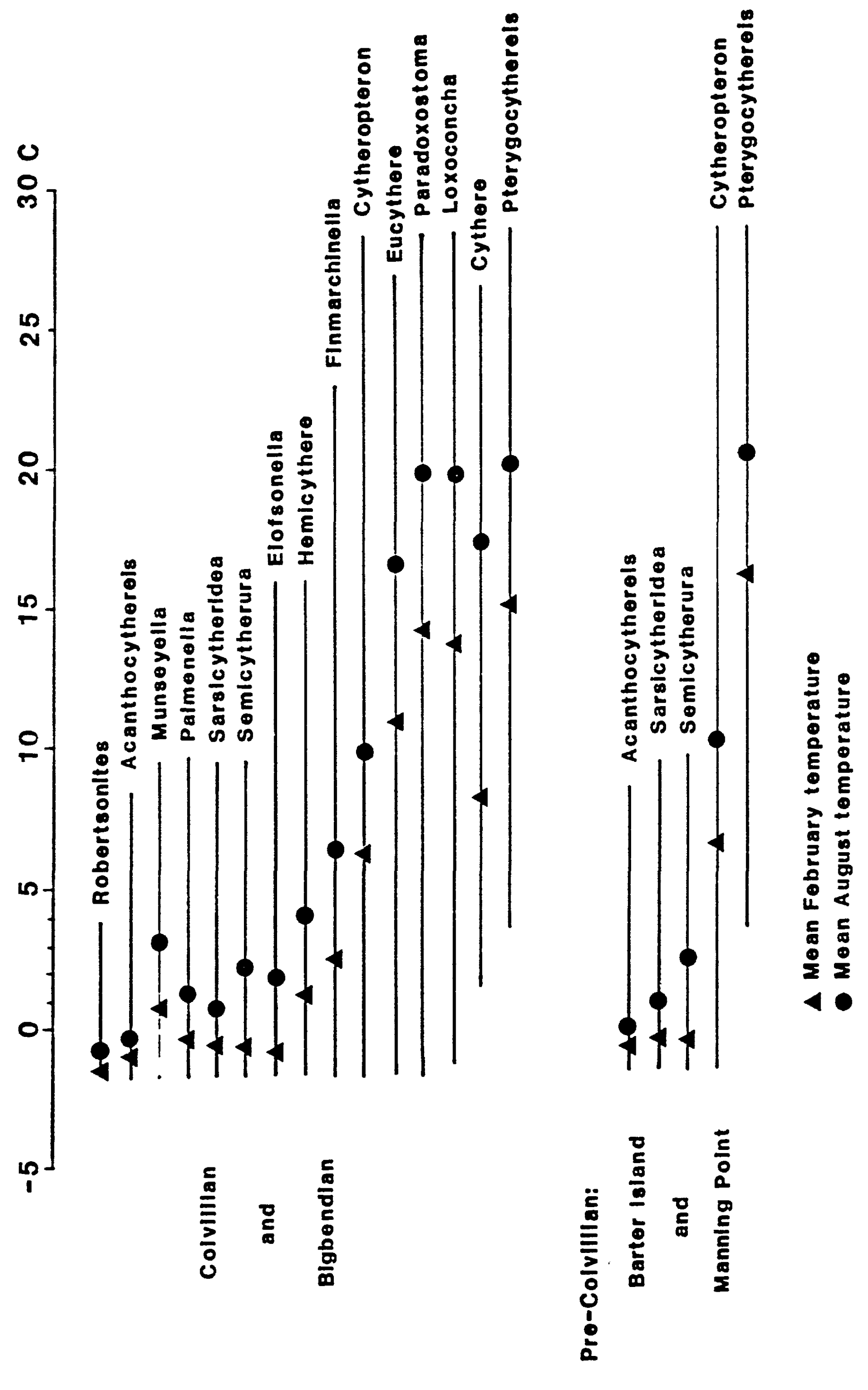

Table 1-- Occurrence chart of ostracode species in samples of the Sagavanirktok and Gubik Formations. Counts refer to number of valves; adults and juveniles are combined. Samples 90ACr-17a5, 19a1, and 19c1 represent the shallow water fauna; the remaining samples represent the deep water fauna.

	81ACr6A	83EB187	83EB188	85ACr120	85ACr229	82ACr23	84EB51	84EB54	84EB60	84EB62	87ACr10	83ACr56	80AHp85D	80AHp92	90ACr17A5 1/4	90ACr19A1	90ACr19C1	83EB68	83EB70	83EB71	83EB86	83EB87	83EB88
Acanthocythereis duneimensis	4	25	2	5		5	7	4		2		1	14	1								2	3
Argilloecia conoicea						3	3				4												
Argilloecia sp. A																					2		
Argilloecia sp. B								6															
Bythocythere sp. B						2																	
Cluthia cluthae						4																	
Cythere lutea																3							
Cytheretta teshekpukensis											2	31				2							
Cytheromorpha macchesneyi	2	1				2	4				4						1						
Cytheromorpha sp. A							9	11	3														
Cytheromorpha sp. B	3					11					1					1						3	2
Cytheropteron arcuatum	3	6				2	4	1						4								1	4
Cytheropteron aff. C. arcuatum																							1
Cytheropteron biconvexum																							1
Cytheropteron chamolainum		1						7	7	1	4	6			5								
Cytheropteron elaeni	5	4								1				1									
Cytheropteron inflatum							3	1															
Cytheropteron latissimum		3																					
Cytheropteron montrosiense	1												1										
Cytheropteron paralatissimum	5													4								1	7
Cytheropteron pseudomontrosiense	1																					1	1
Cytheropteron sedovi								1															
Cytheropteron simplex	1						2							8								8	11
Cytheropteron sp. A		3			2										1								3
Cytheropteron sp. B															3								
Cytheropteron sp. C																		1					
Cytheropteron sp. D															1								
Cytheropteron sp.																		1					
Elofsonia sp.						1																	
Elofsonella concinna	27	33	28	1		8	3	10					2										
Eucythere argus						5	2	3			1		2	1	1								
Finmarchinella logani				1											3								
Hemicythere villosa															46	3							
Heterocyprideis fascis		119		14		1							3										
Heterocyprideis sorbyana	12	25	3	1	1	5	13	3	1			6	33					1				2	2
Howeina sp. A															22								
Jonesia simplex				1		3	2																
Krithe glacialis	9		4								3		1	25					2	1		8	16
Loxoconcha venepidermoidea							1				1					3							
Loxoconcha sp. A	3	1	2			2																	
Munseyella sp. A				2																			
Palmenella limicola	2	2	1			8		10	2				8										
Paracyprideis pseudopunctillata	35	26	7	5	3				20	8		42	1						2	1			
Paracyprideis aff. P. pseudopunctillata						13	18	20	2														
Paradoxostoma sp.									1		2					1							
Pteroloxa venepuncta	3																						
Pterygocythereis vanniewenhuisei	11	10	3			1	7	15				4	28	9					1				
Rabilimis paramirabilis		20		10	1	3	10	19	6	7		37	80	9		3							10
Rabilimis aff. R. paramirabilis																					4		
Rabilimis sp.															1								
Robertsonites tuberculatus	20	17	9	1	1	4	6	5		1		2	27										
Robertsonites sp. A		1																					
Roundstonia globulifera																							1
Sarsicytheridea bradii	14	2							3	3			7		11	3							
Sarsicytheridea macrolaminata	22	57	15	7	1	9	2	3	8	1	4		7	6	1		3					2	
Sarsicytheridea punctillata	12	90	21	13	2				2														
Sarsicytheridea sp. A														1									1
Semicytherura concentrica	1					2		2	3														
Semicytherura complanata	1						3	3															1
Semicytherura nigrescens															1								
Tetracytherura sp.															1								1

