The occurrence of Second-Year and Multiyear Ice in the Eastern Beaufort Sea

by

William J. Stringer

Assisted by

Joanne E. roves.

Richard D. Henzler

Linda K. Schreurs

Janis Zender-Romick

Geophysical Institute

University of Alaska

Fairbanks, Alaska

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Introduction

The strength of sea ice is highly dependent upon its salt content, increasing with decreasing salinity. At freeze-up, considerable salt is trapped within sea ice in the form of brine which collects in small pockets. Ice which has survived smelt season usually has a markedly decreased salt content because with increased temperatures the brine pockets migrate to the under surface of the ice where they drain, leaving the host ice considerably free of salt. Although most of the salt is usually drained the first melt season, additional salt can be drained in subsequent melt seasons.

Because of the change in the properties of ice related to its age, a distinction is made between first-year ice, which should have a high salt content and ice which has survived a melt season and should have a low salt content. Generally, ice which has survived one melt season is called "multiyear ice." However, there is a bit of confusion in terminology currently in use. The World Meteorological Organization (1981) distinguishes between "second-year ice". and "multiyear ice"; multiyear ice being ice which has survived at least 2 melt seasons.:

This distinction is difficult to make operationally. While it is possible to distinguish between annual ice and older ice on the basis of physical appearance, it is not possible to clearly distinguish between second-year and multiyear ice by that method. In fact, because the salt content of sea ice changes most during its first melt season, it is very difficult to distinguish between second-year and multiyear ice even by conducting salinity tests on physical specimens. Therefore, it is impossible by current remote sensing methods to distinguish between them. Finally, the change in the property of 'interest to this report, ice strength, undergoes its greatest change following the first melt season. Therefore, throughout this report "multiyear ice" will refer to ice which has undergone one melt season.

Background

Multiyear ice is relevant to environmental assessment in terms of the potential hazard of stress to man-made structures and subsequent petroleum spillage resulting from structural failure. In general, it is presumed that greater stresses can be transmitted from the surrounding - ice field by multiyear ice than first year ice when in contact with a structure. Furthermore, multiyear ice tends to be thicker than most. first year ice because it often originated from hummocked or ridged ice.. As a result, not only is the ice stronger than first year fee, but it often possess a larger vertical crass section for the transmission of force.

Because the presence of multiyear ice could constitute a hazard to man-made structures beyond that imposed by first-year ice, its rate of occurrence shauld.be.considered when assessing the environments? impact ".. which may occur as a result of destruction of man-made structures related to offshore petroleum activities. This report is intended to provide an estimate of the rate of recurrence and concentration of multiyear ice in the eastern Beaufort Sea region of the Alaskan Coast.

Detection and Mapping of Multiyear Ice

Multiyear ice is usually distinguished visually by its smooth, undulating surface created by undergoing 1 or mare melt seasons. If it is snow-free, it is often somewhat transparent and blue-green in appearance, while first-year ice tends to be either very flat or piled into irregular shapes and is gray-white in appearance. Because sea ice is usually snow-covered, multiyear ice is most often detected by its surface topography. Detection of multiyear ice by visual band satellite imagery is generally ruled out because the snow-cover obscures differing reflectance qualities and the resolution required to identify its surface. characteristics would be 3 orders of magnitude smaller than practical by imaging satellites. Some success has been claimed (see Gray, 1977) at detecting multiyear ice by airborne radar. This is made possible by the difference in conductivity between first-year and multiyear ice due to their differing salinities. Regardless of the reliability of radar imagery for detecting multiyear ice, there is very little radar imagery of the eastern Beaufort Sea study area.

Progress has been made toward detection of multiyear ice by means of passive microwave imagery (Meeks et al, 1 974). Furthermore, data of this nature is available daily by means of the Scanning Multichannel Microwave Radiometer (SMMR) carried aboard the Nimbus/NOAA series of satellites. This data is used regularly by the NOAA/Navy Joint Ice Analysis Center in the preparation of their weekly ice analysis charts. Unfortunate y, the SMMR's resolution elements are on the order of 100 km on a side and, therefore, the imagery is most useful for ice analysis on a global scale rather than in rather limited study areas such as considered here.

One of the methods utilized by the Joint Ice Analysis Center to map multiyear ice (at least-at the beginning of the ice year) is to keep track of previously existing pack ice at the initiation of freeze-up. Analysis of satellite imagery indicates that shortly after freeze-up takes place, the former pack ice is immobilized in a matrix of first-year ice and, therefore, remains at the location it was last observed. Thus, a region of pack ice before freeze-up becomes a region of multiyear ice after freeze-up.

Because of its 80-meter spatial resolution, Landsat imagery would be most useful for this analysis. However, the Landsat 18-day frequency, coupled with the additional statistical handicap resulting from the chance of cloudiness during the opportunities for observation, ruled out Landsat imagery in terms of producing a statistical data base.

The best compromise between. resolution and frequency is provided by the NOAA and Defense Meteorological Satellite Program (DMSP) series of satellites which provide imagery on a frequency of 2 to 3 times daily and with a spatial resolution of around 250 m.

Data Analysis

The Navy/NOAA Joint Ice Analysis Center publishes maps of sea ice occurrence on a weekly frequency. These maps are compiled on the basis of NOAA and DMSP imagery, SMMR data, aircraft observations and surface observations, the latter including regular reports from Barter Island in the center of the eastern Beaufort Sea study area. Hence, while largely based on the NOAA and DMSP imagery, other data sets are also used to produce the weekly ice analysis maps. As a result; these maps are the most dependable source of information on ice presence at specified times, such as at time of freeze-up.

Ice analysis charts were obtained for the years between 1971 and 1981 (1971 being the date which satellite imagery became generally available for ice surveillance). Once the map containing freeze-up was located, the previous map was retained for analysis. In 7 of the 11 years, pack ice was present in the study area at the time of freeze-up. The eastern Beaufort Sea region of each of these maps has been reproduced here as figures 1 through 7. In these figures the concentration of pack ice just before freeze-up (concentration of multiyear ice just after freeze-up) is indicated. Whenever available, Landsat imagery was used to verify ice location and density shown on the ice analysis maps. The concentration-format is dictated by the increments in concentration contained in the original data set: the Ice Analysis Center maps present ice concentration in fractions and 2 additional categories: open water and ice-free. Ice-free indicates an ocean absolutely free of ice while open water indicates an ocean containing ice at concentrations less than .1.

In figures 8 through 12, these yearly multiyear ice.concentrations have been combined in order to give the frequency of occurrence of multiyear ice at various concentrations. . .

Following this, the data have been rearranged to show maximum ice concentrations at given levels of probability. These. figures can also be interpreted as showing the average extreme-ice conditions to be expected at freeze-up over a specified period of time. (The 20% probability map becomes the average 5-year maximum multiyear ice event.)

Finally, 5 zones were identified to have generally uniform ice statistics within each zone. Upon analysis, these statistics were found to exhibit an-exponential relationship between probability and ice concentration. These relationships have been used to determine the. average interval between 100% multiyear ice concentration events for the identified zones (or the probability that 100% multiyear ice concentration will occur in any given year).

Yearly Ice Concentration Prior to Freeze-up (Figures 1-7)

On the following pages, maps of Tate season pack ice in the eastern Beaufort Sea at the initiation of freeze-up are presented for the period 1971-1981. It is assumed that this ice became frozen into newly formed ice, becoming multiyear ice. There are no maps for the years 1972, 1973, 1977, and 1979 because the multiyear ice concentration in the region was 0 an these years.

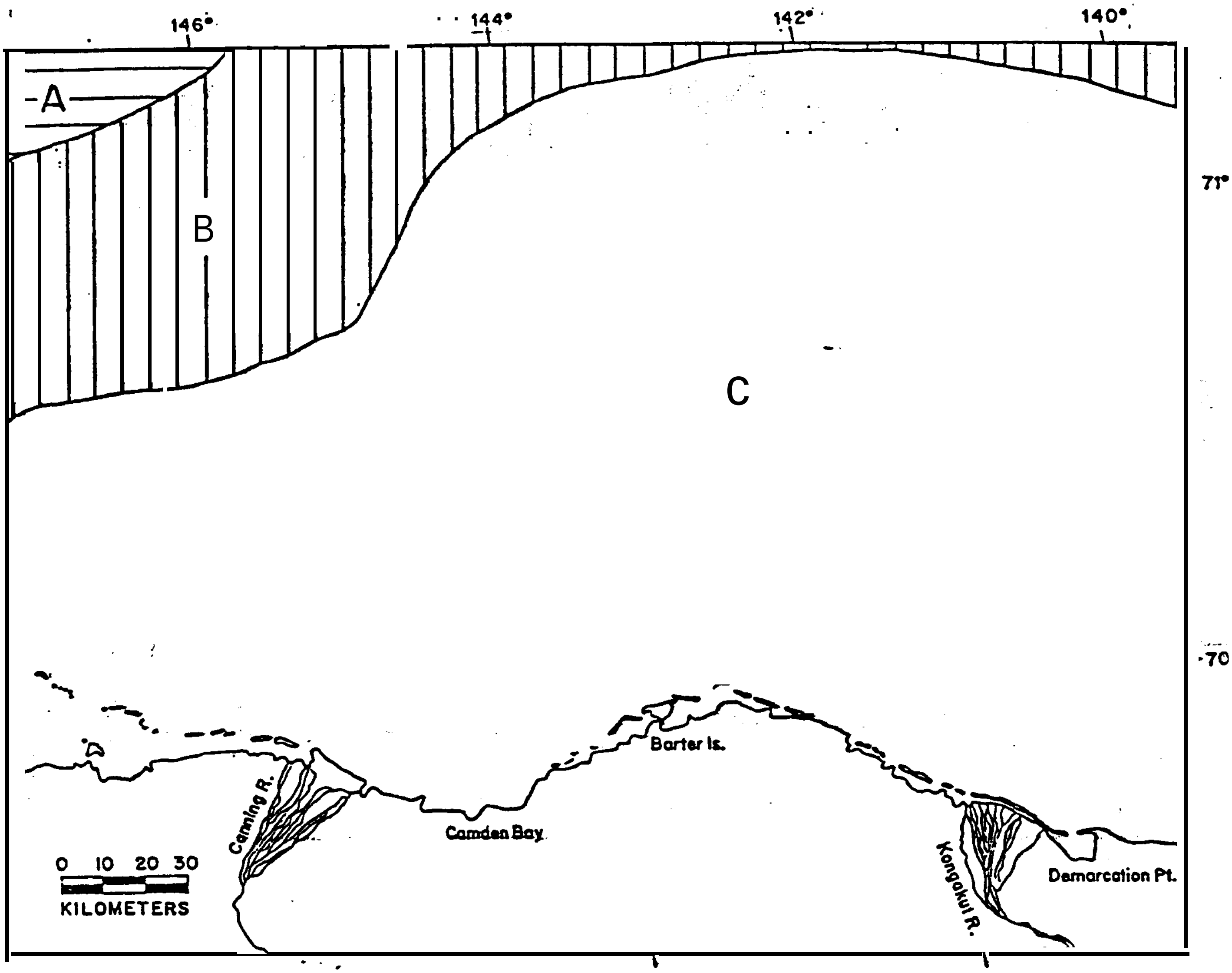


Figure T. Ice Concentration Prior to Freeze-up (September 13) for 1971.

A = 50 to 60% concentration

B = 10 to 40% concentration

C = ice-free

While there was multiyear ice in the vicinity of the study area this year, it was probably not sufficiently close to the nearshore area to be of immediate concern in terms of hazard to man-made. structures.

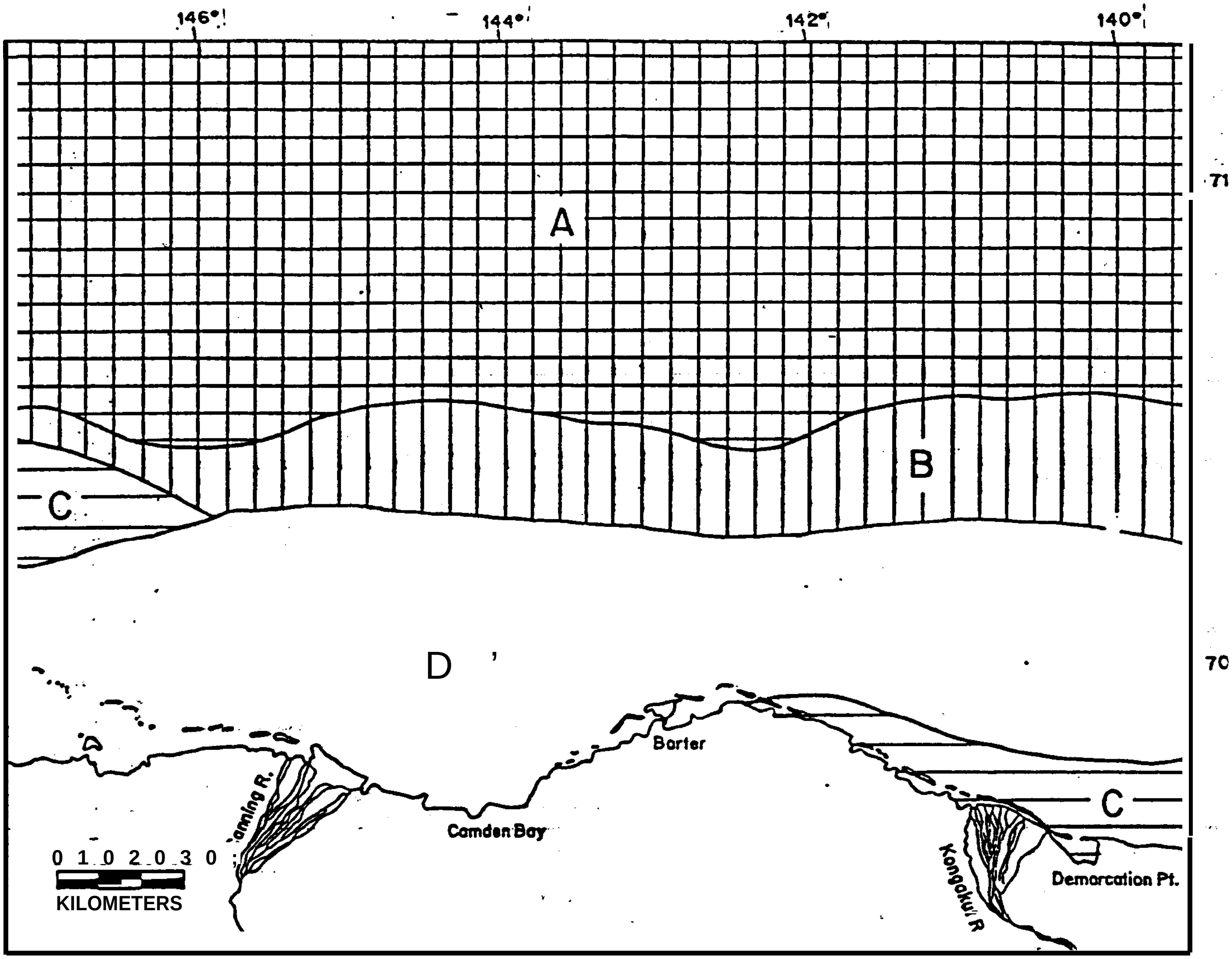


Figure 2. Ice Concentration Prior to Freeze-up (September 17) for 1974.

