A STUDY OF THE OCCURRENCE OF STRUDEL SCOURS IN THE CANADIAN BEAUFORT SEA

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DSS Contract No. 23304-7-5012/10-SS

GEOLOGICAL SURVEY OF CANADA, OPEN FILE NO. 2272

A Study of the Occurrence of Strudel Scours in the Canadian Beaufort Sea; Prepared by Pilkington and Associates, Calgary Alberta and PFL Arctic and Offshore Technology Ltd., Calgary, Alberta; 76p.

DSS Contract Number: 23304-7-5012/10-SS

This report was prepared under contract to:

Atlantic Geoscience Centre
Geological Survey of Canada
Energy Mines and Resources
Bedford Institute of Oceanography
Dartmouth, Nova Scotia.

Scientific Authority: P.R. Hill

Funding was provided under the Northern Oil and Gas Action Plan program (NOGAP) Project D.1: Beaufort Sea Coastal Zone Geotechnics.

EXECUTIVE SUMMARY

In the spring the rivers along the coast of the Canadian and US Beaufort Sea rise and, because the ice near shore extends down to the seabed, the river water floods over the ice forming a layer of water up to 90 cm deep. The water finds holes in the ice (seal holes or cracks) and drains off the ice through these holes forming a vortex or "strudel" which penetrates the water column and scours into the sea floor forming "strudel scours". Strudel scours off the Alaska coast can be over 25 m diameter and 6 m deep, thus a strudel scour below a pipeline could cause a serious foundation stability problem.

Strudel scours have been found off the Alaskan coast but never in the Mackenzie Bay area of the Canadian Beaufort Sea, although one was found in Phillips Bay. This study indicates that most of the elements needed to form strudel scours exist in the Mackenzie Bay from Shallow Bay to North Point, i.e., grounded ice near shore, flooding of the ice in May, soft seabed sediments, etc.

In the Mackenzie Bay, the sea bed is very shallow and most of the flooding occurs over grounded ice. However, in some years the flooding does extend beyond the grounded ice in certain areas. Also, strudel scours have been observed in water depths down to 1.4 m off Alaska as the water is draining off the ice, and the ice is lifting off the sea bed.

An attempt was made to locate strudels and strudel drainage channels on the ice surface, and indeed several "black holes" were found in good quality Synthetic Aperture Radar data (scale 1:250,000 or 4mm-1 km). However, whether these are strudels or surface drainage holes on the ice surface is not known.

In summary we cannot see why there would not be strudels and strudel scours in the Mackenzie Bay area. Such strudel scours would occur:-

- in areas where the flood water extends beyond the 2 m water depth region in mid to late May. That is, seaward of the north arm of the Reindeer channel by the Olivier Islands and off Middle channel.

- in areas that were flooded, in water depths down to 1.4 m - here observations must be made in late May as the flood water is draining and the grounded ice is lifting.

- references and observations made here indicate that the flood water drains off the ice down the tidal crack - seabed soundings of possible scours below the tidal crack should be made.

Any seabed survey with echo sounder or side scan, which would be extremely difficult in the water depths of interest here, would have to be made very shortly after break-up, as wave action on the soft seabed would quickly fill-in any strudel scours.

Strudel scouring would also be expected in Liverpool Bay by the Anderson and Mason rivers and have already been observed in Phillips Bay. These areas are of far less industrial importance than the Mackenzie Bay at this time.

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CHAPTER 1: INTRODUCTION

The purpose of this report is to investigate the potential areas of strudel scouring in the Canadian Beaufort Sea. Prior to a field survey in the spring of 1987, strudel scours had not been observed in Mackenzie Bay and their occurrence was very much a moot point. In 1987 a strudel and strudel scour were observed in Phillips Bay (Ref. #6). No strudels have been observed in the Mackenzie Bay area to this time.

In late May off the Alaska Coast, the rivers rise and because the sea ice along the coast rests on the sea floor, the water floods out over the ice. The flood water drains off the ice through seal holes or cracks forming a stable vortex (or strudel) which penetrates the water column and scours the seafloor. By the end of May or early June the ice is melted out to the 2 m water depth, allowing the flood water direct access to the sea under the ice. At this time the flood water drains off the ice. A similar phenomenon occurs in the Canadian Beaufort Sea.

This report reviews all available references and remote sensing data to examine the extent of flooding in the Mackenzie Bay area each year and the potential areas where strudels and strudel scours might be expected.

CHAPTER 2: SUMMARY AND RECOMMENDATIONS

2.1 Summary

This study has involved a review of all the available references and remotely sensed data applicable to strudels and strudel scouring. The data reviewed included Side Looking Airborne Radar (SLAR and SAR), LANDSAT and NOAA satellite data and aircraft photographs. Only limited SLAR and SAR and aircraft photographs were found for the times and locations required. The LANDSAT data review at the Prince Albert receiving station were fiche and of poor quality so did not allow clear identification of flooding on open water. However, the LANDSAT data purchased were of much better quality and did allow identification of flooding and/or open water. The LANDSAT fiche data were used to determine the extent of water-at-surface (flooding or open water) for as many years as good data were available. The NOAA data are of small scale. They allowed identification of water-at-surface, but whether this was flooding or open water was not discernable. They were useful because of the frequency of the data, and the fact that they covered the entire Mackenzie Bay area.

The references and data indicate that flooding does occur in the Mackenzie Bay area off Richards Island, and also in Phillips Bay and in Liverpool Bay, but these last two sites are of little industrial importance at this time. Flooding starts in early May in the mouths of the Reindeer, Middle and Harry channels just as the Mackenzie River starts to rise, and extends normal to shore out to typically about the 1.6 m to 1.8 m water depths. Whether this limit is always due to water draining down the tidal crack as has been mentioned in references and also noted in one LANDSAT image, or due to limited flood water, is not clear.

In some years (about 30% of the years investigated) the flood water did extend seaward beyond the tidal crack out about 30 km from shore to water depths of 6 m or more. This appears to occur adjacent to the Reindeer (north arm) and Middle channels, but was never noted adjacent to the other channels.

After mid May the flooded areas of ice melt, resulting in open water which gives the river water direct access to the ocean under the ice; this melting and open water extends along the coast.

Most of the flooded ice is grounded and strudels cannot form in grounded ice as the water cannot flow away under the ice. Certainly there is no reason not to expect strudels in the flooded areas beyond the grounded ice, but these areas do appear to be isolated and confined to locations seaward of the Reindeer (north arm) and Middle channels. Observations off Alaska indicate the formation of strudels in water depths down to about 1.4 m when the flood water is draining off the ice and the once grounded ice is lifting off the seabed. This too could also be a region of strudels in the Mackenzie Bay area. If strudels occur in the Mackenzie Bay, strudel scours are expected as the seabed is generally soft in this area, and only minimal seabed freezing occurs in winter.

Attempts to actually identify strudel holes indicated "black holes" on the SLAR and SAR imagery, but this is not considered too reliable. LANDSAT and NOAA images do not have adequate resolution for such an identification.

As mentioned above, references and data presented here indicate that the flood water drains down the tidal crack. It is felt to be unlikely that the fresh water penetrates to the seabed with much force, but it would be worthwhile profiling across this region to see if any scouring is occurring in this region. Any pipeline to shore would have to pass below the tidal crack.

No strudels and strudel scours are expected at or west of North Point along the Tuk Peninsula as there are no rivers in this area.

An approximate analysis indicates that strudel scours are indeed a threat, with a probability of a scour occurring over a 10 km long pipeline being about 22% per year, or a return period of 4.5 years. As all solutions to this problem appear to be expensive, further work on the problem by companies planning pipelines in strudel regions is warranted.

2.2 Recommendations

As strudel scours can cause severe damage to subsea pipelines, and there appears to be no reason why they should not occur in some areas of the Makenzie Bay, the following recommendations are provided.

- In May each year, collect all available sources of remote sensing data for the Mackenzie Bay area and look for flooding beyond the 2 m water depths in the areas north and northwest of Reindeer and Middle channels. If such flooding is observed, fly out over the area and look for strudels. If any strudels are observed, carry out a profile of the seabed to look for a strudel scour.

- Profile across the tidal crack where vigorous floodwater drainage is occurring.

- Look for strudels in late May - early June in flooded areas in water depths of 1.4 m and beyond as the flood water is draining.

CHAPTER 3: REVIEW OF LITERATURE

3.1 Introduction

A detailed review of several papers is provided in Appendix A. Here we will itemize the factors that are felt to be relevant for the occurrence of strudel scours in the American Beaufort Sea, and how they relate to the MacKenzie Bay. Emphasis is placed on the overflooding of the ice in the spring as this is the thrust of this project. A definite cause and effect relationship has been established for flooding and strudel scours in the Alaskan Beaufort Sea. Also counting strudel holes (identified in mid to late May from overflights or aerial photos by their distinct radical drainage channels) is considered to be the most reliable way to determine the number, location and frequency of strudel scours in any given year [3]*.

3.2 Features Relevant to this Study

3.2.1 Timing

Overflooding of the landfast ice occurs immediately after the river starts to flood for a period of about 3 days (1). Within about 13 days all the water has drained off the ice leaving puddles and distinctive drainage channels. No river rise dates are provided in any of the papers for the Alaskan rivers, or timing of the over-ice flooding relative to the river rise. Dates for the spring MacKenzie river rise are provided in Section 4.

3.2.2 Zone of Flooding

Overflooding occurs immediately adjacent to river mouths out to a distance of up to 30 km from shore (2), see Figure 3.1. Figure 3.2 shows the "30 km zone" for the MacKenzie Bay area. Presumably, this is the potential zone of ice flooding.

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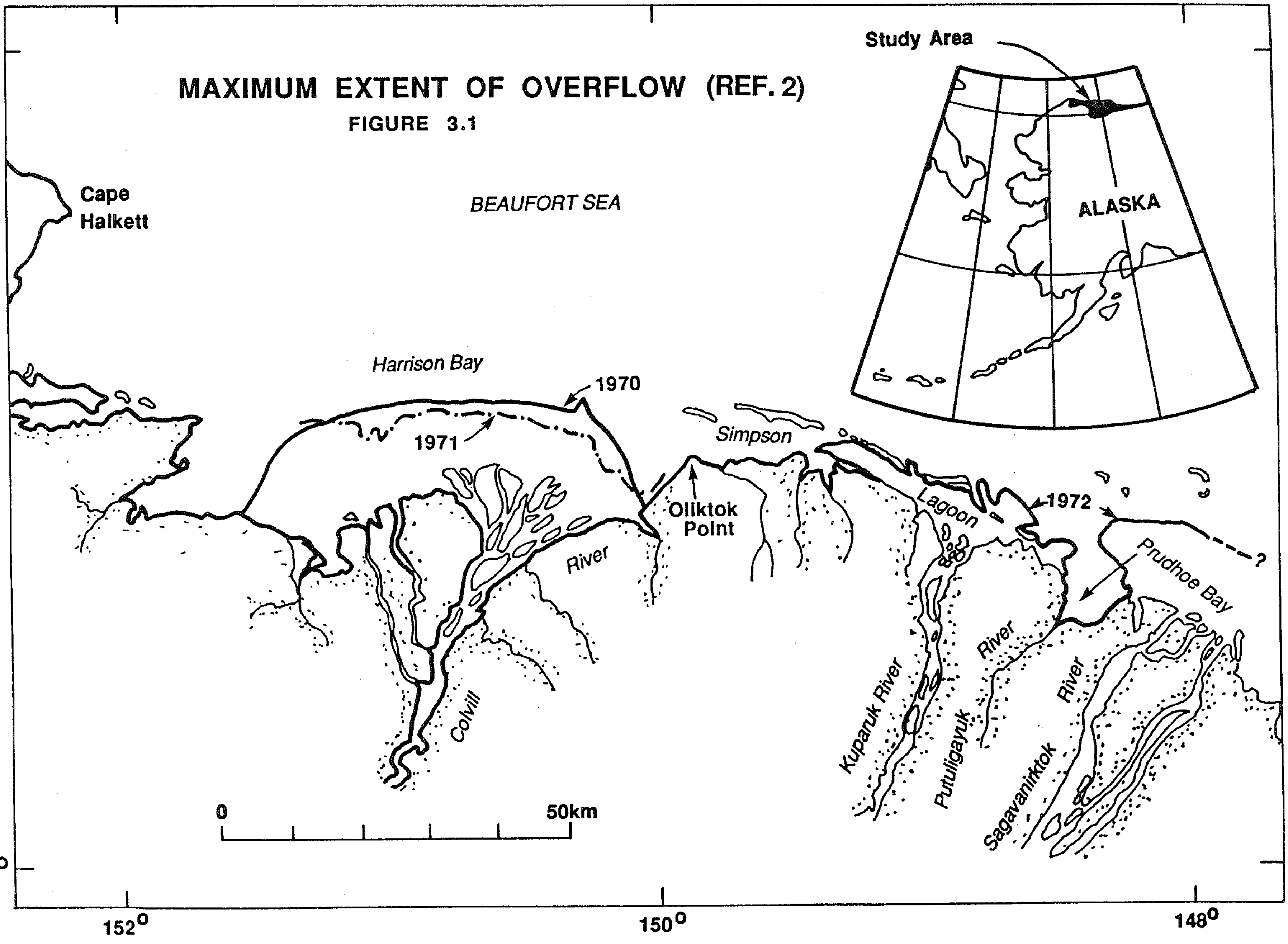
* Numbers refer to references at the back of the report

MAXIMUM EXTENT OF OVERFLOW (REF. 2)

FIGURE 3.1



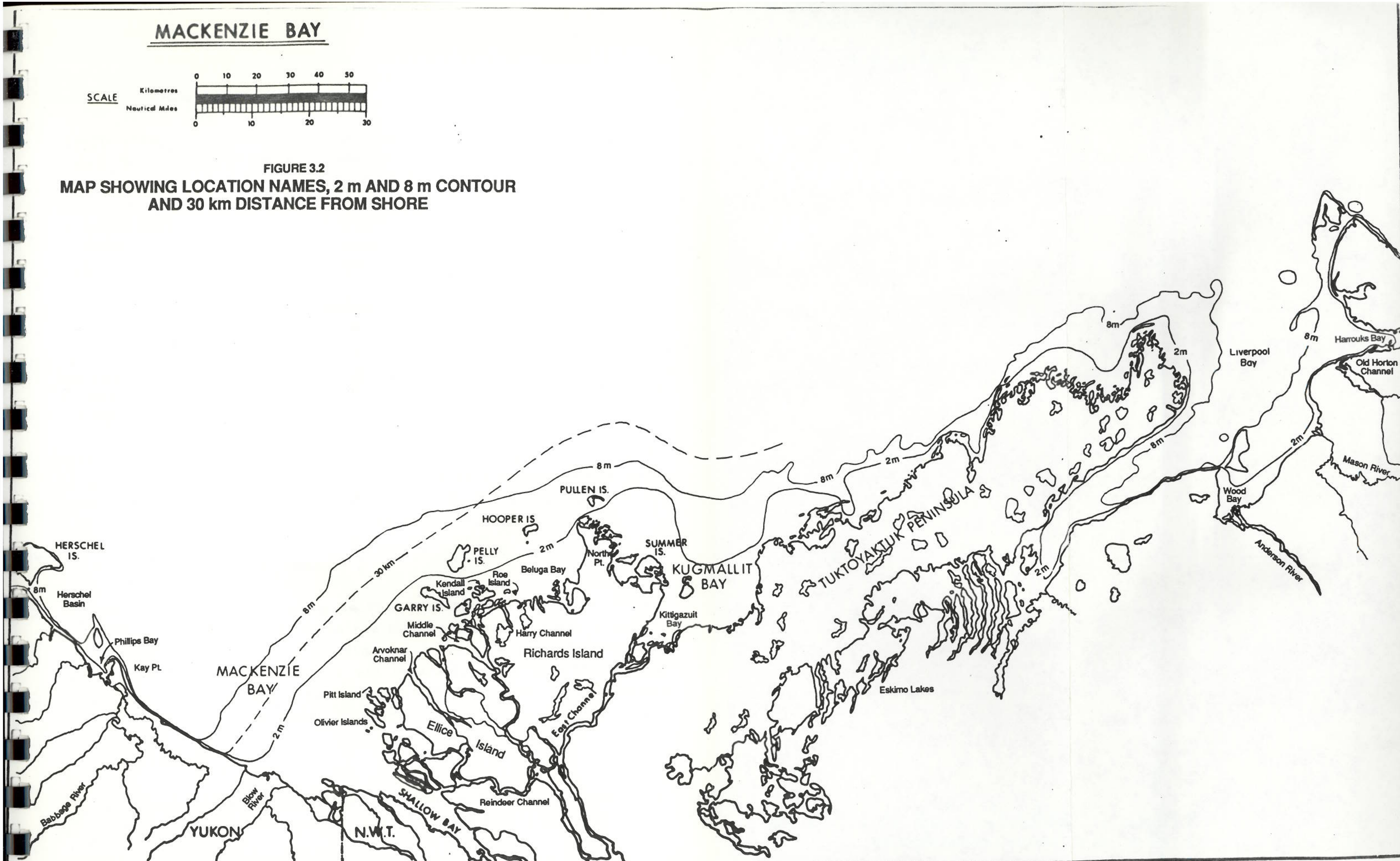


FIGURE 3.2
MAP SHOWING LOCATION NAMES, 2 m AND 8 m CONTOUR AND 30 km DISTANCE FROM SHORE

3.2.3 Reason for Flooding

Overflooding occurs because the landfast ice is resting on and possibly frozen to the seabed in water depths to 2 m, thus restricting or preventing under ice flow. Also, once flooding starts the weight of water will hold the ice down onto the sea bed and, in fact, the ice may be thawed back to close to the 2 m depth contour before the restriction to under ice flow is completely removed; see Figure 3.3. Figure 3.2 shows the 2 m contours for the MacKenzie Bay area.

3.2.4 Frequency of Strudel Scours

Side scan sonar and echo sounder runs off Alaska between the Colville and Sagavaniktok rivers (3) indicate over 6 scours/km from about the 2 m contour out to about 20 km, from river mouths, 1 to 6 scours/km over the next 2 to 10 km and none beyond.

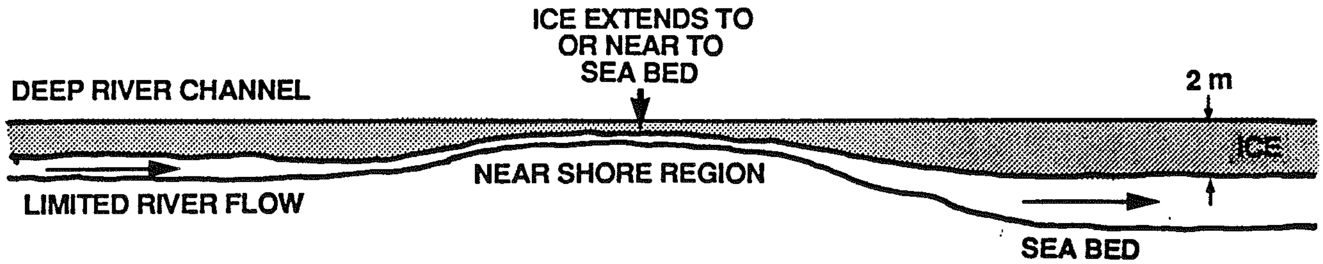
Reference 3 suggests that the 25 scours/km reported in (2) is too high. No scours have been observed in water depths of less than 1.4 m water depths (2) but this was limited by the draft of the survey vessel. Scours form at the rate of about 2.5 km^{-2} $year^{-1}$.

3.2.5 Size of Strudel Scours

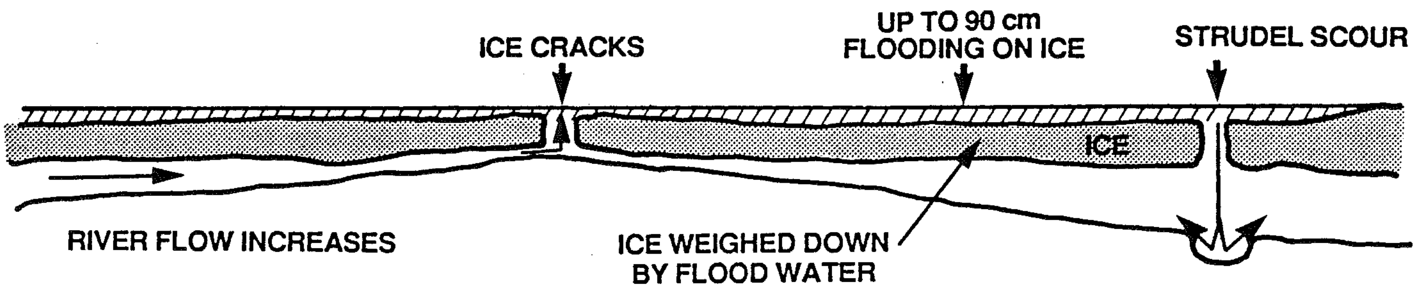
Strudel scours range in size up to 30 m diameter and are approximately circular or elongated, similar to the shape of strudel holes in the ice cover. Depths range up to 6 m. Figure 3.4 (2) is a cross section of a scour. It was noted that there was generally infill in the scours, hence one didn't see their full original depth. Also, they extended down to gravel or harder seabed material.

3.2.6. Fill In

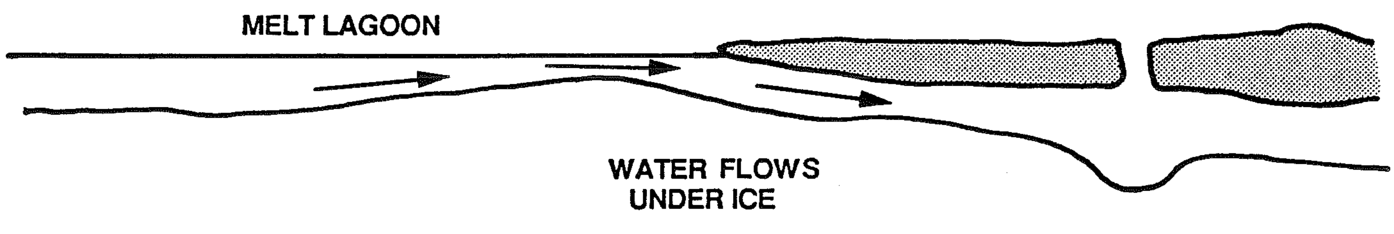
Earlier studies (1) suggested strudel scours filled in slowly, but later studies (3) found that they fill in within 2 to 3 years at a rate



i) EARLY SPRING



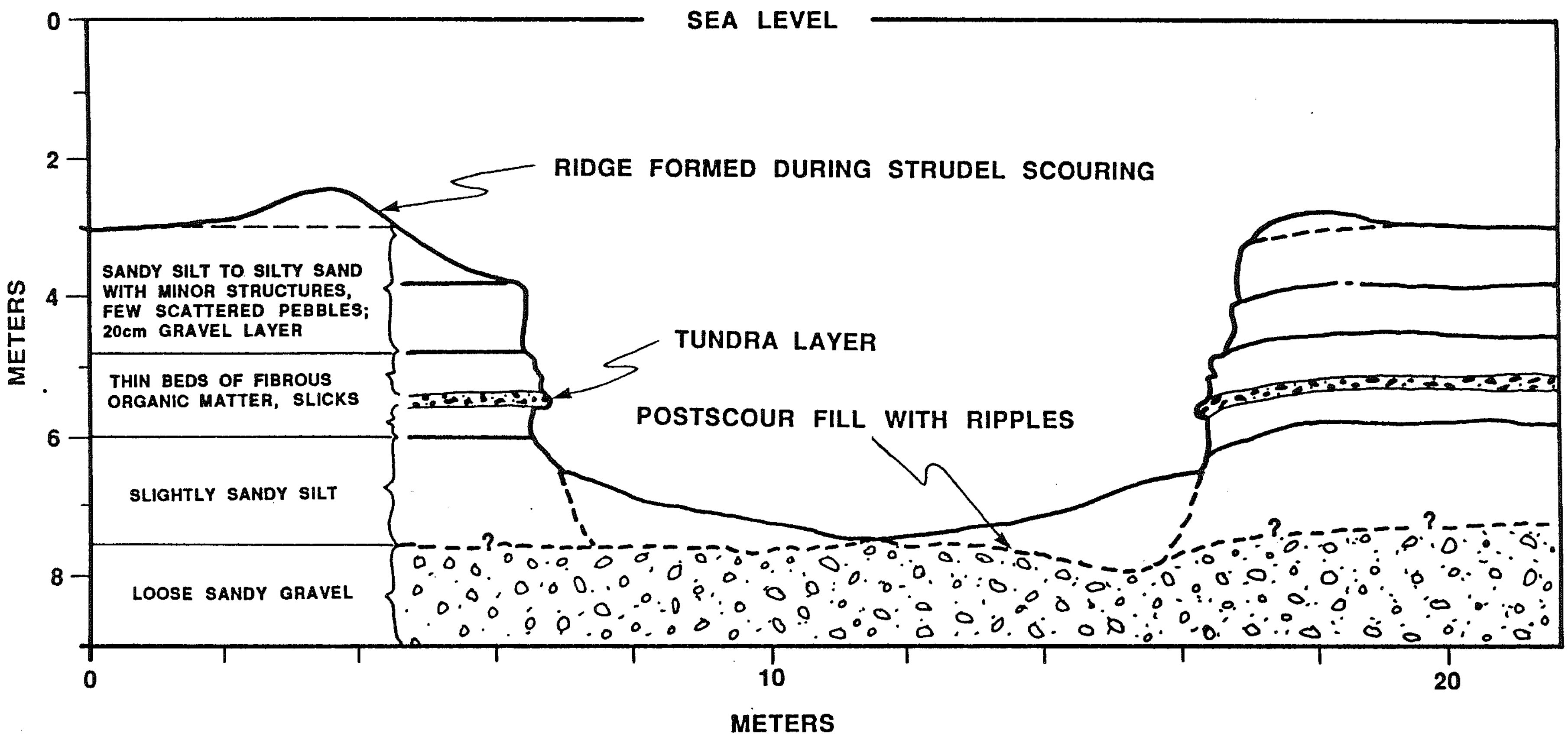
ii) MAY: RIVER WATER FLOODS ONTO ICE SURFACE



iii) JUNE: MELT LAGOON: WATER FLOWS UNDER ICE

FIGURE 3.3

FORMATION OF STRUDEL SCOUR



STRUDEL SCOUR INVESTIGATED BY DIRECT DIVING OBSERVATIONS, SHOWING GENERALIZED STRATIGRAPHY OF THE SEDIMENTS EXPOSED IN STEEP WALLS (REF. 2)

FIGURE 3.4

of 80 cm or more per year depending on their location.