Table 2-- Occurrence chart of species in samples of the Gubik Formation (Colvillian sites other than the type locality and Bigbendian sites), the type Colvillian, and the pre-Colvillian at Manning Point and Barter Island. Note that an asterisk (*) denotes a Pacific-derived taxon.

Species	Gubik (Colv, Bigb)	Type Colvillian	Pre-Colvillian (Barter, Manning)
Acanthocythereis dunelmensis	X		X
Argilloecia conoidea	X		
Argilloecia sp. A			X
Argilleocia sp. B	X		
Bythocythere sp. B	X		
Cluthia cluthae	X		
Cythere lutea		*	
Cytheretta teshekpukensis	X		X
Cytheromorpha macchesneyi	X		X
Cytheromorpha sp. A	X		
Cytheromorpha sp. B	X		X
Cytheropteron arcuatum	X		X
Cytheropteron aff. arcuatum			X
Cytheropteron biconvexum			X
Cytheropteron champlainum	X		X
Cytheropteron elaeni	X		
Cytheropteron inflatum	X		
Cytheropteron latissimum	X		
Cytheropteron montrosiense	X		
Cytheropteron paralatissimum	X		X
Cytheropteron pseudomontrosiense	X		X
Cytheropteron sedovi	X		
Cytheropteron simplex	X		X
Cytheropteron sp. A	X	X	X
Cytheropteron sp. B	X		X
Cytheropteron sp. C			X
Cytheropteron sp. D		X	
Elofsonia sp.	X		
Elofsonella concinna	X		
Eucythere argus	X		X
Finmarchinella logani	*		*
Hemicythere villosa		X	
Heterocyprideis fascis	X		
Heterocyprideis sorbyana	X		X
Howeina sp.		*	
Jonesia simplex	X		
Krithe glacialis	X		X
Loxoconcha venepidermoidea	X		X
Loxoconcha sp. A	X		
Munseyella sp. A	X		
Palmenella limicola	*		
Paracyprideis pseudopunctillata	X		X
Paracypri aff pseudopunctillata	X		
Paradoxostoma sp.	X		X

Pteroloxa venepuncta	X		
Pterygocythereis vannieuwenhuisei	X		X
Rabilimis paramirabilis	X	X	X
Rabilimis aff paramirabilis		X	
Rabilimis sp.		X	
Robertsonites tuberculatus	*		
Robertsonites sp. A	*		
Roundstonia globulifera			X
Sarsicytheridea bradii	X		X
Sarsicytheridea macrolaminata	X	X	X
Sarsicytheridea punctillata	X		
Sarsicytheridea sp. A	X		X
Semicytherura concentrica	X		
Semicytherura complanata	X		X
Semicytherura nigrescens		X	
Tetracytherura sp.		X	X

PLATE 1

All figures are scanning electron photomicrographs.

White bar equals 100 micrometers.

Figure

1. *Rabilimis paramirabilis* (Swain, 1963), sample 83-EB-187, female left valve.
2. *Rabilimis sp.*, sample 90-ACr-17A5, male right valve.
3. *Rabilimis aff. R. paramirabilis* (Swain, 1963), sample 83-EB-186, female left valve.
4. *Robertsonites sp. A*, sample 83-EB-187, male right valve.
5. *Acanthocythereis dunelmensis* (Norman, 1865), sample 85-ACr-120, female left valve.
6. *Robertsonites tuberculatus* (Sars, 1866), sample 80-AHp-85d, female right valve.
7. *Pterygocythereis vannieuwenhuisei* Brouwers, 1987, sample 83-EB-187, female left valve.
8. *Elofsonella concinna* (Jones, 1857), sample 81-ACr-6a, male left valve.