A = 100% concentration

B = 40 to 60% concentration

C = 10 to 40% concentration

D = ice-free

The area of interest here is the region of 10-40% concentration adjacent to shore east of Barter Island. There was a Landsat image obtained on September 19, 1974 which shows the portion of coast between Camden Bay and Demarcation Point. This image is in substantial agreement with the ice analysis map except that the Landsat image shows additional ice in the form of a narrow band of scattered floes extending westward just off the coast from Barter island. Hence, the analysis map is a conservative measure of ice present. However, it is possible that easterly winds would have removed these floes by the time ice formed. Most of the floes present are-quite small ($<.02km^2$).

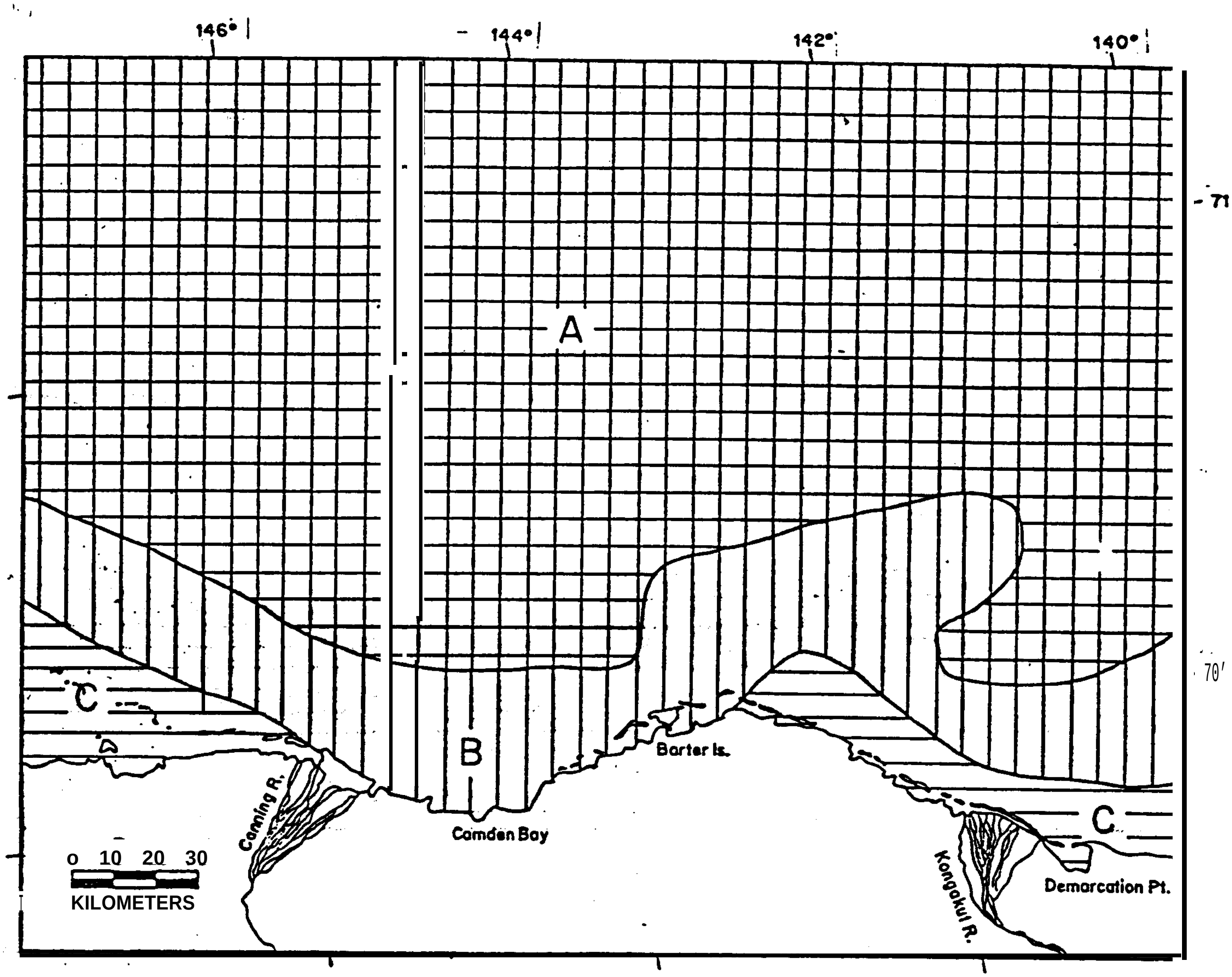


Figure 3. "Ice Concentration Prior to Freeze-up (September 2) for 1975.

A = 100% concentration

B = 50-75% concentration

C = open water (0-10% concentration)

This year is generally recognized as a "heavy" ice year with pack ice remaining close to shore the entire summer. This map certainly agrees with that characterization. Landsat images were obtained on September 9 and 24 showing portions of the study area. These images agree substantially with the map in the regions shown on the Landsat images, with the exception that the concentration shown for zone B may be a bit high, arid the concentration in the portion of zone C, including Demarcation Point may be a bit low. However, in order to maintain the consistency of the data base, these concentrations were not modified..

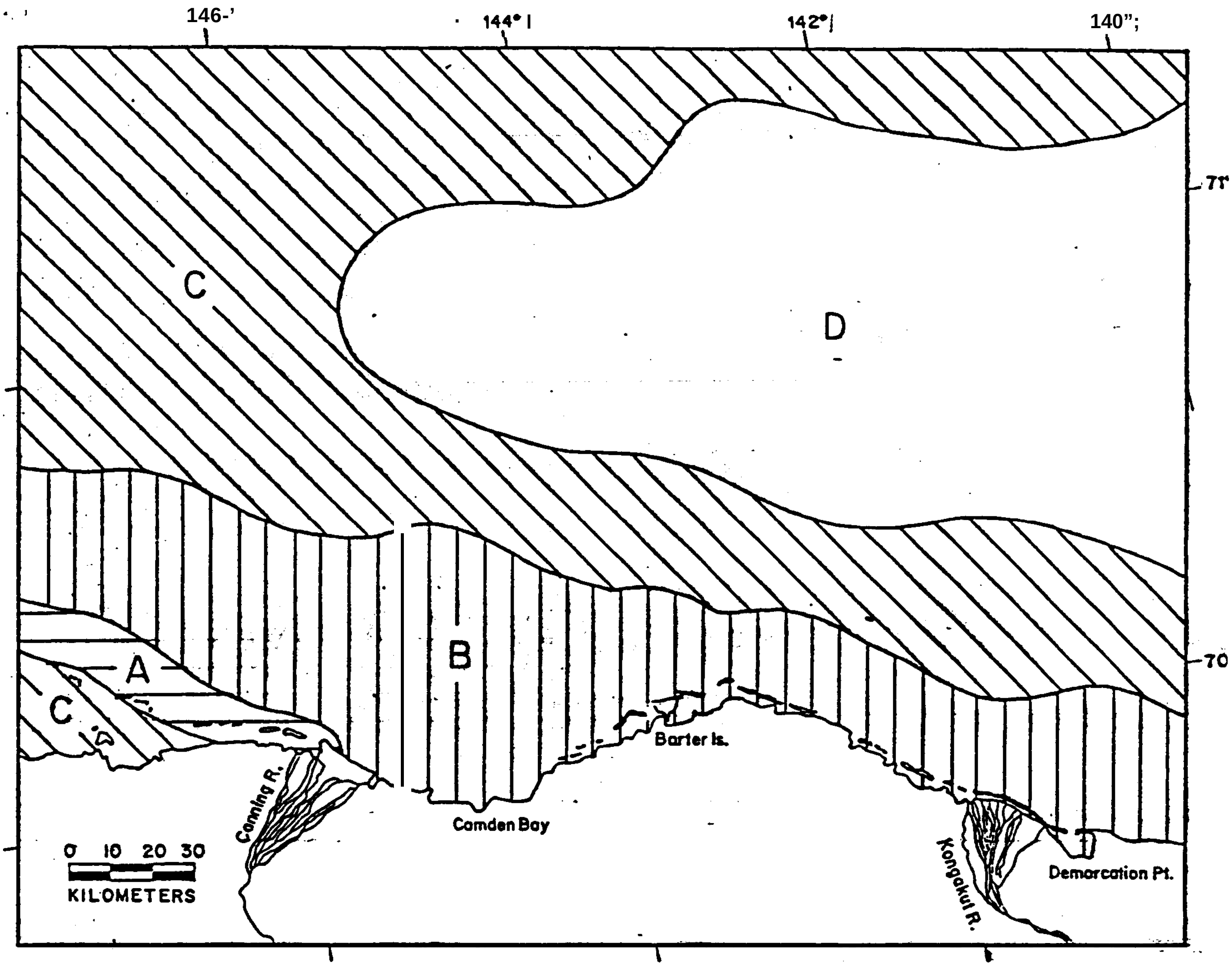


Figure 4. Ice Concentration Prior to Freeze-up (September 21) for 1976.

A = 60-90% concentration

B = 25-50% concentration

C = open water (0-10% concentration)

D = ice free

This map shows a quite different situation from the previous year. In 1975, the pack ice edge remained adjacent to shore with ice concentration increasing steeply with distance from shore. In this case, we have a narrow band of" relatively dense floes adjacent to shore, with-open water and even ice-free conditions seaward. One Landsat image was found showing a portion of the study area on September 21. This image shows the region west from the Canning River delta. The image shows agreement with zone C. However, the" concentration is 90% in zone A (the high end of the indicated range) and the small portion of zone B which can be seen is at the low end of the range given for that zone.

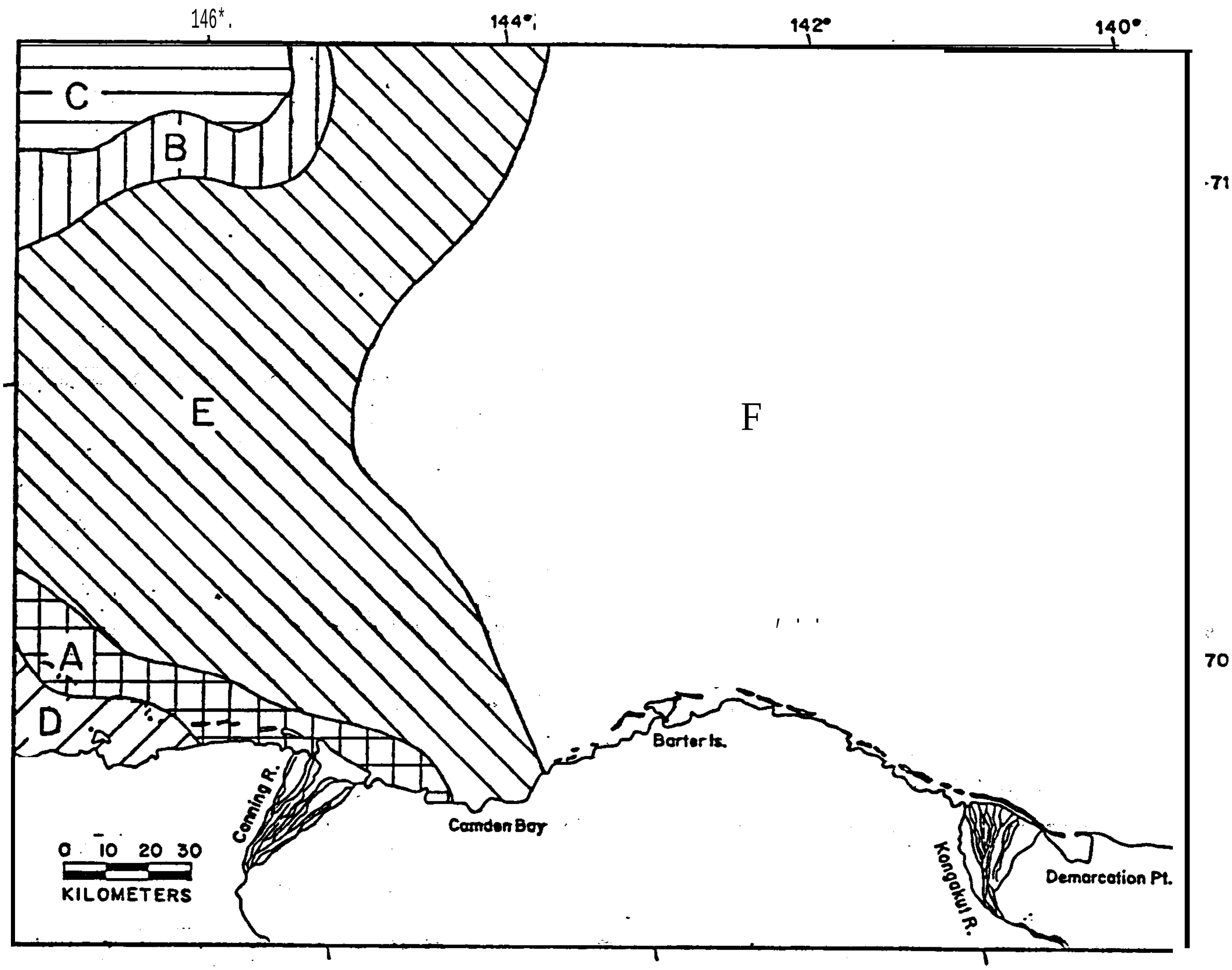


Figure 5. Ice Concentration Prior to Freeze-up (September 19) for 1978.

A = 75-100% concentration

B = 40-60% concentration

C = ?0-40% concentration

D = 0-25% concentration

E = open water (0-10% concentration)

F = ice free

This map shows a situation somewhat similar to the previous year's ice configuration. It appears that retreating nearshore ice tends to concentrate off the Canning River delta, most likely as'a result of westward, wind-driven advection. A Landsat image is available for September 17 showing Camden "Bay and including the Canning River delta on its western edge. This image shows a band of high ice concentration starting at the Canning delta and extending westward. Hence, for the small area covered by Landsat imagery, agreement is indicated.

