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THE APPLICATION OF ERTS IMAGERY TO MONITORING ARCTIC SEA ICE: SUPPLEMENTAL REPORT

ERT Document No. 0408-S

January 1975

SUPPLEMENT TO THE FINAL REPORT
For Period May thru December 1974

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16. Abstract

A supplemental study of the application of ERTS-1 data for detecting and mapping arctic sea ice is conducted. Ice distributions are mapped for selected arctic areas using sequential data from the 1973 summer season; comparative analyses are performed using data from corresponding periods in different years; and the ERTS imagery is compared with composite ice charts derived from environmental satellite data. The additional analyses performed under this supplemental study further substantiate the application of ERTS imagery for observing sea ice.

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PREFACE

A supplemental study of the application of ERTS-1 data for detecting and mapping arctic sea ice is conducted. Ice distributions are mapped for selected arctic areas using sequential data from the 1973 summer season; comparative analyses are performed using data from corresponding periods in different years; and the ERTS imagery is compared with composite ice charts derived from environmental satellite data.

The additional analyses performed under this supplemental study further substantiate the application of ERTS imagery for observing sea ice. The ice breakup in 1973 in two areas, the east coast of Greenland and the north coast of Alaska, could be monitored. Variations in ice extent, deformation, and movement during corresponding periods in 1972, 1973, and 1974 in the M'Clure Strait, Amundsen Gulf, and MacKenzie Bay to Cape Bathurst areas could be mapped. The comparison between ERTS and environmental satellite data showed that the environmental satellite data are very useful for mapping general ice conditions over broad areas, but that ERTS provides far more detailed information on ice structure.

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1. INTRODUCTION

1.1 Results of Initial Investigation

The work described herein represents a continuation of an investigation to evaluate ERTS-1 imagery for detecting and mapping arctic sea ice. The results of the initial investigation have been presented in an earlier report by Barnes and Bowley (1974), as well as in papers at the Second and Third ERTS-1 Symposia (Barnes and Bowley, 1973a; 1973b). In the initial investigation, data were analyzed for various arctic areas including the Bering Sea, the Eastern Beaufort Sea, and the Greenland Sea. The data sample was from the late summer and early fall of 1972 and the spring and early summer of 1973.

The results of the initial investigation have shown that sea ice features at least as small as 80-100 m in width can be detected in ERTS imagery. The visible spectral band imagery is the most useful for mapping overall ice extent, since some types of ice are difficult to detect in the near-IR spectral band imagery. A greater amount of detail in the ice features can be detected in the near-IR imagery, however, and the multispectral analysis of the visible and near-IR data is a powerful tool for identifying ice types and for determining certain ice surface characteristics. In regions such as the eastern Beaufort Sea, the combination of ERTS orbital overlap and a high incidence of cloud free conditions during the spring assures a high frequency of repetitive satellite coverage. The resulting sequential observations permit the deformation and movement of ice features to be mapped.

Ice features that can be identified in ERTS imagery include: the distinction between grey, grey-white, and older forms of ice, as well as the distinction between ice floes and surrounding brash ice; the growth and deterioration of leads; the formation of new grey ice within leads; the deterioration of the ice surface as evidenced by the formation of puddled areas and flooded ice; linear dry areas within flooded ice fields caused by the drainage of meltwater; and icebergs embedded in fast ice or close pack, detectable by their shadows.

Comparative analyses have shown generally good agreement between the locations of ice edges and the ice concentrations as mapped from ERTS imagery and as depicted on aerial ice observation charts. In addition to being compared with the standard aerial observation charts, data from ERTS passes crossing the Bering Sea in early March were compared with ice observations collected in the Bering Sea Expedition (BESEX). On two flights of the NASA-CV-990 aircraft, the ice conditions in the vicinity of St. Lawrence Island reported by the onboard observer are in remarkably close agreement with the ice conditions mapped from the corresponding ERTS imagery. The features identified in ERTS imagery and substantiated by the aerial observer include the locations of boundaries between areas consisting of mostly grey ice and of mostly first-year ice, the existence of shearing leads and the occurrence of open water with the associated development of stratus cloud streaks. Moreover, it appears that essentially all of the significant ice features near St. Lawrence Island visible in aircraft photographs taken from the CV-990 can also be detected in the ERTS imagery.

1.2 Purpose of Supplemental Study

The purpose of the supplemental study was to: (1) map ice distributions for selected arctic areas using the ERTS-1 data sample from the late summer of 1973; (2) perform comparative analyses using ERTS-1 data from corresponding periods in more than one year; and (3) to correlate the 1973 ERTS-1 data with any available ground truth.

Sequential observations during the summer of 1973 were made for several arctic areas. The sequential observations showing the ice break-up in two areas, the Greenland Sea along the east coast of Greenland and the Beaufort Sea along the north coast of Alaska, are discussed in Section 2 of the report.

ERTS-1 has been in operation since late July 1972. Depending on cloud conditions, therefore, it was possible to map ice in certain areas for corresponding periods during two or even all three of the 1972, 1973, and 1974 summer seasons. Discussions of the ice distributions in the M'Clure Strait-eastern Beaufort Sea area during all three years and in the MacKenzie Bay-Cape Bathhurst area during 1973 and 1974 are presented in Section 3. The movements of ice floes in Amundsen Gulf in 1972 and 1973 are also compared in Section 3.

In the initial investigation, ERTS imagery had been compared with aerial survey ice charts and a sample of aircraft photographs. In the supplemental study, ERTS imagery was compared with sea ice charts derived from environmental satellite data since these charts are another source of ice observations used for operational purposes. The comparative analysis is presented in Section 4.

This supplemental report is intended to provide additional examples demonstrating the application of ERTS imagery for detecting and mapping sea ice. Discussions of the characteristics of the ERTS system, the techniques to identify ice and to distinguish ice from clouds, and use of the visible and near-IR bands to obtain information on ice type and ice surface characteristics are presented in detail in the initial report (Barnes and Bowley, 1974). The ice terminology used in this supplemental report follows the glossary of ice terminology given in the Appendix of the initial report.

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2. SEQUENTIAL ICE OBSERVATIONS DURING 1973 SUMMER SEASON

2.1 Greenland Sea Along East Coast of Greenland

Near-IR spectral band (MSS-7) images for three passes crossing the Dove Bay area, including Germania Land and Ile de France to the north and Store Koldeway to the east (see map, Figure 2-1), are shown in Figures 2-2, 2-3, and 2-4. These mosaics display significant seasonal variations in the distribution of coastal fast ice, as well as changes in the overall concentration of the offshore pack ice, over the period from 25 March 1973 through 18 August 1973.

On 25 March (Figure 2-2), a distinct boundary of fast ice extends nearly due south from the southern tip of Ile de France to near the coasts of Germania Land and Store Koldeway, and then southeastward toward the east coast of Shannon Island. A narrow zone of young ice (grey and grey-white) has formed in the flaw lead that separates the uniformly smooth fast ice from the consolidated pack ice located offshore. Grey and grey-white ice has also filled in the areas between the older, thicker ice floes comprising the pack ice. In the western part of Dove Bay between Edvards Island and the adjacent island (one of the Godfried Hansons Island group), a high concentration of icebergs embedded in fast ice can be identified. Storstrommen, a large glacier where the icebergs originate, has its mouth in Borge Fiord, just west of Edvards Island. These icebergs, which appear in each of the 1973 passes, were also observed embedded in a tongue of fast ice in imagery of 25 September 1972. The numerous iceberg shadows stand out particularly well in the March image because of the uniform brightness of the fast ice due to snow cover; also, the sun elevation angle of 16° is considerably lower than in the June or August imagery.

Significant changes in the concentration of the pack ice and the reflectance of the fast ice are evident three months later in the 25 June mosaic (Figure 2-3). Although the boundary of the fast ice appears generally unchanged, the fast ice in Dove Bay and immediately southwest of Ile de France now has a much lower reflectance. In these areas, considerable meltwater has apparently flooded the surface of the fast ice, accounting for the lower reflectance. The lower reflectance that is also observed

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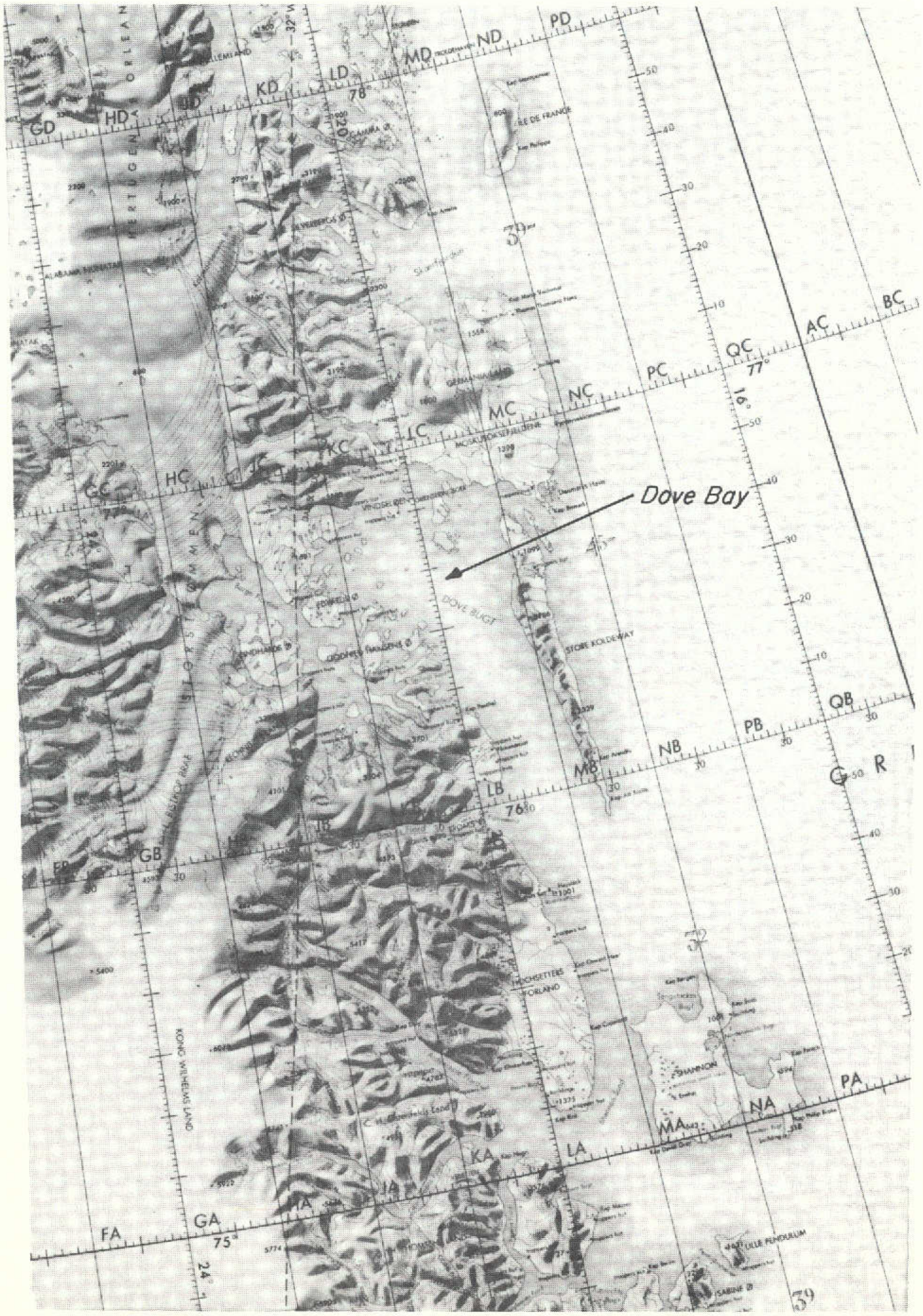

Figure 2-1 Portion of USAF Operational Navigation Chart covering the east coast of Greenland from Shannon Island (south) to Ile de France (north).