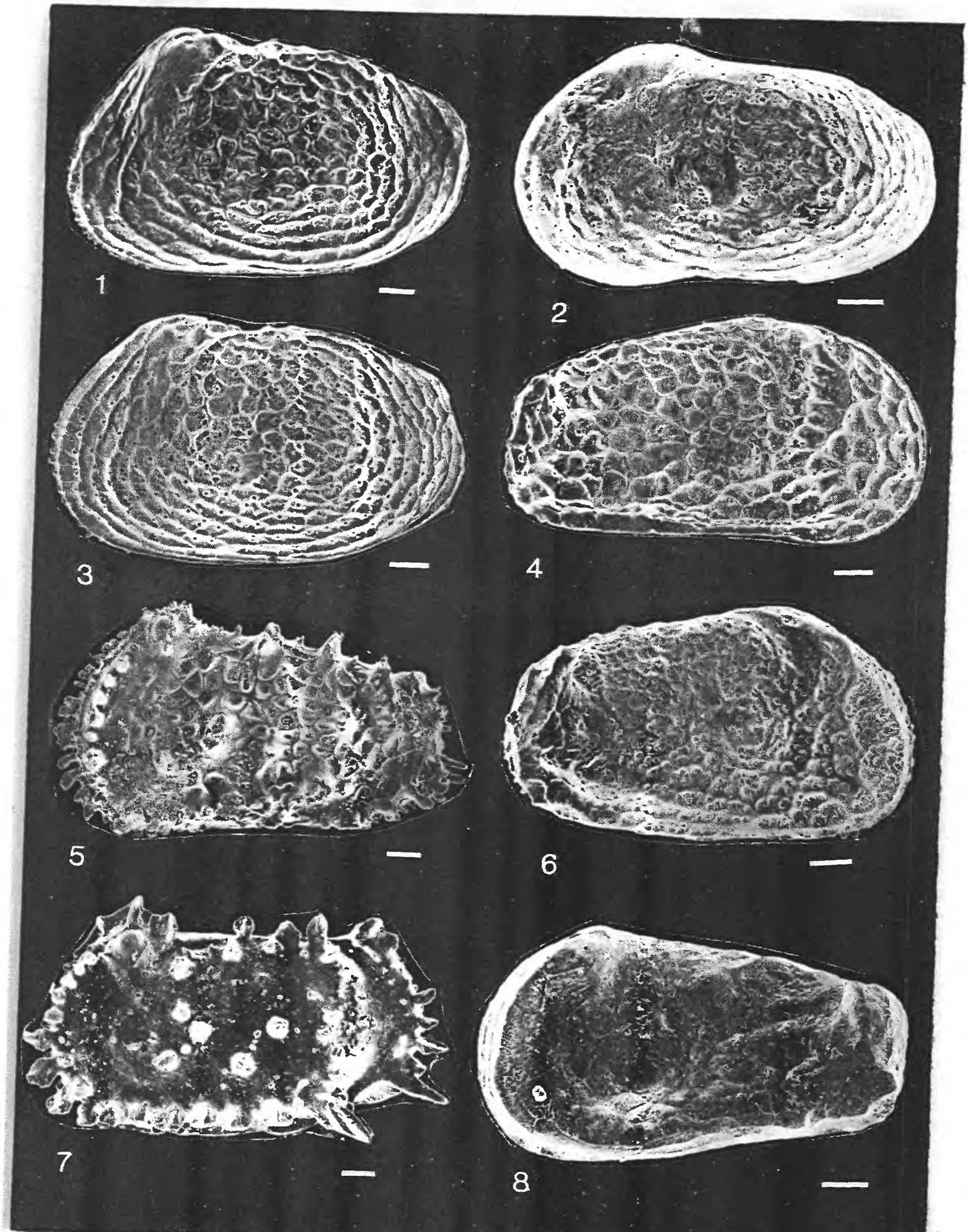
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PLATE 2

All figures are scanning electron photomicrographs.

White bar equals 100 micrometers.

FIGURE

1. *Heterocyprideis sorbyana* (Jones, 1857), sample 81-ACr-6a, male left valve.

2. *Heterocyprideis fascis* (Brady and Norman, 1889), sample 83-EB-187, female right valve.

3. *Cytheretta teshekpukensis* Swain, 1963, sample 83-ACr-56, female left valve.

4. *Hemicythere villosa* (Sars, 1866), sample 90-ACr-17A5 1/4, female left valve.

5. *Finmarchinella logani* (Brady and Crosskey, 1871), sample 90-ACr-17A5 1/4, female left valve.

6. *Cythere lutea* Mueller, 1785, sample 90-ACr-17A5 1/4, right valve.

7. *Palmenella limicola* (Norman, 1865), sample 82-ACr-23, female left valve.

8. *Munseyella sp. A*, sample 85-ACr-120, left valve.

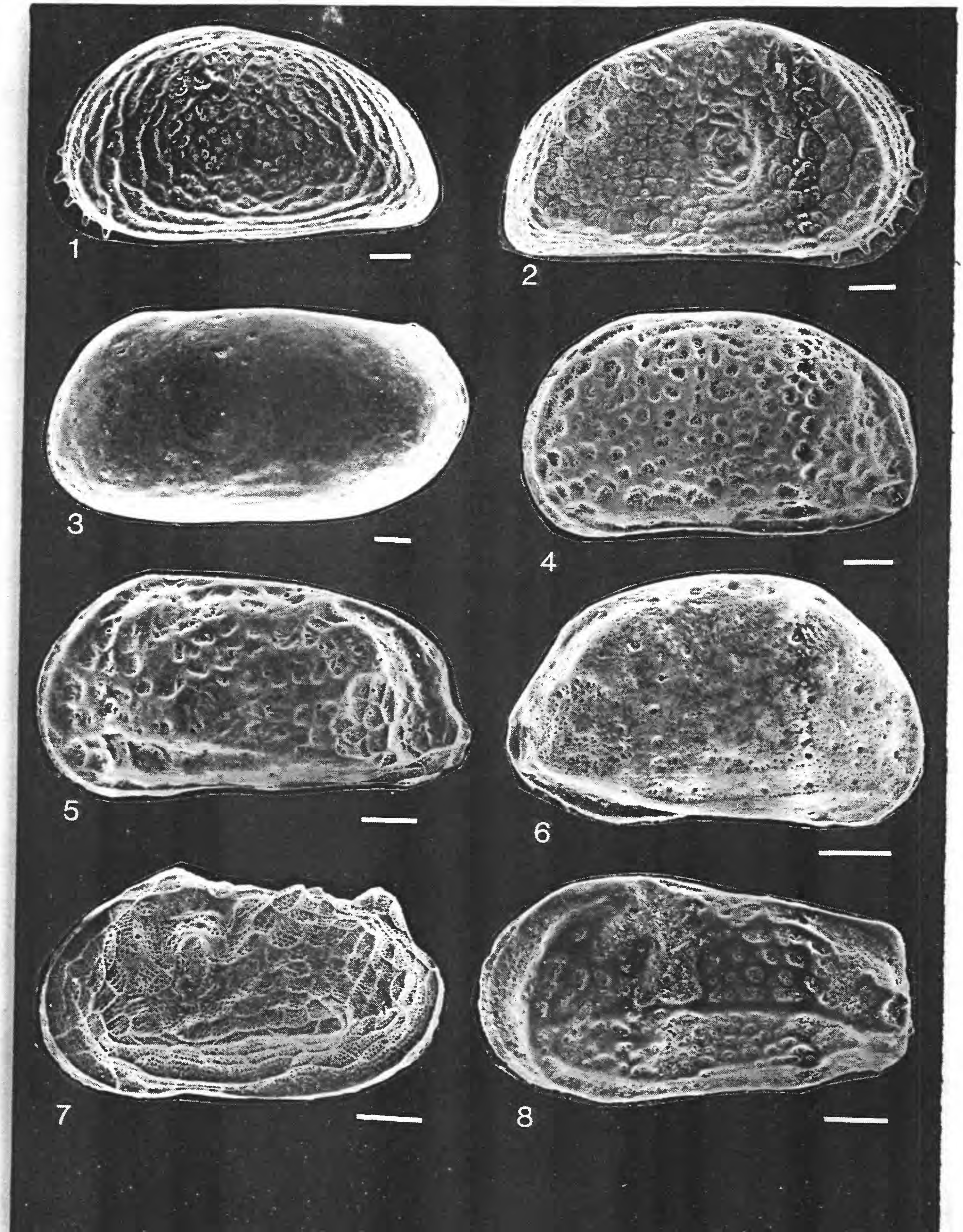
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PLATE 3