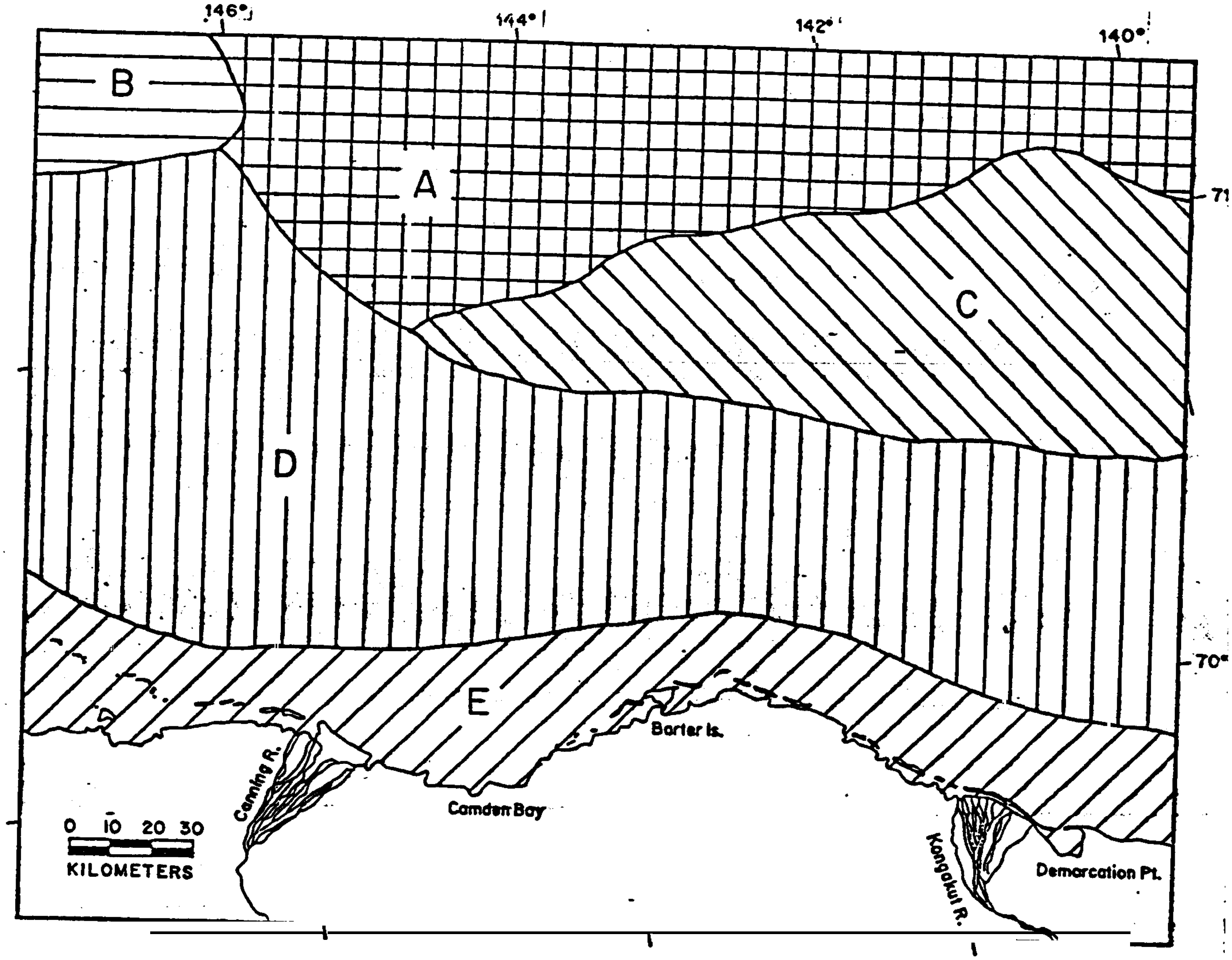


Figure 6. Ice Concentration Prior to Freeze-up (September 16) for 1980.

A = 100% concentration

B = 80% concentration

C = 70% concentration

D = 30% concentration

E = open water (0-10% concentration)

Here a nearshore ice configuration similar to that seen in ?975 and 1976 is found: the pack ice edge is 'located near shore as winter approaches. A Landsat image was acquired showing the portion of the study area west of the Kongakut River on September 25, after-freeze-up had begun. However, it is possible to distinguish between new ice and the whiter, thicker pack ice surviving the previous melt season. This image shows good agreement with the ice analysis map with the possible exception that zone D, showing 30% ice concentration in a band lying 15 to 20 km offshore should, perhaps; be a little closer to shore in places, and " zone E characterized as open water might actually contain a concentration somewhat higher than the upper limit of 10% characterized by that zone designation.

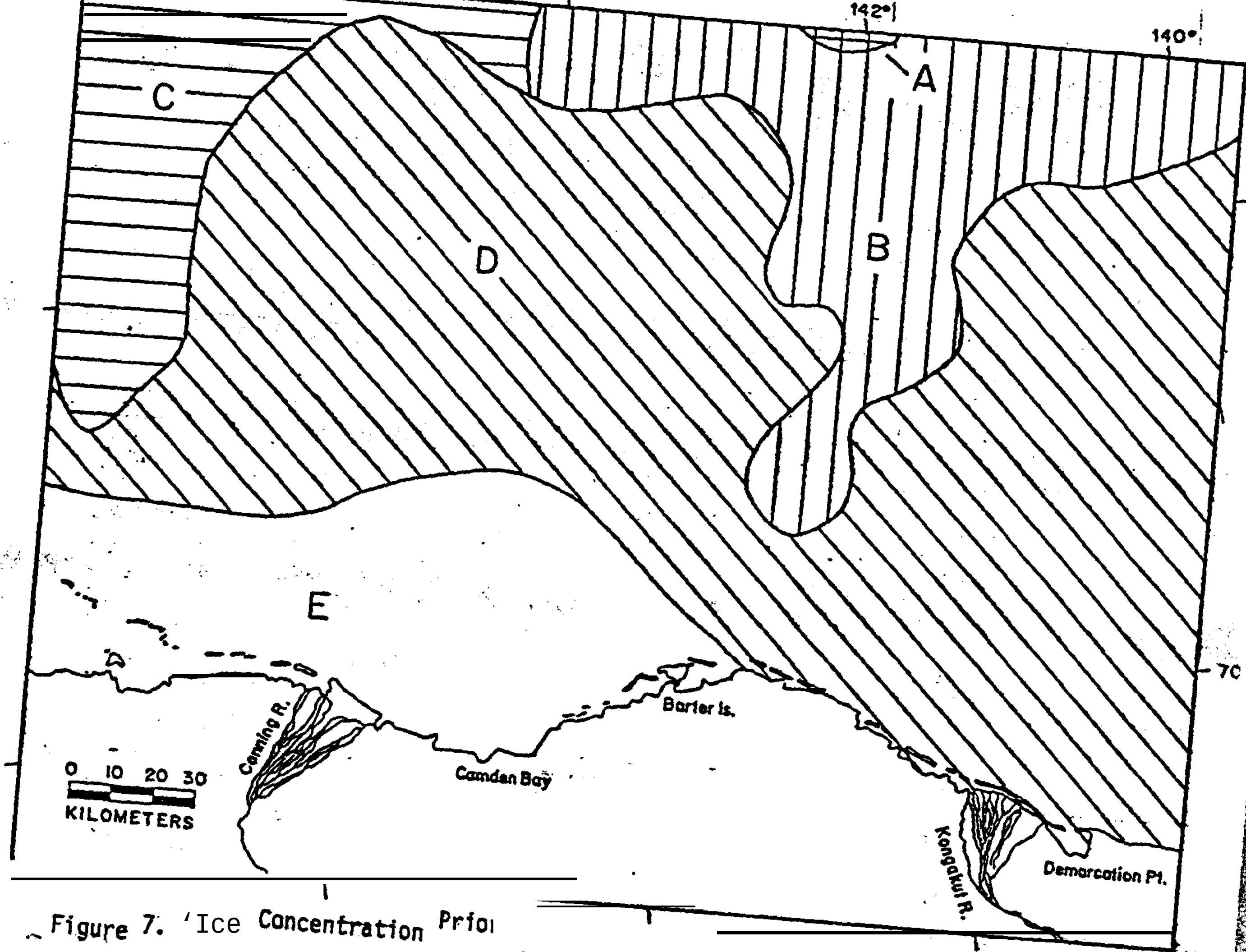


Figure 7. Ice Concentration Prior to Freeze-up (September 15) for 1981.

A = 70% concentration

8 = 20% concentration

C = 10% concentration

D - open water (0-10% concentration)

E - ice free

The late season fce this year is largely located far offshore, although occasional floes can be found over a wide portion of the study area. No Landsat imagery was found with which to compare this data.

-Discussion: Yearly Ice Concentration Prior to Freeze-up

These maps show that on 7 out of the 11 observation years, multiyear ice was found within the eastern Beaufort Sea study area at freeze-up. On 5 of these years; multiyear ice was found in the nearshore zone of the study area in some concentration, including that implied by the "open water" category. Comparison with Landsat imagery has shown that in the cases where Landsat data were available, general agreement was found between those maps based on the Joint Ice Analysis Center maps-and Landsat imagery. However, in some cases it appeared that the mapped concentrations may have been higher or lower than ice actually found in particular areas mapped.

"We were tempted, at first, to correct the maps which are based themselves largely on the lower resolution NOAA satellite image data, to correspond with the high resolution Landsat imagery. However, this was not carried out for the following reason: in generaT, only partial corrections could be made, since the Landsat scenes usually only covered a portion of the study area. The result would be maps which varied considerably in quality-from one region to another. As a result, the 'uniformity of the data base would be destroyed. Review of the individual comparisons will show that in some cases the mapped.concentrations. appeared high, while on others they appeared tow. It is just possible that by persisting with one data base random errors in ice concentration estimates will tend to cancel, leaving the combined results (to be presented next) reasonably accurate. On the other hand, making corrections here and there based on another, partial data set might destroy or skew this error-cancelling effect. However, it should be clear that the data base used here is rather low resolution, both spatially and in terms of ice concentration estimates and, therefore, the results should be interpreted only in the broadest sense.

Because of the well known tendency toward severe ice conditions in the Beaufort Sea approximately every 5 years (particularly in terms of navigation in the western Beaufort), the data were examined to determine whether nearshore ice concentrations that were likely to become multiyear ice followed the same sort of cycle, at least within this shot-t observation period.

Late summer ice is found in the nearshore area in two ways: (1) as part of the Beaufort Sea pack ice which extends to shoreward locations and (2) as ice remnants bordered to the seaward by open water or ice-free. water. The first model was observed in 1975 and 1980, while the other model was observed in 1974, 1976, 1978, and 1981. As mentioned earlier, there was no late season ice found in the area for the years 1972, 1973, 1977, or 1979. In 1971, while late season ice existed in the study area, it was far offshore. In terms of western Beaufort Sea Navigation problems, 1975 has been characterized as an extremely heavy ice year, while 1980 has been characterized as a moderately-heavy ice year. The Ice Analysis Center map for 1975 showed a high concentration of late season ice in the nearshore zone, but in comparison with available Landsat imagery, perhaps the concentration just adjacent. to shore. was actually lower than mapped. In 1980, moderately high ice concentrations were found just offshore with open water just adjacent to shore, but Landsat imagery suggests actual concentrations were higher than the upper limit of 10% concentration imposed by this classification. Overal ?, nearshore ice conditions during the freeze-up period were reasonably similar in 1975 and 1980 and resulted not only in some multiyear ice in the nearshore area, but also very heavy multiyear ice 15 to 20 km offshore.

Ice"conditions in years characterized by the second model resulted in the likelihood of moderately heavy multiyear ice along particular areas of the nearshore zone, but lower concentrations in the area 15 to 20 km offshore. In this respect, the years following this second model were characterized by the worst multiyear ice conditions in terms of highest concentration in the nearshore area at the time of freeze-up while 1975 and. 1980 possessed the highest chance of multiyear ice being engaged in dynamic ice events in the shear zone throughout the winter.

The data base is too small to draw strong conclusions. However, it is safe to say that it is not valid to assume that only the 5-year period heavy ice years are fallowed. by high multiyear ice concentrations in nearshore areas.

Frequency of Occurrence of Specified Ice Concentration (Figures 8-12)

The 11 years of ice concentration data can be combined to yield maps of the relative frequency of a specified concentration. Here, we have combined the data to produce the following maps:

Fig. 8 Frequency of Ice Concentration greater than Ice-Free category. Zones on this map include occasions of open water with ice concentration less than 10%.