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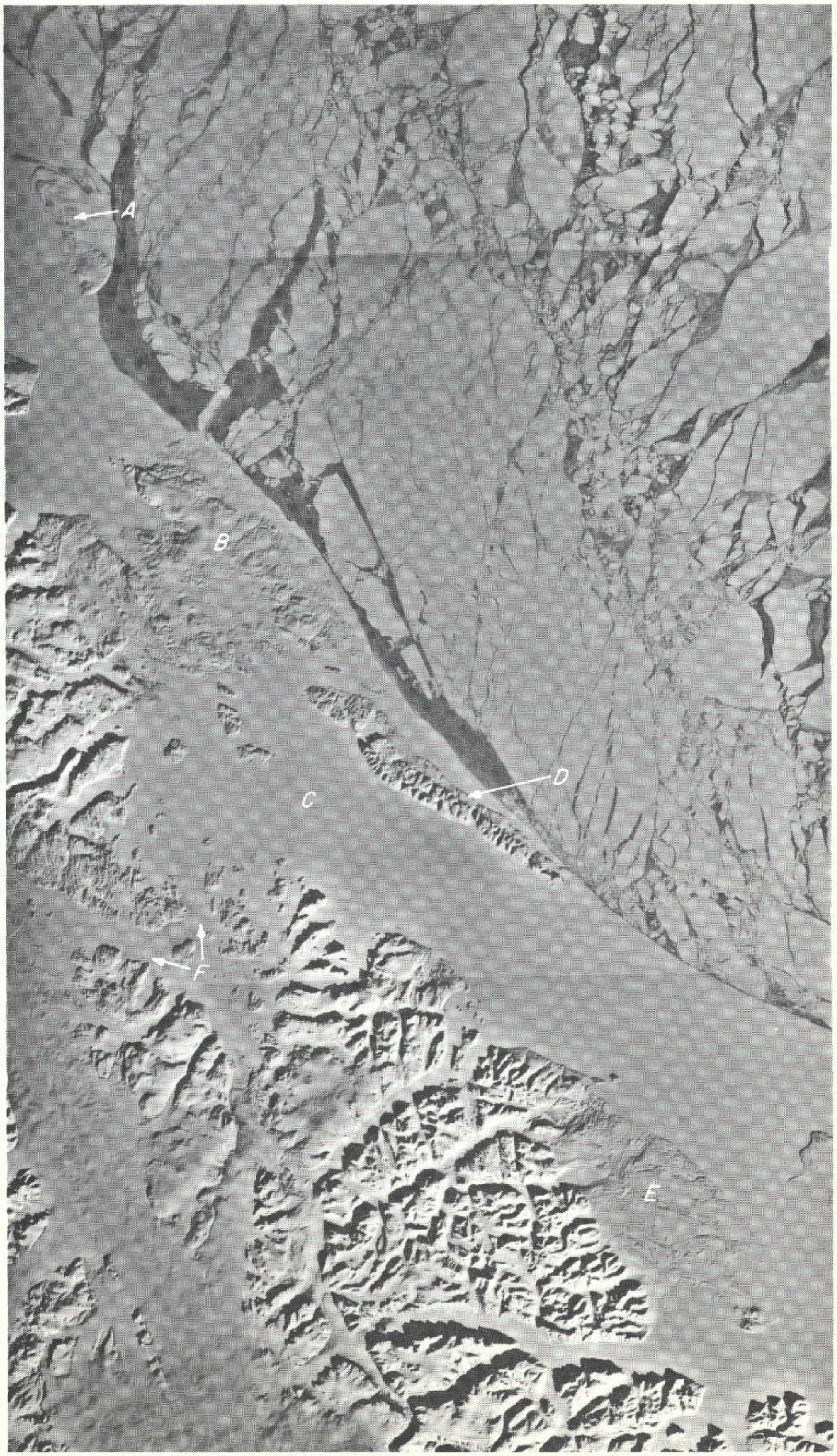

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Figure 2-2 ERTS-1 MSS-7 mosaic, (ID Nos. 1245-13430, 1245-13423 and 1245-13421) 25 March 1973, showing the Dove Bay area along the east coast of Greenland. The following features are indicated: Ile de France (A), Germania Land (B), Dove Bay (C), Store Koldeway (D), Hochsetters Forland (E), and embedded icebergs (F).

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Figure 2-3 ERTS-1 MSS-7 mosaic (ID Nos. 1337-13532 and 1337-13530) 25 June 1973, showing the same area observed in the previous figure. Flooded fast ice (A) is evident in Dove Bay and southwest of Ile de France.

over much of the land areas reveals that substantial snowmelt has occurred since the previous observation. It may even be that a part of the meltwater observed on the ice surface is the result of runoff from the adjacent land. Surface temperature readings on Store Koldeway (0000 GMT) exceeded 0°C for much of June and reached as high as 7°C on both 24 and 25 June.

The areas of darker tone within Dove Bay, which has an overall higher reflectance in the visible-band imagery (not shown), are seen to be interlaced with bright linear features and numerous bright spots. The interpretation of these patterns, which have also been observed in several other arctic regions, particularly in imagery viewing Crozier Channel and Kellett Strait north of M'Clure Strait, is that cracks in the ice too small to be resolved by the satellite have permitted the water on the surface to drain away. In the vicinity of the cracks, the ice becomes drier once again and builds up slightly, and the reflectance in the near-IR band increases. The fast ice located west and north of Ile de France and along the east coasts of Germania Land and Store Koldeway, however, maintains high reflectance and appears free of surface meltwater. On 25 June, large areas of open water separate the boundary of fast ice from offshore pack ice that now shows a concentration of very close pack ice of varying floe sizes.

The 18 August mosaic (Figure 2-4) reveals that overall ice conditions have changed dramatically since late June. The areas of flooded fast ice in Dove Bay and southwest of Ile de France on 25 June now display considerable open water with only very open pack to open pack concentrations. In fact, the boundary of fast ice observed immediately west of Ile de France correlates closely with the extent of flooded fast ice observed in late June. Some surface meltwater is, however, now apparent on the remaining fast ice in this region as indicated by pockets of lower reflectance, particularly at the southern extent. Much of the coastline of Germania Land is now free of fast ice, although some fast ice is still observed along the east coast of Store Koldeway. In addition, the offshore pack ice on this date displays a concentration of close pack ice, as compared to the very close pack ice conditions of late June.

Figure 2-4 ERTS-1 MSS-7 mosaic, (ID Nos. 1391-13523 and 1391-13521) 18 August 1973, showing the same area observed in Figure 2-3. Ile de France (A), Dove Bay (B) and Store Koldeway (C) are indicated.

The sequential ERTS coverage of the east coast of Greenland permitted the ice movement to be determined. Several of the giant floes that are seen in the 25 June mosaic could also be identified in imagery on 15 July (not shown). The relative locations of some of these floes on the two dates, 20 days apart, are shown in Figure 2-5. Ice floes A, B, C and D, located closer to the coast, show an overall direction of motion toward the north-northeast at from 1.8 km (floe A) to 3.4 km (floe D) per day. Floes E and F, located slightly farther east, moved toward the northeast at from 2.2 km (floe F) to 3 km (floe E) per day. It is not until the movements of floes G, H and I are analyzed that the influence of the southward flow of the East Greenland Current becomes apparent. The motion of floe G is toward the southeast at 2.4 km per day, floe H toward the south-southwest at 1 km per day, and floe I toward the south at 1.3 km per day. Examination of weather charts for 0000 GMT and 1200 GMT during the period of 1-15 July shows that surface winds in the area of Germania Land and Store Koldeway ranged from calm to less than 3 mps on 60% of the charts. Another 30% of the charts showed westerly winds of 3-5 mps, whereas only 10% showed westerly flow of as much as 8 mps. This strongly suggests that the movement of floes A, B, C, and D was primarily influenced by a northeasterly flowing coastal current, and that during this 20 day period the southward flow of the East Greenland Current did not extend west of 12° W longitude.

2.2 Beaufort Sea along North Coast of Alaska

Imagery from the near-IR spectral band (MSS-7) for three passes during 1973 crossing the Harrison and Prudhoe Bay areas of the north coast of Alaska are shown in Figures 2-6, 2-7, and 2-8. These data indicate that significant changes have occurred in the overall ice conditions during the 10 week interval between the time of the first pass, 14 June, and the third, 24 August. On the earlier date (Figure 2-6), several small pockets of open water (shore polynyas) exist between the coast and the fast ice, particularly at river mouths. Although a well defined boundary is not evident between the consolidated pack ice and the fast ice, obvious differences in meltwater patterns are observed. A distinctly darker tone, indicative of a large accumulation of meltwater, exists on a large percentage of the ice surface located up to 25 to 50 km off

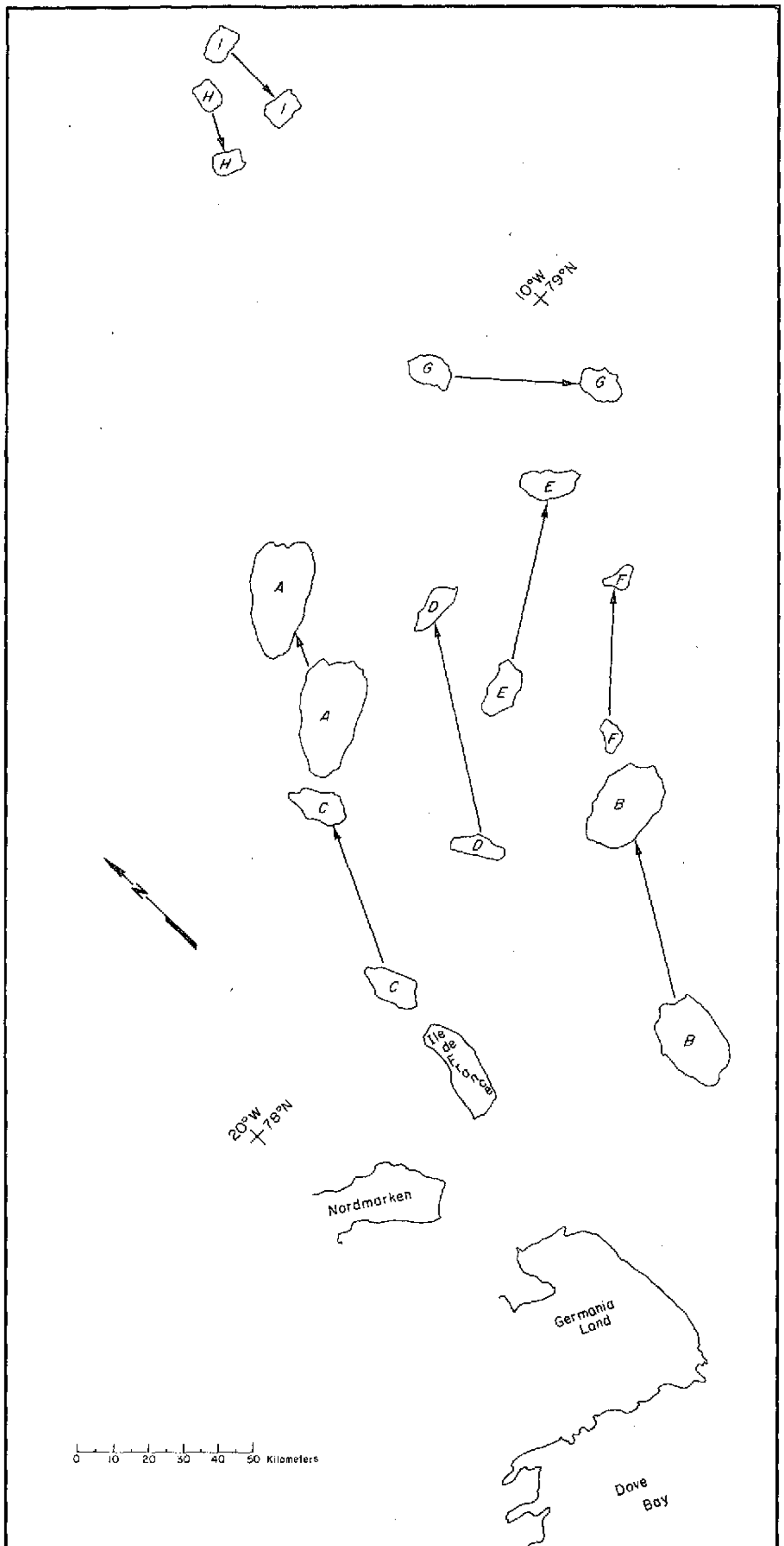

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Figure 2-5 Illustration depicting the movement of ice floes off the east coast of Greenland during the period 25 June to 15 July 1973.

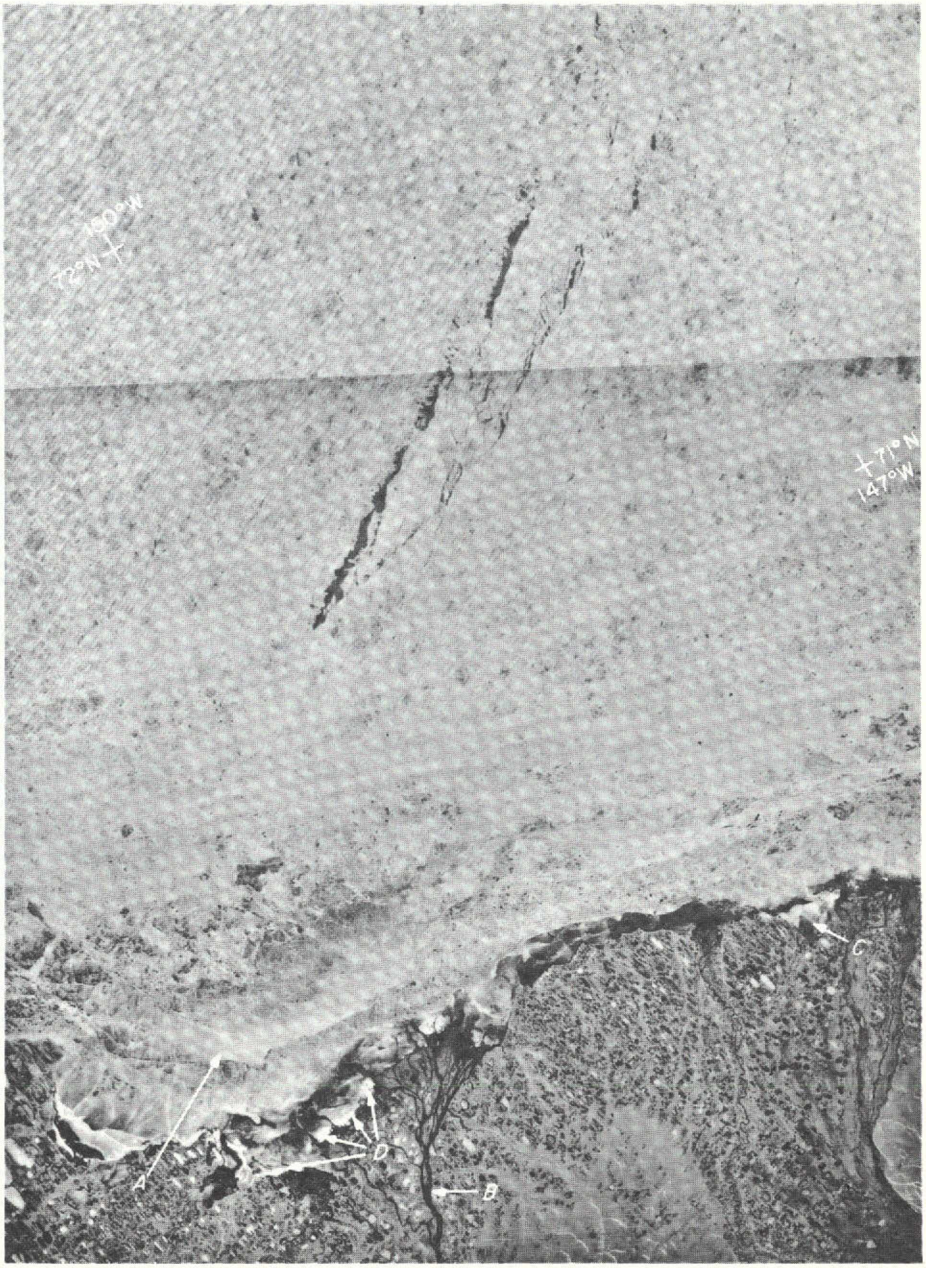

Figure 2-6 ERTS-1 MSS-7 mosaic, (ID Nos. 1326-21284 and 1326-21282) 14 June 1973, showing a portion of Alaska's north coast. The following features are indicated: Harrison Bay (A), Colville River (B), Prudhoe Bay (C), and grounded ice (D).