All figures are scanning electron photomicrographs.

White bar equals 100 micrometers.

FIGURE

1. *Sarsicytheridea bradii* (Norman, 1865), sample 81-ACr-6a, left valve.
2. *Sarsicytheridea macrolaminata* (Elofson, 1939), sample 81-ACr-6a, left valve.
3. *Sarsicytheridea punctillata* (Brady, 1865), sample 81-ACr-6a, female left valve.
4. *Sarsicytheridea sp. A*, sample 83-EB-88, female left valve.
5. *Paracyprideis aff. P. pseudopunctillata* Swain, 1963, sample 84-EB-54, right valve.
6. *Paracyprideis pseudopunctillata* Swain, 1963, sample 81-ACr-6a, left valve.
7. *Krithe glacialis* Brady, Crosskey and Robertson, 1874, sample 81-ACr-6a, left valve.
8. *Krithe glacialis* Brady, Crosskey and Robertson, 1874, sample 82-ACr-23, right valve.

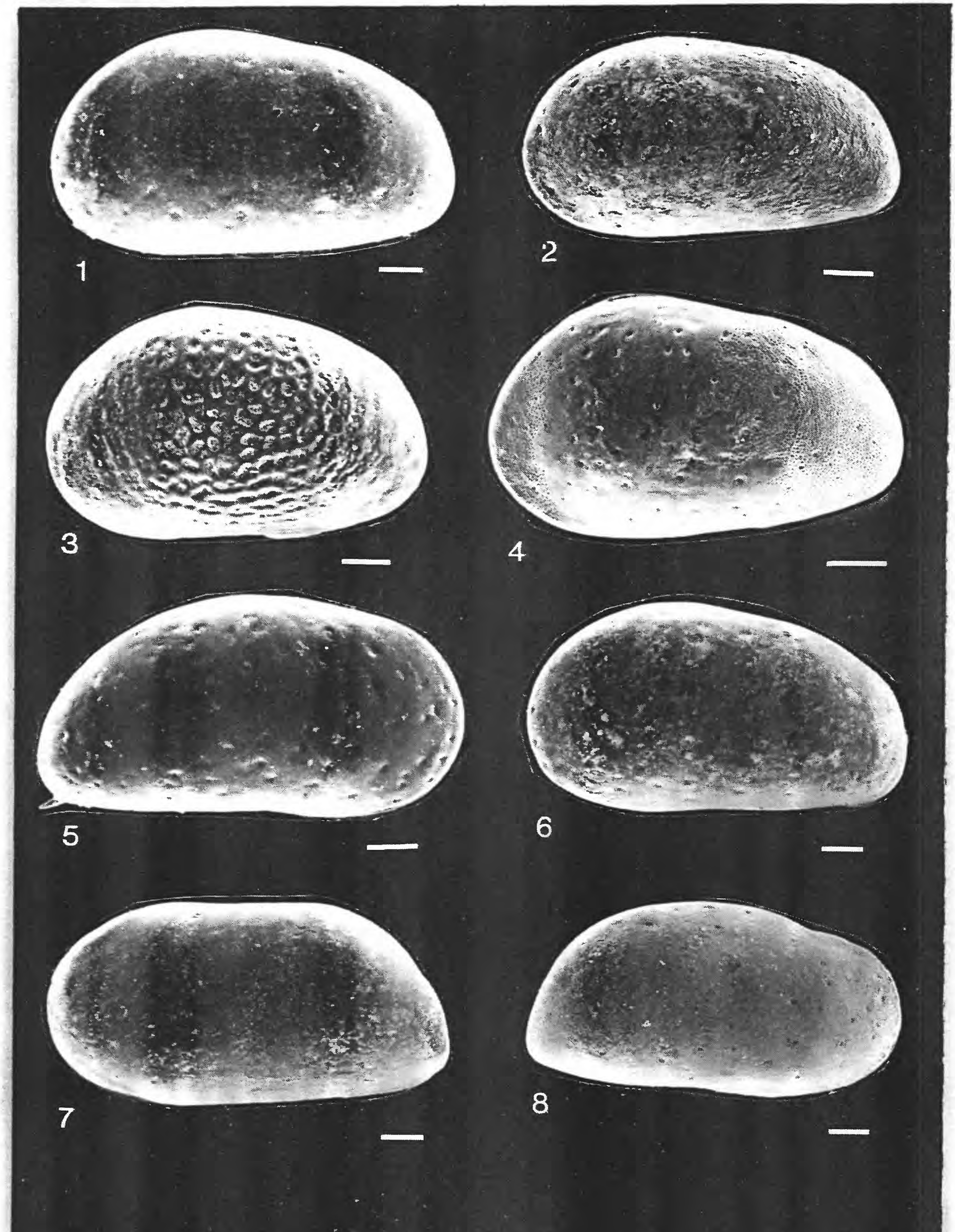
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PLATE 4

All figures are scanning electron photomicrographs.