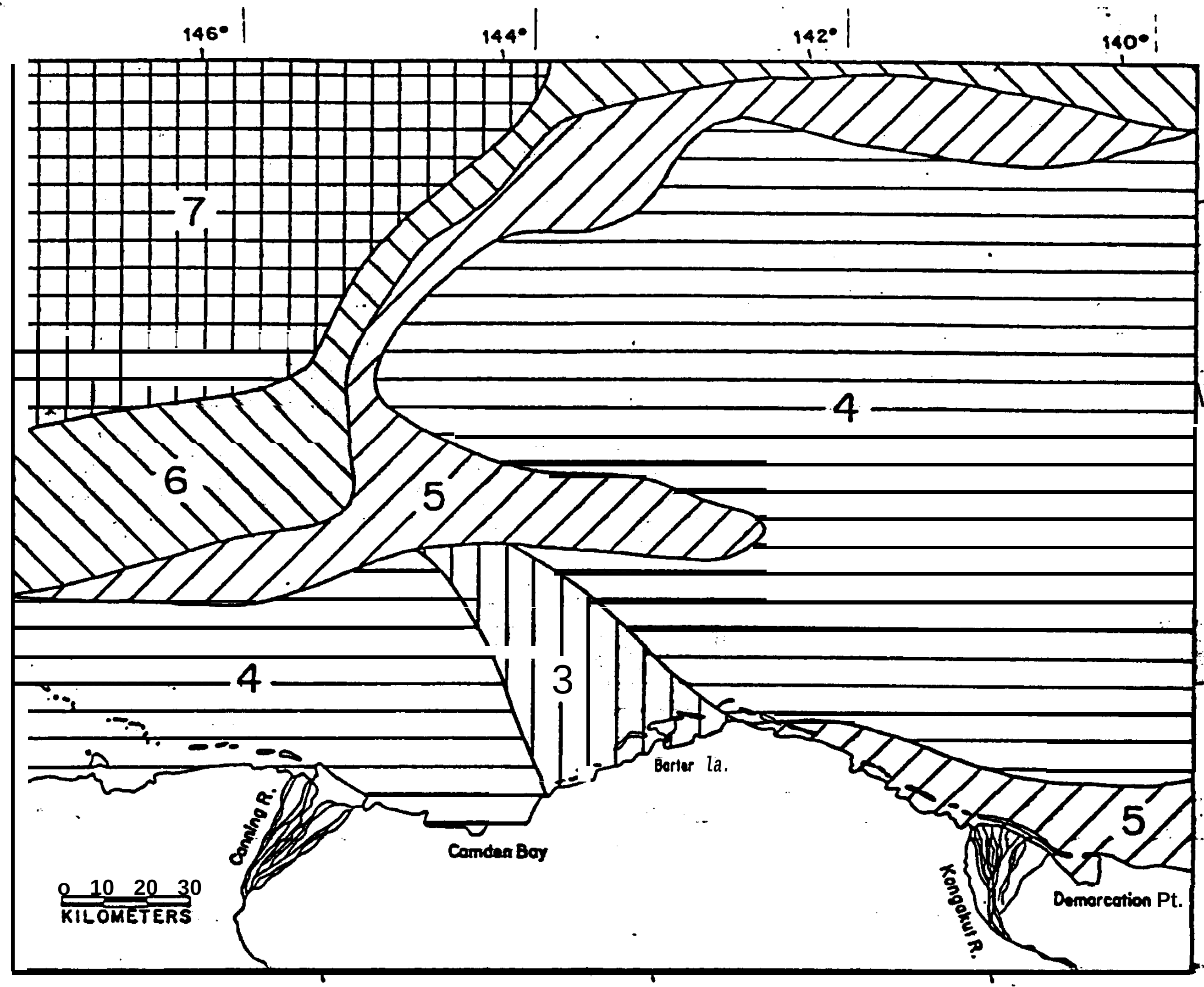
Fig. 9 Frequency of Ice Concentration greater than 25%

Fig. 10 Frequency of Ice Concentration greater than 50%

Fig. 11 Frequency of Ice Concentration greater than 75%

Fig. 12 Frequency of 100% Ice Concentration

When examining these maps it should be recalled that the original data was largely low resolution satellite imagery and that concentration frequencies determined by means of combining these maps should be viewed, for the most part as a general indicator of the frequency of multiyear ice at a specific location. However, some general trends might be expected to emerge.



Figure' 8. Frequency of Multiyear Ice Concentration Greater than Ice-Free Category.

This map shows the number of years out of a total of 11 that ice concentration categories greater than ice-free were found in a given area at freeze-up. The frequency shown includes open water occurrences, which contain ice concentrations between a-few percent up to 10 percent. Therefore, this map should be taken as the relative frequency that multiyear ice will be found in the vicinity of a specified location at any concentration greater than 0.

This map shows that within the nearshore zone, multiyear ice is found from 3 to 5 years out of 11. This corresponds to a.probability of 30 to 45% in any given year. However, it must be emphasized that this is the probability of multiyear ice in any concentration greater than 0.

Although it is not justified to place great emphasis on the precise configuration of the boundaries of these zones-of relative ice frequency, it is probably worth noting that the eastward-facing coasts appear to possess a greater chance of being frequented by multiyear ice than west-facing coasts. A possible explanation for this is-that the predominantly westward-drifting ice tends to accumulate on eastward-facing coasts. This trend can also be seen on later figures.

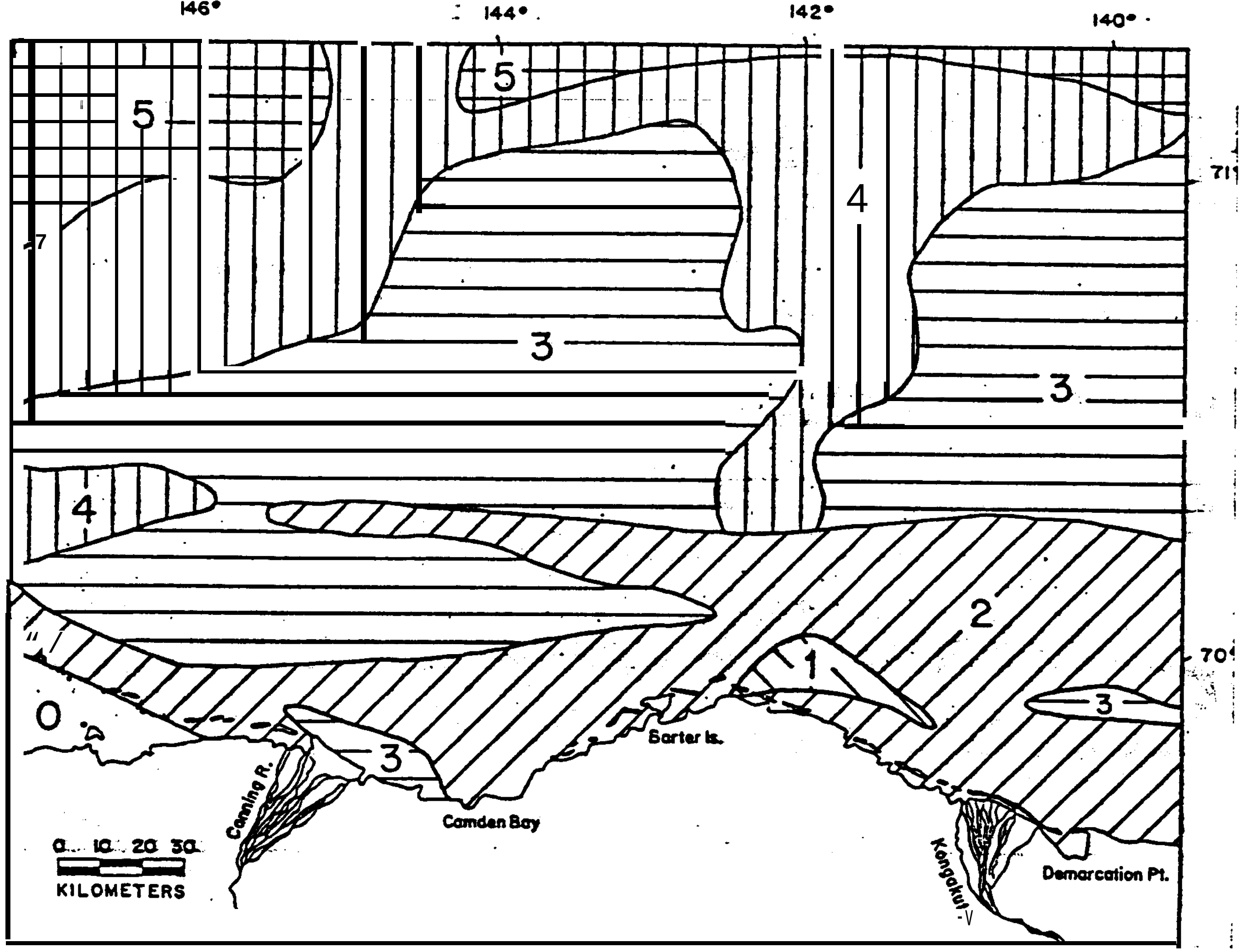


Figure 9. Frequency of Multiyear Ice Concentration greater than 25%.

The frequency of ice concentrations greater than 25% ranges from 3 to 0 occurrences in 11 years, corresponding to a probability ranging from 0 to roughly 30%. Most of the coastal area appears to have a probability of around 20% for ice at this concentration, with the exception of an area of lower probability east of Barter Island and an area of higher probability just off the Canning River delta.. While the data set is probably too small to place any great significance an these zones, subsequent maps of greater concentrations will continue to show a high frequency in the Camden Bay region and an increase in the size of the zone of low frequency east of Barter Island, lending some credibility to this trend-

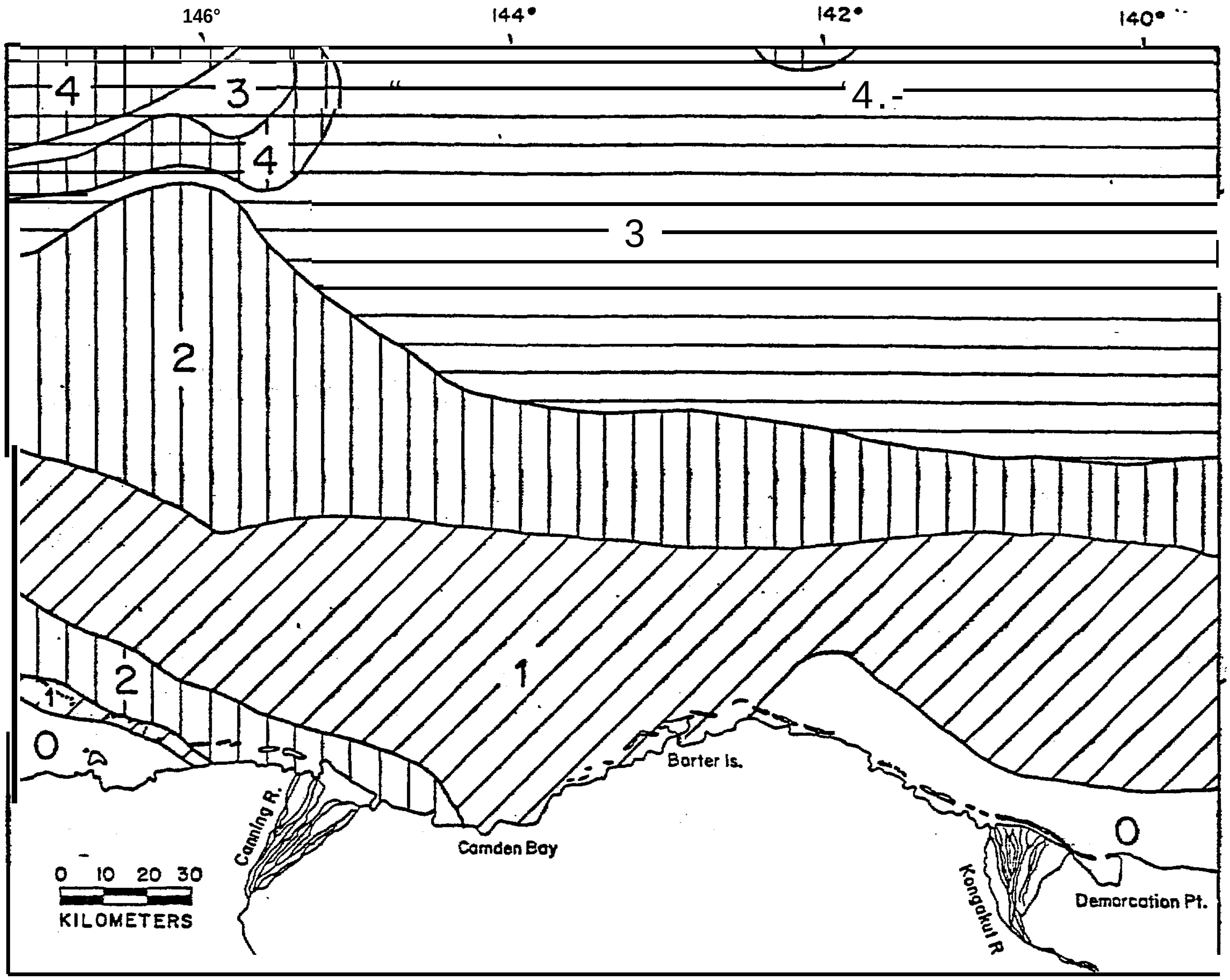


Figure 10. Frequency of Multiyear Ice Concentration Greater than 50%.

Trends in frequency appear mare systematic on this map than on the previous 2, with parallel contours of frequency increasing with distance from shore found extending across the study area. One glaring exception to this trend can be seen extending westward from the Canning River. Here we find a band-like zone more likely to contain multiyear ice than waters to the shoreward or seaward. This band becomes even more pronounced on the next map (75% concentration) and will be discussed in detail there. Also notable on this map is the zone of 0 frequency of multiyear ice east of Barter Island.

At this concentration, we see a multiyear ice frequency trend . ranging from 0 occurrences in 11 years at the east of Barter Island to 1 along the eastern shore of Camden Bay to 2 along the western shore of Camden Bay, then quickly decreasing through 1 to 0 in the very western portion of the study area. This pattern suggests a westerly flow of late season ice to the west, away from the MacKenzie Bay region (located to the east of the study area). This flow tends to cleanse the eastern portion of the study area and accumulate ice offshore from barrier islands in the western portion of the study area.

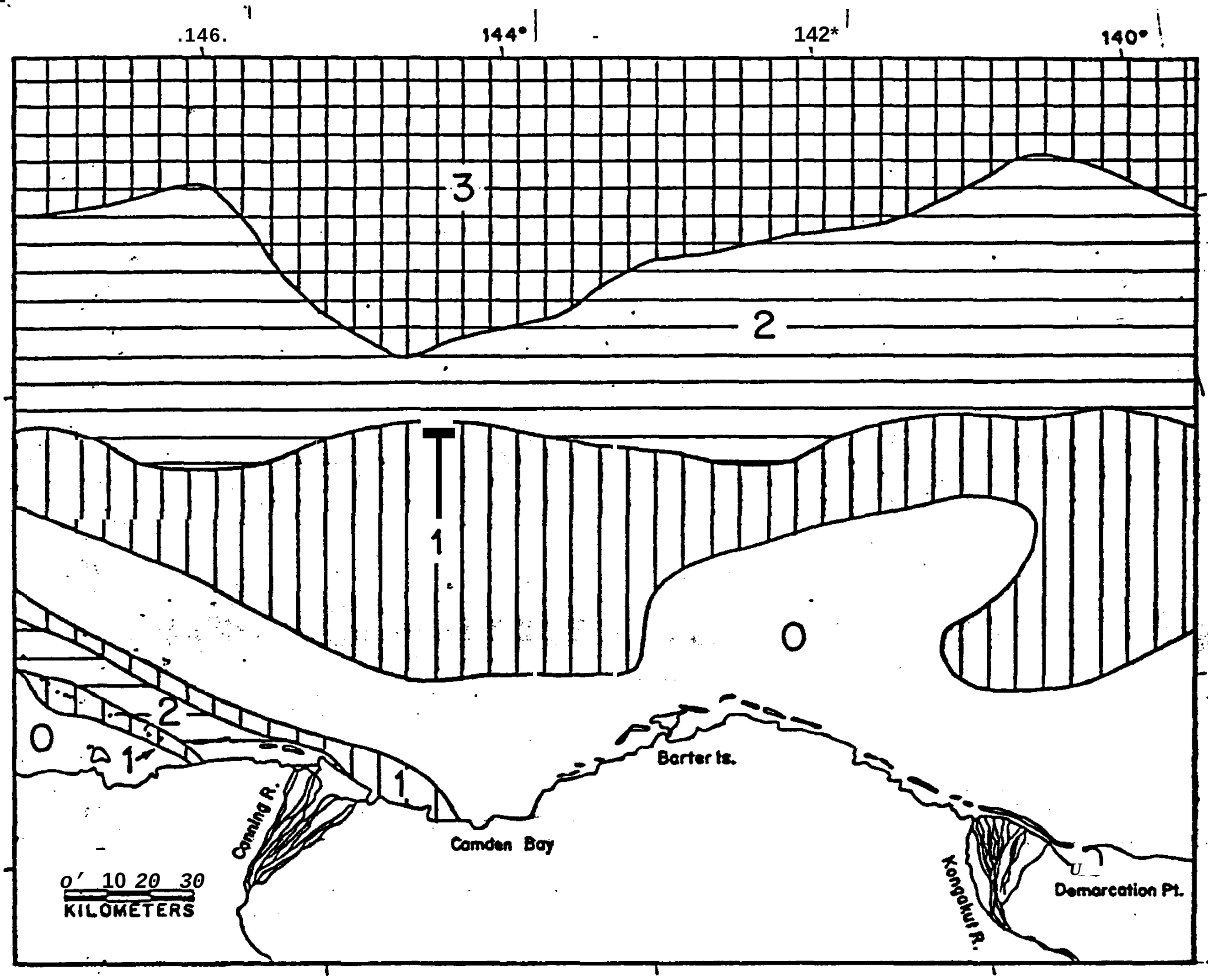


Figure 11. Frequency of Multiyear Ice Concentration greater than 75%.