3.2.7 Water Depth of Scouring

Scours have been observed in water depths from 1.4 to about 8 m (2). It is postulated that the scouring action is too weak beyond the 8 m water depth. The 8 m contour is indicated in Figure 3.2 for the MacKenzie Bay area.

3.2.8 Flooding in the Mackenzie Bay

The work by Esso (see references 7 to 13) indicates that flooding occurs in the Mackenzie Bay area starting in late April or early May. By late May or early June melt lagoons have been thawed into the ice giving the river water direct access to the sea under the ice. At this time the flood water drains off the ice.

3.3 Sea Bed Material

References 2 and 3 indicate that strudel scouring is stopped by harder sediments in the sea floor. Thus the nature of the seabed soils is extremely important.

3.3.1 U.S. Beaufort Sea Shelf

In the U.S. Beaufort Sea in the region of the Colville and Sagavaniktok rivers, a region of extensive strudel scouring, the sea bed is made up of Holocene marine silty sand sediments 2 to 10 meters thick, which is excavated rather easily (2). Although the seabed temperature has indicated $-3.5^{o}C$ at 3m below the seabed, no solidly frozen ground has been found so far (4). The depth of Strudel scours seem to be limited by the resistance of the underlying pre-Holocene materials which are stiff, over-consolidated, silty clay. In one case the base of the strudel scour was pre-Holocene, loose, coarse gravel. High resolution seismic records showed that some scours go deeper than the base of the Holocene sediments by several metres. It is possible that the deep scours are ice scours rather than strudel scours.

3.3.2 MacKenzie Bay Area

The seabed soils in the Mackenzie Bay area are reviewed in the EIS, (Ref. 18). In most locations, the sea bed consists of 0.5 to 35 m of recent marine clays as silty clays which have been carried onto the continental shelf from the mouth of the Mackenzie River. These sediments are gray to black, soft to firm and often contain traces of fine sand and organics, usually in the form of thin layers. Near the shorelines the clays are replaced by gray loose to very loose silts. Coarse materials such as sands and fine gravels may also be encountered over small areas of the seafloor, usually at depths from 0.5 to 3 m which may have originated either as a relict beach or were carried by ice to their present location. A discontinuous and highly variable series of sand, silt and clay beds often underlies the recent marine clays.

Thus the ease with which the soils in the Mackenzie Bay area can be scoured by water strudels depends on location. The areas near shore comprised of loose to very loose silts and soft marine clays should scour easily, whereas the firm silty clays, sands and fine gravels would scour less easily. Also scours in the loose to very loose silt in shallow water would fill-in very quickly from wave action or sediment transportation.

In late winter, the ice freezes down to the seafloor in water depths of less than 2 m, thus freezing of the seafloor sediments might be expected. Observations (Ref. 18) indicate that there are ice crystals in the seabed sediments but the ground is not solidly frozen. This freezing is unlikely to present much resistance to strudel scouring. Beyond the grounded ice regions - the prime areas for strudel scouring - no freezing of the seabed is expected.

CHAPTER 4: OVER FLOODING OF THE ICE

The reason for strudel scours is the overflooding of the landfast ice in the spring prior to breakup. It is thus useful to review when the rivers rise in the spring to determine when to look for satellite, aerial or SLAR/SAR photographs for comparison purposes.

4.1 Dates for Alaskan River

None of the papers reviewed indicated discharge rates for the Alaskan rivers. However, data provided indicate that flooding occurs within about 3 to 4 days and is finished after about 14 days. Reference 5 says that rivers begin carrying water to the sea by the end of May or early June.

Dates quoted in various references are:

Reference 3: Satellite photo June 6, 1976
June 26 ice had drained of water

Reference 1: River breakup May 26, 1970;
by May 29 the fast ice was flooded to 8km from shore.
Within a few days water had drained through the ice.

These are the only dates for Alaska provided in the papers reviewed.

4.2 Dates of MacKenzie River Flow Discharges

MacKenzie River daily flow discharges are provided in publications put out by Environment Canada "Surface Water Data, Yukon and Northwest Territories". An example of discharge for East Channel at Inuvik and East Channel above Kittigazuit Bay are shown in Figure 4.1. Note i) the enormous increase in river flow at Inuvik in late May - a factor of

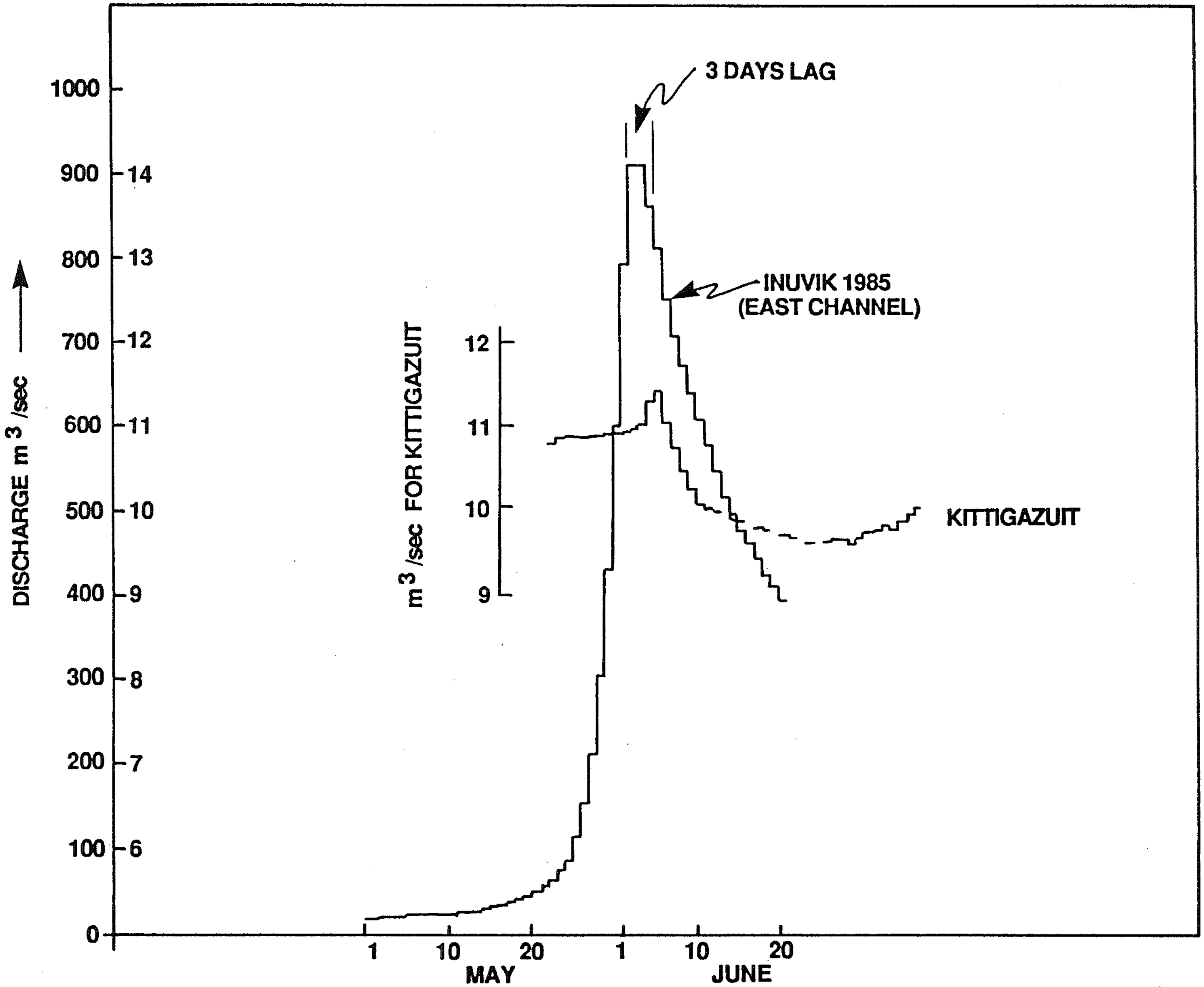


FIGURE 4.1

MACKENZIE RIVER DISCHARGE DURING SPRING RISE

about 50; ii) the relatively small increase in flow at Kittigazuit Bay - about 6%; iii) the peak discharge at Kittigazuit Bay is about 3 days behind Inuvik. Schooner Channel (see Figure 3.2) on the Aklavik channel peaks on June 1, 1 day ahead of Inuvik, and shows an increase of 27%. The relatively small flow increase at Kittigazuit is because most of the water that passes Inuvik flows down Middle channel and relatively little down East channel passed Kittigazuit.

Table 4.1 provides the dates of peak discharge for three MacKenzie delta sites for different years.

The data presented in Table 4.1 suggest a peak discharge at the mouth of the MacKenzie river channels in late May or during the first week of June. Flooding occurs at some earlier date while the river is rising. As indicated in Figure 8.1 in Section 8, the river starts to rise typically 20 days prior to the date of peak discharge and flooding of the ice occurs during this period.

TABLE 4.1
Dates of Peak Discharge on Mackenzie River

Year	Inuvik	Kittigazuit (East Channel)
1987	N/A	N/A
1986	June 6	N/A
1985	June 2	June 5
1984	May 29	June 2
1983	June 6	after May 31
1982	June 3	N/A
1981	May 24	N/A
1980	June 4	N/A
1979	May 31	N/A
1978	June 9	N/A
1977	May 31	N/A
1976	May 29	N/A
1975	June 3	N/A
1974	June 6	N/A

1973	N/A	N/A
1972	N/A	N/A

N/A means data not available.

CHAPTER 5: DATA AVAILABLE FOR ANALYSIS

In order to attempt to assess the extent of flooding of the fast ice in the spring in the Mackenzie Bay area, all possible sources of remote sensing data were reviewed. Reviewed were:

5.1 LANDSAT Data

These were accessed at the Satellite Receiving Station in Prince Albert, Saskatchewan. All data back to 1974 were reviewed from early May to mid-June. Cloud cover greatly reduces the number of useful photographs available. Also, due to the orbit pattern of these satellites, three images cover the area of interest over a 3-day period every 18 days. Images are generally available at a scale of 1:1,000,000. At this scale a strudel hole, 30 m diam., is less than 0.03 mm, and the drainage channels which are 300 m long, are 0.3 mm long. Hence it is unlikely that one could identify strudels or drainage channels in LANDSAT data. Further, the poor image quality of microfiche available for general viewing in Prince Albert makes interpretation of the photos very difficult and identification of strudel holes impossible. Fortunately, the actual photographs that can orders are of much better quality as shown in Section 6.

5.2 <u>SLAR/SAR</u>

Flooding of the landfast ice in the spring is caused by a layer of fresh water up to 1 m thick. Whether such a layer of non-conducting fluid can be detected by Side Looking Airborne Radar (SLAR) or Synthetic Aperture Radar (SAR) is debatable (B. Mercer, Intera- private communication). As far as is known, nobody has attempted to ground truth such data, however, one sees evidence of dark areas in the Mackenzie River mouths in the spring in SLAR and SAR and these agree in most cases with NOAA and Landsat data. Unfortunately there are only limited data each year. The Atmospheric Environment Services (AES) generally flew May 15, then not again until June 15 and the oil industry was interested from June 15 on. Also both groups operated out of Inuvik, so data from the coastal area of interest have tended to suffer from aircraft altitude or course changes and instrument adjustments.

5.3 Aerial Photographs

Esso, Dome and Gulf have flown aerial photo flights in the Mackenzie Bay area in the spring. One or two flights of Esso's cover the period of interest and do indeed show the early stages of flooded ice near Roe Island. Gulf's photos were generally for the wrong area or time and showed nothing of interest to this study. Two photo series over Herschel Basin showed drainage holes and channels in the ice, but these data sets were for June 15 and 21, hence the drainage holes were probably caused by surface snow and ice melt rather than flooding.

5.4 NOAA Data

The National Oceanic & Atmospheric Administration (NOAA) satellite provides large scale photos of the earth's surface and AES provides daily photos of the Mackenzie Bay area at a scale of 1:3,000,000 (i.e., 3 km equal 1mm). Despite the scale, these images are an excellent source of data which allow identification of flooded ice or open water areas in the spring, showing day-to-day progress of overflooded or open water areas. Unfortunately they do not permit the differentiation of flooding or open water, or recognition of strudel holes or drainage channels.

Gulf's NOAA data from 1986 to 1982 were examined. For 1980 and '81, Chris Hill (of CANATEC Consultants Ltd., Calgary) made his images available, and data from 1972 to 1979 were reviewed in Esso reports and summarized here.

CHAPTER 6: DATA ANALYSIS

6.1 Introduction

Data from the available sources have been collated chronologically for each year to develop a picture of the occurrence and extent of on-ice flooding in the spring in the Mackenzie Bay, and the subsequent development of open water areas. The interpretation of "water at the surface" in NOAA data is felt to be reliable, however, whether the condition is flooded ice, or open water is not known. The interpretation of "water at the surface" in SLAR and SAR is not totally unambiguous, as mentioned in 5.3.

As mentioned earlier, analysis of LANDSAT was carried out predominantly from the microfiche which are available for viewing in the Prince Albert Satellite receiving station. These data are of low quality and only "dark areas" are evident in the images where there is open water or flooding. A few LANDSAT images were chosen for quality reproduction and inclusion in this report, and these show the areas of flooding and/or open water quite distinctly.

The analysis of all available data, as presented here, shows the extent and regional variation of what is believed to be flooding in mid to late May.

In the figures that follow, flooding and/or open water have been identified on the maps of the Mackenzie Bay by shaded areas (either solid or crosshatch) or lines indicating the seaward perimeter, when several years of data are displayed.

6.2 1974

Some open water or flooding is noted in river channels on April 6 NOAA (Figure 6.2.1). Flooding is noted around Olivier Islands and Middle channel May 12 and May 14 (the dotted line indicates the maximum seaward extent). The flooding has spread by May 16 and by May 20 there is open water along most of the NW coast of Richard's Island close to shore.

As shown here, and in later images, flooding in early May often starts around Olivier Islands and to the SW of these islands. Hydrographic chart 7662 of Richards Island (see Fig. 6.2.5) shows a narrow, deep (5 to 20 m) channel along the north arm of Reindeer Channel which extends out along Ellice Island to the NW tip of this island and also to the west of Olivier Islands into Shallow Bay (this particular channel appears to be unnamed, if it is not Reindeer Channel). It appears that this deep channel directs the rising river water into the Olivier Islands (in preference to directly into Shallow Bay along the west arm of Reindeer Channel which is possibly blocked off by a short section 2 metres or less deep) and to the west of Olivier Islands which explains why flooding is first noted in these areas. No water depth readings are provided for the area to the N and W of the Olivier Islands; presumably the river water is trapped at this location and forced onto the ice surface.

On May 26, the flooding has receded to numerous isolated patches. By June 8, flooding and/or open water extend along the coast-line and to the 2 m water depth contour in several places.

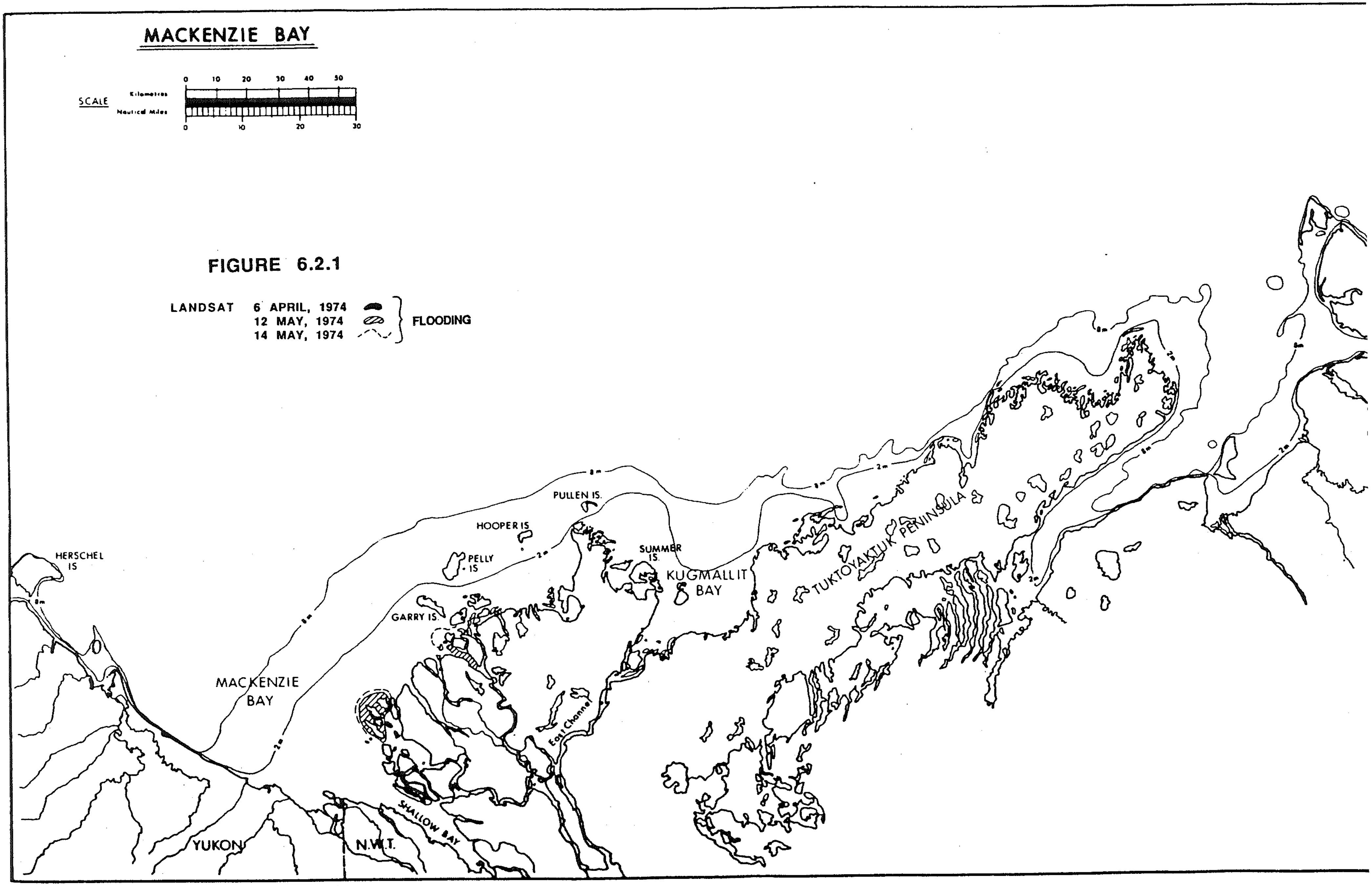
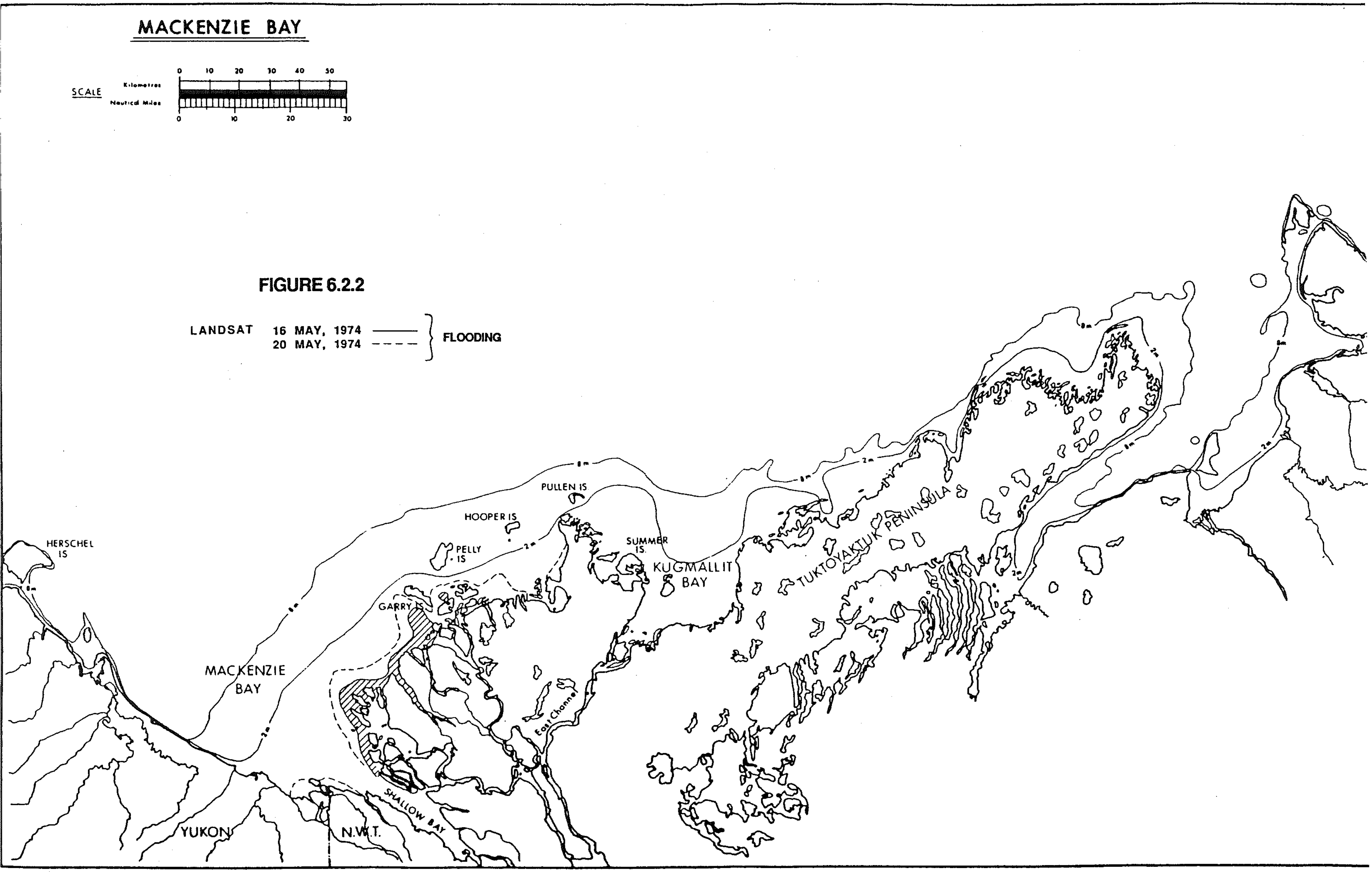