White bar equals 100 micrometers.

FIGURE

1. *Jonesia simplex* (Norman, 1865), sample 84-EB-51, left valve.
2. *Bythocythere sp. A*, sample 82-ACr-23, left valve.
3. *Argilloecia conoidea* Sars, 1923, sample 84-EB-54, left valve.
4. *Argilloecia sp. A*, sample 83-EB-86, right valve.
5. *Argilloecia sp. B*, sample 84-EB-54, left valve.
6. *Eucythere argus* (Sars, 1866), sample 90-ACr-17A5 1/4, female left valve.
7. *Loxoconcha venepidermoidea* Swain, 1963, sample 90-ACr-19A1, left valve.
8. *Loxoconcha sp. A*, sample 81-ACr-6a, left valve.
9. *Loxoconcha venepidermoidea* Swain, 1963, sample 87-ACr-10, right valve.

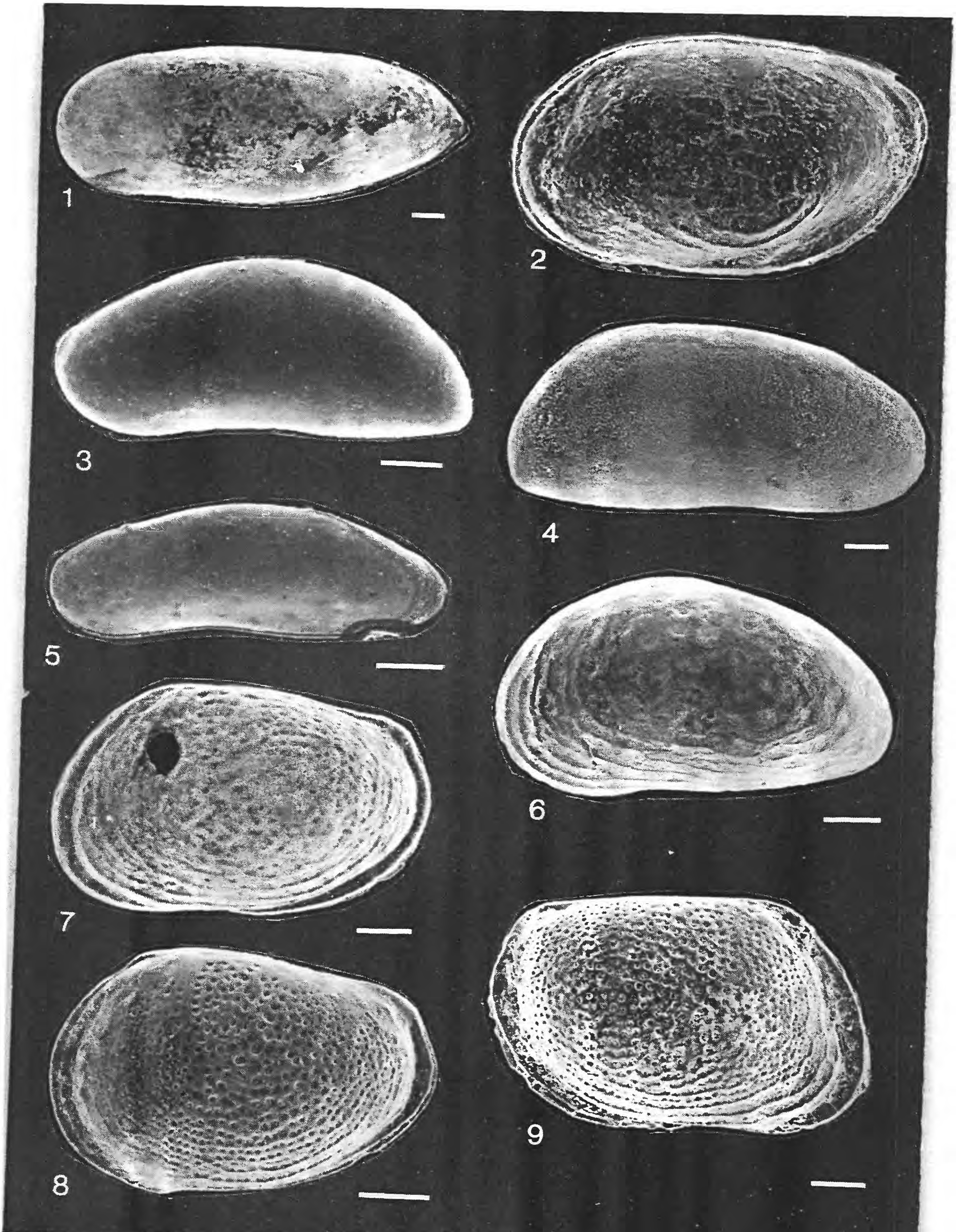
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PLATE 5

All figures are scanning electron photomicrographs.

White bar equals 100 micrometers.

FIGURE

1. *Roundstonia globulifera* (Brady, 1868), sample 83-EB-88, left valve.
2. *Cluthia cluthae* (Brady, Crosskey and Robertson, 1874), sample 84-EB-54, right valve.
3. *Tetracytherura sp.*, sample 90-ACr-17A5 1/4, right valve.
4. *Cytheromorpha macchesneyi* (Brady and Crosskey, 1871), sample 90-ACr-17A5 1/4, male left valve.
5. *Cytheromorpha sp. A*, sample 81-ACr-6a, female left valve.
6. *Pteroloxa venepuncta* Swain, 1963, sample 81-ACr-6a, right valve.
7. *Cytheromorpha sp. B*, sample 83-EB-87, right valve.
8. *Howeina sp. A*, sample 90-ACr-17A5 1/4, right valve.