Most of the nearshore regions of the study area have a low or 0 frequency of multiyear ice of 75% multiyear ice concentration. However; the band of high frequency occurrence offshore from the western barrier islands seen on the previous map can also be seen here. On 2 of the 11 observation years, a band of high ice concentration was found here. It would appear very likely that this is not mere coincidence and these accumulations here represent a systematic trend. These observations were in 1976 and 1978. Therefore, these high concentrations did not occur during heavy ice years, but rather years when ice accumulated as a result of slang-shure drift while the bulk of the pack ice was located far offshore. As was noted in the discussion of each year's ice concentration map, these 2 observations 'were confirmed on the basis of Landsat imagery which showed dense bands of ice floes of at least 75% concentration. (In the basis of this, we must conclude that there is a high likelihood of finding quite dense multiyear ice off these barrier islands on approximatately one out of 5 years. .

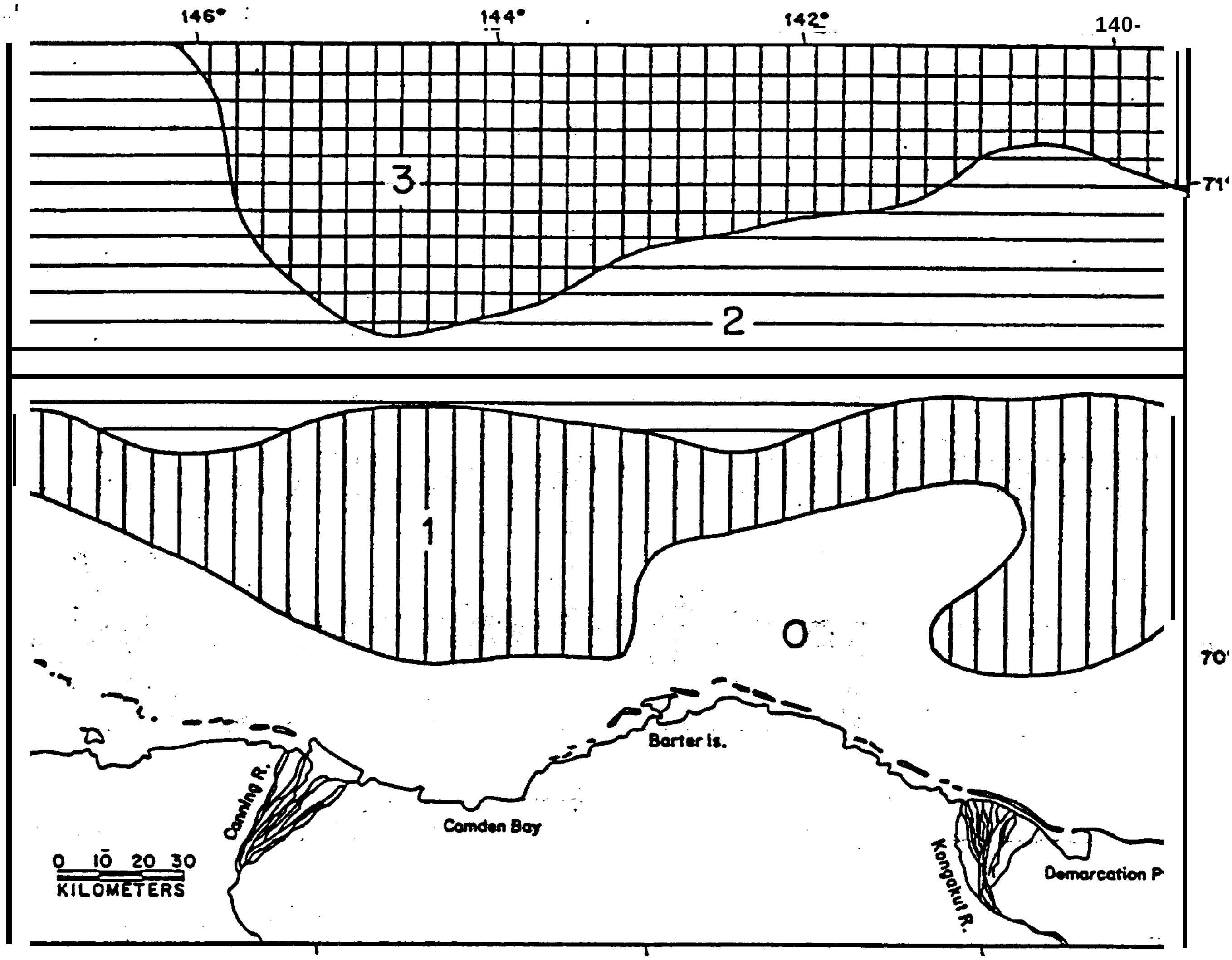


Figure 12. 'Frequency of Multiyear Ice Concentration of-100%.

This map. is quite similar to the previous map except that the band of ice extending westward from the Canning River delta is gone. It does show that at least once during the 11 year observation period, multiyear ice at 100% concentration was found relatively close to shore in this study area.

Discussion: Frequency 'of Occurrence of Specified Ice "Concentration

This set of composite maps shows that multiyear ice is found in-the eastern Beaufort Sea nearshore study area in measurable concentrations (greater than a few percent) at the beginning of any given ice season at a yearly frequency between 30% to 40%. At this concentration, strongly localized trends are not very evident. However, there is a slight tendency for higher concentrations to be found on eastward-facing coasts.

Increasing the multiyear ice concentration threshold to 25% results in much lower frequencies than found using the threshold defined by the open water category. Generally speaking, the frequency of multiyear ice over the whole nearshore area at this concentration is around 20%." This result reflects data largely from 1975 and 1976. Categorized as a heavy ice year, 1975 was characterized by Beaufort Sea pack ice remaining close to shore the whole summer. In 1976 the pack ice retreated westward and northward from the MacKenzie Bay area, leaving a band of relatively high concentration ice just seaward of much of the coastal area. Therefore, we see that at the 25% concentration level, multiyear ice in the study area can result from heavy ice years or years when westward-moving pack ice leaves a band of remnant ice along the coast.

At the 50% concentration level, multiyear ice again shows a frequency variability of from 0% to roughly 20% along the nearshore region of the study area. A large area of the eastern portion of the study area shows no occurrence. of multiyear ice at this concentration, while in the west, just off the barrier islands is a linear band showing the highest frequency of multiyear ice. 'The 2 occasions responsible for this band of high ice concentration were in 1976 and 1978 when westward-retreating pack ice left a band of ice here, apparently concentrated beyond the adjacent pack ice by interaction with the barrier islands west of the Canning River. Significantly, just inshore from these islands the frequency of multiyear ice even at 25% concentration drops to O. Between Camden Bay and Barter Island there is a region of 50% concentration at the 10% frequency level. This resulted from data obtained during the heavy ice year of 1975. (Note: "The other heavy ice year during the period of observation did not contribute in this case.)

The major change in the probability pattern from 50% to 75% concentration is that the region of 0 observations of multiyear ice in the eastern portion of the study area has now progressed westward, crossing the entire study area. However, it leaves the coast west of Camden Bay and continues offshore from the band of high ice concentration noted earlier. In a later section of this report, the observed frequency vs. concentration data will be used to extrapolate the frequency at which high concentrations might be expected at-locations where high frequencies were not observed during the relatively short period covered by this report.

Multiyear Ice Concentration at Specified Probabilities (Figures 13-17)

Data of this nature-lend themselves most easily to the type of analysis just presented: the frequency with which specified multiyear ice concentrations are found. However, naturally-occurring events are often analyzed in terms of the average "size" of maximum event to be anticipated at a specified frequency or probability. Thus, floods are designated as "hundred-year flood" or "thousand-year flood." What is meant in these cases is that a hundred-year flood would be equivalent in extent to the average of the maximum floods occurring in a large number of 100-year periods. Therefore, the hundred-year event is the average maximum event to be expected during a hundred year period. By this reasoning, the longer the period involved, the greater the size of the average maximum event to be anticipated because over a greater span of time, chances are that a greater event will be experienced. Alternatively, in terms of what event can be expected during any particular period, the hundred-year event, for instance, has a 1% chance of occurring in any given year.

In order to be able to discuss the multiyear ice data in these terms, it would be useful to invert the data displayed on figures 8 through 12 from contours of frequency of ice at specified concentrations to contours of average maximum concentration to be anticipated at specified frequency or probability.

In order to perform this inversion, it is necessary to construct a new set of maps, each potentially containing data from several maps of the previous set. For instance, one might desire a map of maximum ice concentrations to be expected ante every 11 years (or maximum concentrations to be expected each year at roughly the 10% level of probability). On some of the maps of frequency of specified concentration, regions of 1 occurrence and 2 occurrences in 11 years can be found. . The boundary between these 2 areas delineates the location where ice frequency at the specified concentration changes from once to twice in 11 years. Looking at the next map in the series will show changes in frequency boundaries resulting from increasing the concentration criteria, and therefore, the boundary of 10% probability for the concentration range between the two frequency map criteria (i.e. 25%-50%) will be defined. The area between the boundary of ?-2 occurrences at 25% and the 1-2 occurrences boundary at 50% has as a maximum concentration the higher of the two (50%) and a minimum concentration is the lower of the two (25%). Therefore, within the area between these two boundaries, one would expect the concentration for a 10-year period to 1 ie between 25% and 50%.

By following this method and identifying all the boundaries between 1 and 2 events per 11 years, the roughly 10% probability map can be compiled, Similarly, other maps can be compiled for other levels of specified probability.

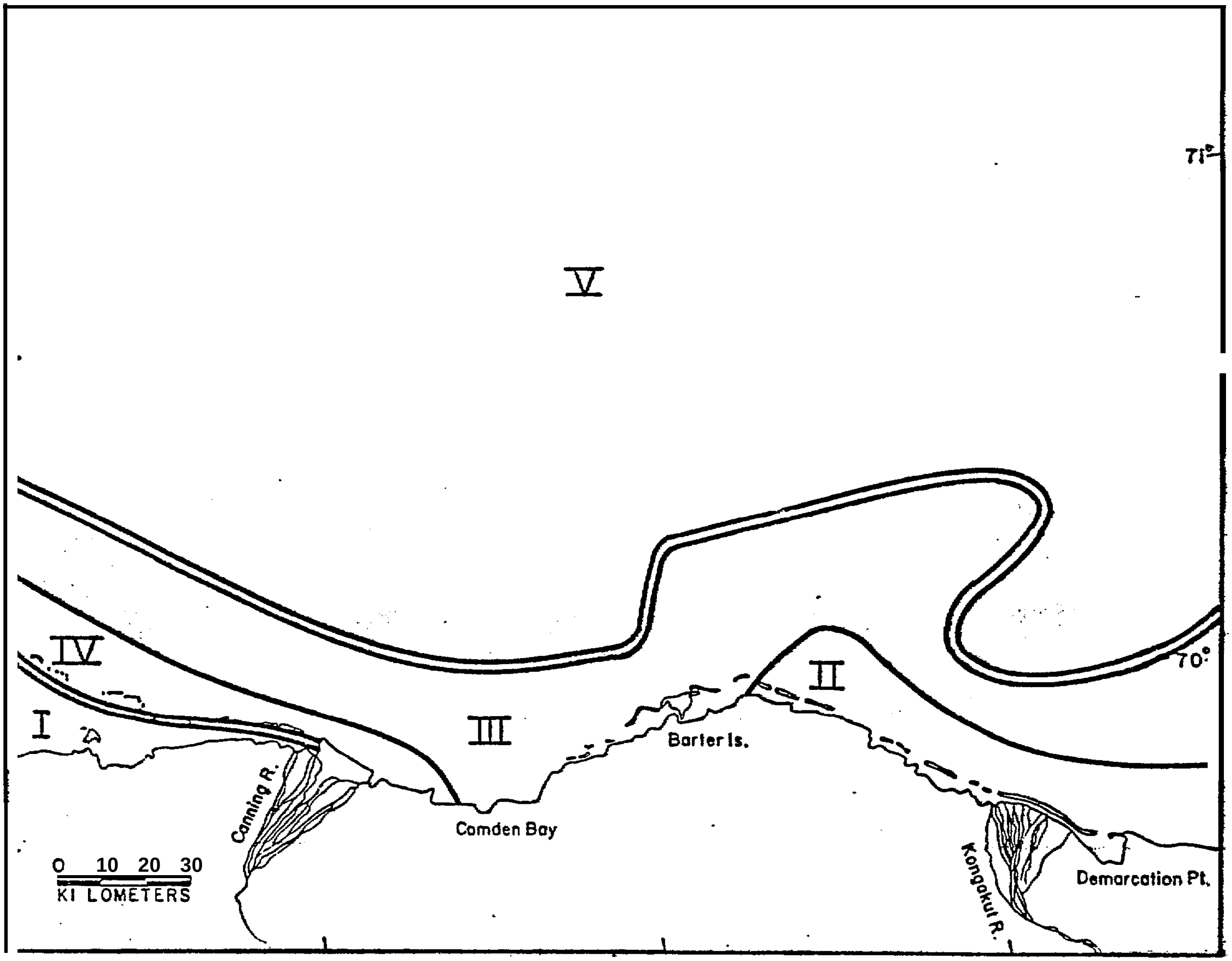


Figure 13. Multiyear Ice Concentrations to be Expected at the 10% Probability Level. (Average Maximum 10-year Ice Concentration.)