MACKENZIE BAY
SCALE
Kilometres
Nautical Miles
0 10 20 30 40 50
0 10 20 30
LANDSAT 6 APRIL, 1974
12 MAY, 1974
14 MAY, 1974
FLOODING
HERSCHEL IS
MACKENZIE BAY
GARRY IS.
PELLY IS
HOOPER IS
PULLEN IS.
SUMMER IS.
KUGMALLIT BAY
TUKTOYAKTUK PENINSULA
East Channel
SHALLOW BAY
YUKON
N.W.T.
8m
2m

FIGURE 6.2.1



MACKENZIE BAY
SCALE
Kilometres
Nautical Miles
0 10 20 30 40 50
0 10 20 30
LANDSAT 16 MAY, 1974
20 MAY, 1974
FLOODING
HERSCHEL IS
MACKENZIE BAY
YUKON
N.W.T.
SHALLOW BAY
GARRY IS
PELLY IS
HOOPER IS
PULLEN IS
SUMMER IS.
KUGMALLIT BAY
East Channel
TUKTOYAKTUK PENINSULA

FIGURE 6.2.2

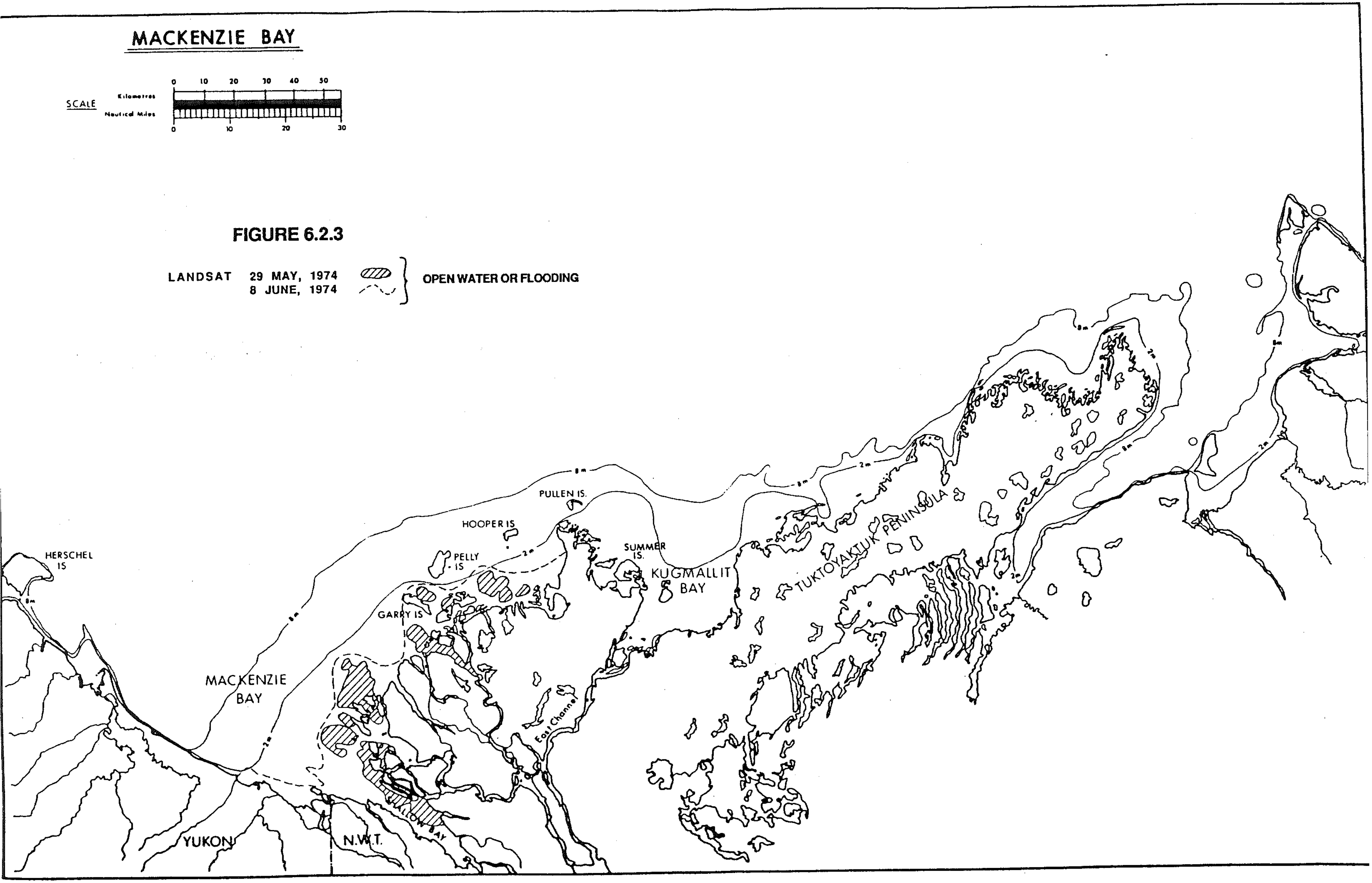
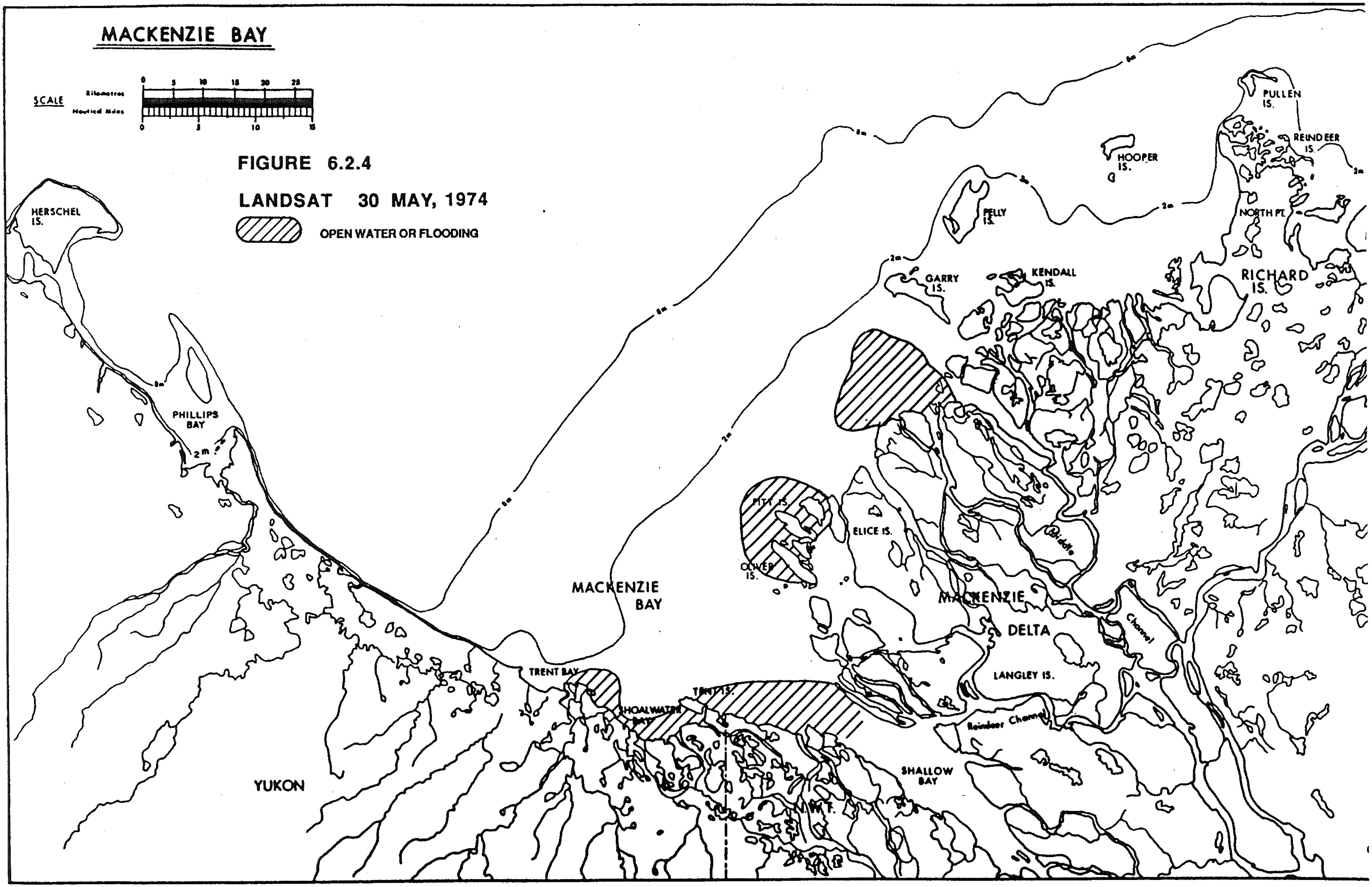

MACKENZIE BAY
SCALE
Kilometres
Nautical Miles
0 10 20 30 40 50
0 10 20 30
LANDSAT 29 MAY, 1974
8 JUNE, 1974
OPEN WATER OR FLOODING
HERSCHEL IS
PULLEN IS.
HOOPER IS
PELLY IS
GARRY IS
SUMMER IS.
KUGMALLIT BAY
TUKTOYAKTUK PENINSULA
MACKENZIE BAY
East Channel
YUKON
N.W.T.

FIGURE 6.2.3


MACKENZIE BAY
SCALE
Kilometres
Nautical Miles
0 5 10 15 20 25
0 5 10 15
FIGURE 6.2.4
LANDSAT 30 MAY, 1974
OPEN WATER OR FLOODING
HERSCHEL IS.
PHILLIPS BAY
YUKON
TRENT BAY
SHOALWATER BAY
MACKENZIE BAY
PITT IS.
OLIVER IS.
ELICE IS.
GARRY IS.
PELLY IS.
KENDALL IS.
HOOPER IS.
PULLEN IS.
REINDEER IS.
NORTH PT.
RICHARD IS.
MACKENZIE DELTA
LANGLEY IS.
Channel
Reindeer Channel
SHALLOW BAY
N.W.T.

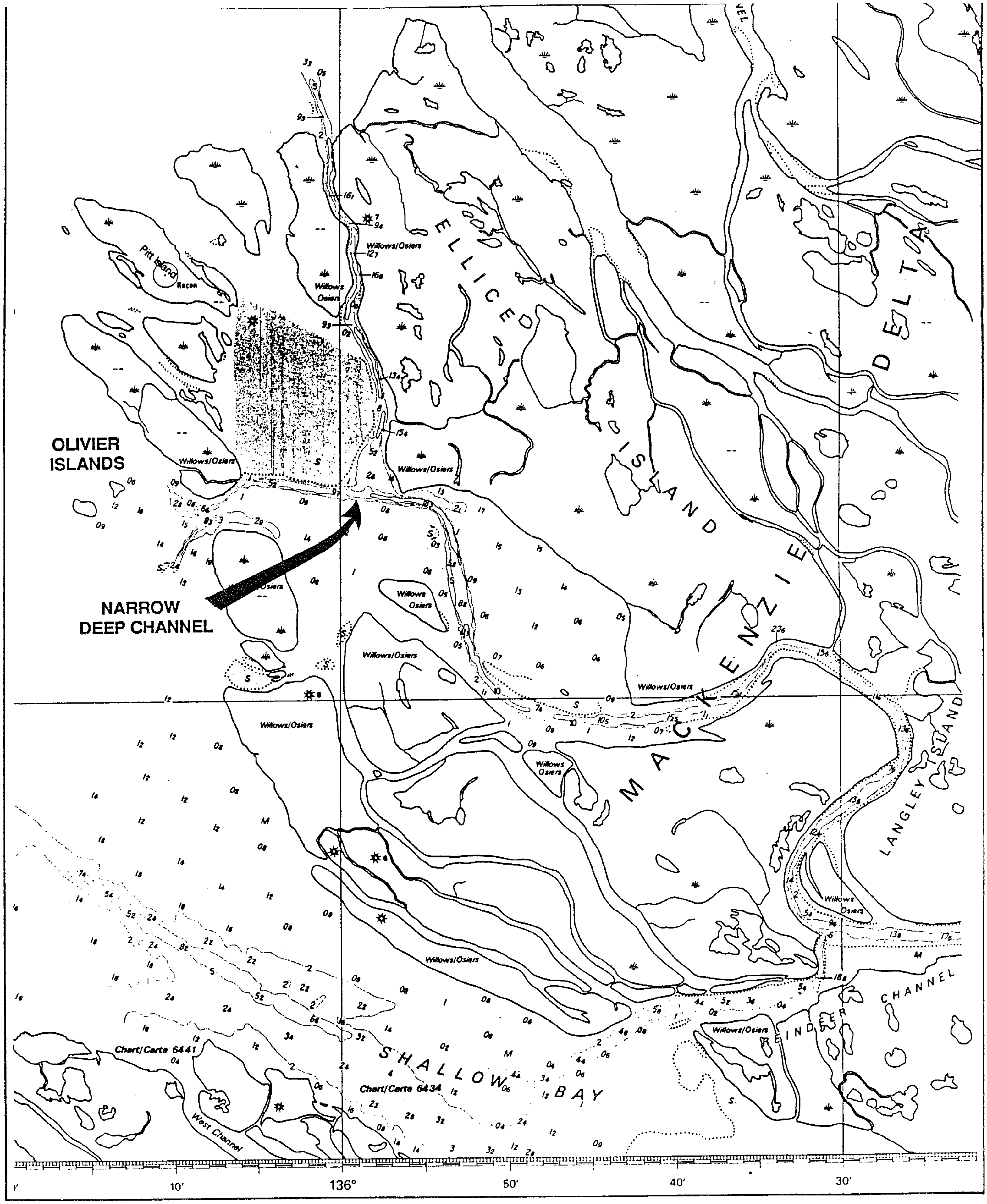


FIGURE 6.2.5

NARROW CHANNEL EXTENDING INTO OLIVIER ISLANDS

6.3 1975

Only June 9 data could be located for this year. This indicates isolated patches of flooding or open water around Olivier Islands, Arvoknar and Middle Channel, and Harry Channel. Dark areas were noted along the coast in Beluga Bay, which are extremely shallow (less than 40 cm deep); these areas would melt rapidly in the spring due to the thin ice and absorption and reflection of sunlight by the ground below.

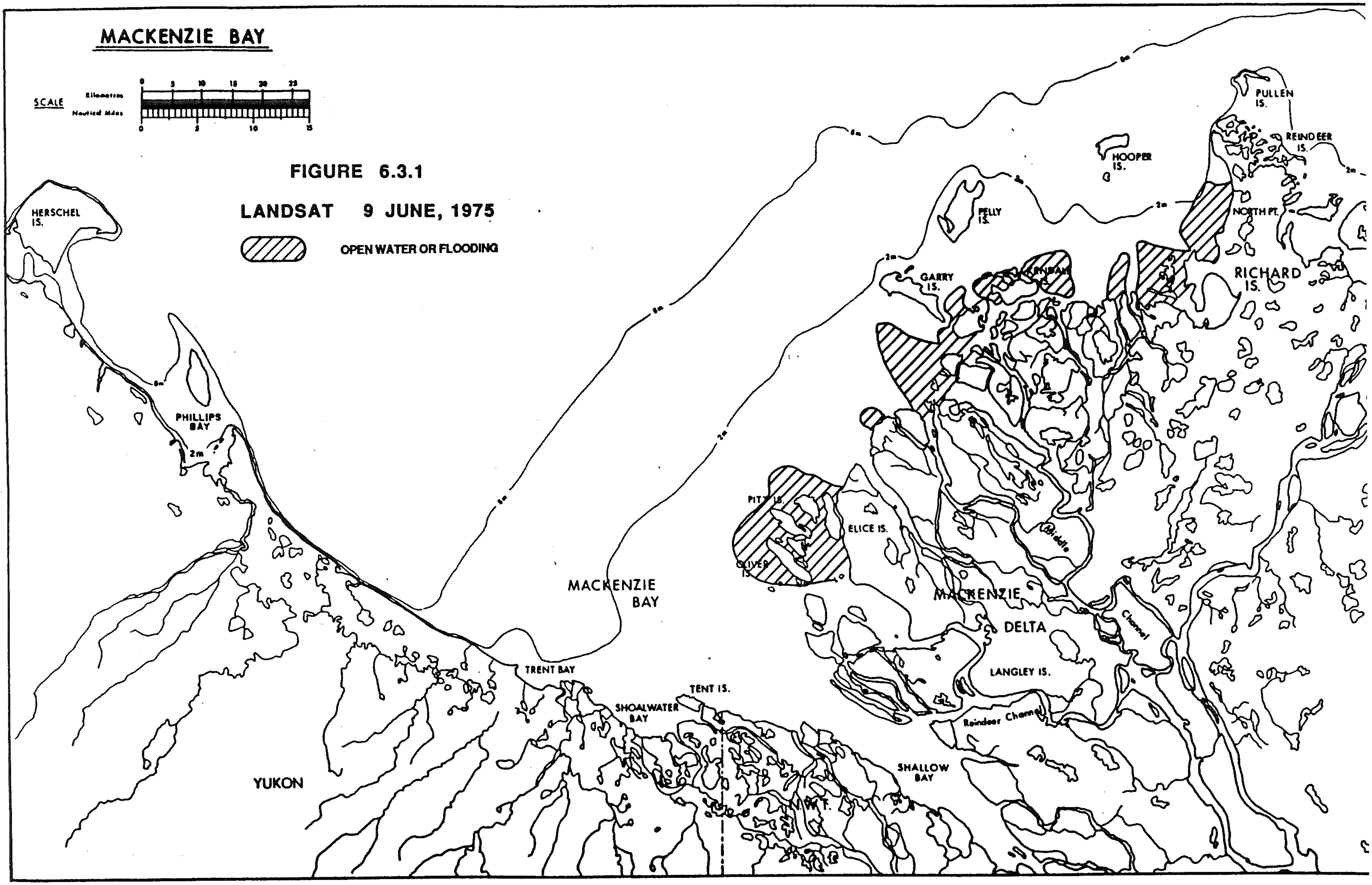
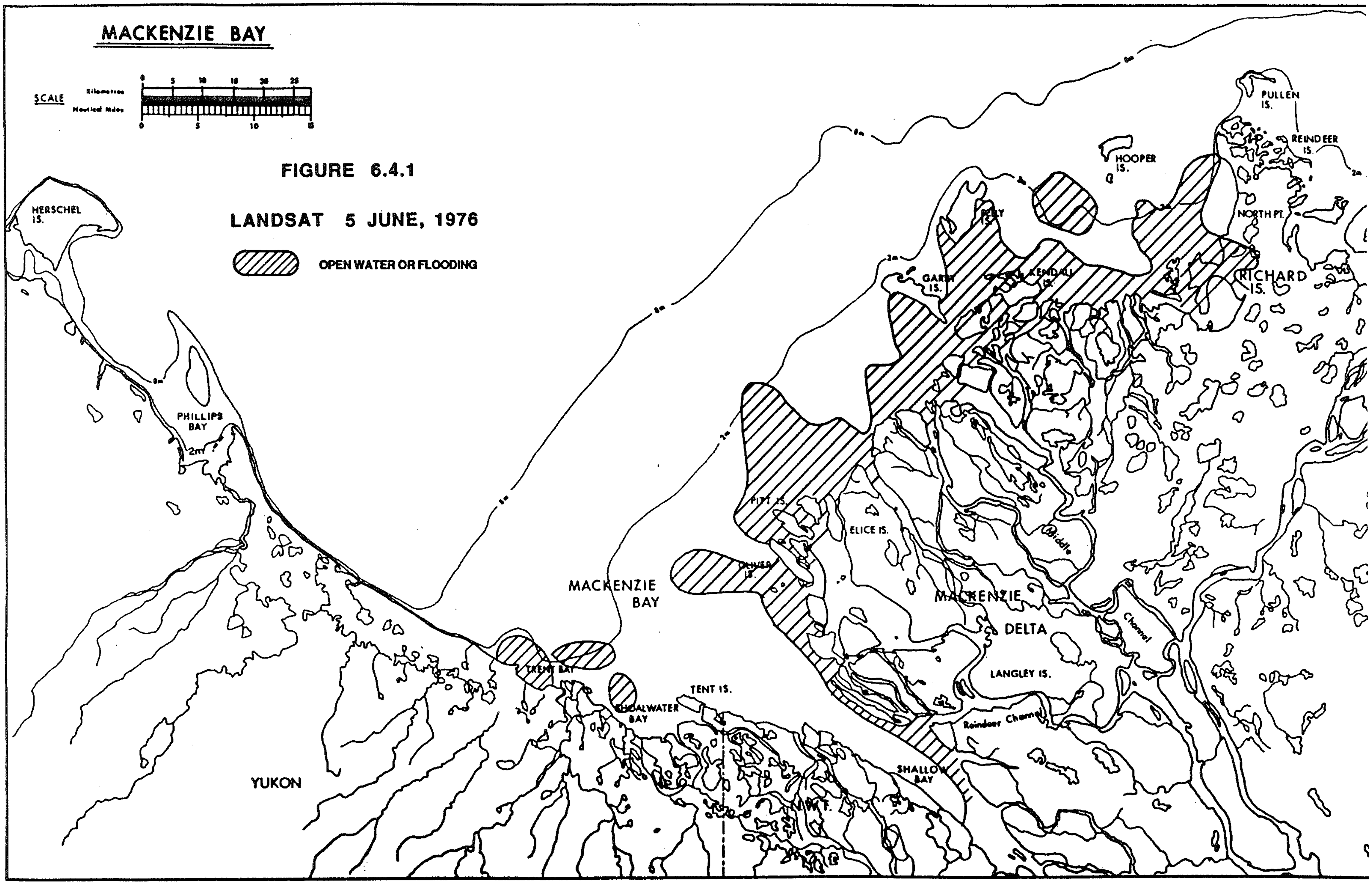


FIGURE 6.3.1

LANDSAT 9 JUNE, 1975

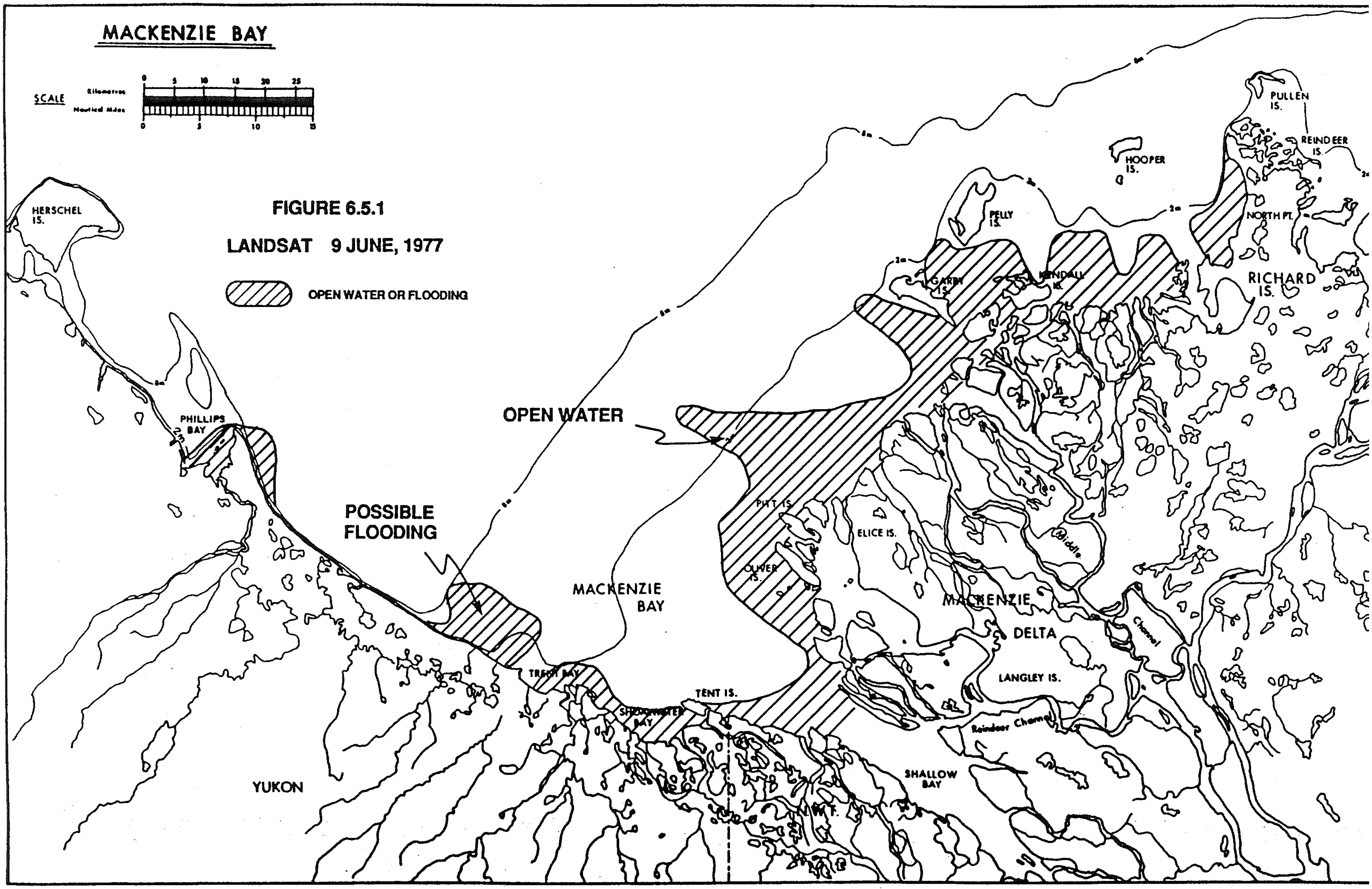
6.4 1976

June 5 data indicates flooding or open water along most of the coast of Richards Island.