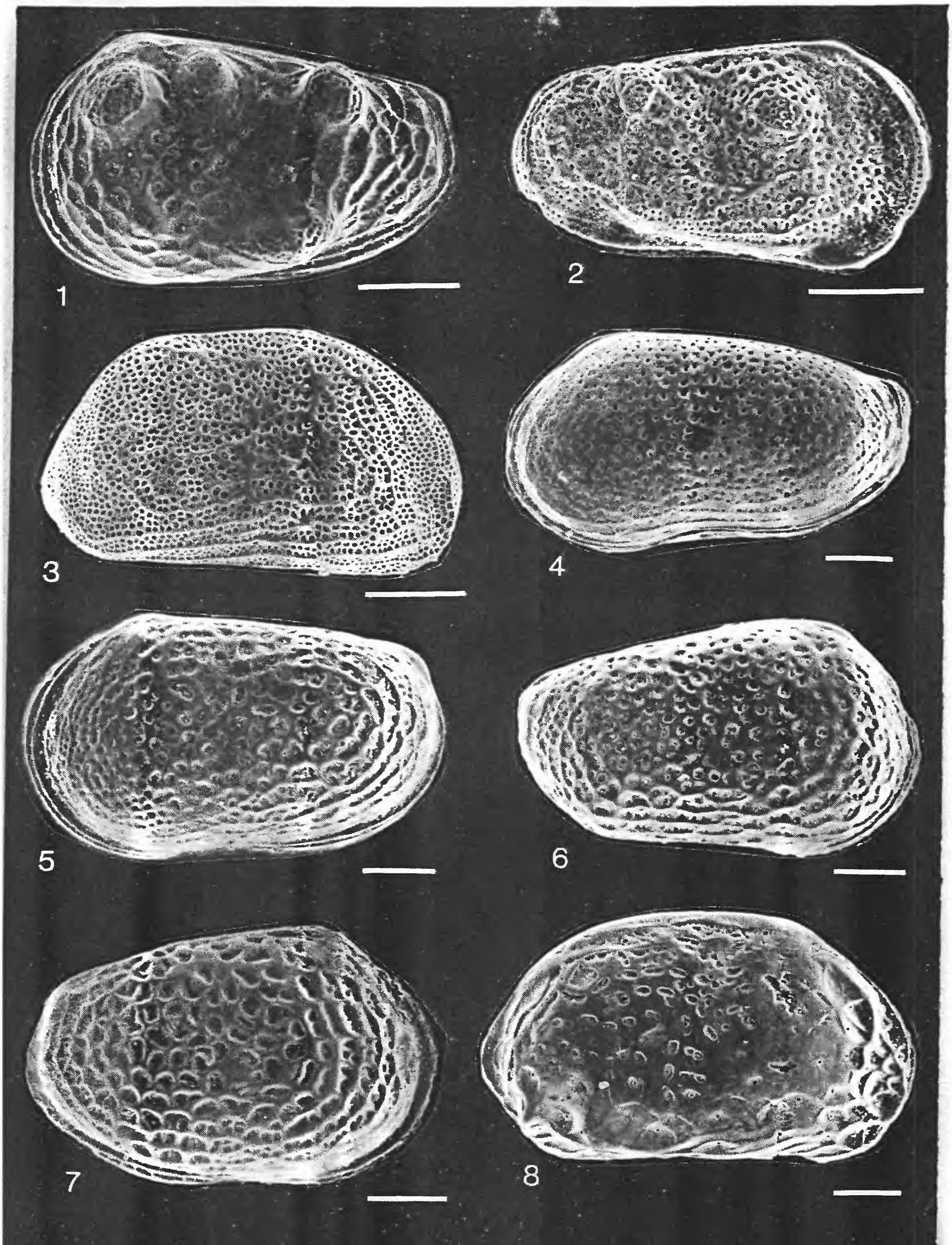
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PLATE 6

All figures are scanning electron photomicrographs.

White bar equals 100 micrometers.

FIGURE

1. *Semicytherura concentrica* (Brady, Crosskey and Robertson, 1874), sample 81-ACr-6a, right valve.
2. *Semicytherura complanata* (Brady, Crosskey and Robertson, 1874), sample 84-EB-51, right valve.
3. *Semicytherura concentrica* (Brady, Crosskey and Robertson, 1874), sample 84-EB-54, right valve.
4. *Semicytherura nigrescens* (Baird, 1838), sample 90-ACr-17A5 1/4, right valve.
5. *Elofsonia sp.*, sample 84-EB-51, left valve.
6. *Cytheropteron arcuatum* Brady, Crosskey and Robertson, 1874, sample 81-ACr-6a, right valve.
7. *Cytheropteron paralatissimum* Swain, 1963, sample 83-EB-88, right valve.
8. *Cytheropteron aff. C. arcuatum* Brady, Crosskey and Robertson, 1874, sample 83-EB-88, left valve.