This figure shows the maximum multiyear ice concentrations which could be expected in the Eastern Beaufort Sea study-area at a 10% probability.

Clearly, a low probability threshold will correspond to high concentrations. Alternately, the average maximum 10-year ice concentration would be expected to be higher than shorter-term extreme concentrations.

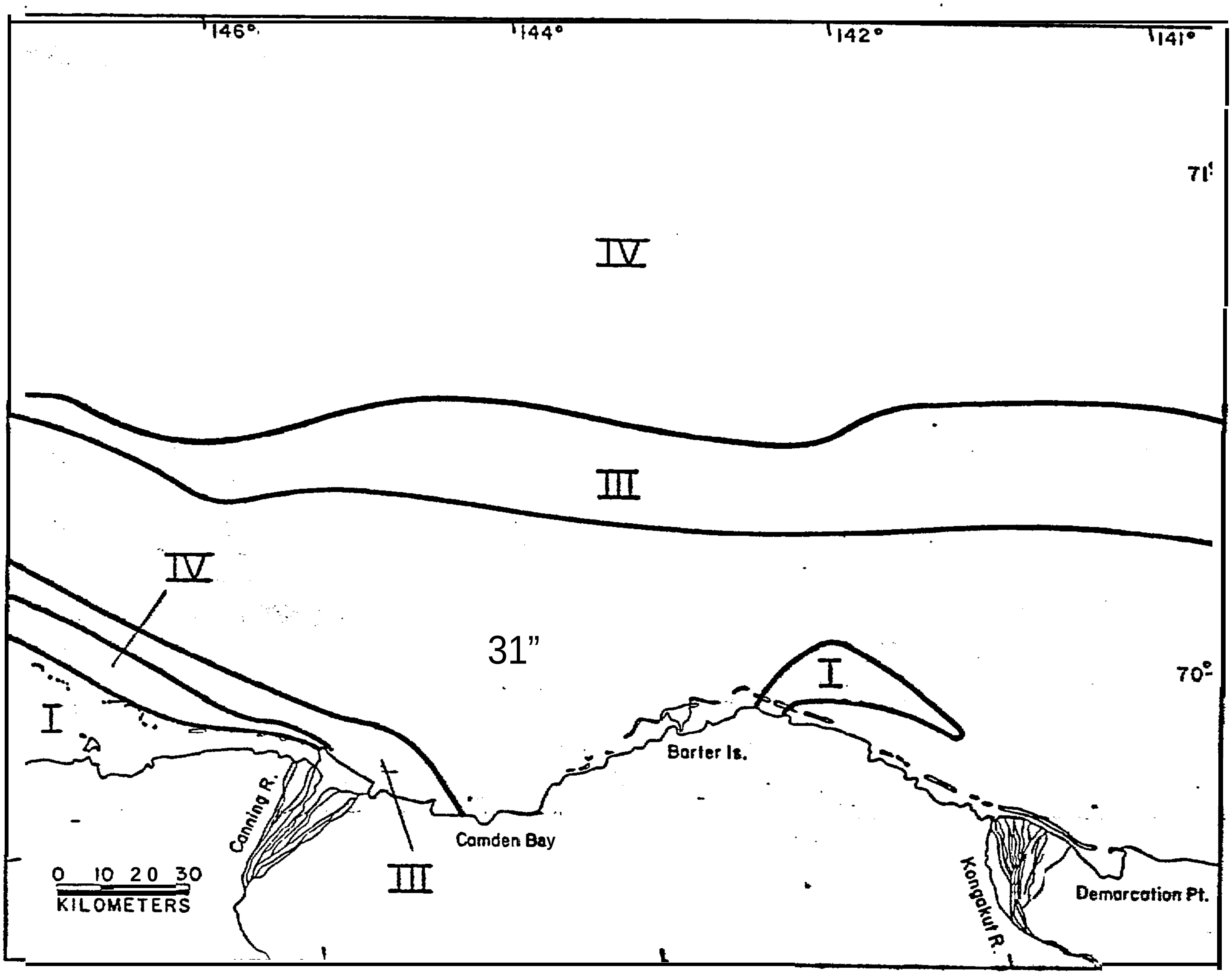


Figure 14. Multiyear Ice Concentrations to be Expected at the 20% Probability Level. (Average Maximum 5-year Ice Concentration)

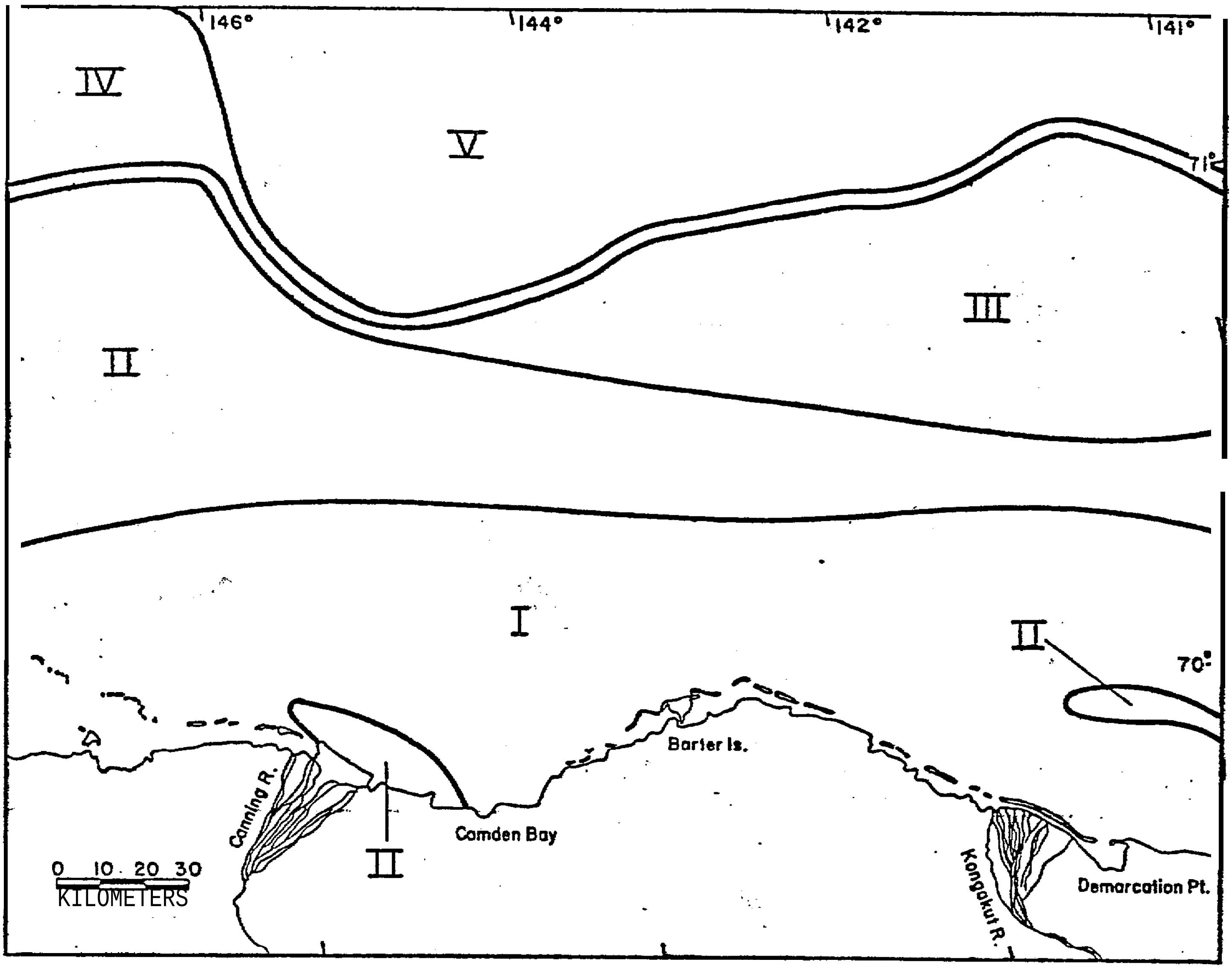


Figure ?5. " Multiyear Ice Concentrations to be Expected at the 30% "
Probability Level. (Average Maximum 3-year Ice Concentration)

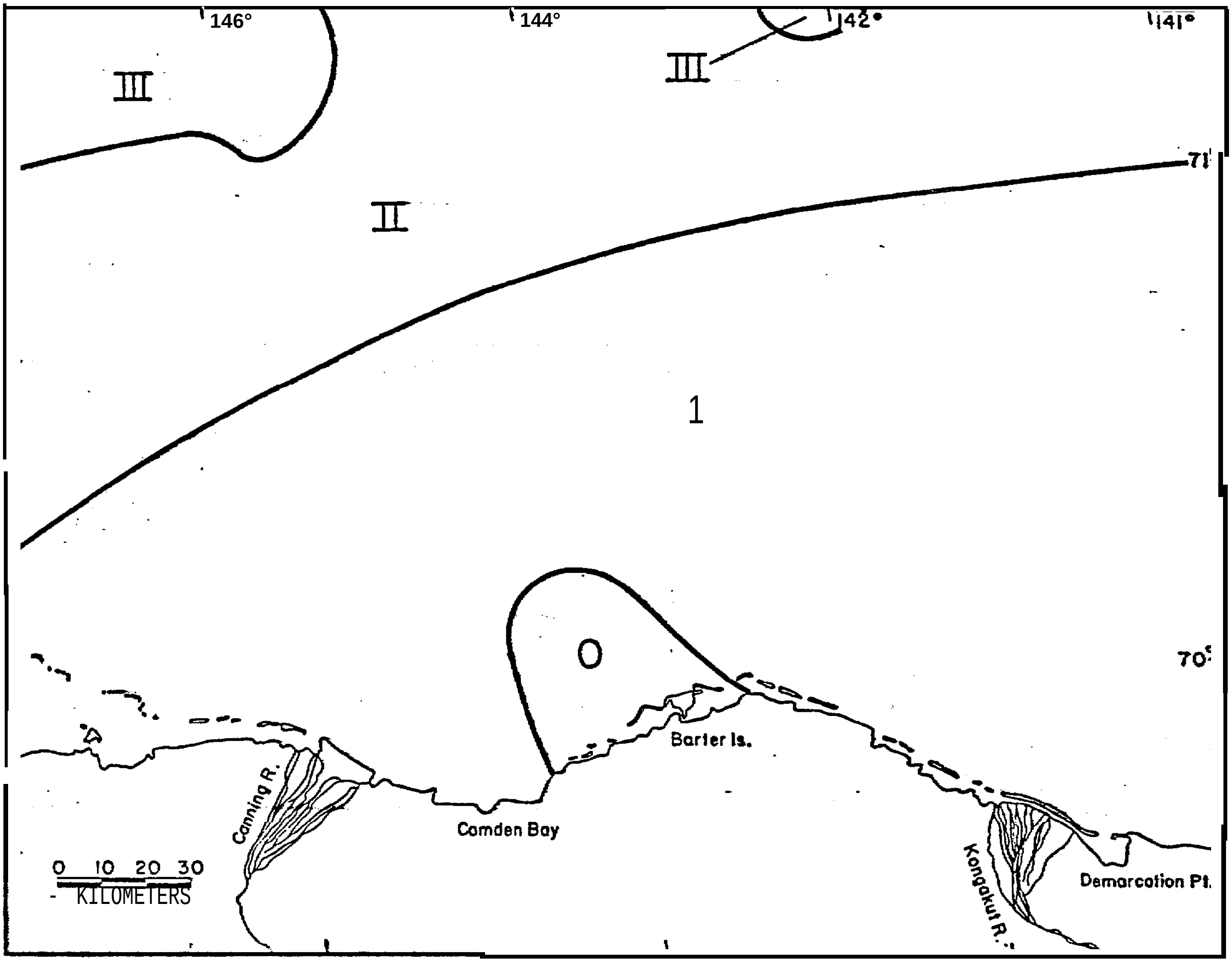


Figure 16. Multiyear Ice Concentrations to be Expected at the 40% Probability Level. (Average Maximum 2.5-year Ice Concentration)