MACKENZIE BAY
SCALE
Kilometres
0 5 10 15 20 25
Nautical Miles
0 5 10 15
FIGURE 6.4.1
LANDSAT 5 JUNE, 1976
OPEN WATER OR FLOODING
HERSCHEL IS.
PHILLIPS BAY
2m
YUKON
MACKENZIE BAY
TRENT BAY
SHOALWATER BAY
TENT IS.
SHALLOW BAY
PITT IS.
OLIVER IS.
ELICE IS.
GARRY IS.
PELLY IS.
KENDALL IS.
HOOPER IS.
PULLEN IS.
REINDEER IS.
NORTH PT.
RICHARD IS.
MACKENZIE DELTA
Middle
Channel
LANGLEY IS.
Reindeer Channel

6.5 1977

June 9 data indicates open water along most of the coast of Richards Island from Shallow Bay to North Point. This is clearly the result of melting of the ice adjacent to the channel mouths and direct solar melting of the shallow coastal ice.


MACKENZIE BAY
SCALE
Kilometres
Nautical Miles
0 5 10 15 20 25
0 5 10 15
FIGURE 6.5.1
LANDSAT 9 JUNE, 1977
OPEN WATER OR FLOODING
HERSCHEL IS.
PHILLIPS BAY
POSSIBLE FLOODING
OPEN WATER
MACKENZIE BAY
YUKON
TENT IS.
SHALLOW BAY
PITT IS.
OLIVER IS.
ELICE IS.
MACKENZIE DELTA
LANGLEY IS.
Reindeer Channel
Middle
Channel
GARRY IS.
KENDALL IS.
PELLY IS.
HOOPER IS.
PULLEN IS.
REINDEER IS.
NORTH PT.
RICHARD IS.
N.W.T.

6.6 1979

Figure 6.6.1 shows what is interpreted as flooding adjacent to Reindeer Channel around Olivier and Pitt Islands out to over 20 km from shore on 14 and 15 May (SLAR data). Flooding is also evident adjacent to Middle Channel and to the east by Kendall Island and south of Hooper Island, presumably from Harry Channel. By June 15 there is extensive open water around the shore line out to 10 km around Beluga Bay and south to Garry Island; no information is available for the more westerly region for this date.

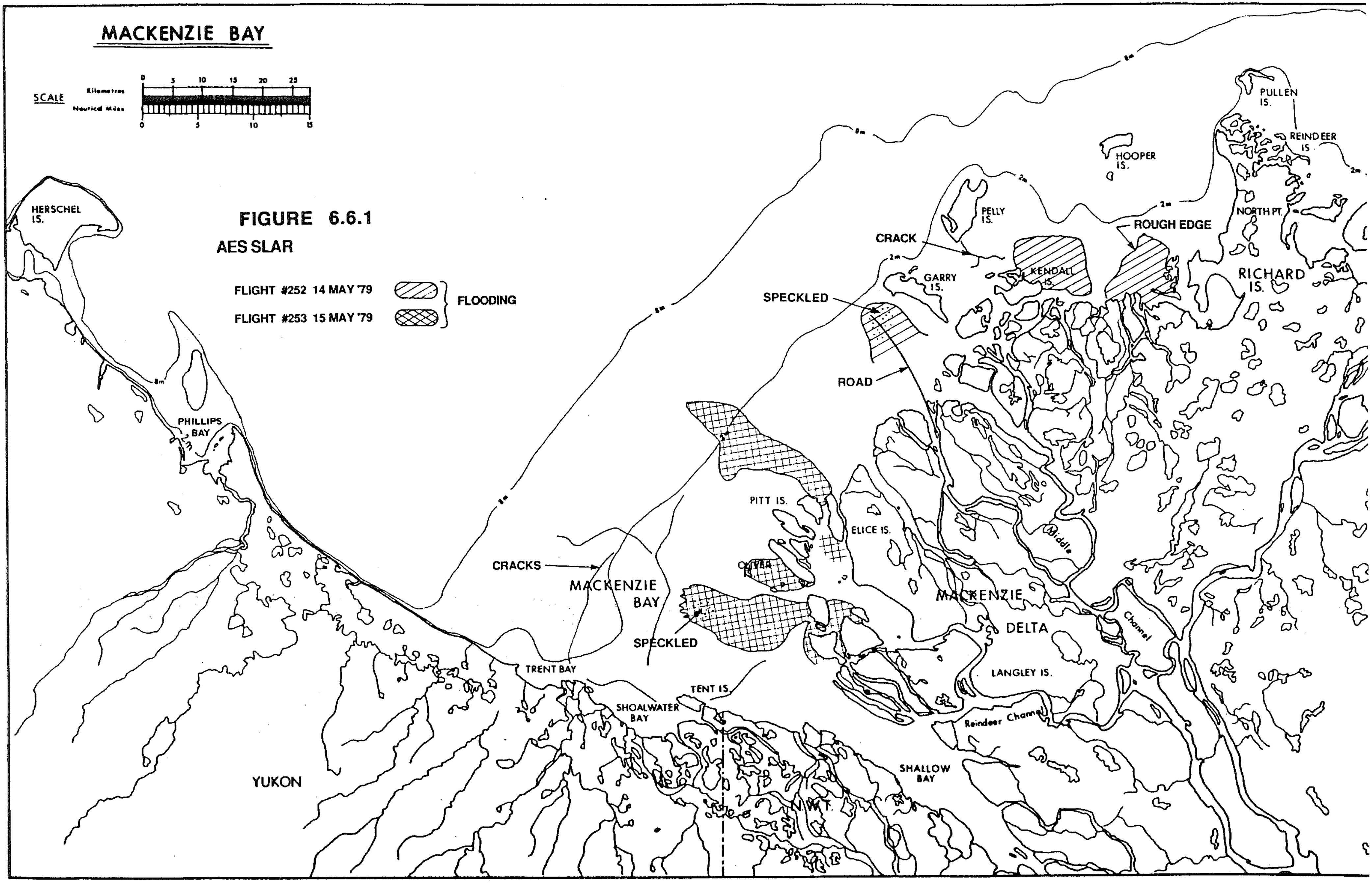
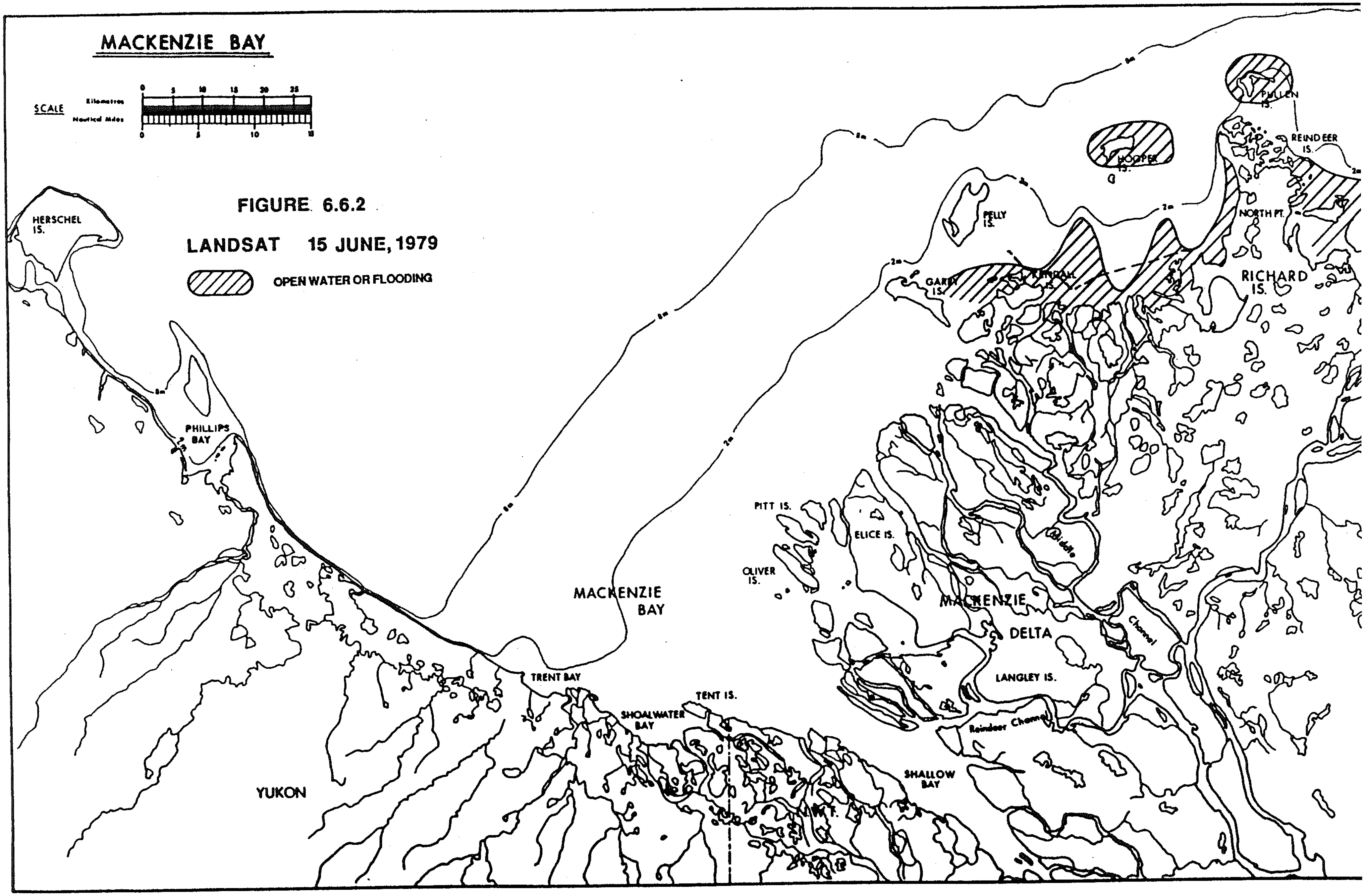


FIGURE 6.6.1

AES SLAR


MACKENZIE BAY
SCALE
Kilometres
Nautical Miles
0 5 10 15 20 25
0 5 10 15
FIGURE 6.6.2
LANDSAT 15 JUNE, 1979
OPEN WATER OR FLOODING
HERSCHEL IS.
PHILLIPS BAY
YUKON
TRENT BAY
SHOALWATER BAY
TENT IS.
MACKENZIE BAY
PITT IS.
OLIVER IS.
ELICE IS.
GARRY IS.
PELLY IS.
HOOPER IS.
PULLEN IS.
REINDEER IS.
NORTH PT.
RICHARD IS.
MACKENZIE DELTA
LANGLEY IS.
Reindeer Channel
Channel
Middle
SHALLOW BAY
N.W.T.
2m
5m

6.7 1980

No early May data are available. By 10 June there was extensive open water along the shore of Richards Island as indicated in the LANDSAT data. This photo also shows regions of grey ice seaward of the open water areas which are interpreted as regions of flooded ice. Looking carefully at the grey (flooded) region in Shallow Bay to the west of Olivier Islands, one notes that flooding occurs in fingers that extend seaward. In some regions flooding stops at a distinct line on the ice at about the 1.6 m water depth, which is presumably the tidal crack. The flood fingers extend out beyond 6 km past the tidal crack into water depths of 6 metres or more.

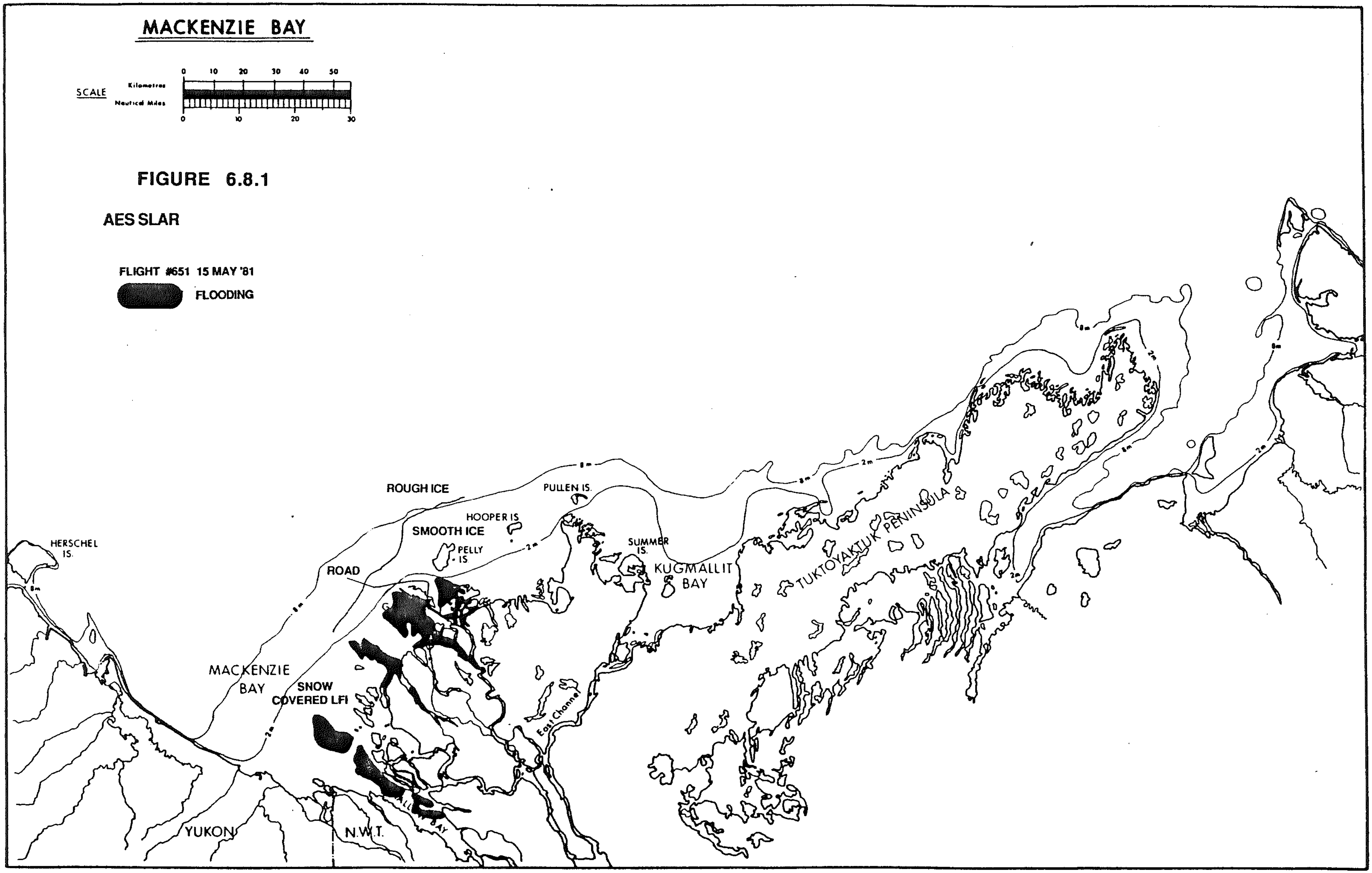
It is noted that some of the shallow lakes and the coastal areas in Beluga Bay are quite grey in contrast to the fast ice further offshore; this is presumably indication of very rotten, water covered ice.

FIGURE 6.7.1
LANDSAT
10 JUNE, 1980

6.8 1981

May 15 AES SLAR data is interpreted as showing there was extensive flooding adjacent to Reindeer, Middle and Harry Channels extending to 20 km from shore These data showed no open water or flooding around Olivier Islands. Fig. 6.8.2 shows the LANDSAT data for May 18. The dark areas seen off the coast line are interpreted as areas of open water where the ice has been melted away in the mouths of the various channels and the grey areas further offshore (to the left in photo) are areas of flooding. Note that these grey areas differ from the "wispy" grey areas caused by clouds, and indeed appear as one would expect flooded areas to appear - grey from wet snow and irregular on the outer perimeter due to the uneven ice surface.

The SLAR and LANDSAT data shown here are very similar except for the open water area in Beluga Bay and open water and flooding around Olivier Islands shown in the LANDSAT and not in the SLAR. It is unlikely that the 3-day difference accounts for this discrepancy.


MACKENZIE BAY
SCALE
Kilometres
Nautical Miles
0 10 20 30 40 50
0 10 20 30
FIGURE 6.8.1
AES SLAR
FLIGHT #651 15 MAY '81
FLOODING
ROUGH ICE
SMOOTH ICE
ROAD
HERSCHEL IS.
PULLEN IS.
HOOPER IS
PELLY IS
SUMMER IS.
KUGMALLIT BAY
TUKTOYAKTUK PENINSULA
MACKENZIE BAY
SNOW COVERED LFI
East Channel
YUKON
N.W.T.

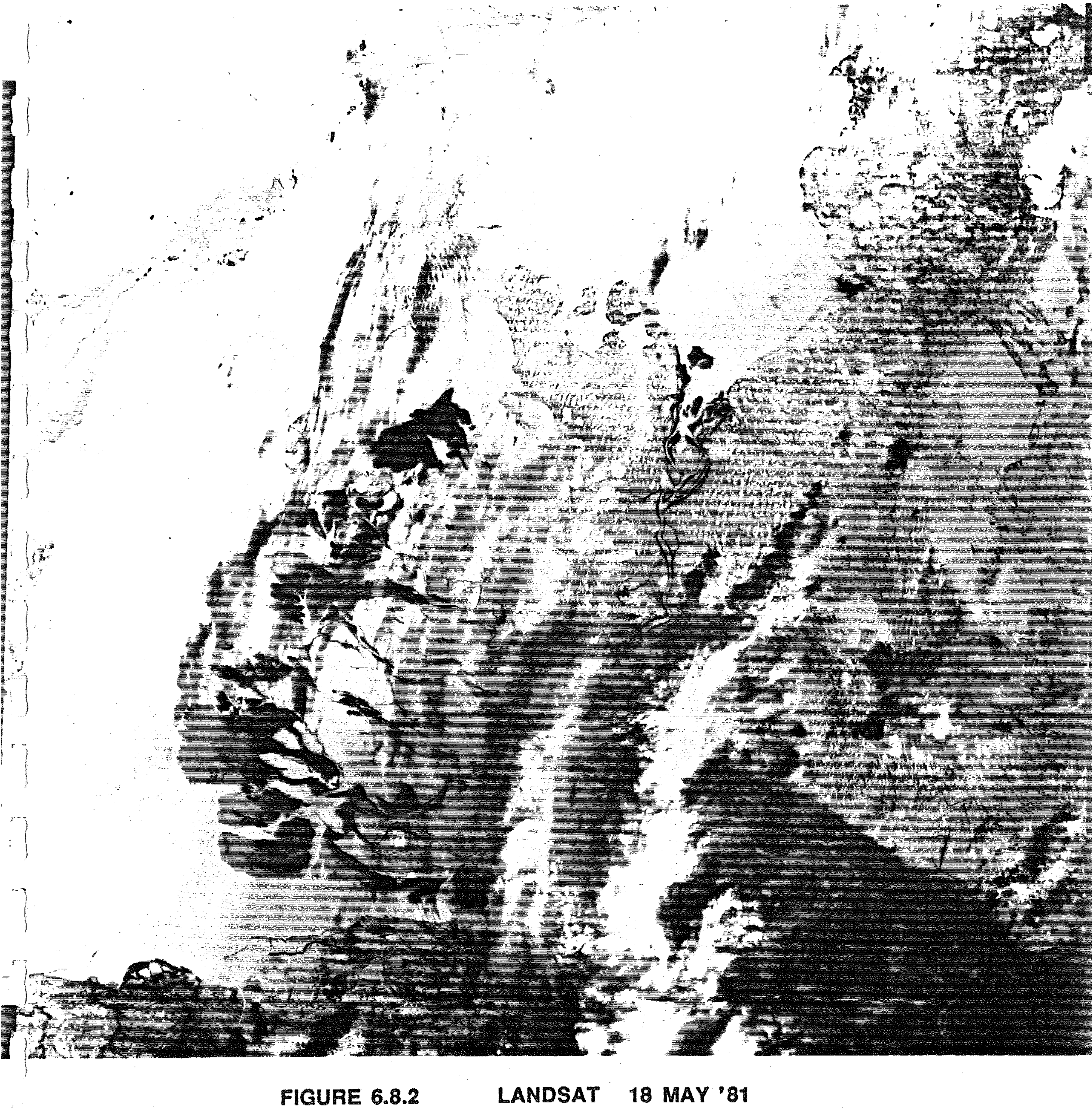
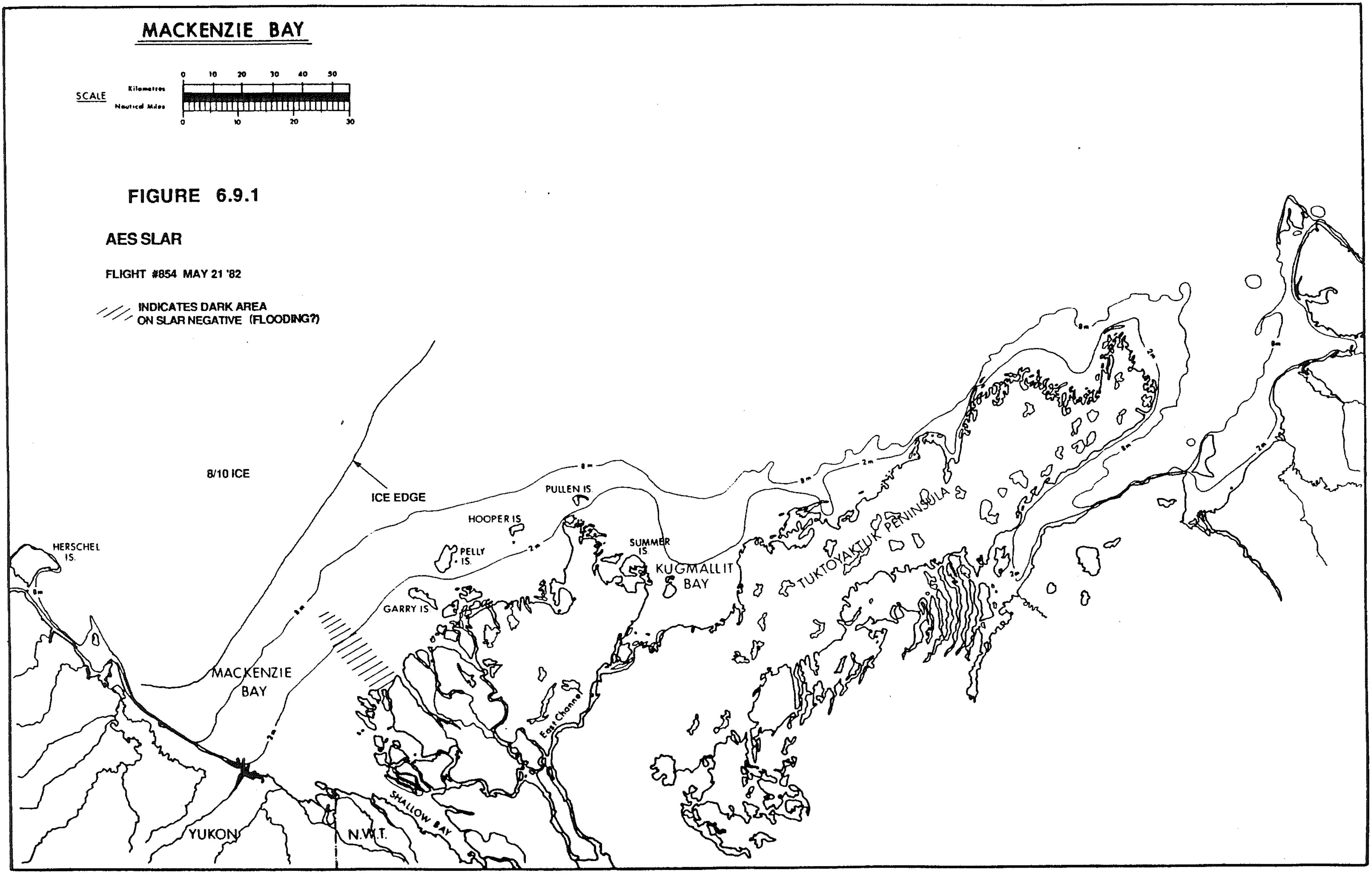


FIGURE 6.8.2 LANDSAT 18 MAY '81

6.9 1982

The May 28 NOAA data shows extensive flooding or open water adjacent to the various channels off Richards Island, Shallow Bay and adjacent to Anderson River in Liverpool Bay. This becomes more extensive and presumably becomes open water by June 7, except that some of the flooded areas decrease in size most noticeably in Shallow Bay and adjacent to Harry Channel. By June 11, the Landsat data shows open water lagoons to the 2 m depth contour. Figure 6.9.2 show similar dark areas as noted on the May 21 AES SLAR, and the NOAA data for May 28 and June 6 agree reasonably well considering the one week difference.