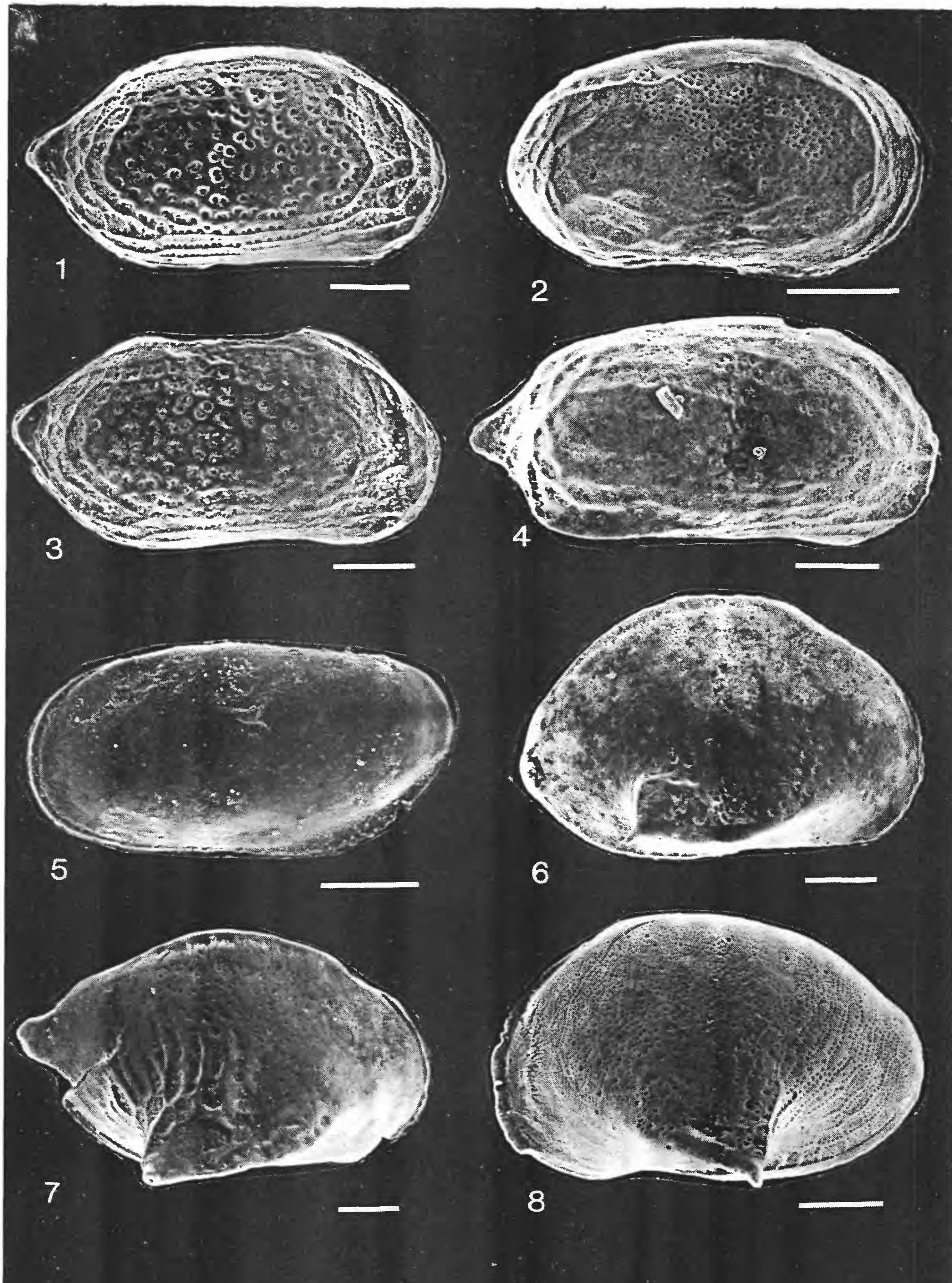

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PLATE 7

All figures are scanning electron photomicrographs.

White bar equals 100 micrometers.

FIGURE

1. *Cytheropteron simplex* Whatley and Masson, 1979, sample 83-EB-88, left valve.
2. *Cytheropteron elaeni* Cronin, 1988, sample 81-ACr-6a, left valve.
3. *Cytheropteron pseudomontrosiense* Whatley and Masson, 1979, sample 81-ACr-6a, left valve.
4. *Cytheropteron biconvexum* Whatley and Masson, 1979, sample 83-EB-88, right valve.
5. *Cytheropteron sedovi* Lev, 1979, sample 83-EB-54, left valve.
6. *Cytheropteron sp. A*, sample 83-EB-88, left valve.
7. *Cytheropteron sp. B*, sample 90-ACr-17A5 1/4, left valve.
8. *Cytheropteron sp. B*, sample 90-ACr-19A1, right valve.