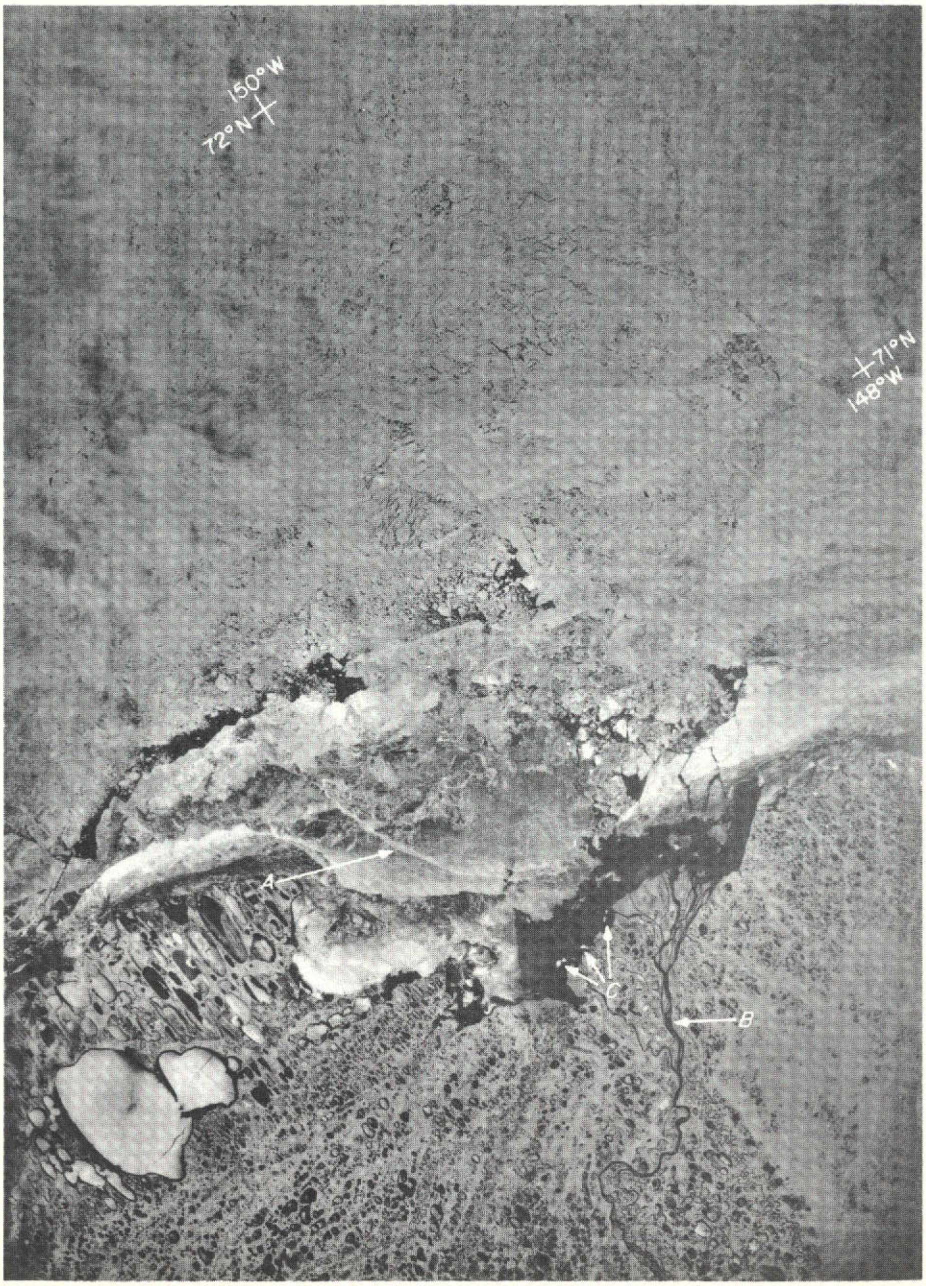

Figure 2-7 ERTS-1 MSS-7 mosaic, (ID Nos. 1345-21342 and 1345-21335) 3 July 1973, showing approximately the same area observed in the previous figure. Harrison Bay (A), Colville River (B), and grounded ice (C) are indicated.

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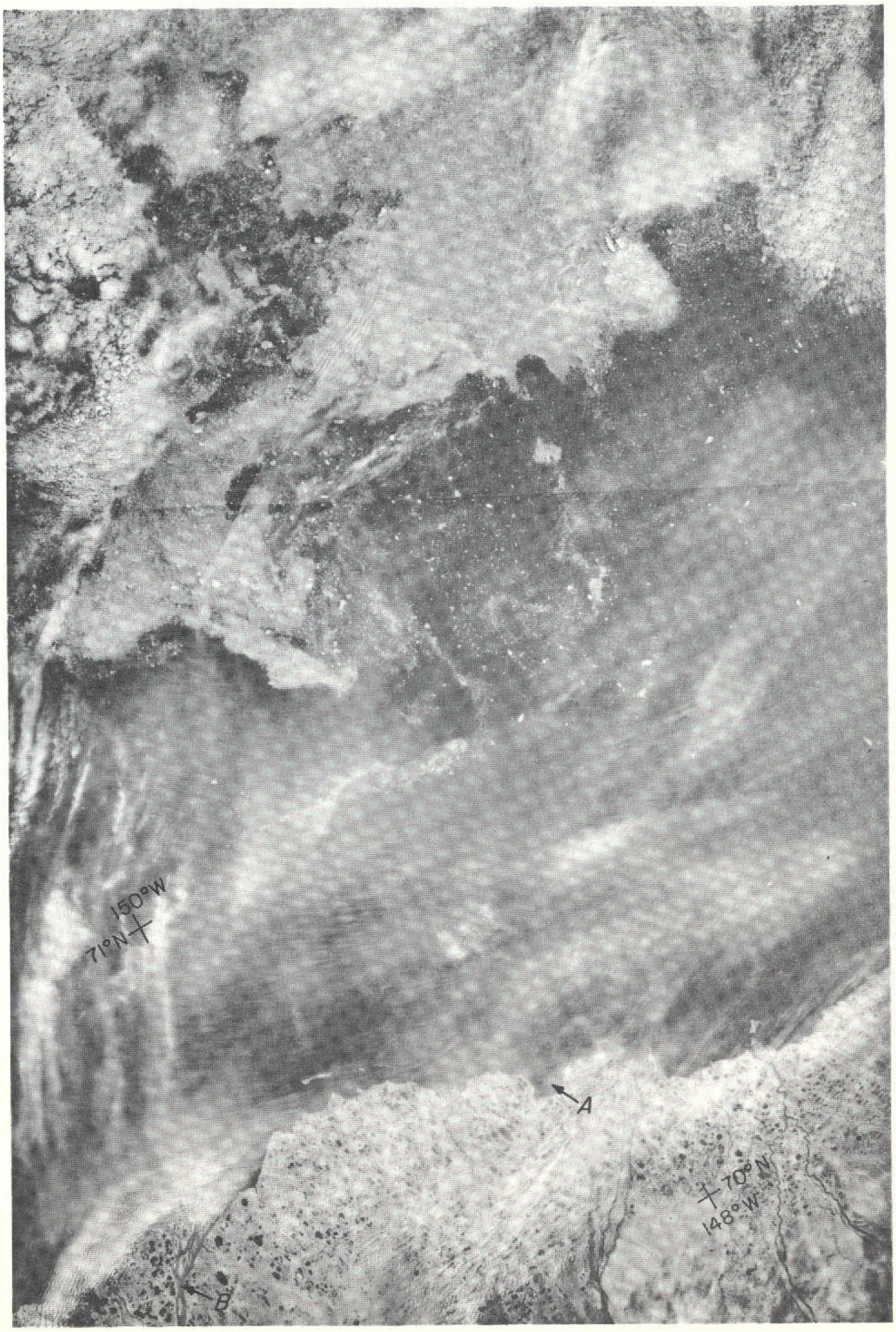

Figure 2-8 ERTS-1 MSS-7 mosaic, (ID Nos. 1397-21220 and 1397-21214) 24 August 1973, showing the pack ice off the north coast of Alaska. Prudhoe Bay (A) and the Colville River (B) are indicated.

the coast. Farther north, however, the darker tones appear considerably more patchy. Narrow bands of higher reflectance immediately adjacent to the coast suggest that the ice is free of meltwater and may be grounded in the shoal areas. Further evidence of grounded ice is provided in the early July pass (Figure 2-7), where small bright patches of ice are observed in these same locations. A fracture zone, one of the initial stages of the ice deformation process, is located between 148°W and 150°W, near 71°30'N.

Nearly three weeks later (Figure 2-7), significant changes in the overall ice conditions are evident. The extreme southern extent of the pack ice has deteriorated into very close pack ice comprised of individual vast, big and medium floes. Therefore, the outer boundary of the fast ice is clearly defined. Also, the fast ice/pack ice interface is marked by several pockets of open water (flaw polynyas). A substantial amount of meltwater still exists on the fast ice, particularly in western Harrison Bay as evidenced by the darker tone. In addition, the shore polynya at the mouth of the Colville River has grown noticeably longer in extent, and contains remnants of the very bright grounded ice noted on the 14 June imagery.

Although thin, broken cirrus and scattered stratocumulus clouds are evident on 24 August (Figure 2-8), the remaining ice is readily detected as a result of its more uniform brightness and more distinct edges of the floes. Cloud penetration is considerably greater in the near-IR data than in the shorter wavelengths. The region viewed is slightly east of the area observed in the previous two passes; however, the extent of the northward progression of the pack ice, as well as the absence of fast ice, is quite obvious. Generally open water conditions exist south of about 71°N, while varying concentrations of pack ice, comprised mostly of big, medium and small floes, separate the open water from the edge of the consolidated pack located near 72°N.

3. COMPARATIVE ANALYSIS OF ICE CONDITIONS DURING THREE SUMMER SEASONS

3.1 M'Clure Strait - 1972, 1973, and 1974

ERTS imagery of the M'Clure Strait area is available from the 1972, 1973, and 1974 summer seasons. In 1972, the first coverage of the area was on 29 July, soon after ERTS-1 was launched. In 1973, although cloud-free imagery was collected early in the summer, no data were obtained after 26 July, presumably due to cloud interference. In 1974, data were collected during both July and August. The ice conditions during the late summer of 1972 are discussed in the earlier report; that analysis is summarized below to facilitate comparison with the data from the other two years.

3.1.1 July-September 1972

ERTS images of M'Clure Strait on 29 July and 4 September are shown in the earlier report. At the end of July, fast ice exists along the north coast of Banks Island with some shore polynya evident near the mouths of the rivers. Much of M'Clure Strait is covered by fast ice with numerous fractures and leads toward the western end of the Strait. On 4 September, the entire ice sheet in M'Clure Strait has broken up. Fast ice is evident along Prince Patrick Island and in Crozier Channel and Kellett Strait. The ice concentration appears to be close or very close pack ice, consisting of ice floes surrounded by brash ice.

A later observation from the 1972 summer season, on 21 September, is shown in Figure 3-1. On this date the pack ice is more consolidated, although open water still exists along the west coast of Banks Island. In contrast to the observations earlier in the summer, the ice and land areas have become snow covered once again. Some ice floes in M'Clure Strait can be identified on both 4 and 21 September; two of the floes are indicated in Figure 3-1. During the 17 day interval the two floes have moved from their initial position (indicated on Figure 3-1) eastward along the northern coast of Banks Island at a rate of approximately 4 km per day.