MACKENZIE BAY
SCALE
Kilometres
Nautical Miles
0 10 20 30 40 50
0 10 20 30
FIGURE 6.9.1
AES SLAR
FLIGHT #854 MAY 21 '82
INDICATES DARK AREA ON SLAR NEGATIVE (FLOODING?)
8/10 ICE
ICE EDGE
HERSCHEL IS.
MACKENZIE BAY
YUKON
N.W.T.
SHALLOW BAY
GARRY IS
PELLY IS.
HOOPER IS
PULLEN IS.
SUMMER IS.
KUGMALLIT BAY
East Channel
TUKTOYAKTUK PENINSULA
8m
2m

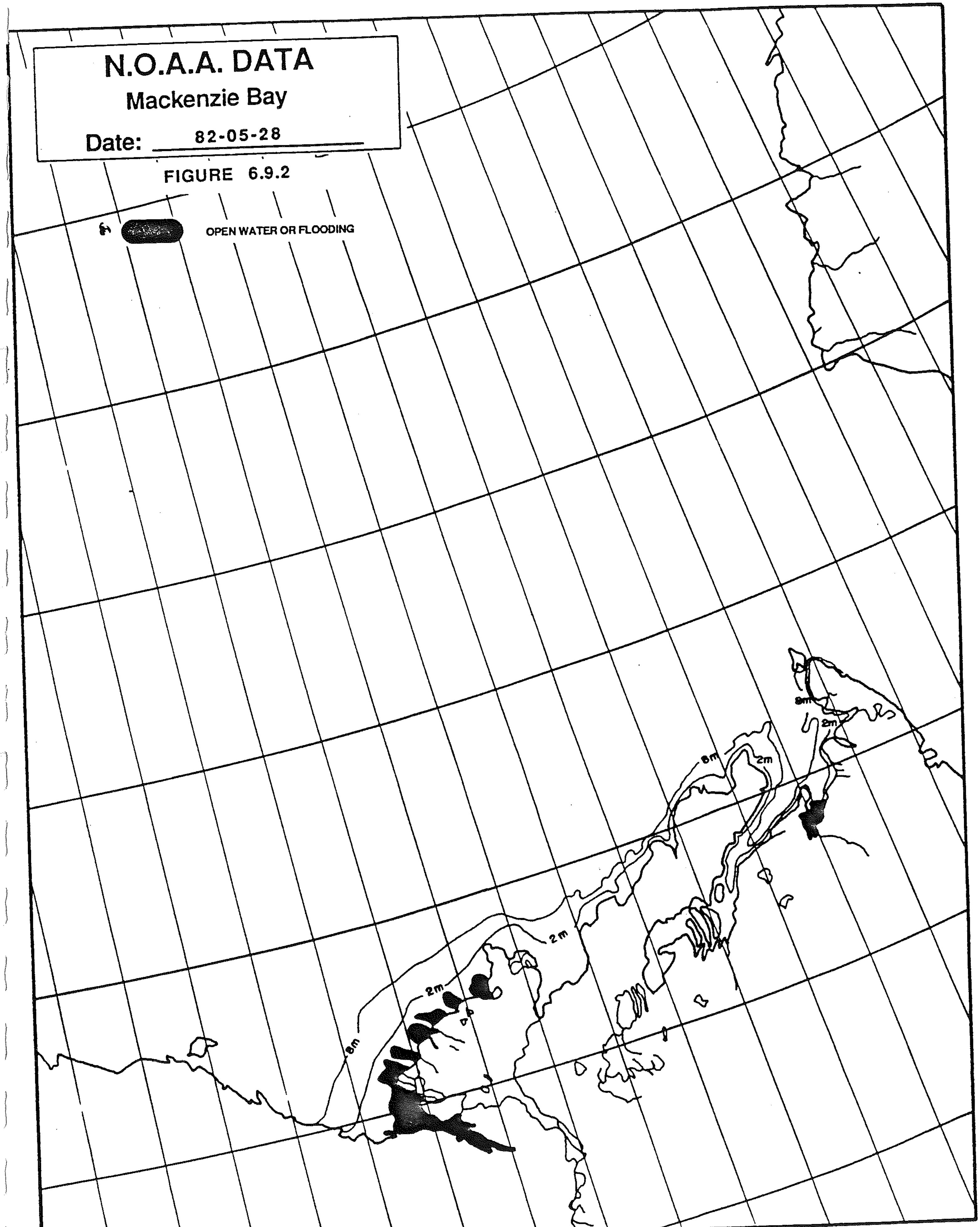
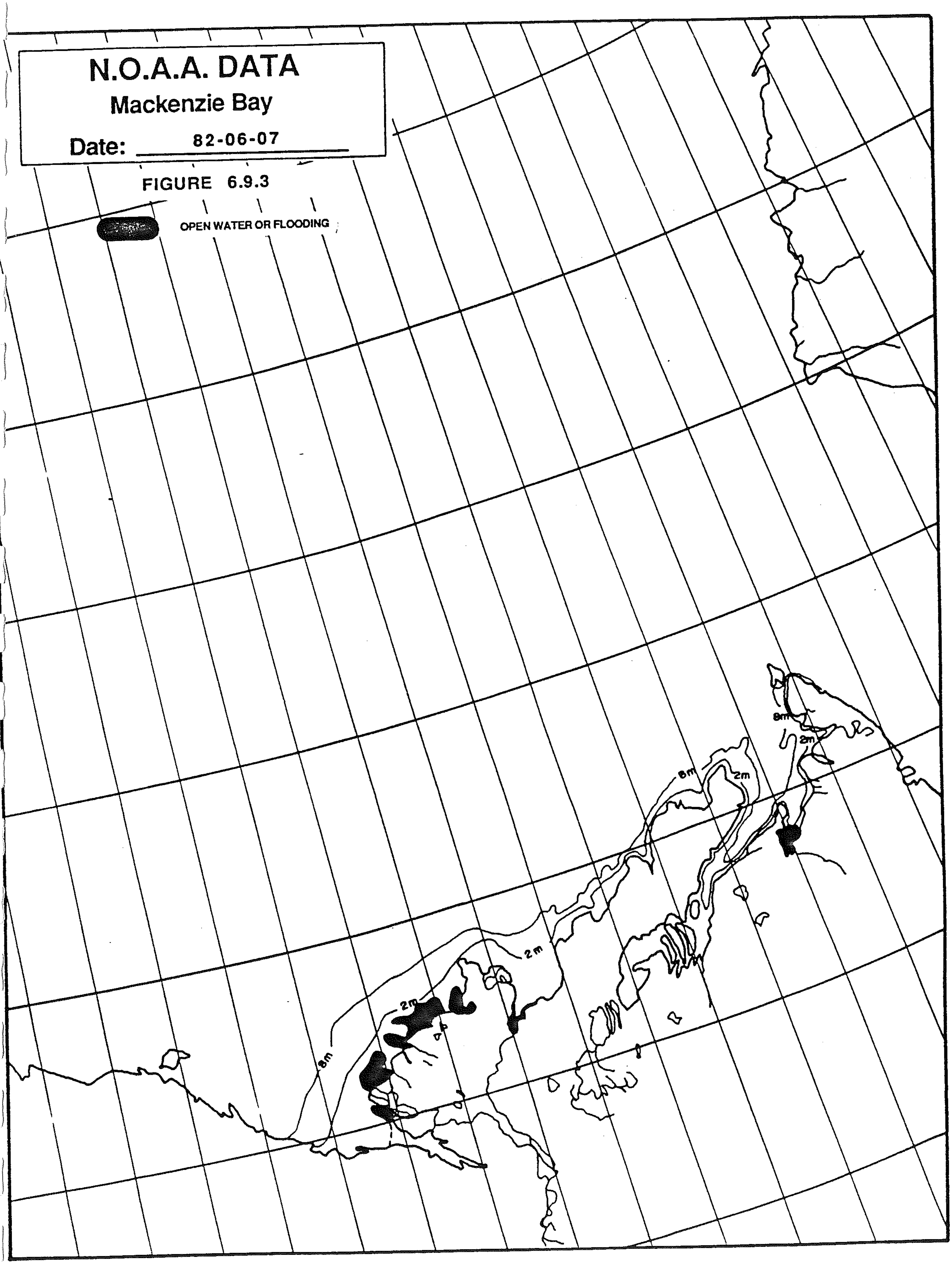
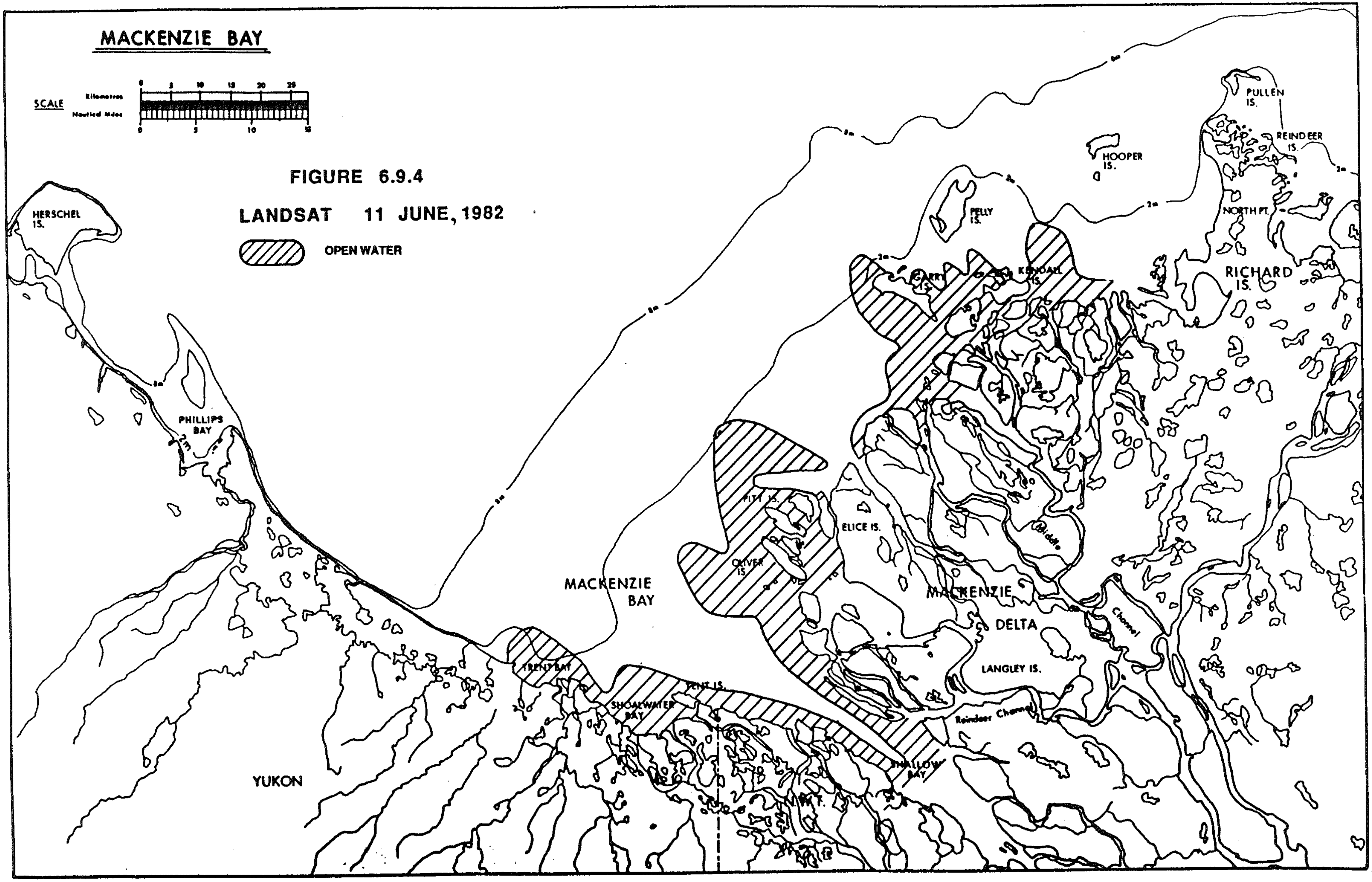

N.O.A.A. DATA
Mackenzie Bay
Date: 82-05-28
OPEN WATER OR FLOODING
8m
2m
2m
8m
2m
2m
8m
2m
8m

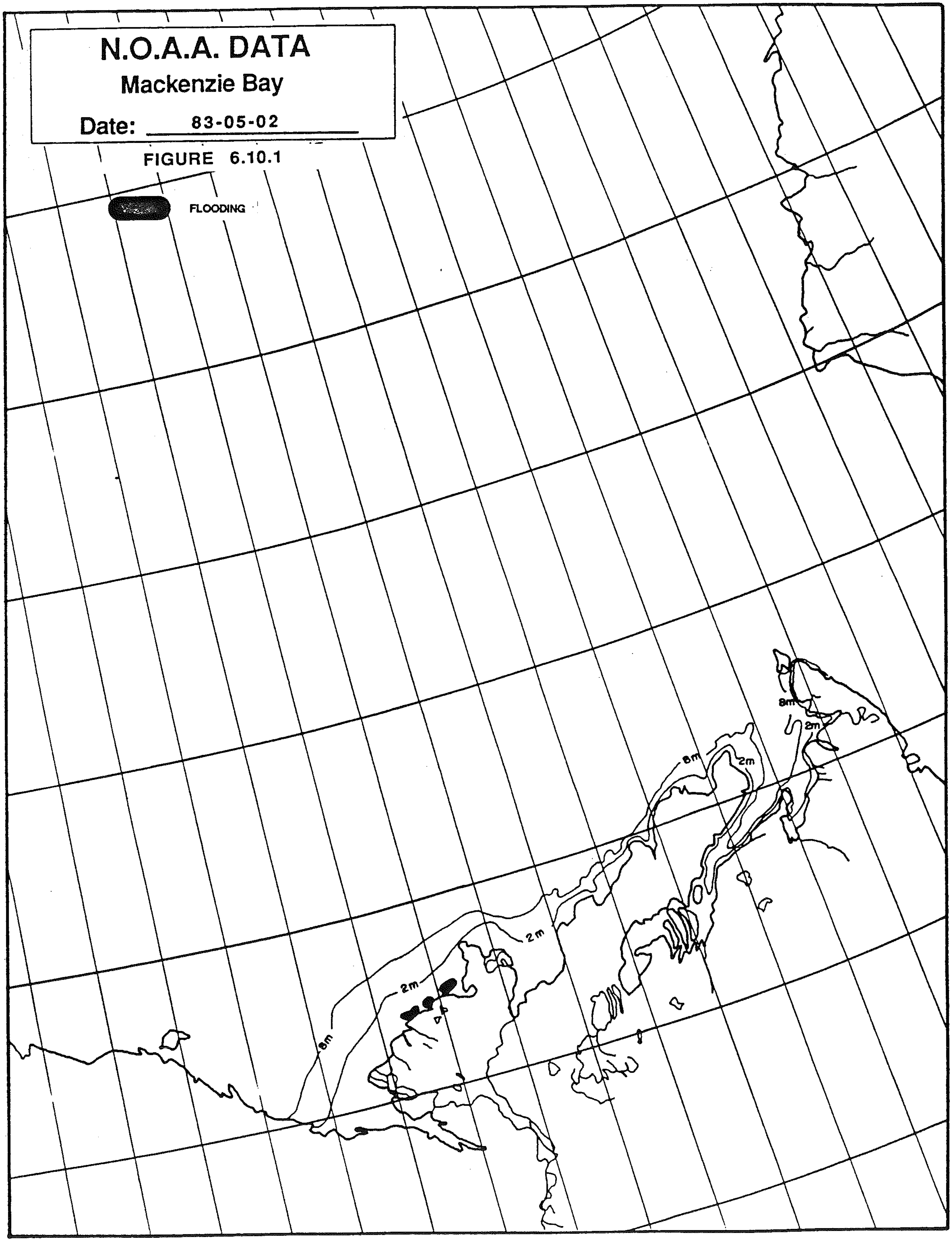
FIGURE 6.9.2


N.O.A.A. DATA
Mackenzie Bay
Date: 82-06-07
FIGURE 6.9.3
OPEN WATER OR FLOODING
8m
2m
8m
2m
2m
2m
8m


MACKENZIE BAY
SCALE
Kilometres
0 5 10 15 20 25
Nautical Miles
0 5 10 15
FIGURE 6.9.4
LANDSAT 11 JUNE, 1982
OPEN WATER
HERSCHEL IS.
PHILLIPS BAY
YUKON
MACKENZIE BAY
TRENT BAY
SHOALWATER BAY
PITT IS.
OLIVER IS.
ELICE IS.
MACKENZIE DELTA
LANGLEY IS.
Reindeer Channel
SHALLOW BAY
Middle
Channel
KENDALL IS.
PELLY IS.
HOOPER IS.
PULLEN IS.
REINDEER IS.
NORTH PT.
RICHARD IS.
2m

6.10 1983

Small areas of flooding are first evident on May 2 around Middle Channel and Harry Channel to the east (Figure 6.10.1). On May 10 and 18 these areas have expanded and a tongue of flooding has formed seaward of Middle Channel, which extends about 15 km from shore by May 24. By May 25 flooding and/or open water is evident adjacent to all the river channels including Kittigaziut. The tongue adjacent to the Middle Channel now extends about 20 km. Lack of evidence in the May 24 image of all the flooding seen on May 25 is accredited to some cloud cover in the May 24 image.

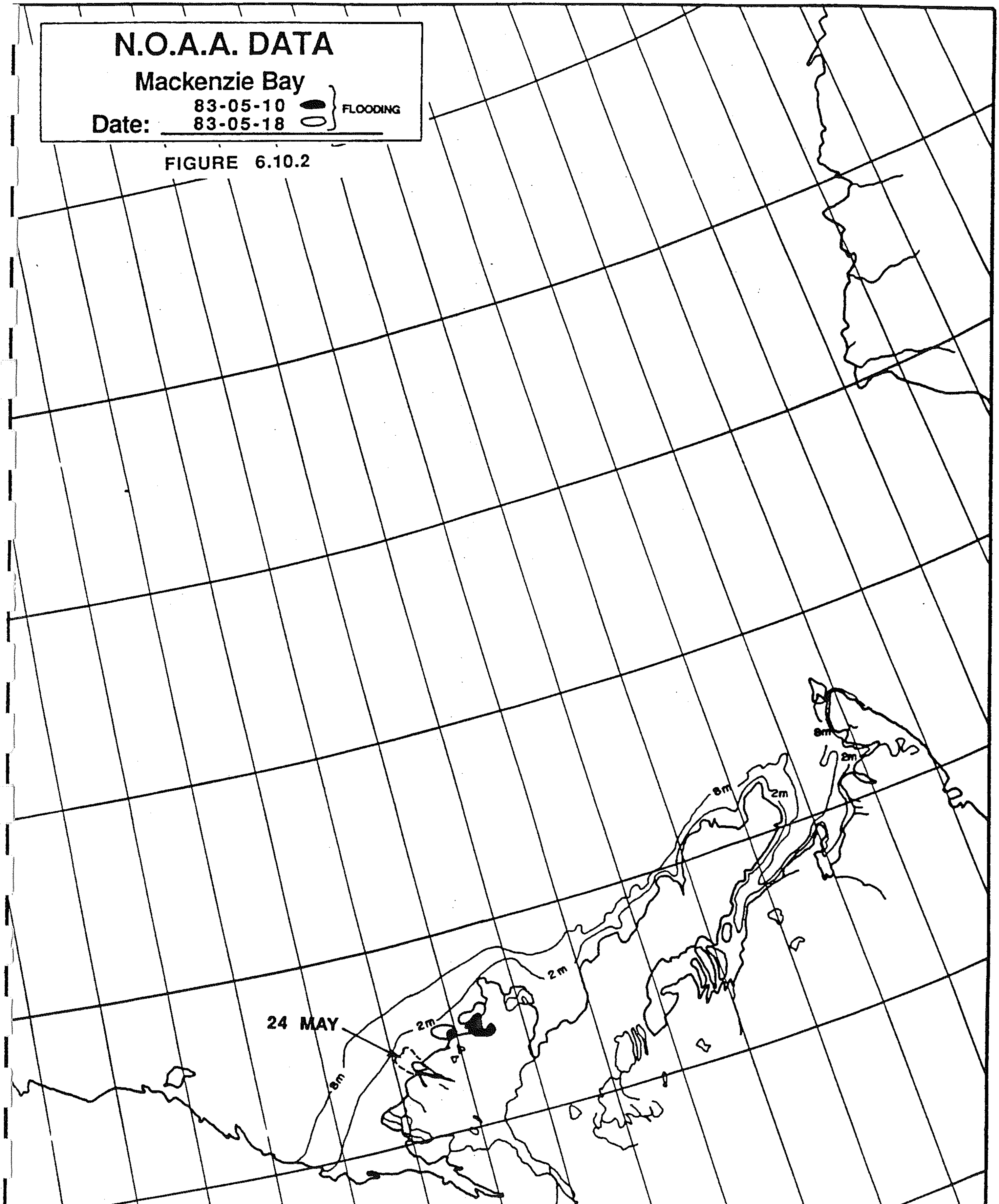

N.O.A.A. DATA
Mackenzie Bay
Date: 83-05-02
FLOODING
8m
2m
8m
2m
2m
2m
8m
FIGURE 6.10.1