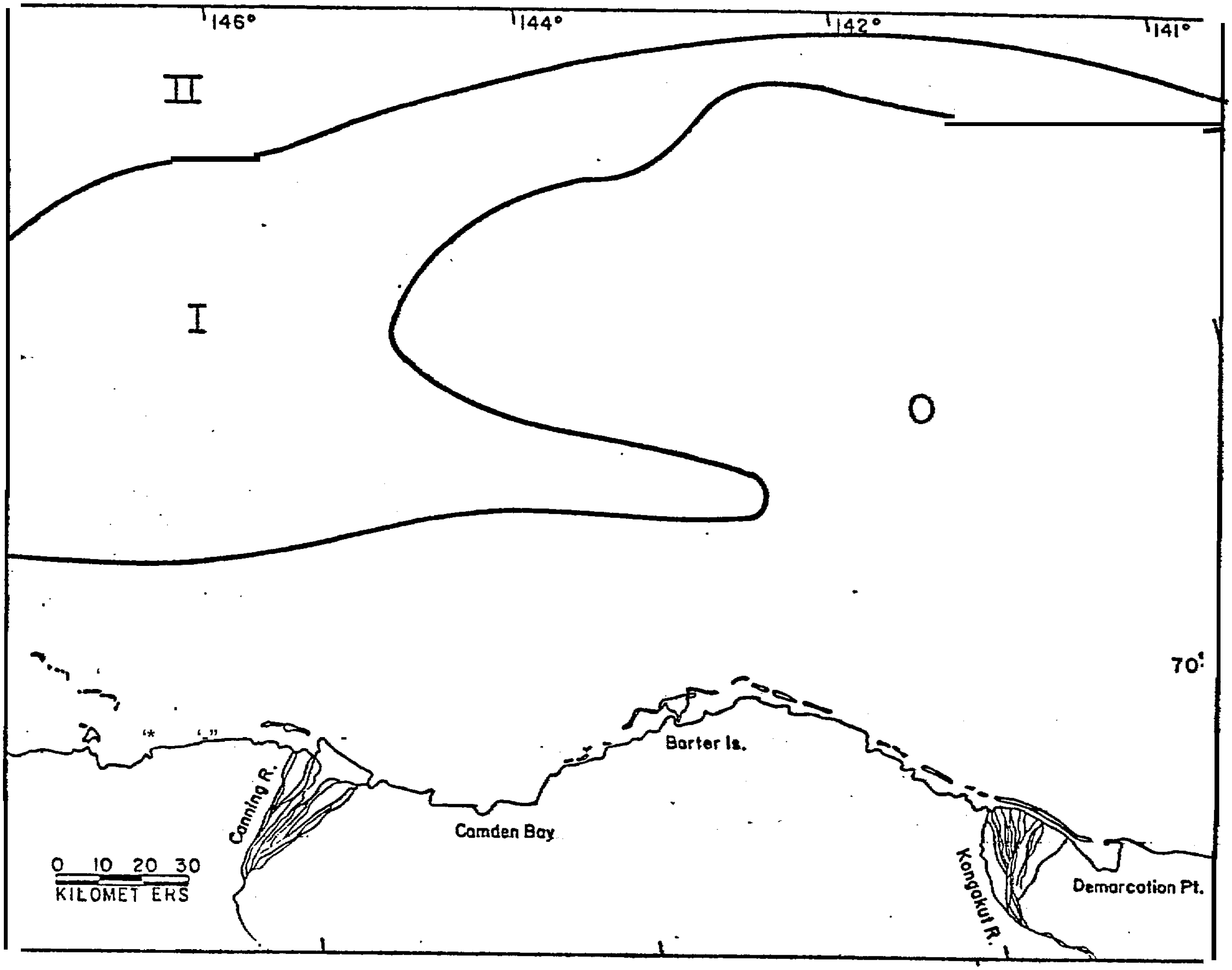


Figure 17. Multiyear Ice Concentrations to be Expected at the 50% Probability Level. (Average Maximum 2-year Ice Concentration)

Discussion: Multiyear Ice Concentration at Specified Probabilities

This set of figures may be the most meaningful representation of the data set in terms of nearshore petroleum exploration and development within the eastern Beaufort Sea study area. However, their interpretation may be rather difficult. For instance, the last figure in the series shows no nearshore multiyear ice within the study area at the 50% probability level. This says that for a year chosen at random, there is an even chance of no ice. There were no ice concentrations at probabilities greater than 50%. Therefore, 50% is the probability that no multiyear ice will be found over all the study area in a given year except the small region around Barter Island shown in the 40% figure as having no concentration at that level. The small area with 0% concentration on the 40% probability figure disappears on the 30% figure so that 40% is the probability that that area will not have multiyear ice in some concentration on a year chosen at random.

At the other end of the observed scale, the 10% probability figure shows the maximum multiyear ice concentration to be expected over an average span of 10 years. These concentrations are indeed formidable. If a test drilling structure were to be constructed only to be used for 1 year, in all likelihood the design requirements would need to take into consideration ice conditions occurring at this level of probability. A permanent installation with an expected life of 20 to 30 years could be expected to encounter even more severe ice conditions than shown here at some time within its span of use. Thus, from the point of view of offshore facilities, the 10% probability figure is very likely the most significant of this set in terms of anticipating physical hazards to facilities related to offshore petroleum development.

Because of the significance placed on this figure, some comment should be made concerning the existence of multiyear ice in shallow water areas shown here, and in particular, in the lagoons between the coast and barrier islands. First, the spatial resolution of this study precluded highly detailed consideration of those areas. Second, much of the late season ice mapped in this study in the nearshore areas appeared to be grounded in waters at least several meters deep, offshore from the barrier islands. - Multiyear ice found in shallow areas would clearly consist of rather shallow-draft floes that were also small in spatial extent. Therefore, hazard assessments of multiyear ice shown for coastal lagoons and other shallow areas should take these factors into account. In-general, it is thought by the author that #e concentrations for these areas are probably lower than shown here. In arty case, because of the small multiyear floe size and limited ice dynamics in these areas, . . multiyear ice in these areas does not represent nearly as great a hazard as does multiyear ice in offshore areas with water depths greater than a few meters.

Extreme Event Analysis

The concentration v.s. probability data lend themselves to analysis which should help predict the average time between extreme ice events in various portions of the study area. Generally speaking, the study area can be divided into 5 zones, each with roughly uniform statistics. These are shown on figure 18. The concentration and probability data were platted on various coordinate papers and found to display the most linear relationship on semi-log paper, implying a realtionship $p=ke^{-nc}$, where c is a chosen multiyear ice concentration, p is the corresponding probability of that concentration, and k and n are constant parameters. Figures 19 through 23 show these plots.

These plots were projected to the 100% concentration level in order to determine the frequency with which this condition might be expected to occur within each zone. The Inverse of this number is the average periodicity with which this concentration might be expected to occur. This extreme event period has been indicated on figure 18 within parentheses. These projections indicate that in the nearshore area, extreme events occur from once every 5 years for the region off the barrier islands west of the Canning River to once every 25 years in the coastal zone in the eastern portion of the study area.