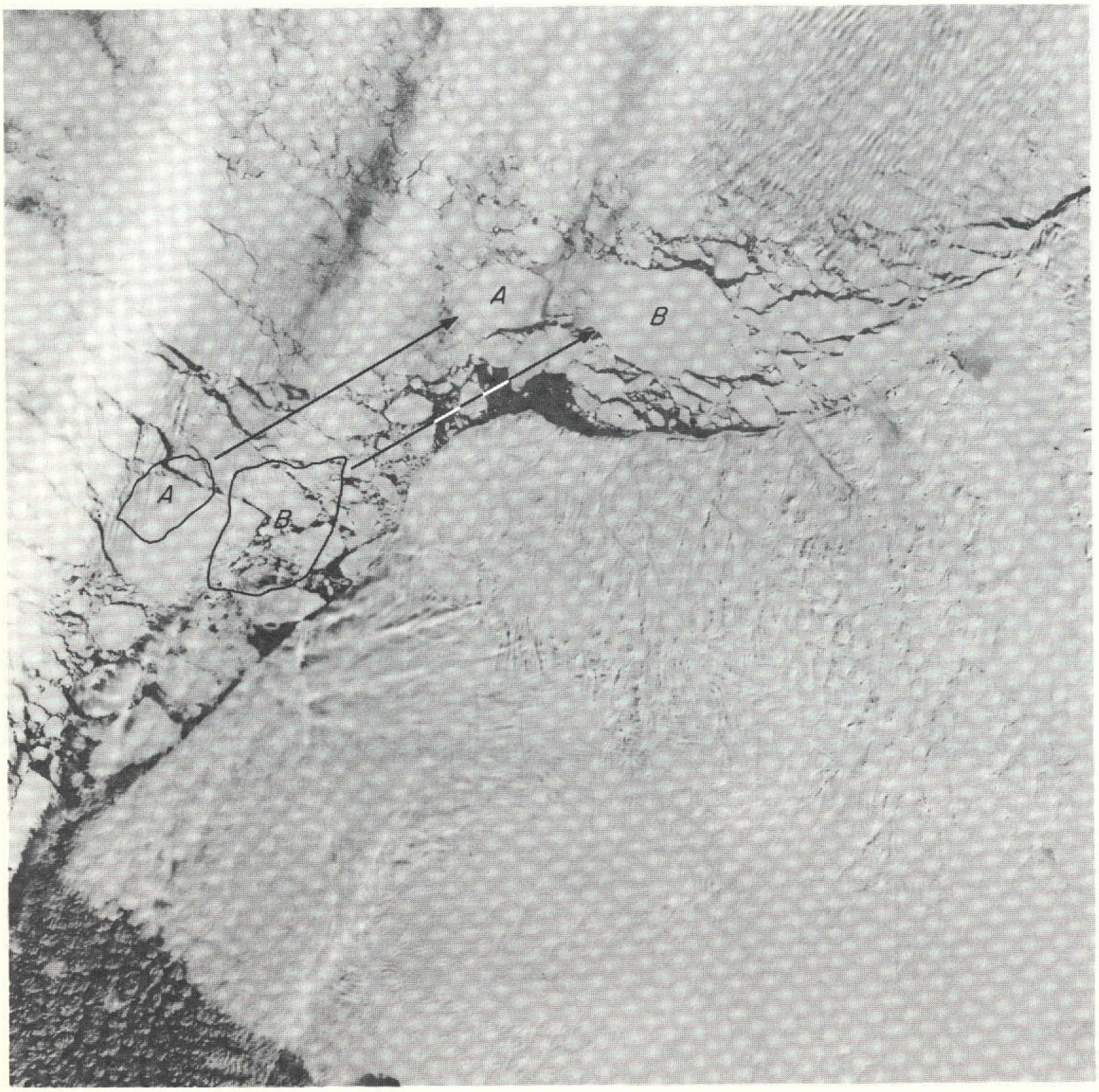

Figure 3-1 ERTS-1 MSS-6 image, (ID No. 1060-20063) 21 September 1972, showing the northwest portion of Banks Island and western extent of M'Clure Strait. The locations of floes A and B are indicated.

3.1.2 July 1973

An ERTS image for 26 July 1973 covering northwest Banks Island and westernmost M'Clure Strait is shown in Figure 3-2. The structure of the pack ice is somewhat different than at the same time the previous summer. In 1973 the pack is more consolidated, whereas in 1972 the pack consists of larger floes with more open water between the individual floes. Additionally, the shore-fast ice that still exists along the west coast of Banks Island in July 1972 does not exist in 1973.

3.1.3 July-August 1974

In 1974, good ERTS coverage of M'Clure Strait is available in July and August. On 18 July (Figure 3-3), fast ice covers all of M'Clure Strait, Crozier Channel and Kellett Strait. A fracture has developed off the northwest coast of Banks Island and extends northwestward toward Prince Patrick Island. Much of the fast ice in M'Clure Strait south of Melville Island is covered with puddles of meltwater (which appear dark on the near-IR image) and numerous cracks and drainage features.

A 9x enlargement produced from the 70 mm negative (Figure 3-4) shows in detail the structure of the meltwater patterns in Crozier Channel and Kellett Strait on 18 July. The linear features (A), which have a high reflectance in the near-IR band, are similar to those in Dove Bay (Greenland), discussed in the previous section. In this enlarged image, the darker cracks can be detected within some of the more predominant bright, linear features. Careful inspection reveals that these cracks seem to be bridged by evenly spaced bright features. Although the regularity of the features might imply that they are an artifact associated with the scanning mechanism of the sensor, the features do not match the scan lines, which are detectable in other parts of the image. It may be that the features are real, and are associated with areas where the crack is not continuous but is bridged over with ice.

These linear features were mapped on 1972 and 1974 images, and their locations were compared. The features at (A) seem to be recurring fractures with their locations being nearly identical in both years. Many of the white linears in the bays of Prince Patrick and Melville Islands also occur in nearly the same locations each year. The small white spots

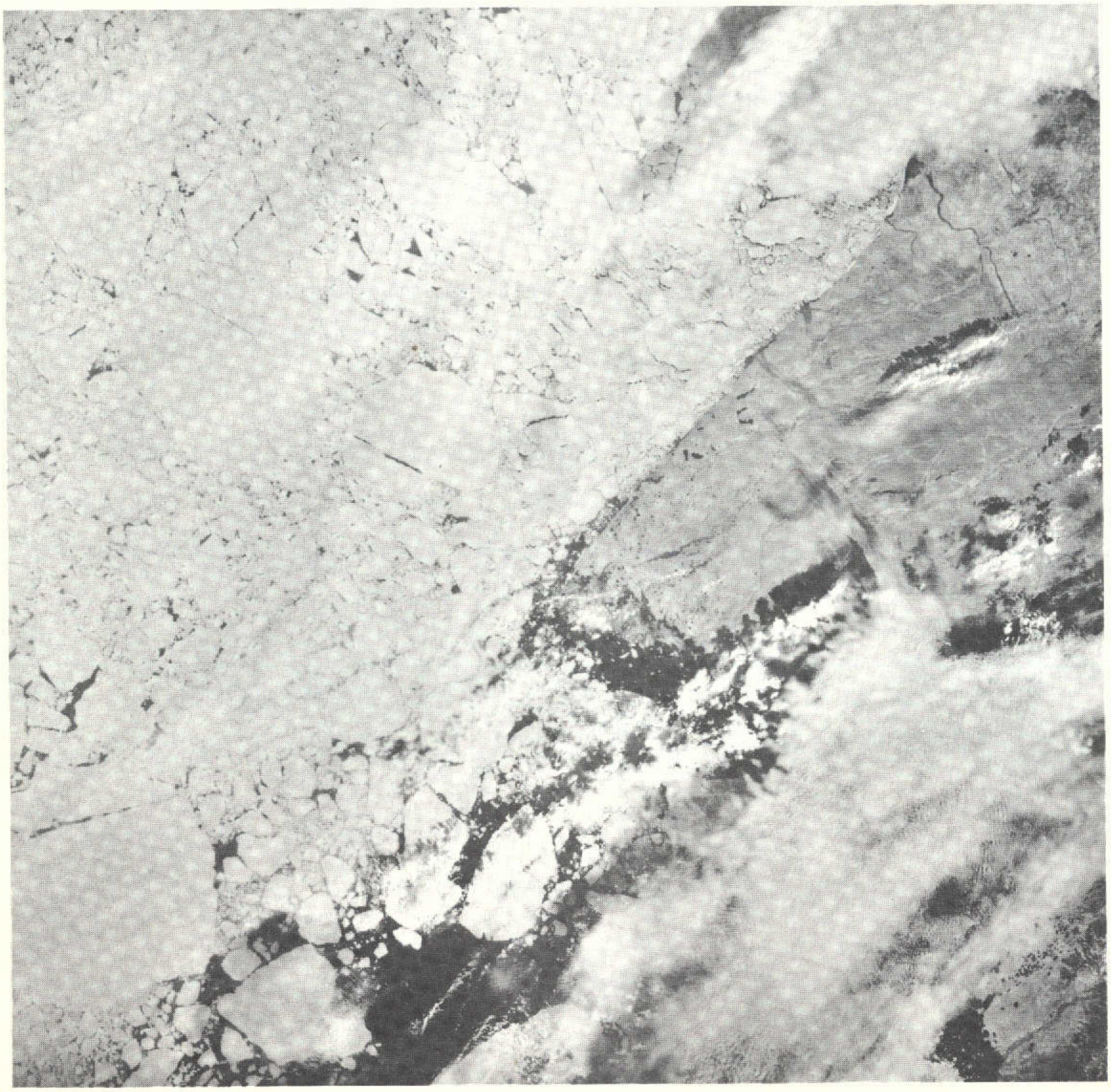

Figure 3-2 ERTS-1 MSS-7 image (ID No. 1368-20181) 26 July 1973, showing northwest Banks Island and the western extent of M'Clure Strait.

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Figure 3-3 ERTS-1 MSS-7 mosaic, (ID Nos. 1725-19525 and 1725-19523) 18 July 1974, showing ice distribution in M'Clure Strait. Crozier Channel (A), Eglinton Island (B), Kellett Strait (C), Melville Island (D), and Banks Island (E) are indicated.

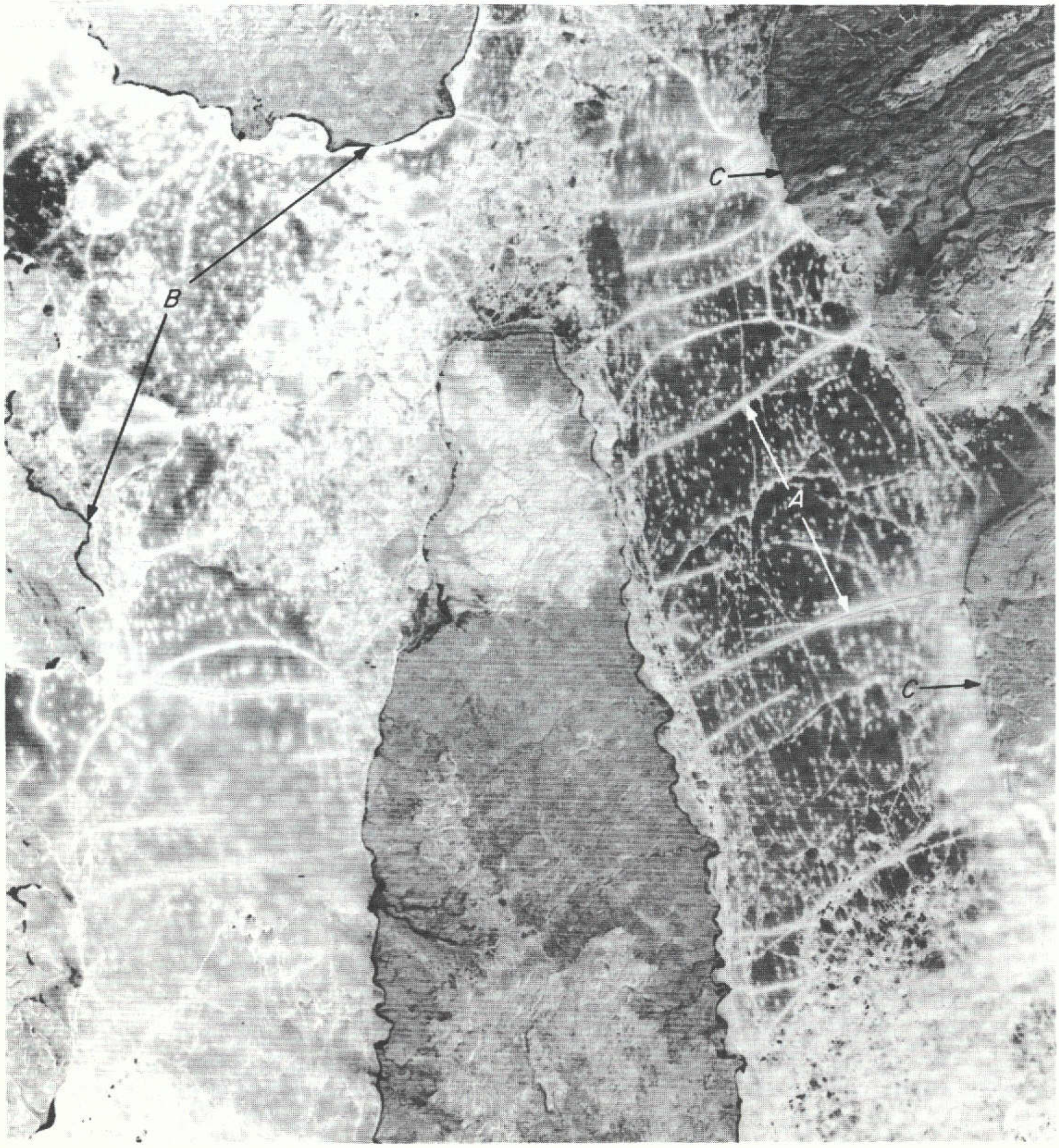

Figure 3-4 Enlargement of a portion of the previous figure showing Eglinton Island, Crozier Channel and Kellett Strait.

on the ice surface are probably thaw holes through which meltwater has drained. It can also be seen that much of the coastline in this image has a black outline (B); since these areas also appear black in the visible band (not shown), they are deduced to be open water. The areas where no black outline along the coast is present (C) correspond closely to areas that are indicated on Operational Navigation Charts as having steeper elevation gradients along the coast.