N.O.A.A. DATA

Mackenzie Bay

Date: 83-05-10 / 83-05-18 FLOODING

FIGURE 6.10.2

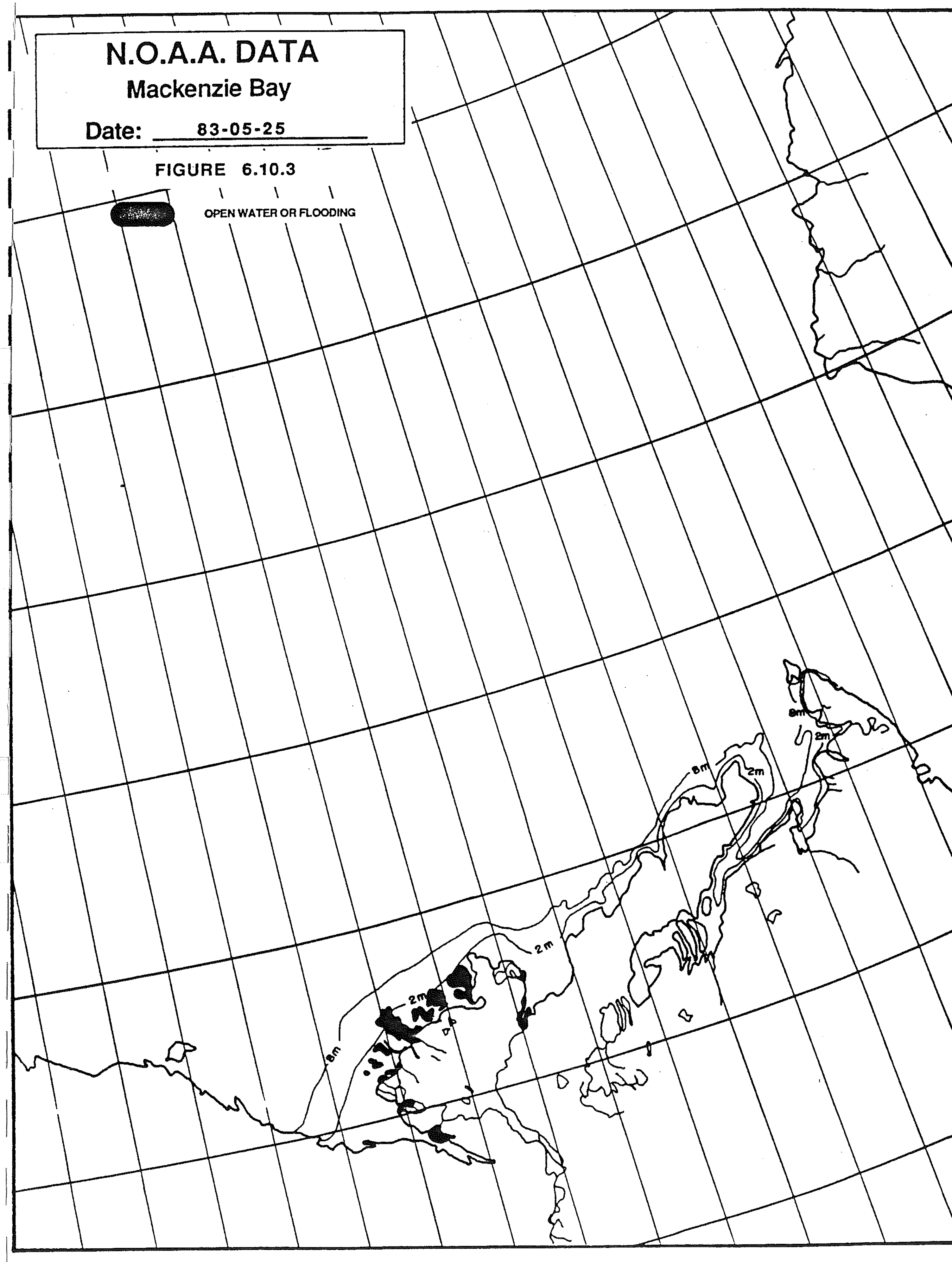


N.O.A.A. DATA

Mackenzie Bay

Date: 83-05-25

FIGURE 6.10.3



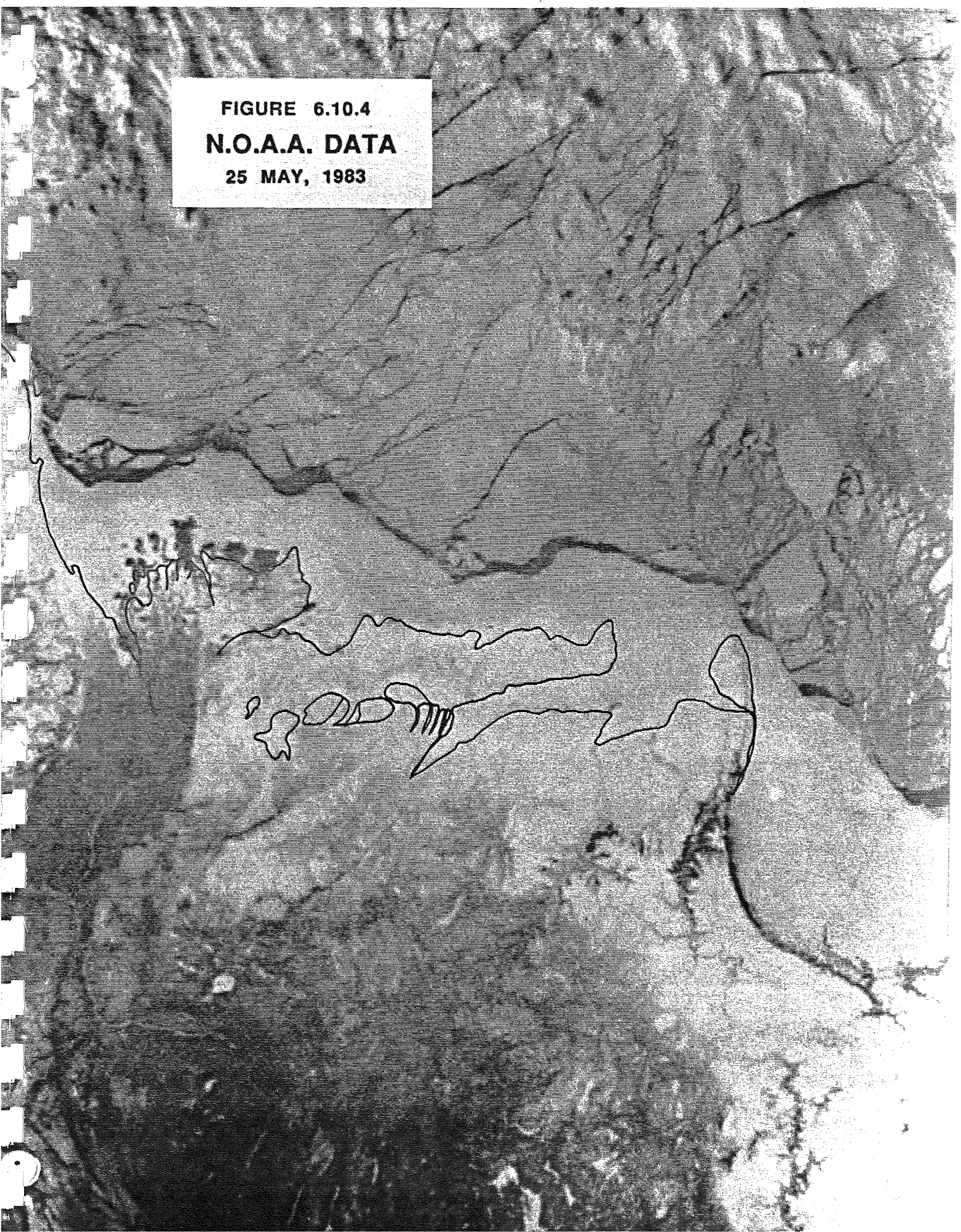


FIGURE 6.10.4
N.O.A.A. DATA
25 MAY, 1983

6.11 1984

Figures 6.11.1 to 6.11.14 show the growth of flooding and open water along the coast of Richards Island and in Liverpool Bay from May 15 to June 16 in 1984. For this year there is a large quantity of data available and so a detailed history is provided.

The SLAR data for 15 May (Fig. 6.11.1) indicates dark areas around the Olivier Islands, to the SW of these islands, and in Shallow Bay as a result of water in the Reindeer Channel.

As mentioned in Section 6.2 the rising water in Reindeer Channel is channeled into the areas shown here by narrow deep water channels. Flooding is also evident both within and seaward of Middle Channel. In all these cases, the areas are shore normal and there is no evidence of water on the ice along the shoreline. Flooding or open water is also evident in various river channels and at the Blow River on the Yukon coast.

The NOAA data for 16 May (Fig. 6.11.2) does not show the large areas of flooding seen in Fig. 6.11.1. This image shows flooding in Middle Channel, and at the mouths of Harry Channel to the east. No shore parallel melting or flooding is seen.

Figures 6.11.4, 5, and 6 show considerably more flooding adjacent to Middle and Harry Channels and in Shallow Bay, but still no evidence of flooding around Olivier Islands. The LANDSAT data for May 10, Fig. 6.11.7 shows some flooding around Olivier Islands and extensive flooding/open water from Middle Channel out to Garry Island. Fig. 6.11.8 and 9, NOAA data, for May 21 show flooding or open water around Olivier Islands and very extensive open water from Middle Channel east. Flooding or open water is noted at Anderson River in Liverpool Bay.

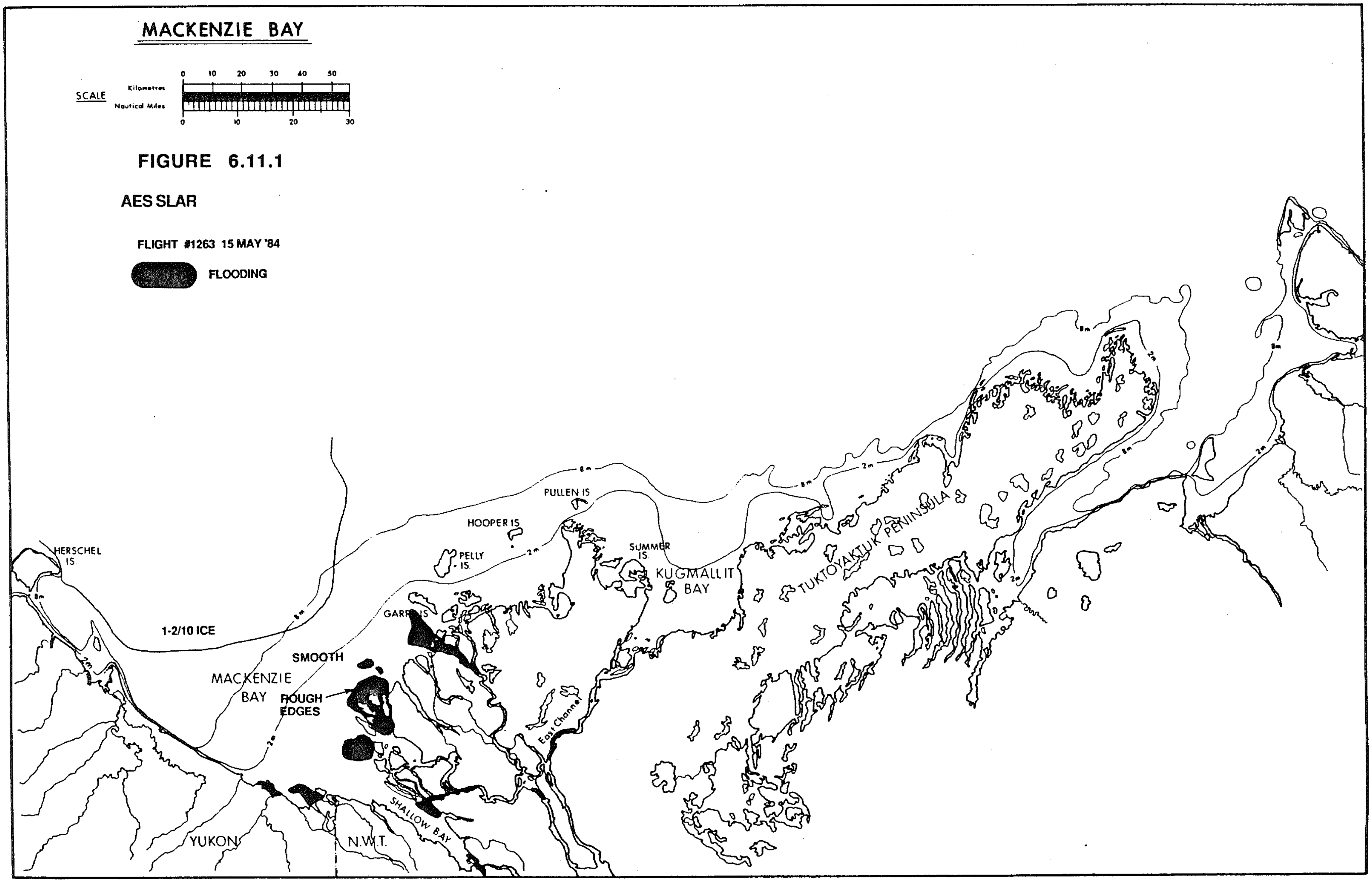
LANDSAT data for May 22, Fig. 6.11.10, shows extensive areas of open water (dark areas) and flooded areas (grey, mottled areas) around Reindeer, Middle and Harry Channels. Note that the river channels are still frozen with narrow areas of open water or flooding evident in places along the edges of the channels. Note also that the still-frozen river channels extend out into the landfast ice flooded landfast ice areas, particularly adjacent to Harry Channel within the islands south of Kendall Island. A possible explanation for this is that the ice in the deep river channels can grow much thicker than that in the areas around, as here the ice thickness is limited by water depth. In the spring the thinner ice melts faster than the thicker ice in the river channels due to absorption of sunlight by the ground below and so is depressed relative to the river channels as water floods on to the ice surface.

Figure 6.11.10 shows areas that are clearly flooded, as irregularities in the ice surface show above the flooding. In this image there is no evidence of the tidal crack limiting the extent of flooding, as was seen in Fig. 6.7.1 and mentioned frequently by Spedding (Refs. 7 to 13). However, the flooding here (and in most of the other examples shown) does appear to be limited to water depths of about 1.6 to 1.2 m which is where the tidal crack would be expected to be.

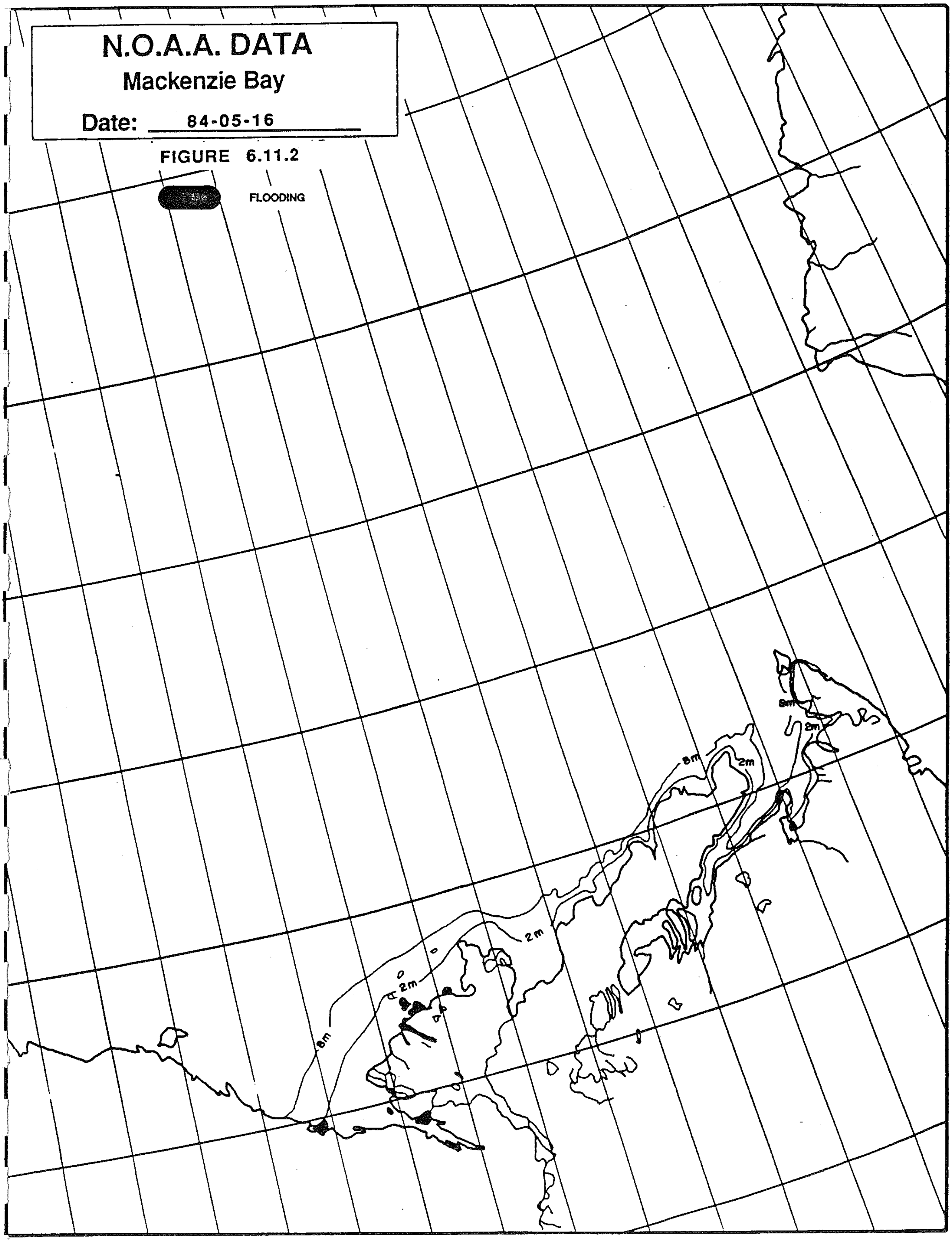
The flooding around Pitt Island extends out to about the 1.6 m water depth and in Beluga Bay to about 2 m.

Comparing Fig. 6.11.9 and 6.11.10, one sees that the flooding has receded between May 21 and 22, particularly seaward of Middle and Arvoknar Channels. Further it is noted that some narrow strips of melting are evident along the coastline in places and also that the wide unnamed channel just NE of Ellice Island does not appear to carry much water at this time of year.

LANDSAT data for June 6, Fig. 6.11.12, shows that large flooded areas in Fig. 6.11.10 have since drained (note around Olivier Islands and in Beluga Bay). Also, the river channels are now ice free and the river channel extensions into the flooded areas are no longer visible. There is now about 1 km of open water along most of the coastline between river channels, but far less along sections of coastline where there are no channels (west side of Beluga Bay and around North Point). There is also open water and possibly flooding at Blow River, flooding in Phillips Bay, and patches of open water in Kittigazuit Bay.



MACKENZIE BAY
SCALE
Kilometres
Nautical Miles
0 10 20 30 40 50
0 10 20 30
FIGURE 6.11.1
AES SLAR
FLIGHT #1263 15 MAY '84
FLOODING
HERSCHEL IS.
1-2/10 ICE
MACKENZIE BAY
SMOOTH
ROUGH EDGES
GARRY IS.
PELLY IS.
HOOPER IS.
PULLEN IS.
SUMMER IS.
KUGMALLIT BAY
TUKTOYAKTUK PENINSULA
East Channel
SHALLOW BAY
YUKON
N.W.T.
8m
2m


N.O.A.A. DATA
Mackenzie Bay
Date: 84-05-16
FIGURE 6.11.2
FLOODING
8m
2m
2m
8m
2m
8m
2m
2m

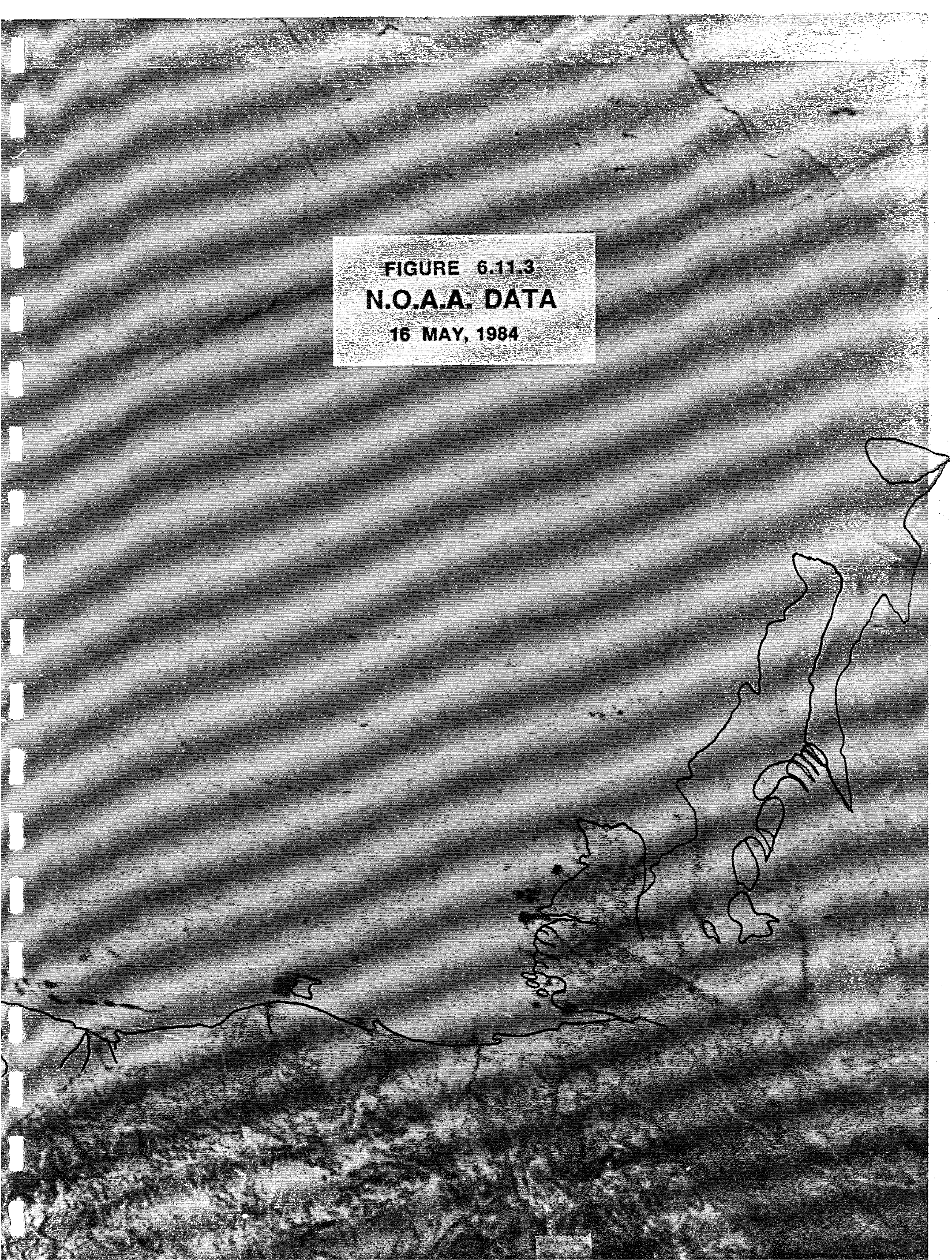


FIGURE 6.11.3
N.O.A.A. DATA
16 MAY, 1984

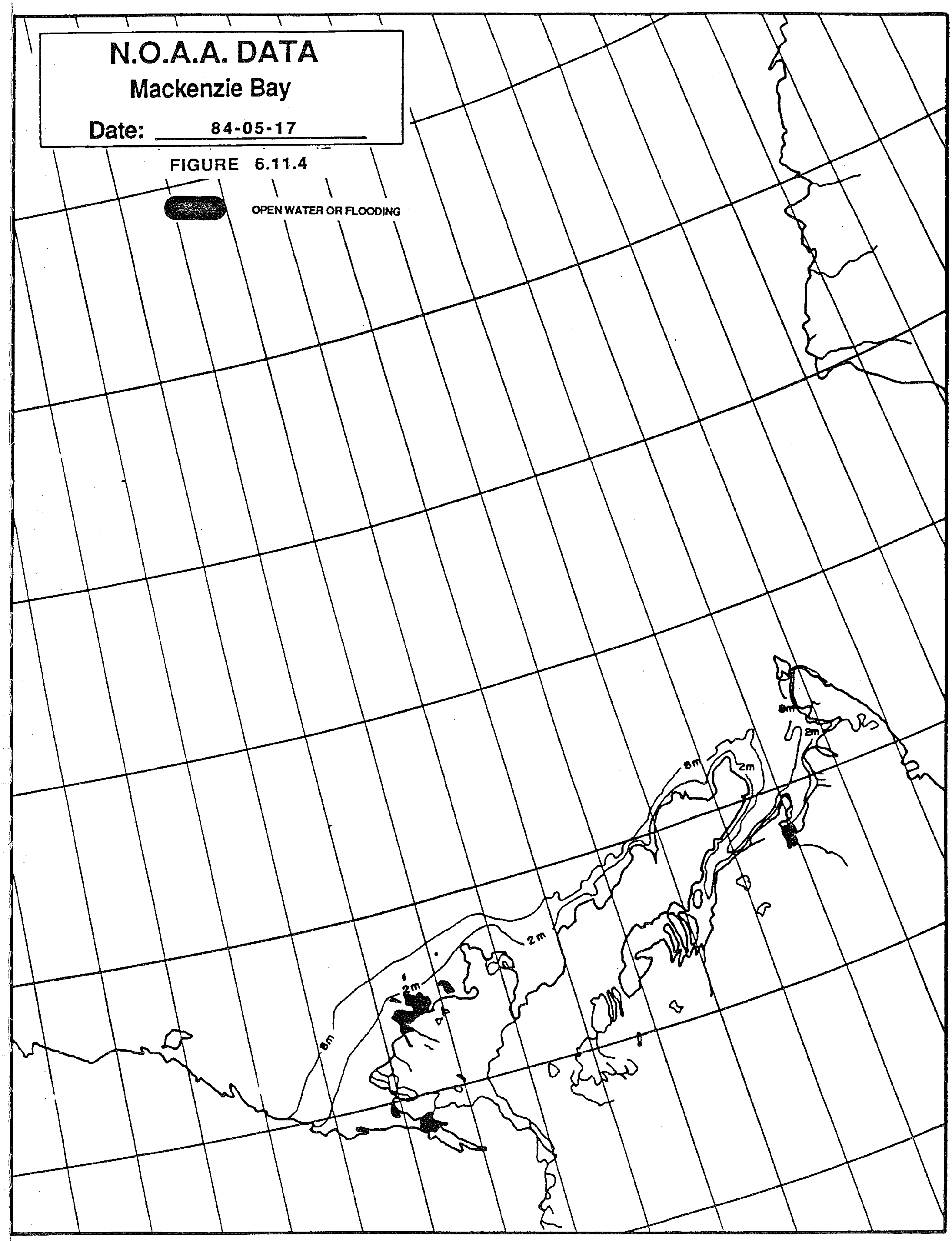

N.O.A.A. DATA
Mackenzie Bay
Date: 84-05-17
OPEN WATER OR FLOODING
8m
2m
2m
8m
2m
2m
8m