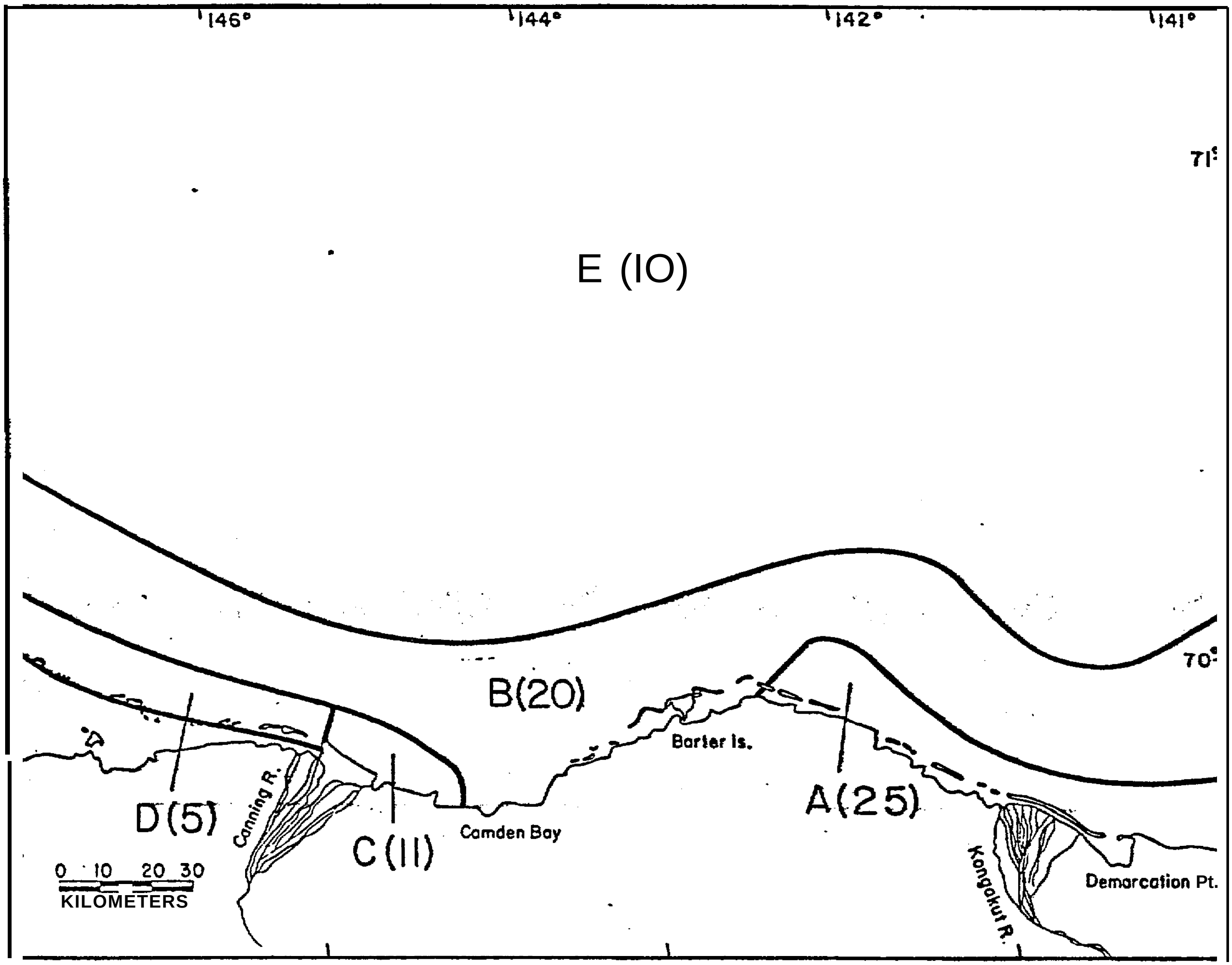


Figure 18. Map of Zones with Similar Probability vs. Concentration Statistics

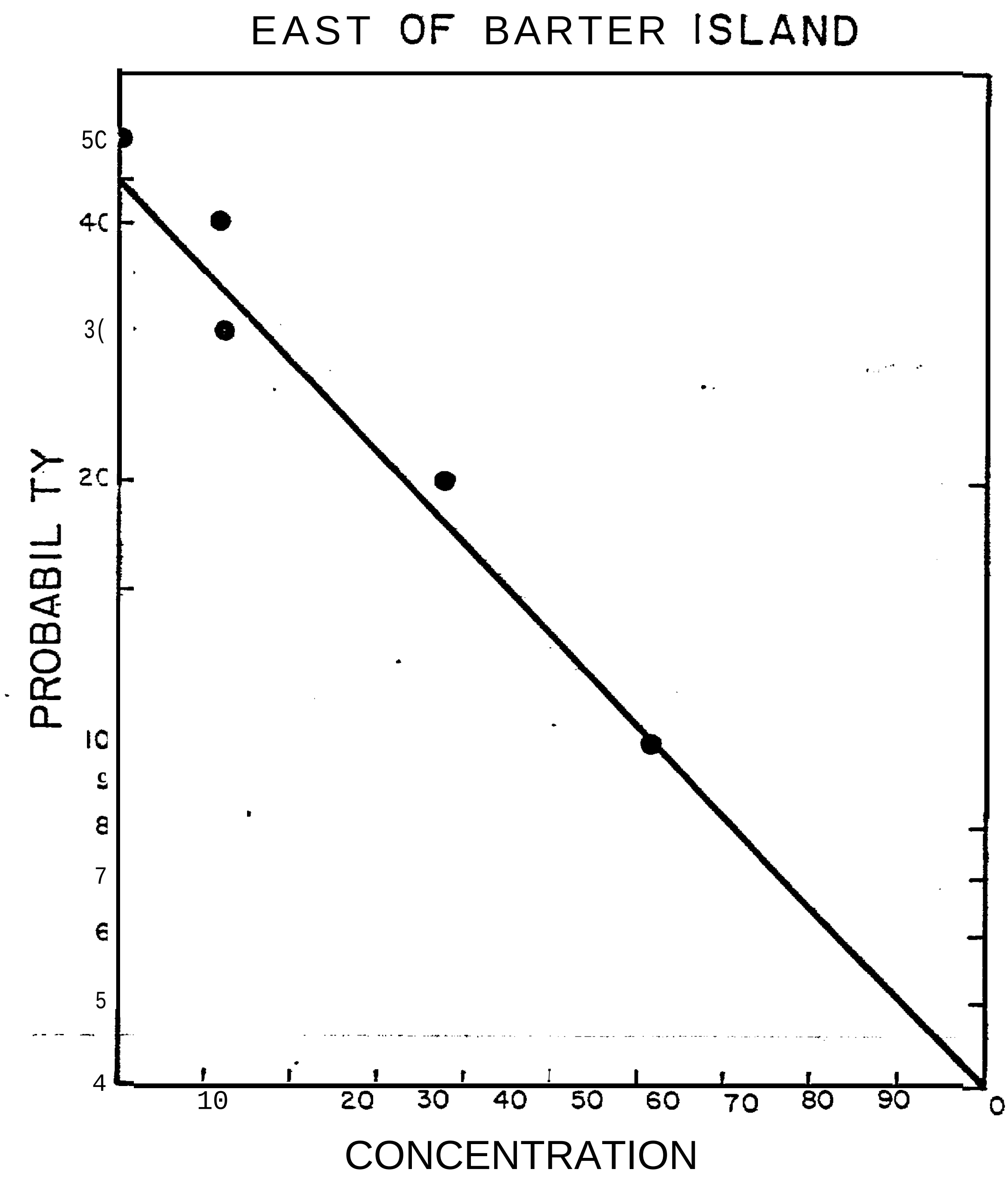


Figure 19. Plot of Concentration vs. Probability for Zone A

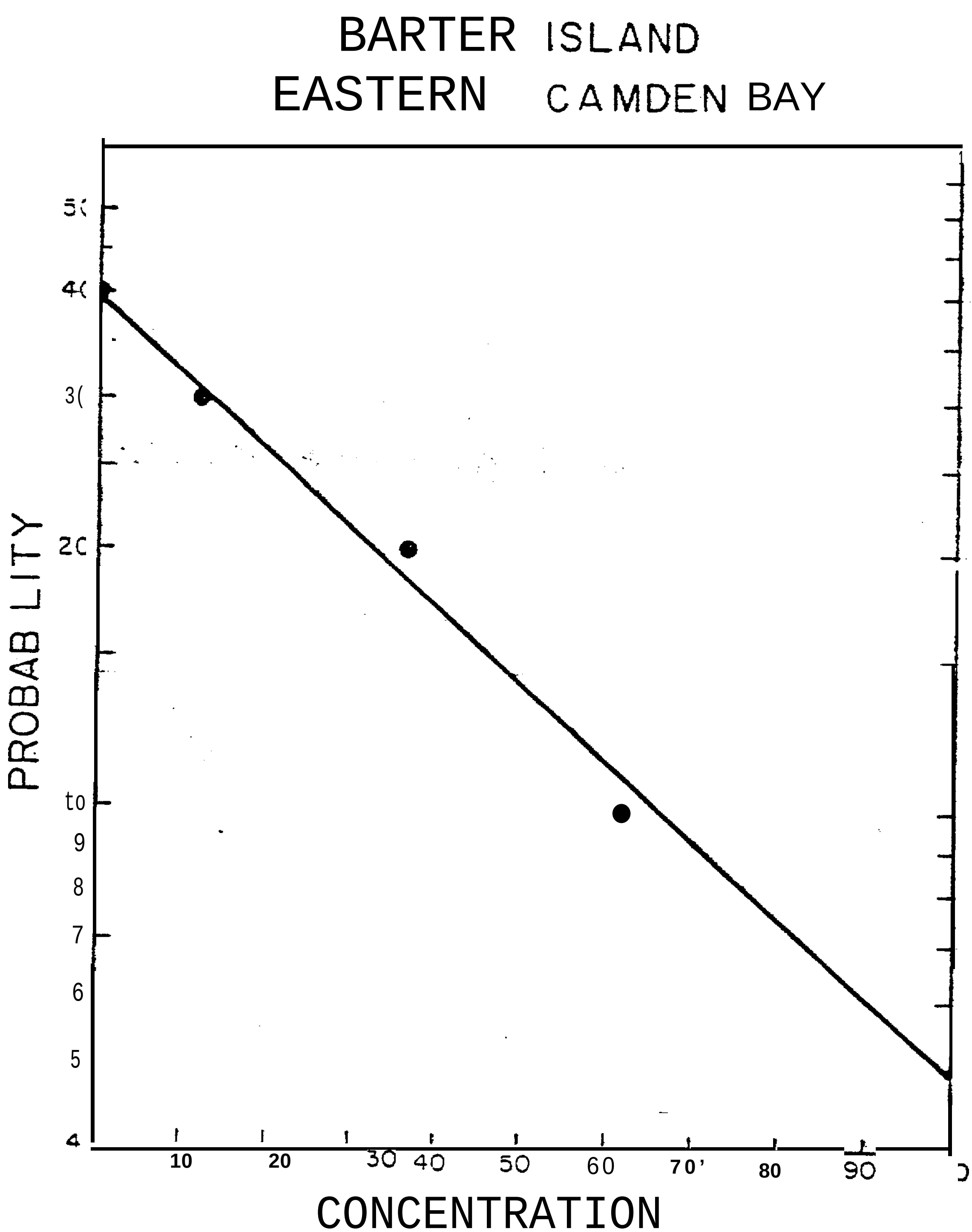


Figure 20. Plot of Concentration vs. Probability for Zone B

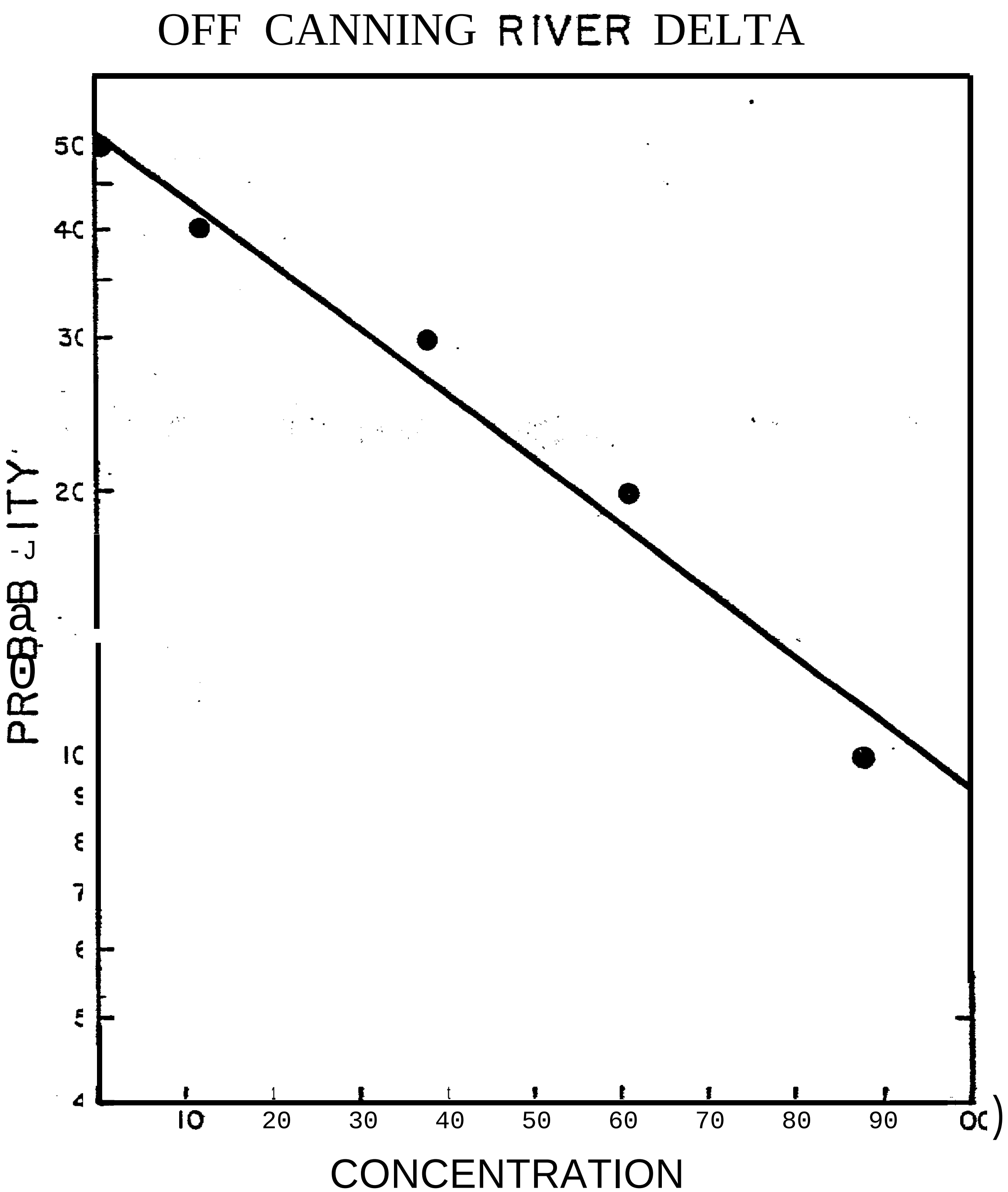


Figure 21. Plot of Concentration vs. Probability for Zone C .

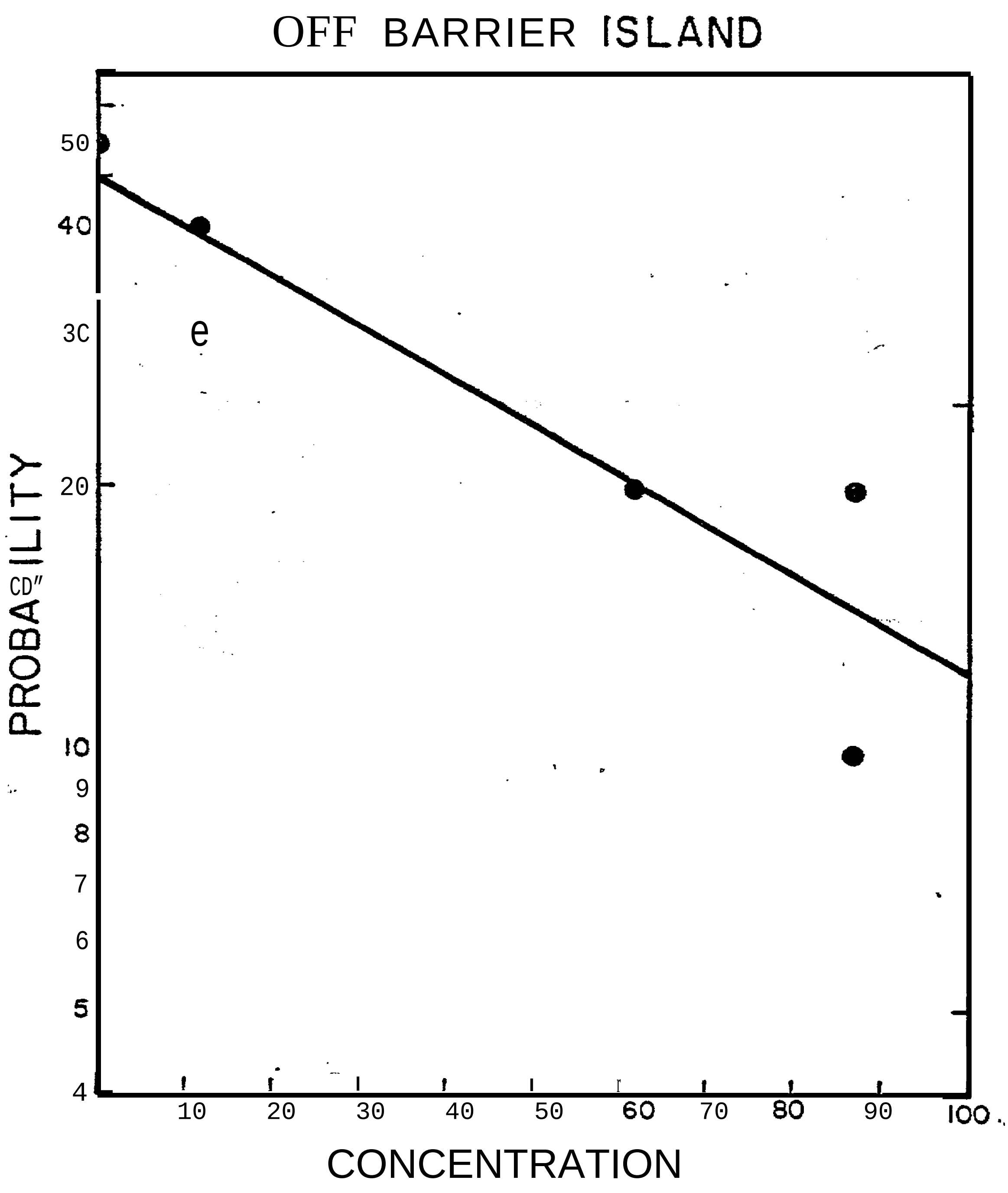


Figure 22. Plot of Concentration vs. Probability for Zone D

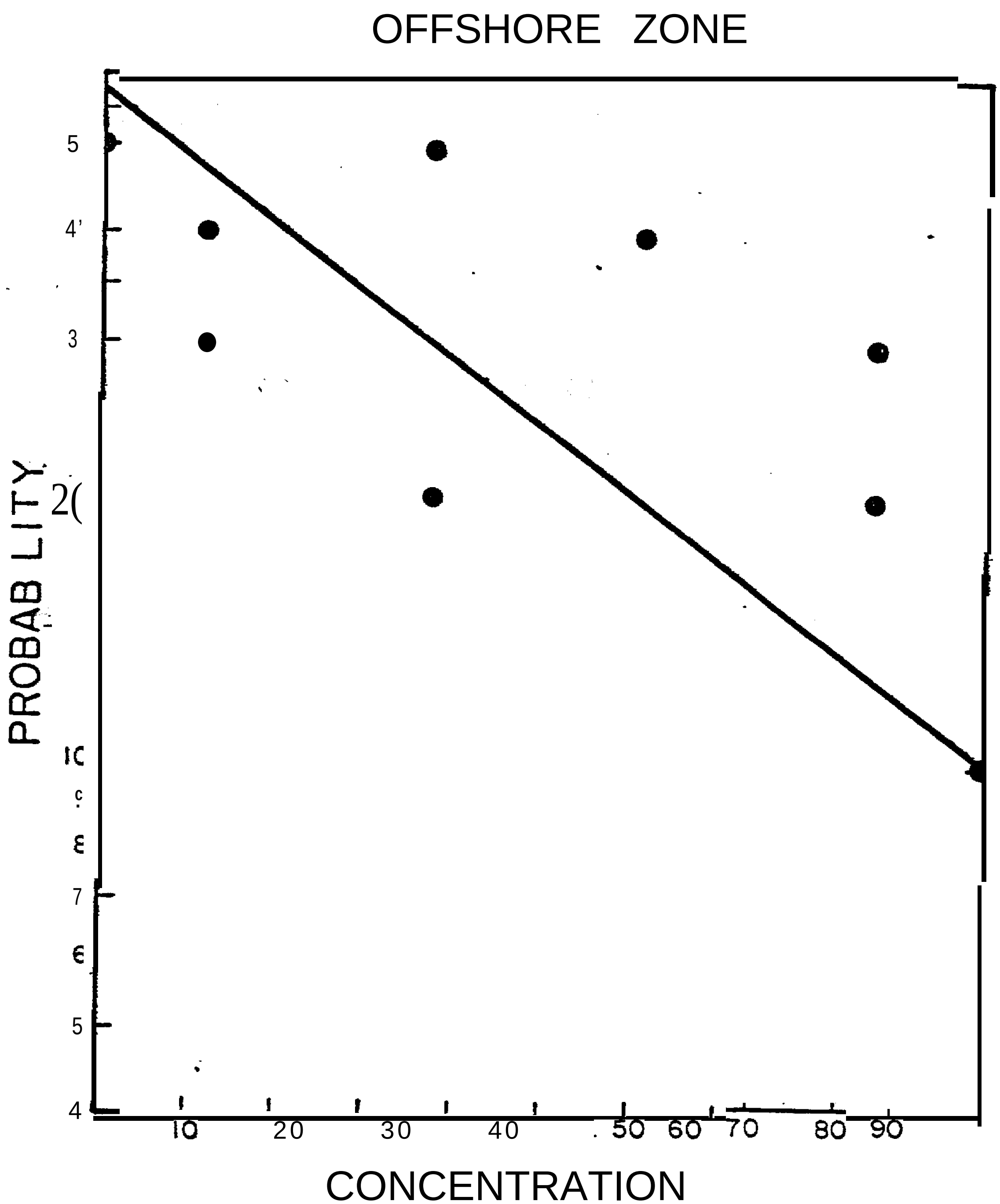


Figure 23. Plot-of Concentration vs. Probability for Zone E

Conclusions

Multiyear ice has been found to occur within the nearshore portions of the eastern Beaufort Sea study area at relatively high concentrations and frequencies. Two general patterns of pack ice behavior resulting in late season ice becoming multiyear ice were found:

a. heavy ice years where the Beaufort Sea ice pack remained close to share all summer.

b. a late season retreat of the pack ice characterized by westward-moving floes across the study area.

Of these 2 patterns, the latter resulted in very high concentrations of multiyear ice off the barrier islands west of the Canning River, while the former resulted in generally high concentrations throughout the study area.

Projections of the interval between extreme (100% concentration) ice events shows that a periodicity ranging between 5 to 25 years can be expected within the portion of the study area offshore from the coast or barrier islands, wherever they are found.

These results imply that not only permanent, but also temporary offshore petroleum activities should he planned with the possibility that high concentrations of multiyear ice might be encountered.

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