Cloud-free images for two days in late August 1974 are shown in Figures 3-5 and 3-6. The structure of the ice has changed drastically in comparison to the 18 July observation. The ice sheet has broken up into consolidated pack ice, and a considerable amount of open water exists in Crozier Channel and Kellett Strait and in the smaller bays of the islands. These open water areas are not observed in either the July or early September images of 1972. In fact, in the September 1972 image (Figure 3-2), there is no indication that the fast ice in these channels and bays has broken up at all.

The observations on 22 and 25 August show the influence of the wind on the ice pack. On the 22nd, open water exists along the south coasts of Eglinton and Melville Islands. Three days later, the small floes and brash ice have been pushed against these shorelines. On the other side of the Strait, along the coast of Banks Island, the ice has moved away during the three-day period. These motions would be expected under the effect of a wind regime that shifted from a northerly wind to a wind with a southerly component during the period between observations.

3.2 Flaw Lead - West of Prince Patrick Island

In the earlier report, much discussion was devoted to a flaw lead that developed off the west coast of Prince Patrick Island and extended southwest across the mouth of M'Clure Strait during April-June of 1973. This same area was analyzed using imagery from the spring ice season of 1974. On 6 April 1974, a fracture is seen along the west coast of Prince Patrick Island and extends into M'Clure Strait. A zone of fragmentation occurs along the northern extent of the fracture.

Figure 3-5 ERTS-1 MSS-7 mosaic, 22 August 1974, showing M'Clure Strait area. Note open water areas at (A).

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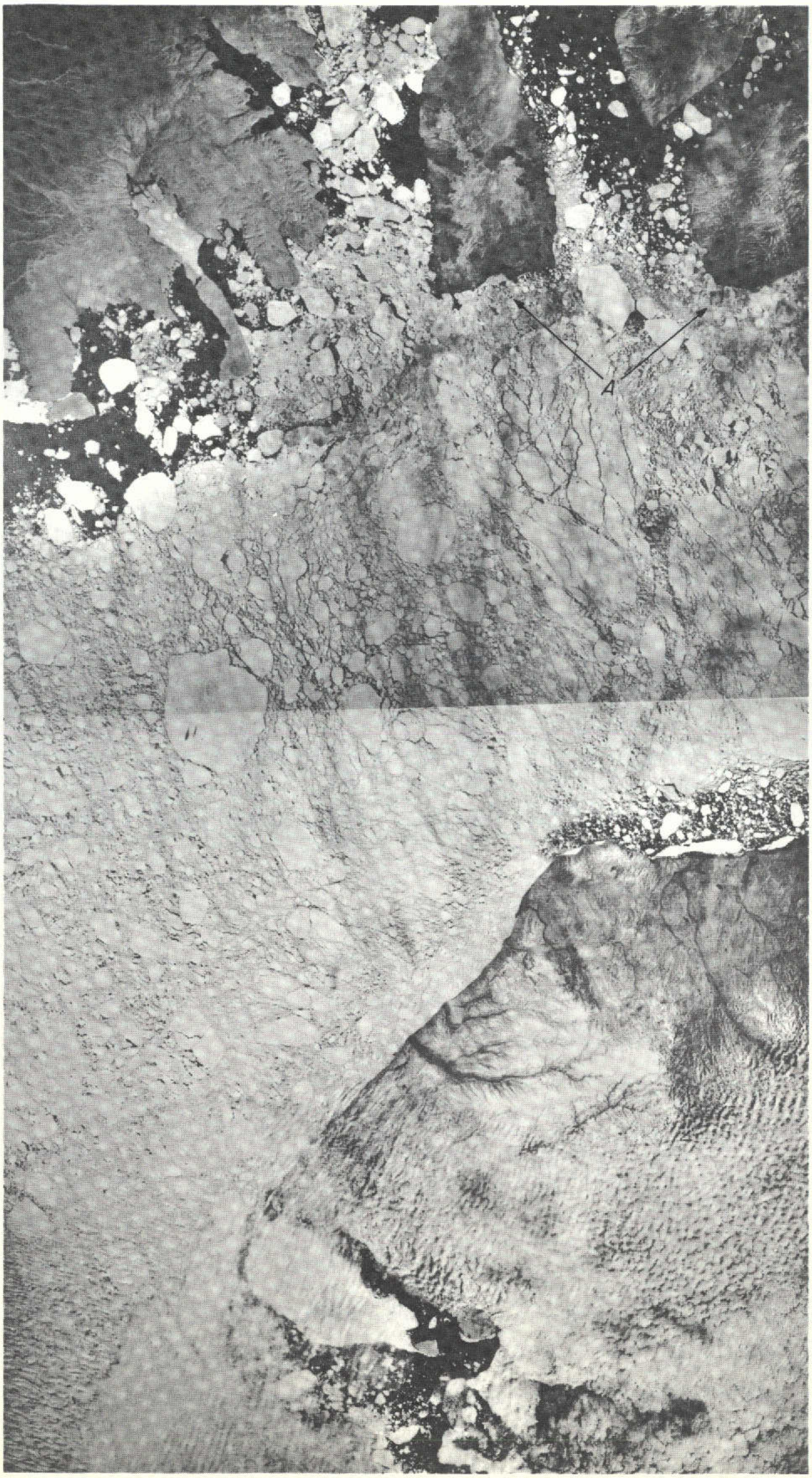

Figure 3-6 ERTS-1 MSS-7 mosaic, (ID Nos. 1763-20030 and 1763-20023) 25 August 1974, showing approximately the same area as the previous figure. Open water areas on previous figure are no longer evident (A).

On 7 April 1974 the ice configuration has changed considerably, with the fracture observed the previous day now a well developed flaw lead 5 km wide to the south and 8-10 km wide to the north. The southern extent of the flaw lead is very distinct and zones of light nilas, grey and grey-white ice are forming along the western edge of the lead. The northern end of the flaw lead contains floes of all sizes, brash ice, and grey-white ice. Also, many fracture zones have developed in the pack, west of the lead. On the next pass over this area (23 April) the lead has closed, but on 10 May it has opened up again, with an average width of 2-3 km.

When compared with the spring 1973 imagery of this area, some interesting similarities became apparent. The lead shows significant growth from early April until late April, then closes almost completely, followed by a reopening of the lead in mid-May. A map (Figure 3-7) shows that the eastern edge of the lead on 28 April 1973 and on 23 April 1974 is in the almost identical location. This preferred location for development of the large flaw lead in the spring may be associated with a slight eastward deflection of currents of the Beaufort Gyral towards and into M'Clure Strait.

3.3 Cape Bathurst to MacKenzie Bay - 1973 and 1974

The ice breakup along the northwestern Canadian coast in the Cape Bathurst to MacKenzie Bay area (see map, Figure 3-8) can be mapped in both the 1973 and 1974 summer seasons. ERTS images covering this area in May, June, and July 1973 and in June, July, and August 1974 were analyzed.

3.3.1 1973 Summer Season

Imagery on 14 May (not shown) indicates a solid expanse of snow covered, fast ice from MacKenzie Bay to Cape Dalhousie. Eskimo Lakes and Liverpool Bay are also frozen and snow covered. A large area of open water, 35 km wide, separates the fast ice from the edge of the very close pack ice farther to the west.

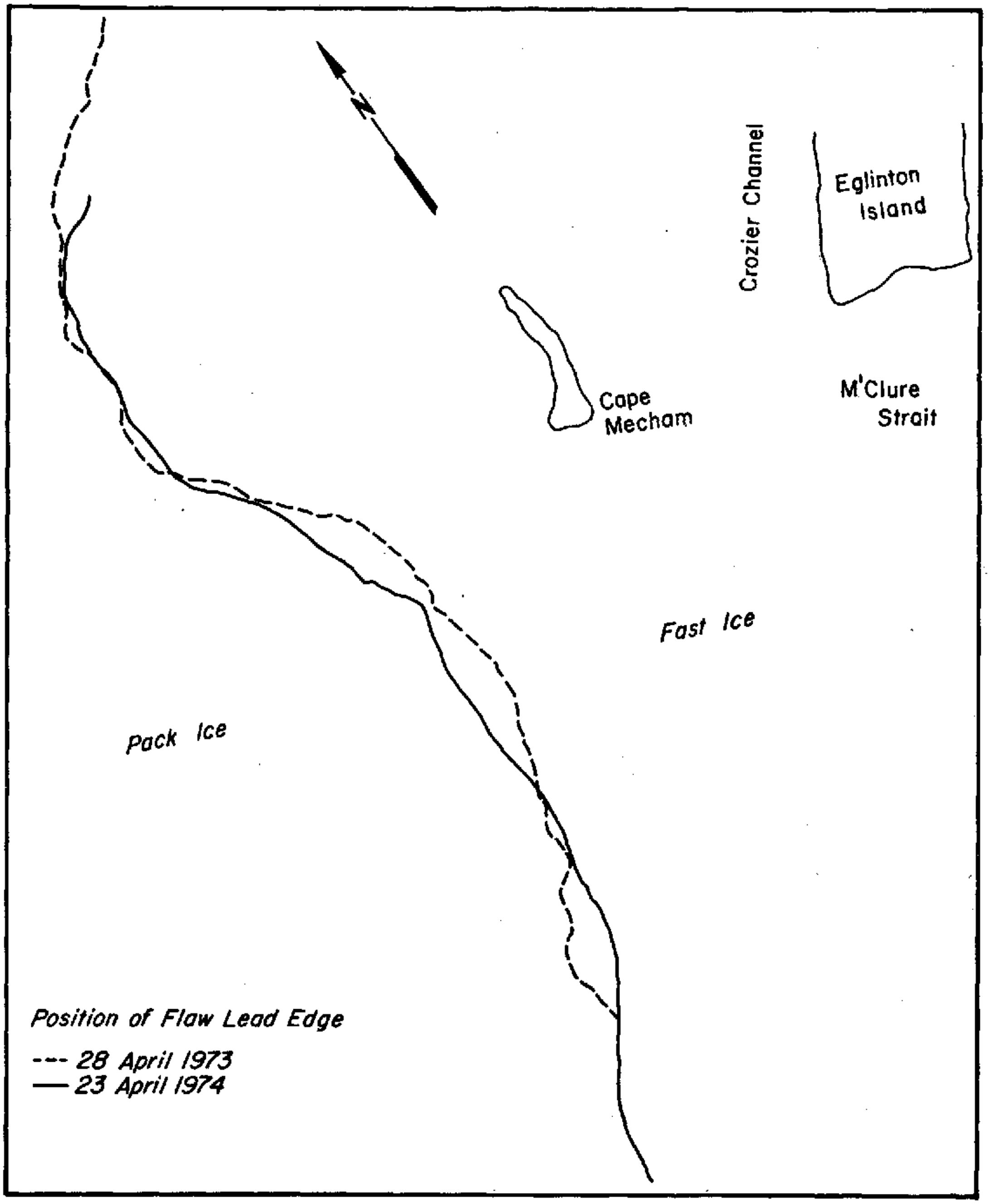

Figure 3-7 Illustration showing the location of the eastern edge of the flaw lead off the west coast of Prince Patrick Island in late April of 1973 and 1974.

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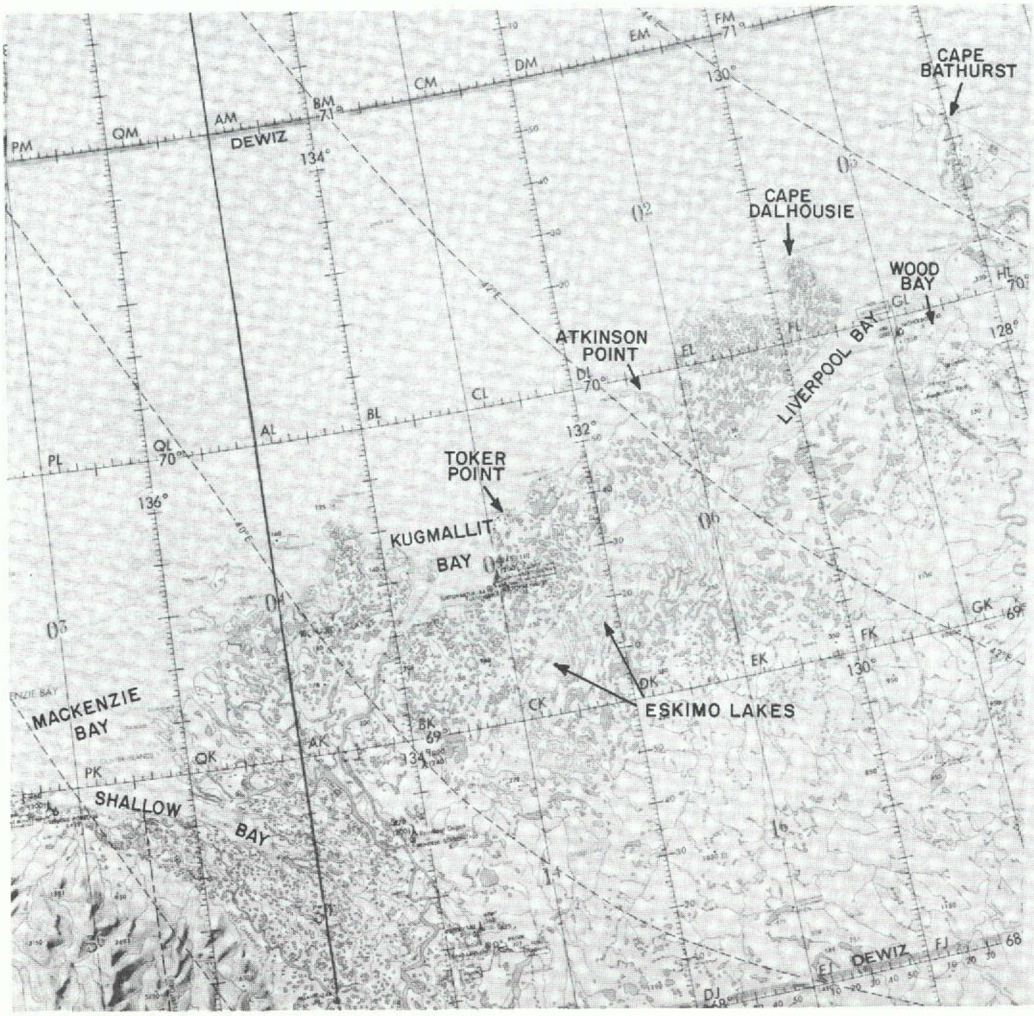

Figure 3-8 Portion of USAF Operational Navigation Chart covering the Cape Bathurst to McKenzie Bay area.