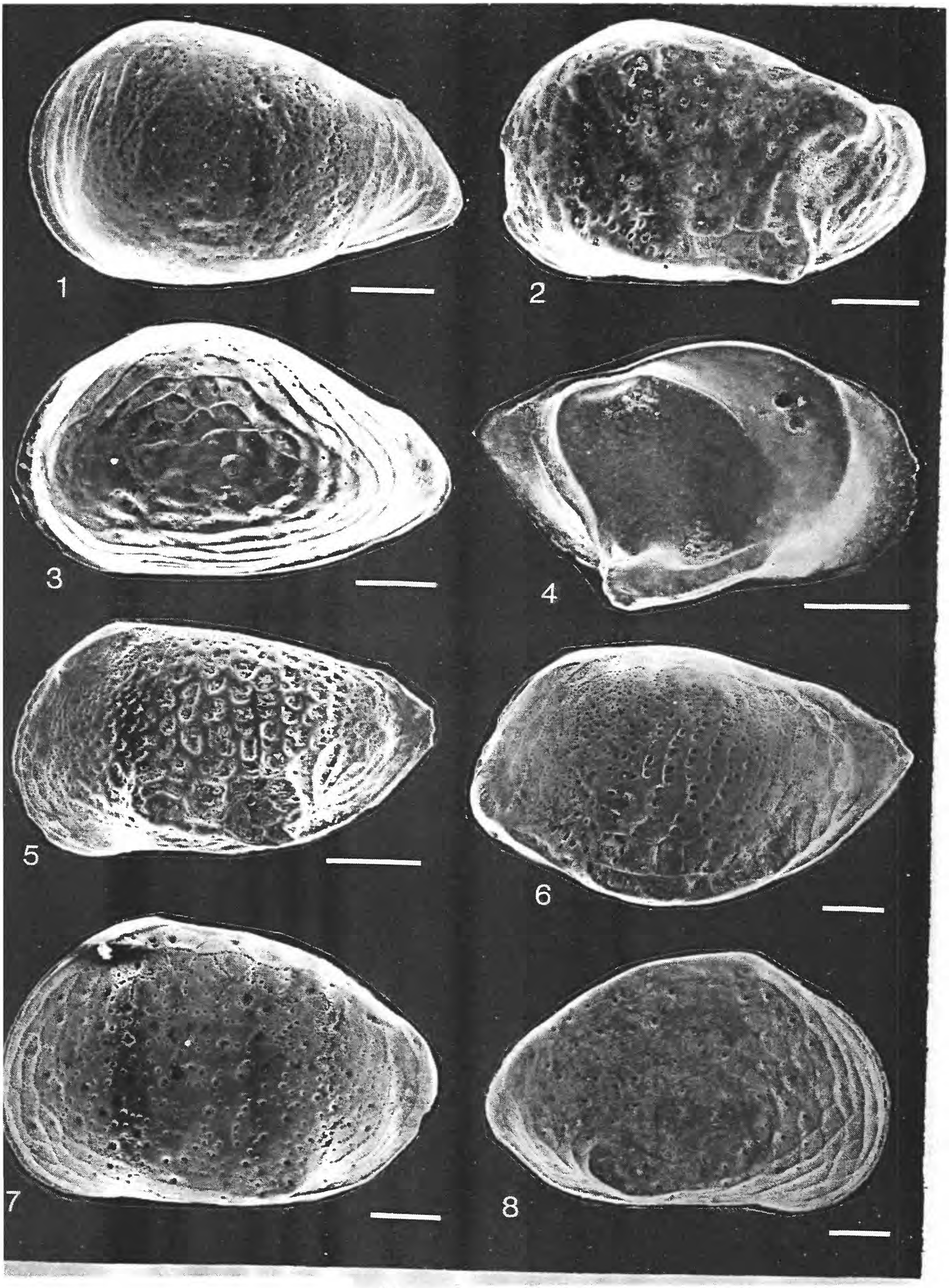
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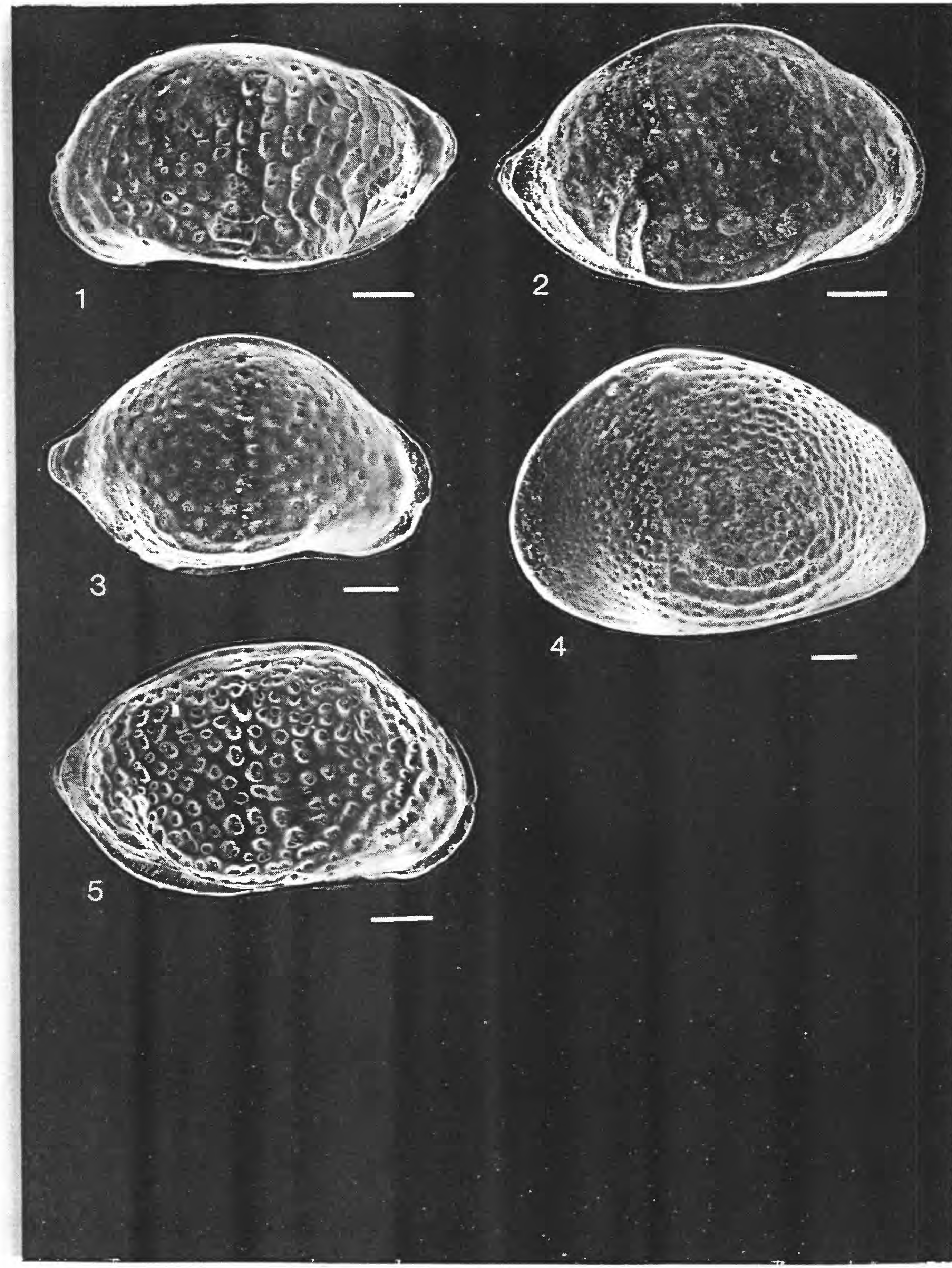
PLATE 8

All figures are scanning electron photomicrographs.

White bar equals 100 micrometers.

FIGURE

1. *Cytheropteron champlainum* Cronin, 1981, sample 83-EB-187, left valve.
2. *Cytheropteron champlainum* Cronin, 1981, sample 84-EB-60, right valve.
3. *Cytheropteron inflatum* Brady, Crosskey and Robertson, 1874, sample 84-EB-51, right valve.
4. *Cytheropteron sp. C*, sample 84-EB-68, left valve.
5. *Cytheropteron latissimum* (Norman, 1865), sample 83-EB-187, right valve.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