FIGURE 6.11.4

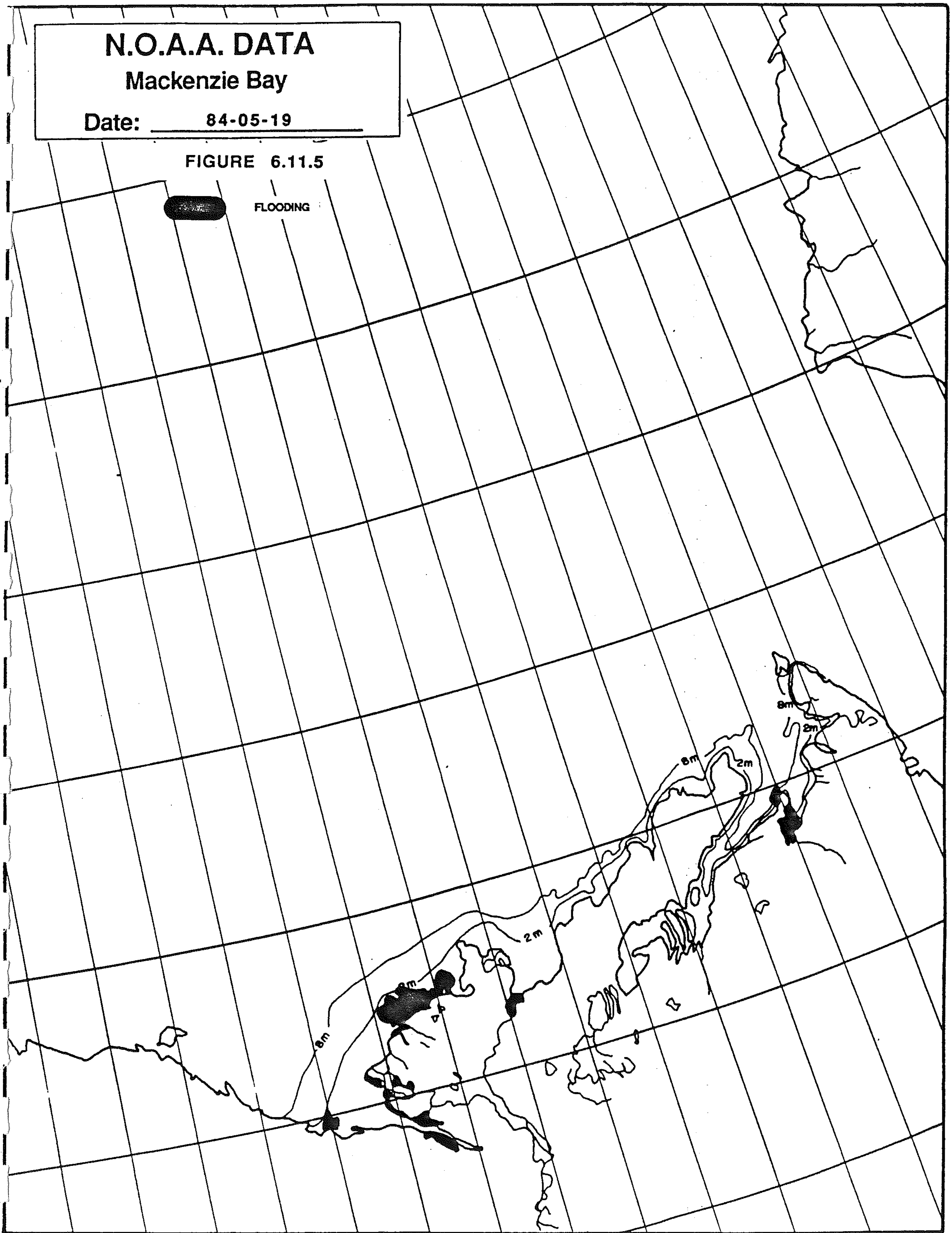
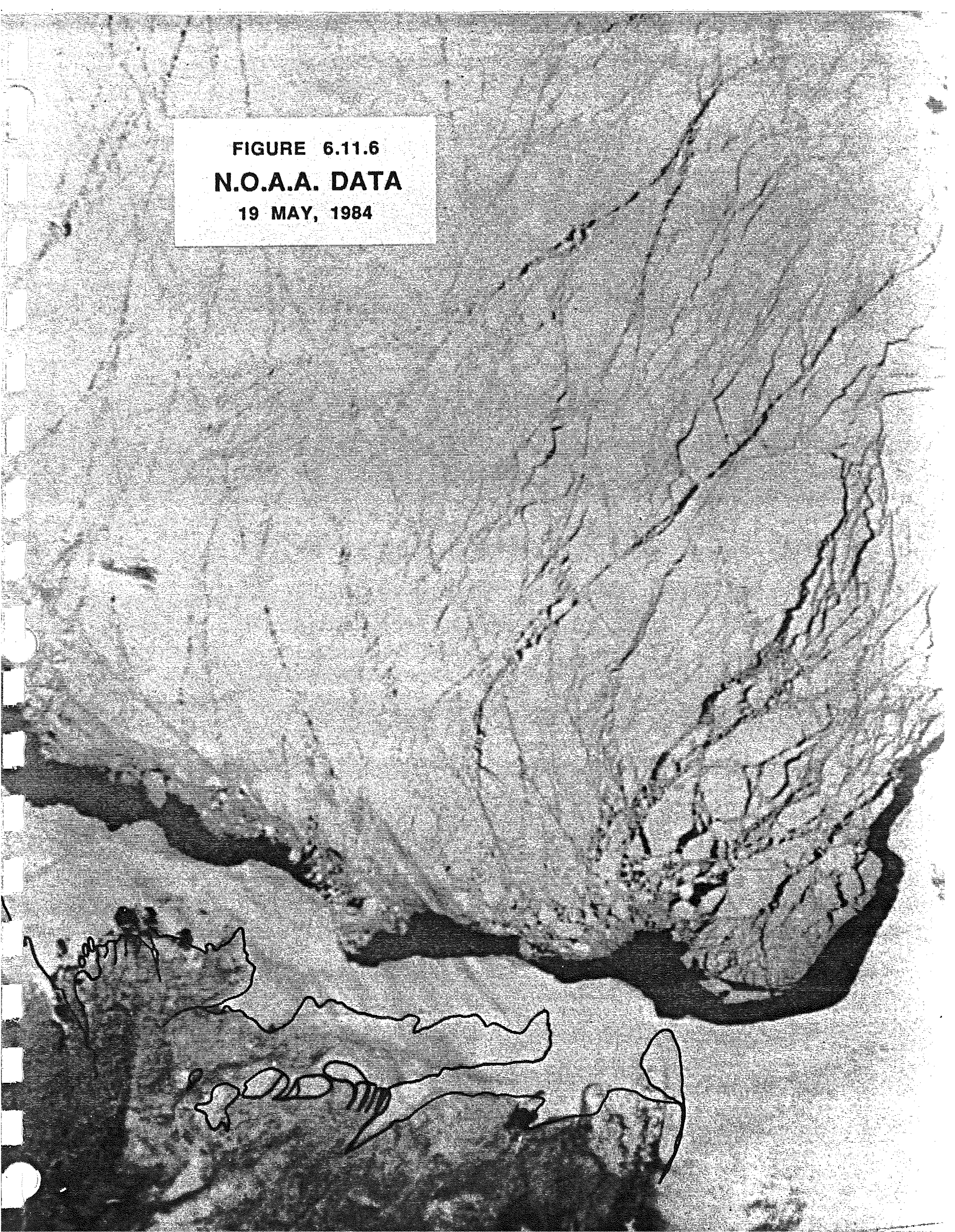
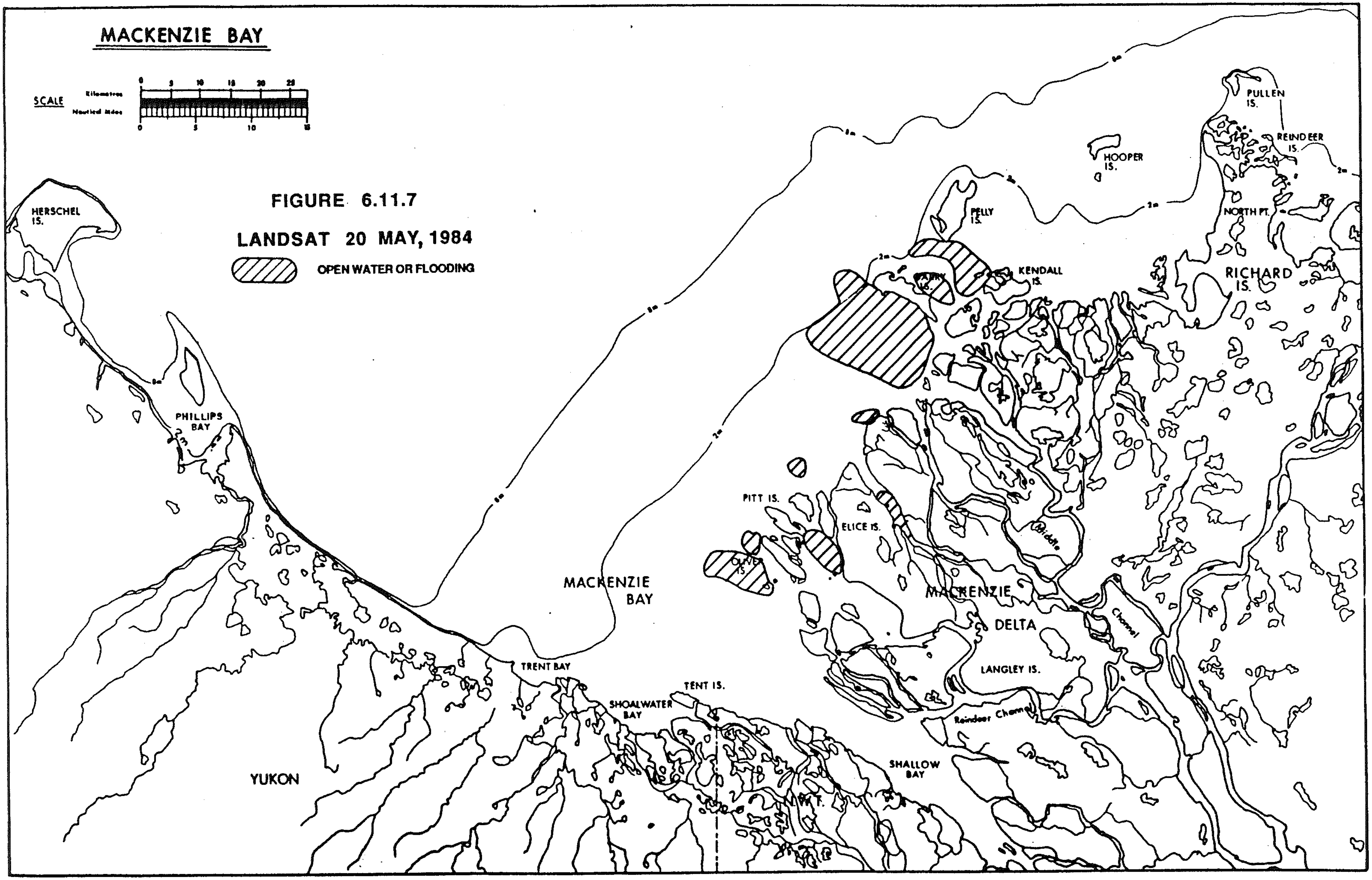
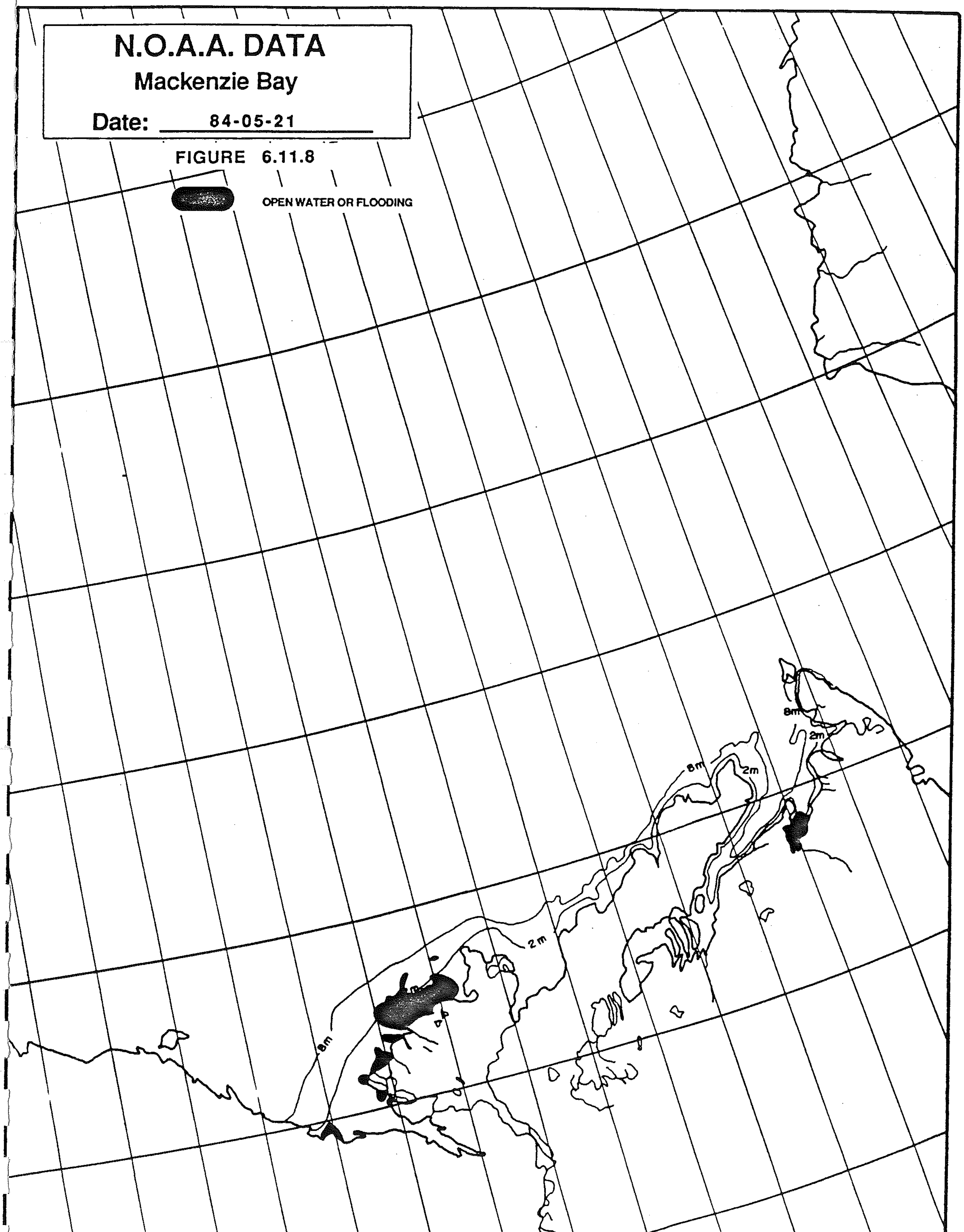


FIGURE 6.11.5

FIGURE 6.11.6
N.O.A.A. DATA
19 MAY, 1984




MACKENZIE BAY
SCALE
Kilometres
Nautical Miles
0 5 10 15 20 25
0 5 10 15
FIGURE 6.11.7
LANDSAT 20 MAY, 1984
OPEN WATER OR FLOODING
HERSCHEL IS.
PHILLIPS BAY
YUKON
TRENT BAY
SHOALWATER BAY
TENT IS.
MACKENZIE BAY
SHALLOW BAY
PITT IS.
ELICE IS.
MACKENZIE DELTA
LANGLEY IS.
Reindeer Channel
Channel
Middle
PELLY IS.
KENDALL IS.
HOOPER IS.
PULLEN IS.
REINDEER IS.
NORTH PT.
RICHARD IS.
2m
8m


N.O.A.A. DATA
Mackenzie Bay
Date: 84-05-21
FIGURE 6.11.8
OPEN WATER OR FLOODING
8m
2m
2m
8m
8m
2m