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On 18 June (Figure 3-9) the fast ice is free of snow cover and a comparison between the visible and near-IR MSS bands can be made to distinguish ice types and meltwater patterns. Large ice-free shore polynyas have formed at the mouth of the MacKenzie River at Kugmallit Bay and at Shallow Bay where the Middle and West Channels of the MacKenzie River empty. The Anderson River is clearing the ice from Wood Bay and appears to be flooding the isthmus leading to Nicholson Peninsula, creating a polynya on the Liverpool Bay side of the peninsula. The width of the fast ice near Toker Point, which had been 43 km on 14 May, has decreased to a width of 27 km by 18 June. The seaward extent of fast ice near Cape Dalhousie and Cape Bathurst has decreased in width by less than 3 km.

Part of the pack is visible on the 20 June image (not shown), and it appears that the concentration varies from open pack to close pack in the area of MacKenzie Bay. A large area of open water exists north of Kugmallit Bay and separates the pack to the west from the open to close pack ice concentrations in the ice fields of Amundsen Gulf and Banks Island to the east. On 4 July (Figure 3-10), coverage of the area of Liverpool Bay indicates that all fast ice has disappeared and that brash ice and floes in concentrations of 1/10 to 3/10 now exist in the immediate area.

On 25 July (Figure 3-11), the coastal waters in the area from Garry Island to Cape Dalhousie are ice free, and the very close pack ice now lies approximately 120 km north of the coastline. An intermediate zone of open water (ice concentration of less than 1/10) exists between the coast and the pack ice.

3.3.2 1974 Summer Season

The 13 June 1974 image (Figure 3-12) covers the area of Kugmallit Bay and Eskimo Lakes. Cracks can be seen in the ice on many of the larger inland lakes which appear dark on the Band 7 imagery due to a layer of meltwater on the ice surface. The zone of coastal fast ice in this region extends for approximately 40 km into the Beaufort Sea. Much of the fast ice near Kugmallit Bay also appears to have a layer of meltwater on the ice surface. A flaw lead with an average width of 3 km separates the fast ice from very close pack ice to the west.

Figure 3-9 ERTS-1 MSS-7 mosaic, (ID Nos. 1330-20085 and 1330-20082) 18 June 1973, showing Kugmallit Bay (lower left) to Cape Bathurst (upper right).

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Figure 3-10 ERTS-1 MSS-7 mosaic, (ID Nos. 1346-19571 and 1346-19564) 4 July 1973, showing the Cape Bathurst and Liverpool Bay area.

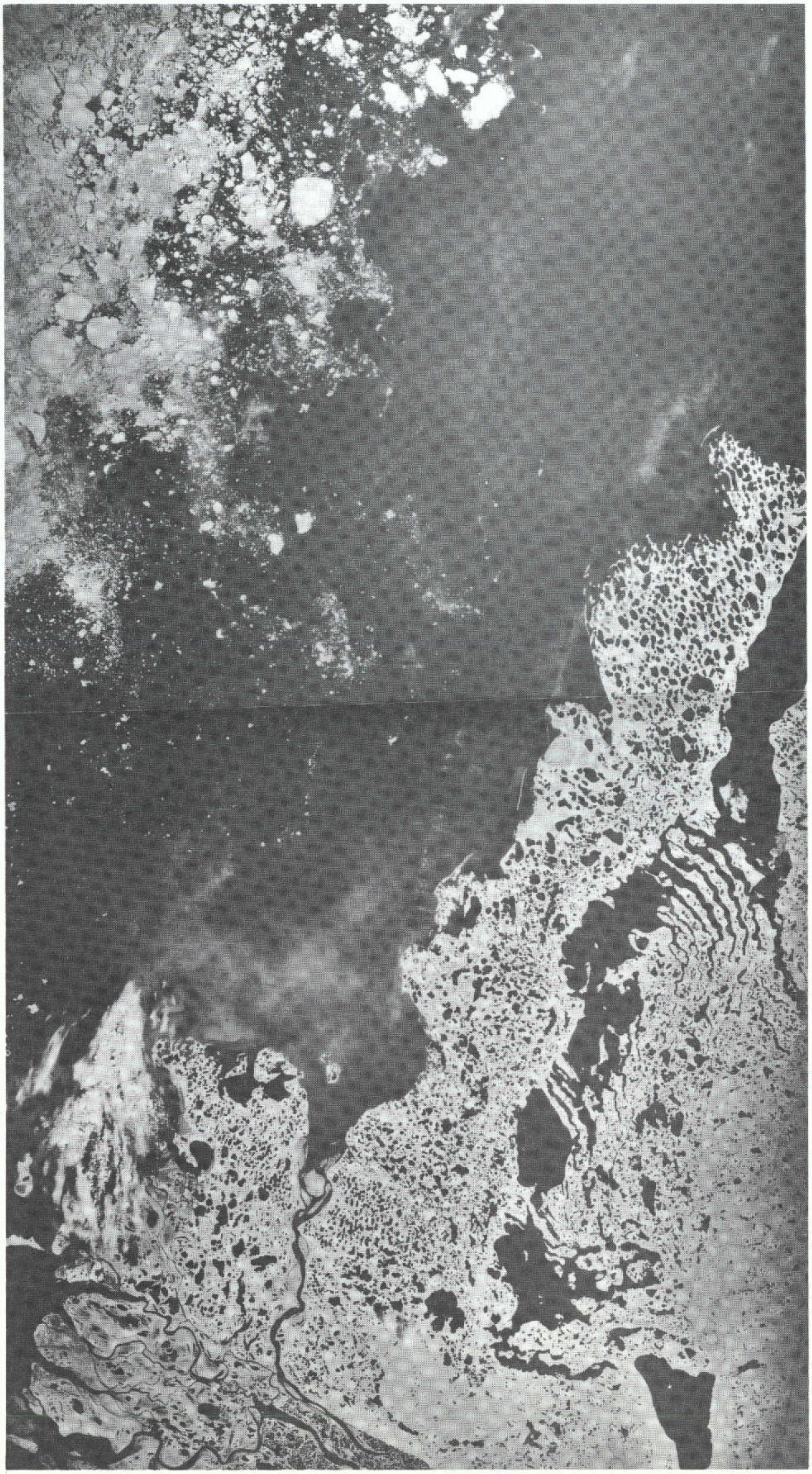

Figure 3-11 ERTS-1 MSS-7 mosaic, (ID Nos. 1367-20140 and 1367-20134) 25 July 1973, showing the same area viewed in the previous two figures.

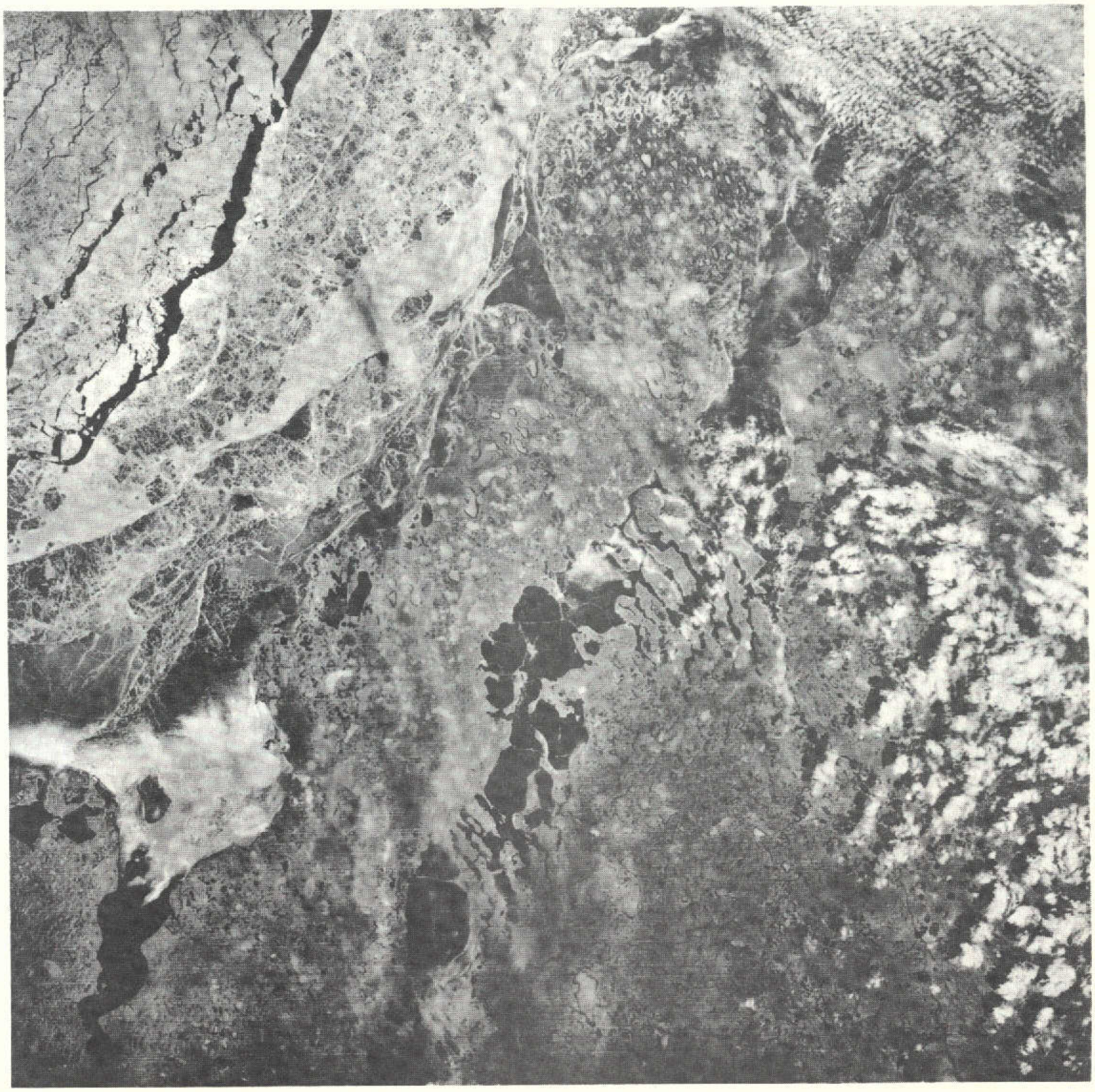

Figure 3-12 ERTS-1 MSS-7 image, (ID No. 1690-20013) 13 June 1974, showing Kugmallit Bay and Eskimo Lakes.

On 18 July (Figure 3-13) much of Liverpool Bay appears to be open water and the inland lakes are only partially ice covered. Most of the ice in Liverpool Bay and near Cape Dalhousie consists of brash ice and floes of various sizes. Although the fast ice still exists along the coastline, the average width of this ice has decreased to approximately 30 km. Consolidated pack ice exists in the Beaufort Sea just northwest of Cape Dalhousie; northeast of Cape Bathurst, very close pack ice is predominant.

No fast ice is evident in the 7 August image (Figure 3-14), and a zone of open water borders the coastline. The edge of the compact pack ice is located approximately 50 km to the northwest of the coastline, and an intermediate zone of very open to open pack ice is evident. Eighteen days later on 25 August (Figure 3-15), little change in ice concentrations is visible, although the extent of the different ice boundaries has changed somewhat. The zone of open water has increased in width near Atkinson Point, whereas the area of very open to open pack ice has decreased somewhat in width. The edge of the compact pack ice now lies about 75-100 km offshore and some deformation of the pack can be seen near the center of the mosaicked images.

3.4 Ice Floe Movement in Amundsen Gulf - 1972 and 1973

The repetitive ERTS passes across this area in 1973 made it possible to measure ice floe movements in Amundsen Gulf over a 24-hour period from 17 to 18 June and over a 17-day period from 18 June to 5 July. On 18 June, a concentration of close pack ice, comprised of numerous giant floes was centered in western Amundsen Gulf approximately 100 km north of Cape Bathurst. Comparison with imagery on the previous day showed that three giant floes, located in the northern extent of this ice field, had moved due west at a rate of 7-9 km per day. This suggests that the ice field was originally part of the consolidated pack ice (first year ice) observed throughout Amundsen Gulf in late April. On 5 July, several of the giant floes can be positively identified based on their sizes and shapes. Figure 3-16 illustrates the movement of five giant floes over the period from 18 June to 5 July.

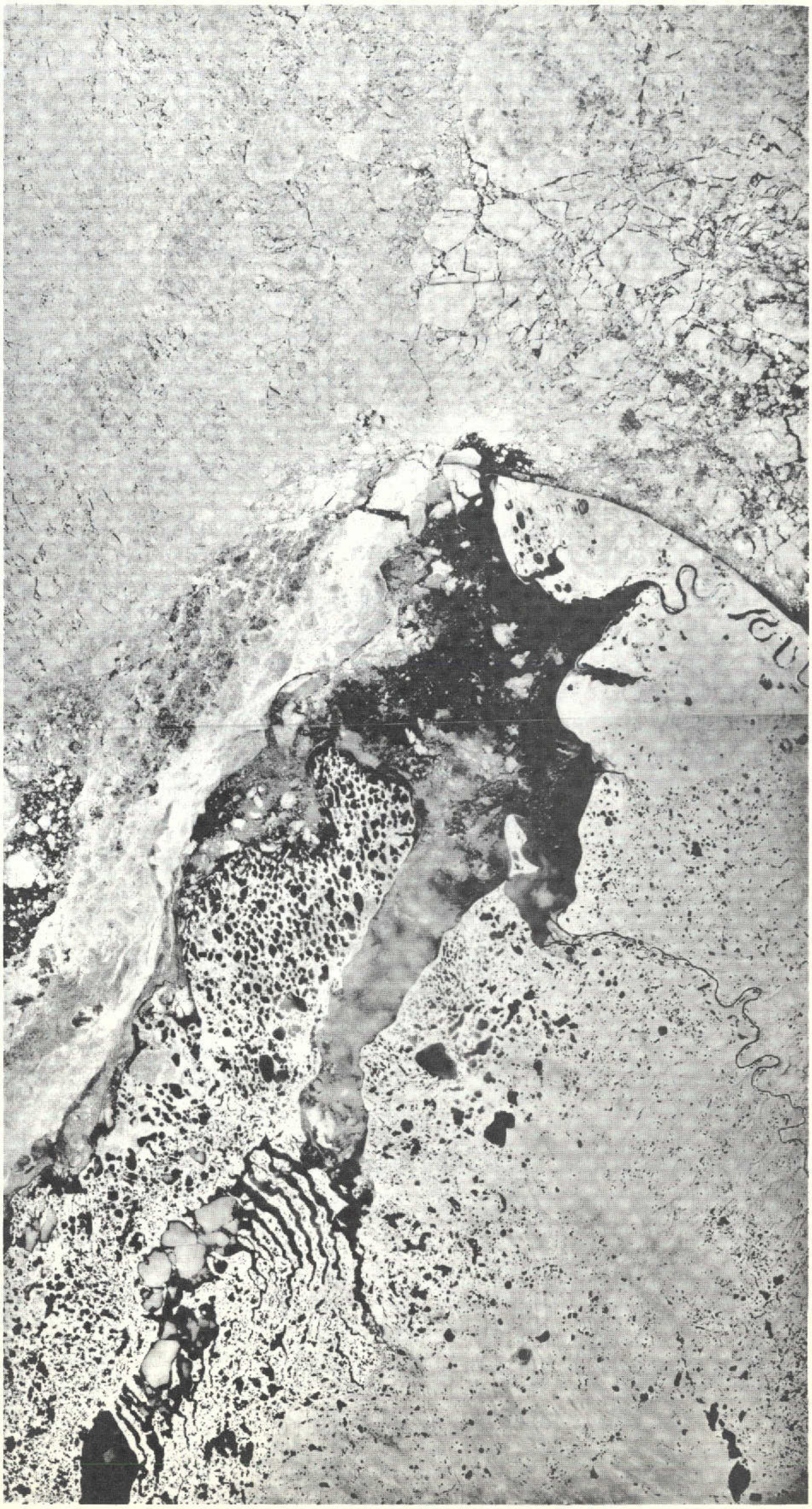

Figure 3-13 ERTS-1 MSS-7 mosaic, (ID Nos. 1725-19543 and 1725-19541) 18 July 1974, showing same area viewed in Figure 3-12.

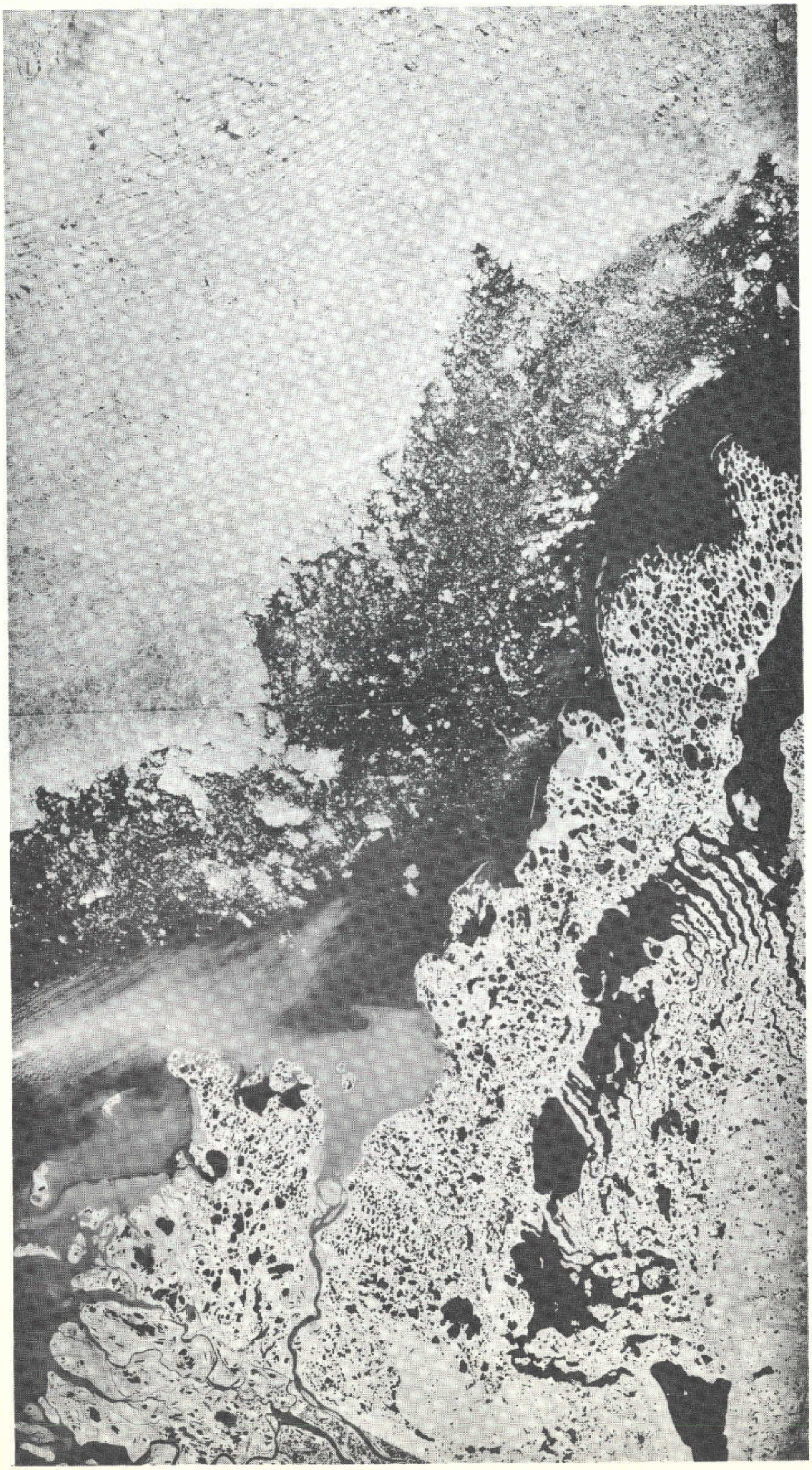

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Figure 3-14 ERTS-1 MSS-7 mosaic, (ID Nos. 1745-20052 and 1745-20045) 7 August 1974, showing same area viewed in the previous two figures.

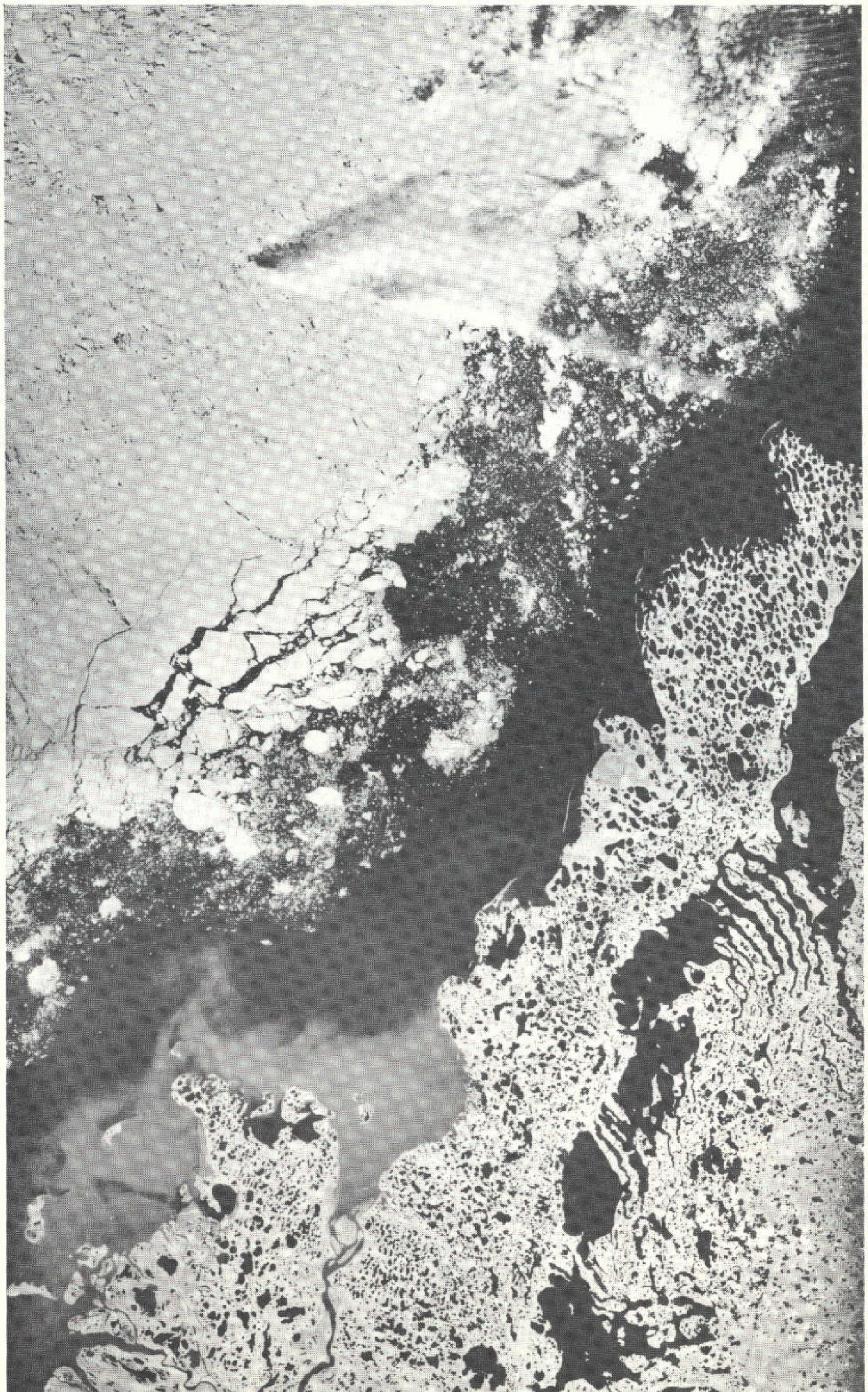

Figure 3-15 ERTS-1 MSS-7 mosaic, (ID Nos. 1763-20044 and 1763-20041) 25 August 1974, showing same area viewed in the previous three figures.

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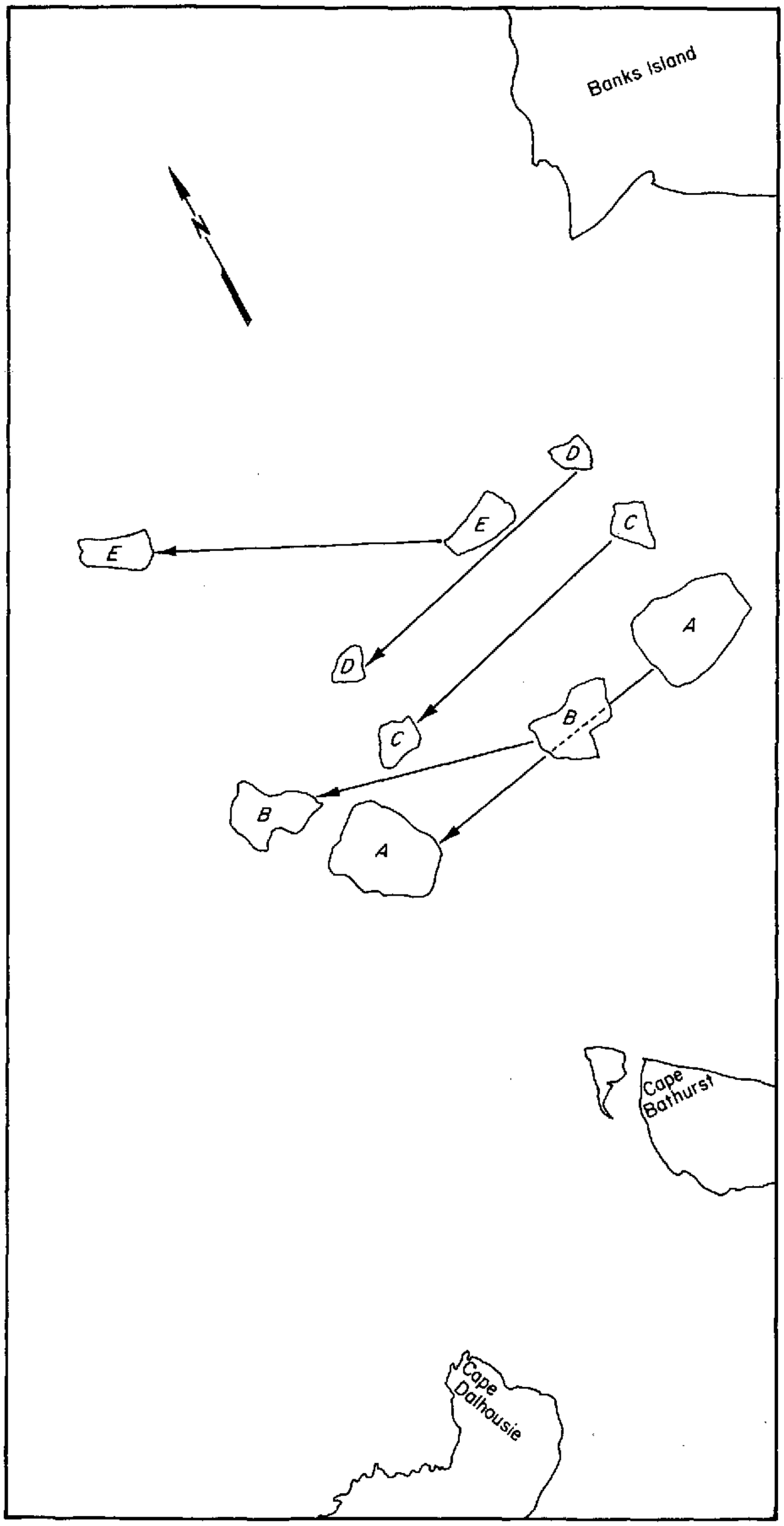

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Figure 3-16 Illustration depicting the movement of ice floes in Amundsen Gulf during the period from 18 June to 5 July 1973.

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The movement of floes A, B, C and D is generally toward the west-southwest, whereas floe E has moved toward the west-northwest. The average rate of movement of the five floes is 4.2 km per day. Surface synoptic maps indicate that light variable winds ($\leq$ 3 mps) prevailed across this region from 18 through 27 June, However, for the period from 28 June through 5 July, surface winds were out of the east and north-northeast averaging 4 mps (approximately 15 km per hour). These winds correlate well with the direction of the ice movement, suggesting that any movement of the floes resulting from the influence of surface wind flow occurred after 28 June. The rate of movement, therefore, would probably have been greater over the last eight days of the period.

Measurement of the movement of one giant floe in open water located within the same area over a two-day period in late July 1972 showed that it had moved almost due west at 10 km per day. Surface weather charts for the period of 27-29 July 1972 indicate that surface winds were generally easterly at about 5 mps (approximately 19 km per hour) throughout most of the period. As this wind speed is only slightly greater than that during the eight-day period in June and July 1973, the difference in wind speed cannot account for the significantly greater rate of ice movement in 1972. Other factors, such as the concentration of the ice field surrounding the floes, as well as the actual size of the floe greatly affect the wind induced movement of ice. Even in areas of strong coastal currents, it has been observed that the rate of movement of ice floes is greatly influenced by their respective sizes.

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4. COMPARATIVE ANALYSIS OF ERTS AND NOAA-VHRR DATA

In the initial part of the ERTS sea ice monitoring investigation, ERTS imagery was compared with aerial survey ice charts and with aircraft photographs. The comparative analysis showed generally good agreement between the locations of ice edges and concentrations as mapped from ERTS and as depicted on the aerial survey charts; moreover, the results showed that essentially all of the significant ice features visible in aircraft photographs taken over the Bering Sea on the BESEX experiment can also be detected in ERTS imagery. In this supplemental study, a comparative analysis of ERTS and environmental satellite data was performed, since the environmental satellite data are used as one input to operational ice charts.

The sensor system that has the greatest operational use for ice monitoring at this time is the VHRR (Very High Resolution Radiometer) flown on the NOAA satellites. The VHRR is a two-channel radiometer, with one channel sensitive in the visible portion of the spectrum (0.6-0.7 μm) and the other in the thermal infrared (10.5-12.5 μm); the spatial resolution of each channel is approximately 1 km. Small scale, experimental ice analyses of the Beaufort and Bering Sea regions are prepared on a routine basis using VHRR data by the National Oceanic and Atmospheric Administration, National Environmental Satellite Service. Typically, these analyses are prepared once each week, so are actually 3 to 6 day composite ice distributions.

The detail that can be mapped from an ERTS image as compared to the VHRR composite analysis is illustrated in Figure 4-1, where the VHRR analysis for the 27 July-1 August 1973 period is superimposed on the ERTS image for 26 July. In this area of the eastern Beaufort Sea, the location of the boundary of 8 oktas ice concentration mapped in the VHRR analysis actually falls within a narrow zone of open pack that separates very close pack (7/8 to less than 8/8) from open water (navigable water in which sea ice is present in concentrations less than 1/8). The term ice-free used on the VHRR analysis denotes no ice present. Northeast of this area, on the same VHRR analysis, a giant floe is shown off the west coast of Banks Island between 73°N and 74°N, extending from 125°W to

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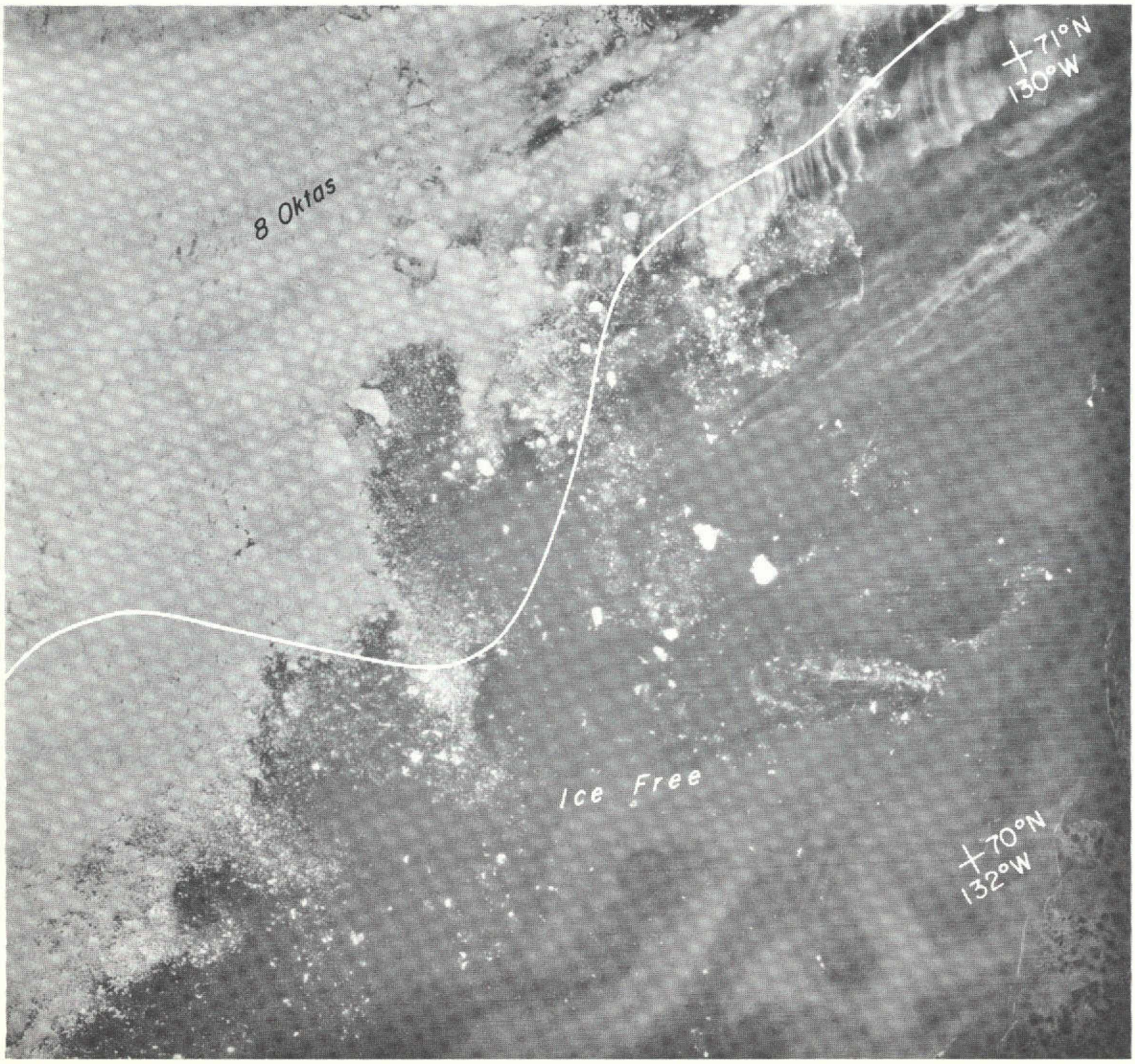

Figure 4-1 Comparison of ERTS-1 MSS-5 image (ID No. 1368-20192) 26 July 1973, with superimposed NOAA VHRR composite ice analysis for the period of 27 July - 1 August 1973.

127°20'W. A careful gridding of the ERTS image viewing this area on 26 July shows that the giant floe (92 km across) actually was located slightly over 40 km farther west, between 73°N and 73°50'N, extending from 126°10'W to 128°50'W.

It must be remembered that the VHRR ice charts represent composite ice conditions over a period of a week. More detailed ice features can be mapped from an individual VHRR image. VHRR data are useful for mapping general ice patterns on an operational basis for relatively large areas (one VHRR pass covers the entire Bering-Beaufort Seas region). The comparative analysis illustrates, however, that ERTS provides a far more detailed ice map, such as would be necessary for precise ship routing or for the design and monitoring of port and offshore drilling facilities. As a result of the overlapping of ERTS orbits at higher latitudes, it is possible to obtain a considerably broader overall view of current ice conditions than can be obtained from a single pass alone.

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5. SUMMARY OF RESULTS

Sequential ERTS observations have showed the ice breakup during the 1973 summer season along the east coast of Greenland and the north coast of Alaska. In the Dove Bay area of Greenland, flooded ice similar to that observed in the Prince Patrick-Melville Islands area could be detected. Measurements of the movements of ice floes over a 20-day period from late June to mid-July showed that ice near the coast was moving in a northeastward direction; the influence of the East Greenland Current was evident farther to the east, where floes located some 150 km off the coast were moving southward at a rate of 1-2 km per day. Along the north coast of Alaska, significant changes in the ice conditions over a 10-week period from mid-June to late August could be mapped. Also, it appears that grounded ice near the mouth of the Colville River can be detected in the ERTS images.

A sufficient amount of ERTS-1 data have been accumulated to permit comparison of ice distributions in more than a single summer season. The comparison between the 1972 and 1974 ice seasons in the M'Clure Strait area indicates differences in the extent of fast ice deformation and the time at which this deformation occurred. During 1972, only a very limited amount of fast ice deformation in Crozier Channel and Kellett Strait had occured by 4 September; in 1974, however, the breakup of the ice sheet in M'Clure Strait as well as extensive breakup of the fast ice in Crozier Channel and Kellett Strait (with many areas of open water evident) had occurred by 22 August. Just west of M'Clure Strait, the extensive flaw lead that had been mapped in the spring of 1973 was also observed with rather similar characteristics in the spring of 1974.

A comparison between the 1973 and 1974 ice seasons in the MacKenzie Bay to Cape Bathurst area shows variations in the location of the pack ice edge as well as the extent of fast ice. In 1973, fast ice had disappeared by 25 July and the edge of the pack was well to the northwest of the coastline. In 1974, coastal fast ice bordered by compact pack ice existed on 18 July, and even as late as 7 August the edge of the pack extended much farther southeast than in the previous year. A comparison of the movements of ice floes in Amundsen Gulf just north of Cape Bathurst in 1972 and 1973 shows significantly greater movement

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in 1972 even though the wind regimes during the corresponding periods did not differ greatly. The movements may be influenced by other factors, such as the sizes of the floes and the concentration of ice surrounding the individual floes.

A comparative analysis of ERTS imagery and composite ice charts derived from operational NOAA-VHRR imagery shows that the environmental satellite data are very useful for mapping general ice conditions over broad areas, but that ERTS provides far more detailed information on the ice structure. It appears that the resolution and multispectral characteristics of ERTS are required to obtain the ice information that would be necessary for precise ship routing or for the design and monitoring of port facilities and offshore drilling operations in the arctic.

These additional analyses further substantiate the application of ERTS for detecting and mapping sea ice. A sufficient amount of ERTS data have now been accumulated to enable extensive studies to be undertaken of ice deformations and movements and their year-to-year variations. It is now possible to initiate the compilation of sea ice statistics related to parameters such as floe size and the spatial and temporal frequencies of leads and polynyas. Also, detailed studies of ice types and surface characteristics using ERTS digitized data have yet to be accomplished.

6. REFERENCES

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