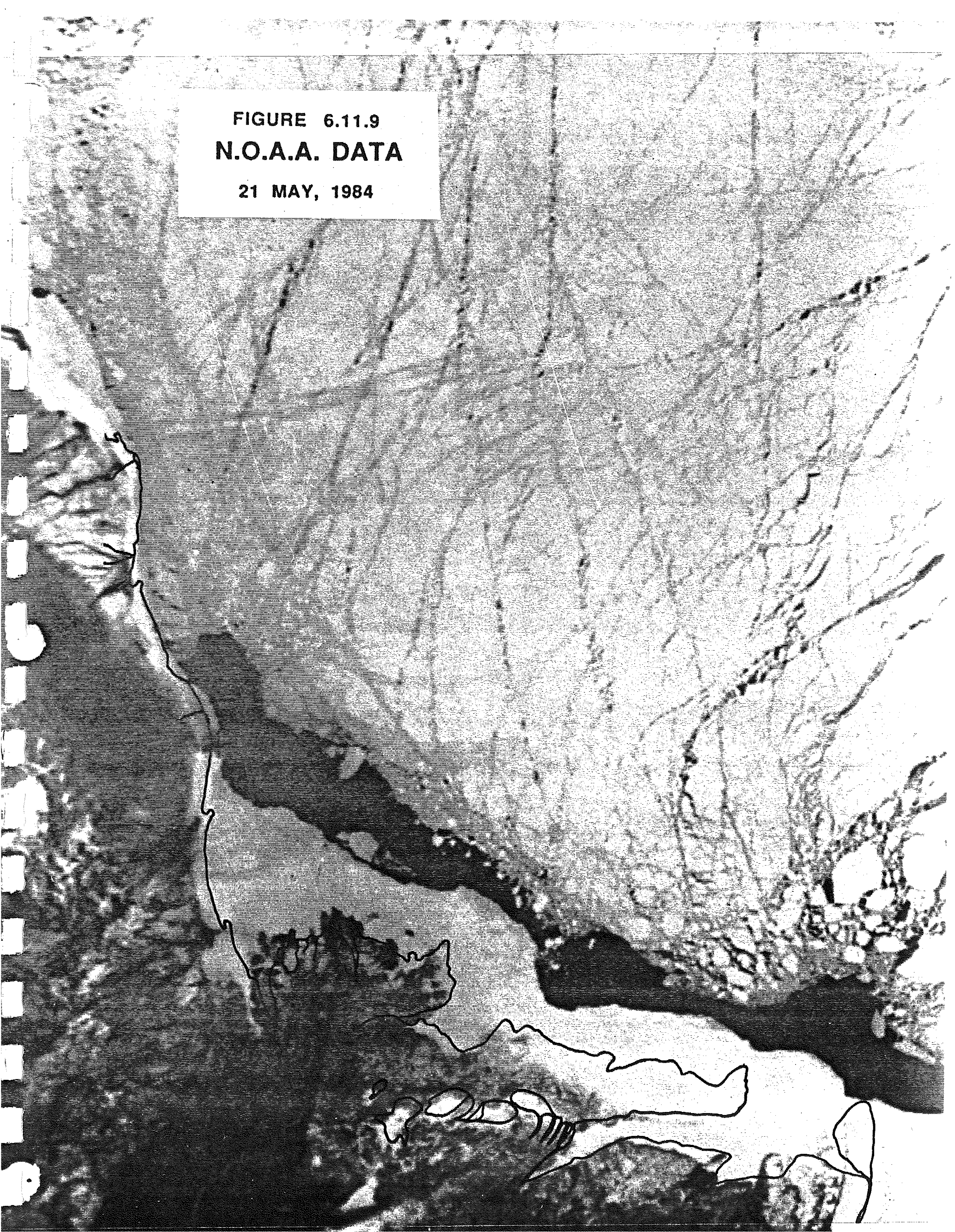


FIGURE 6.11.9
N.O.A.A. DATA
21 MAY, 1984

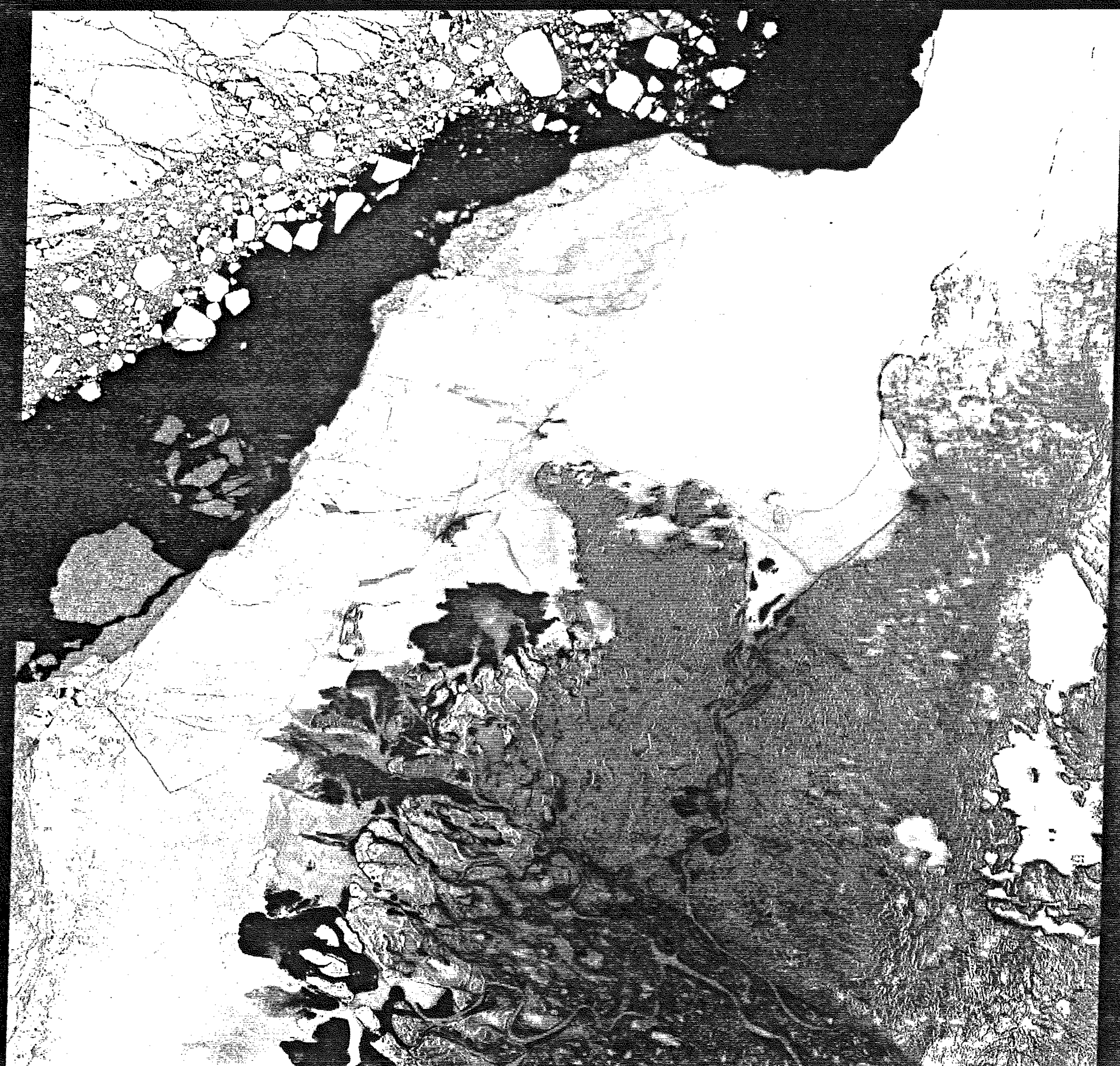


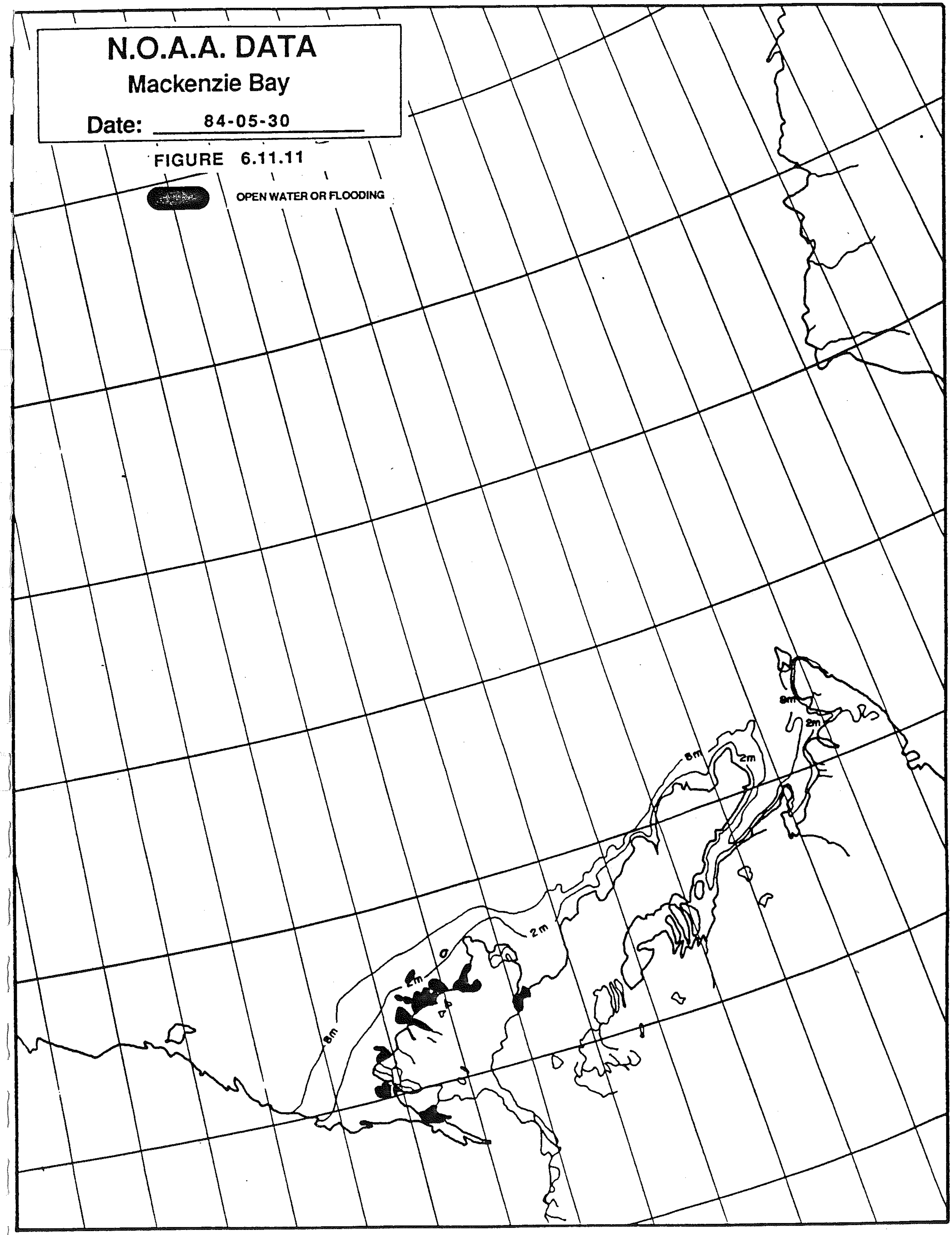
FIGURE 6.11.10 LANDSAT 22 MAY '84

N.O.A.A. DATA

Mackenzie Bay

Date: 84-05-30

FIGURE 6.11.11



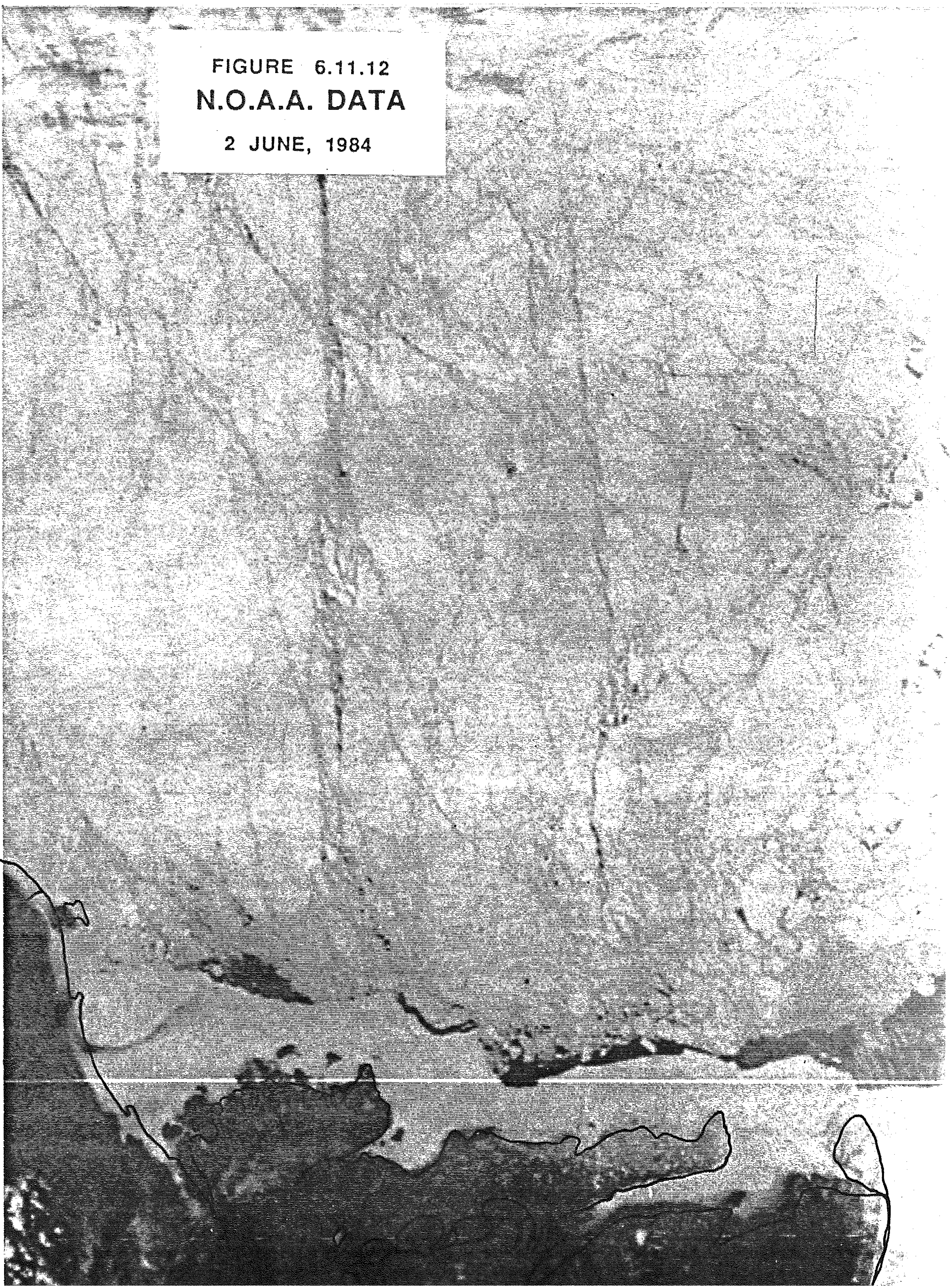


FIGURE 6.11.12

N.O.A.A. DATA

2 JUNE, 1984

FIGURE 6.11.13 LANDSAT 6 JUNE '84

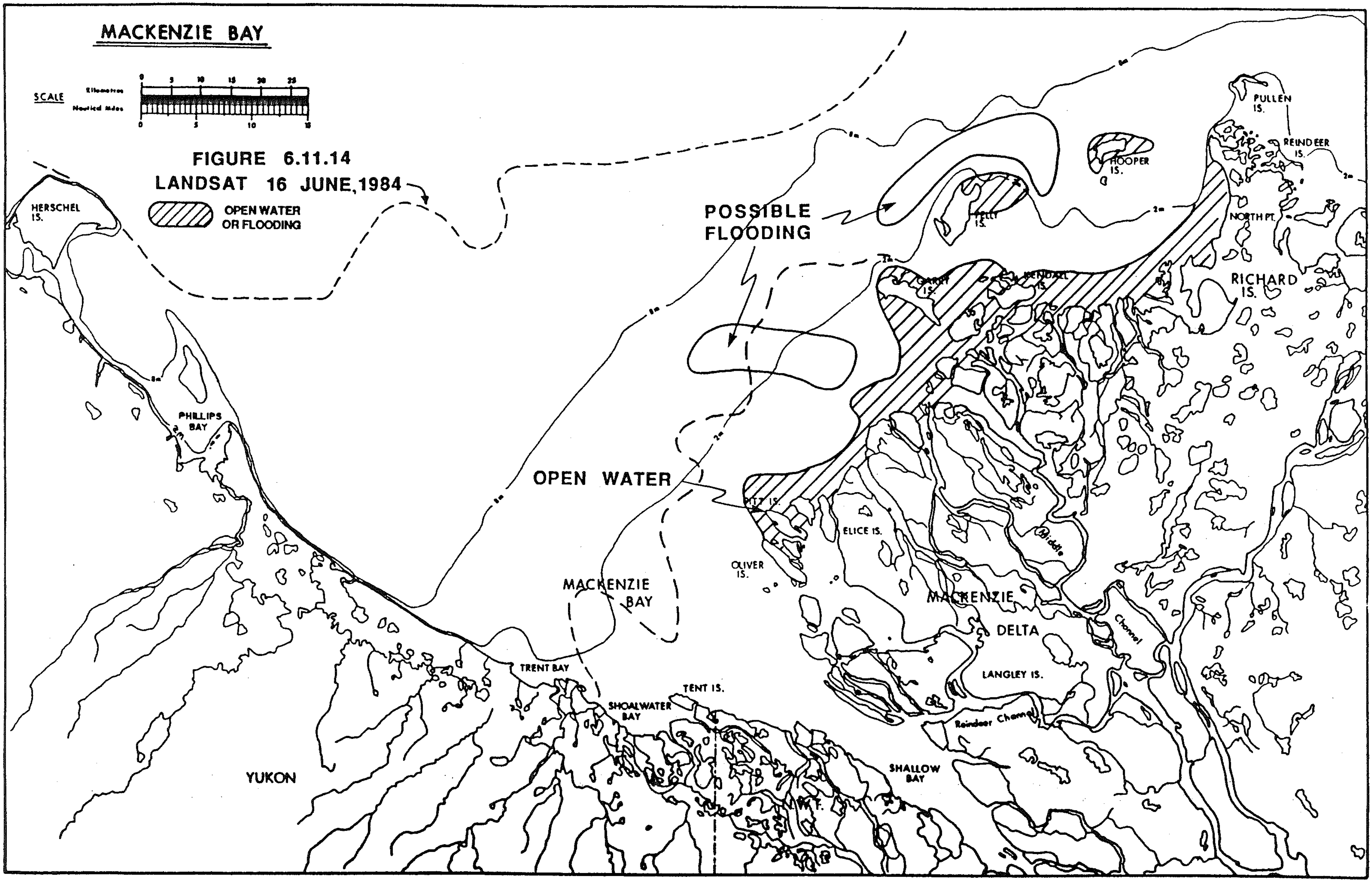


FIGURE 6.11.14
LANDSAT 16 JUNE, 1984

6.12 1985

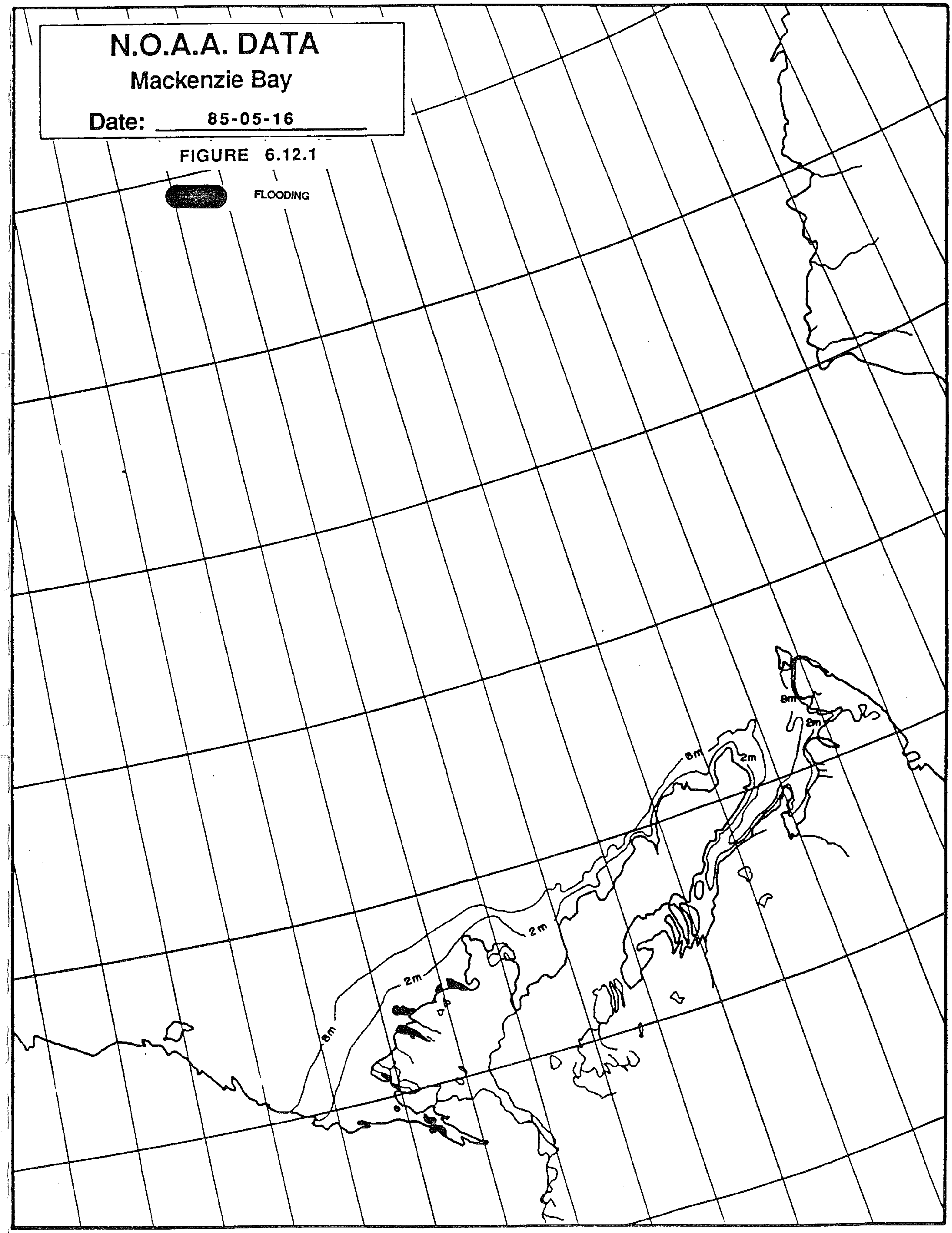
The NOAA data for May 16 shows flooding adjacent to Middle and Reindeer Channels. Figure 6.12.2 shows flooding around Olivier Islands with a tongue extending out of Middle Channel some 20 km. By May 31 there is open water extending about 5 km around the coastline, which slowly widens.

N.O.A.A. DATA

Mackenzie Bay

Date: 85-05-16

FIGURE 6.12.1



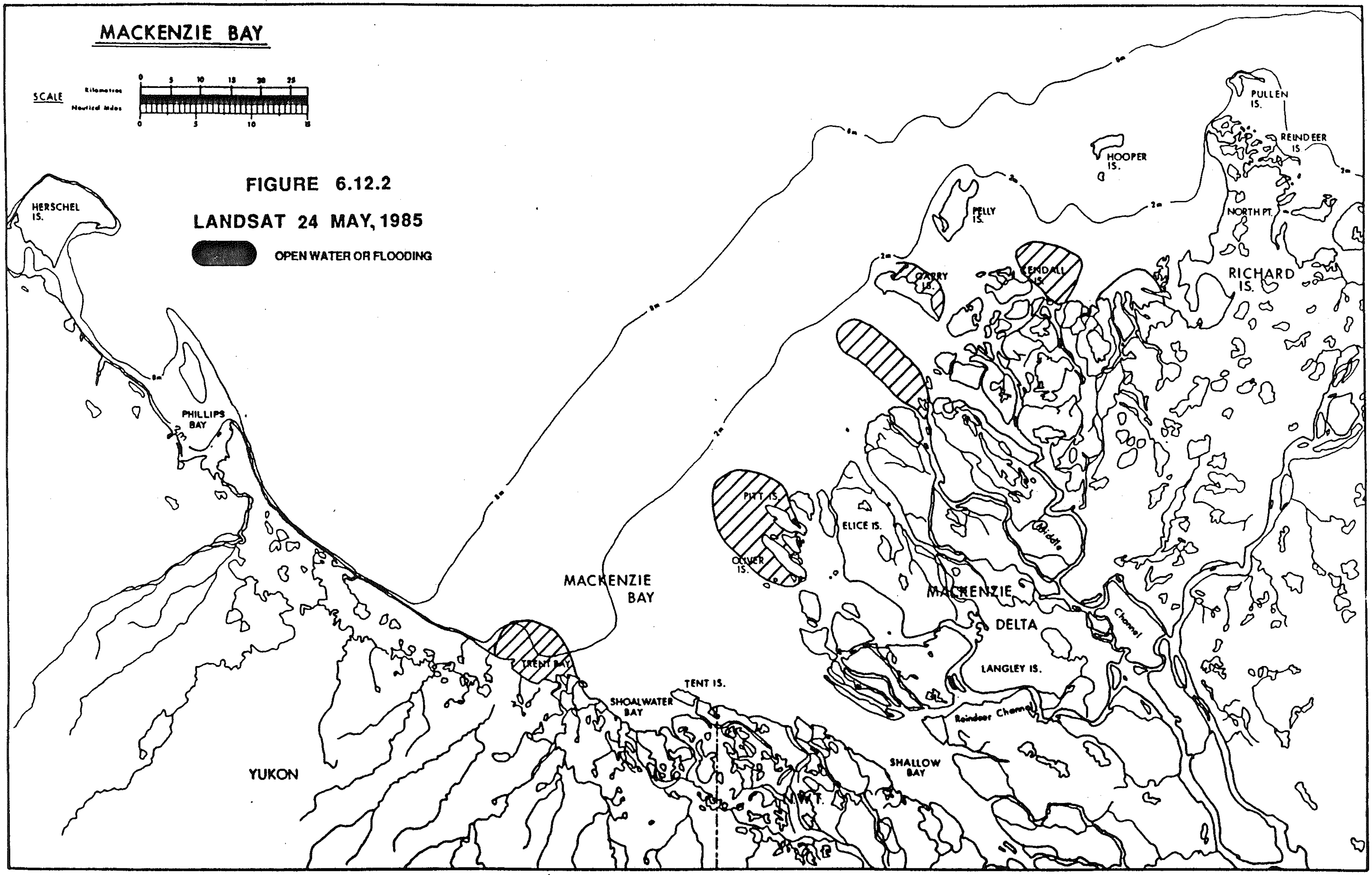
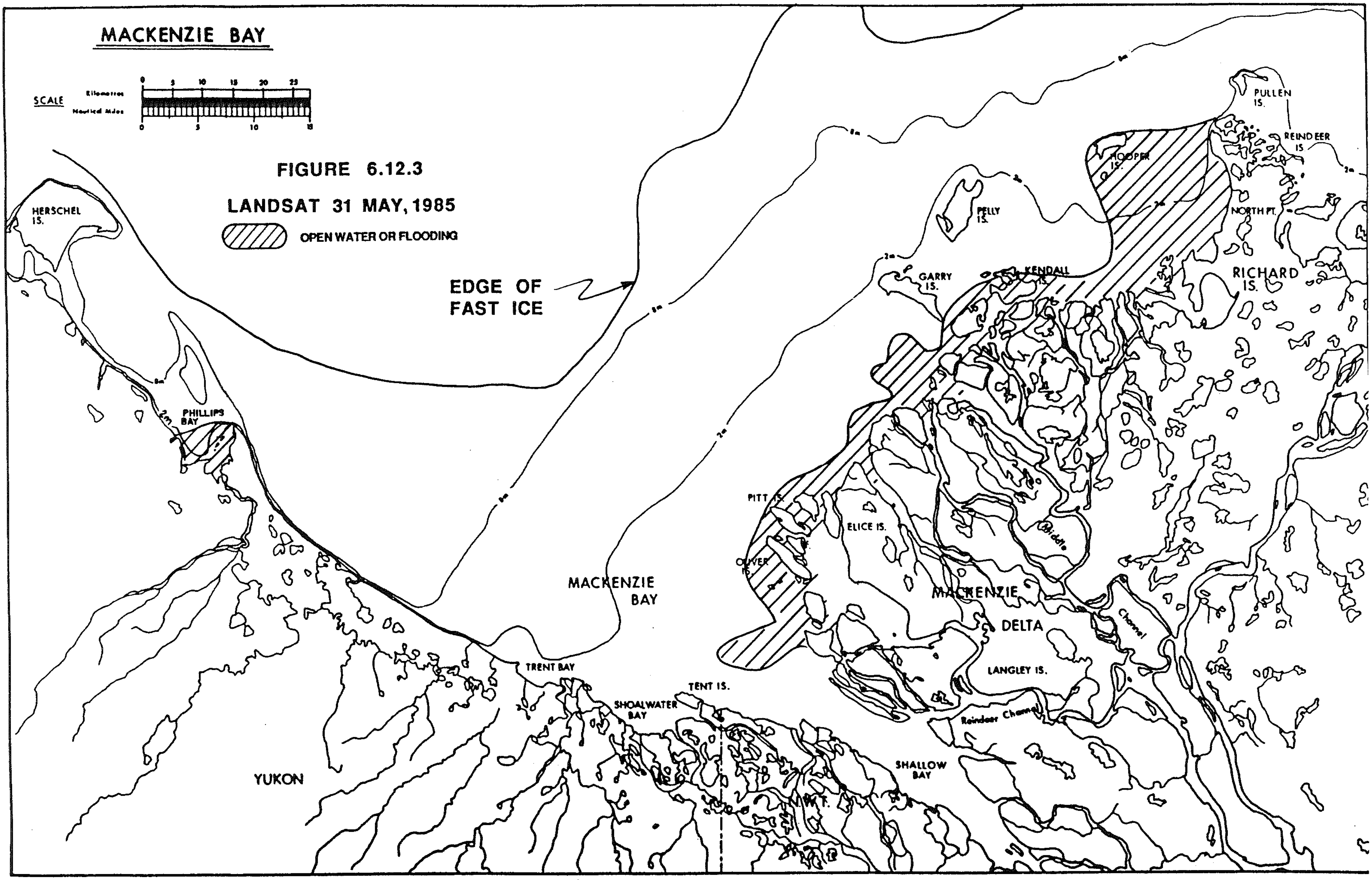


FIGURE 6.12.2

LANDSAT 24 MAY, 1985


MACKENZIE BAY
SCALE
Kilometres
Nautical Miles
0 5 10 15 20 25
0 5 10 15
FIGURE 6.12.3
LANDSAT 31 MAY, 1985
OPEN WATER OR FLOODING
EDGE OF FAST ICE
HERSCHEL IS.
PHILLIPS BAY
YUKON
TRENT BAY
MACKENZIE BAY
TENT IS.
SHOALWATER BAY
SHALLOW BAY
N.W.T.
PITT IS.
OLIVER IS.
ELICE IS.
GARRY IS.
KENDALL IS.
PELLY IS.
HOOPER IS.
PULLEN IS.
REINDEER IS.
NORTH PT.
RICHARD IS.
MACKENZIE DELTA
Middle
Channel
LANGLEY IS.
Reindeer Channel

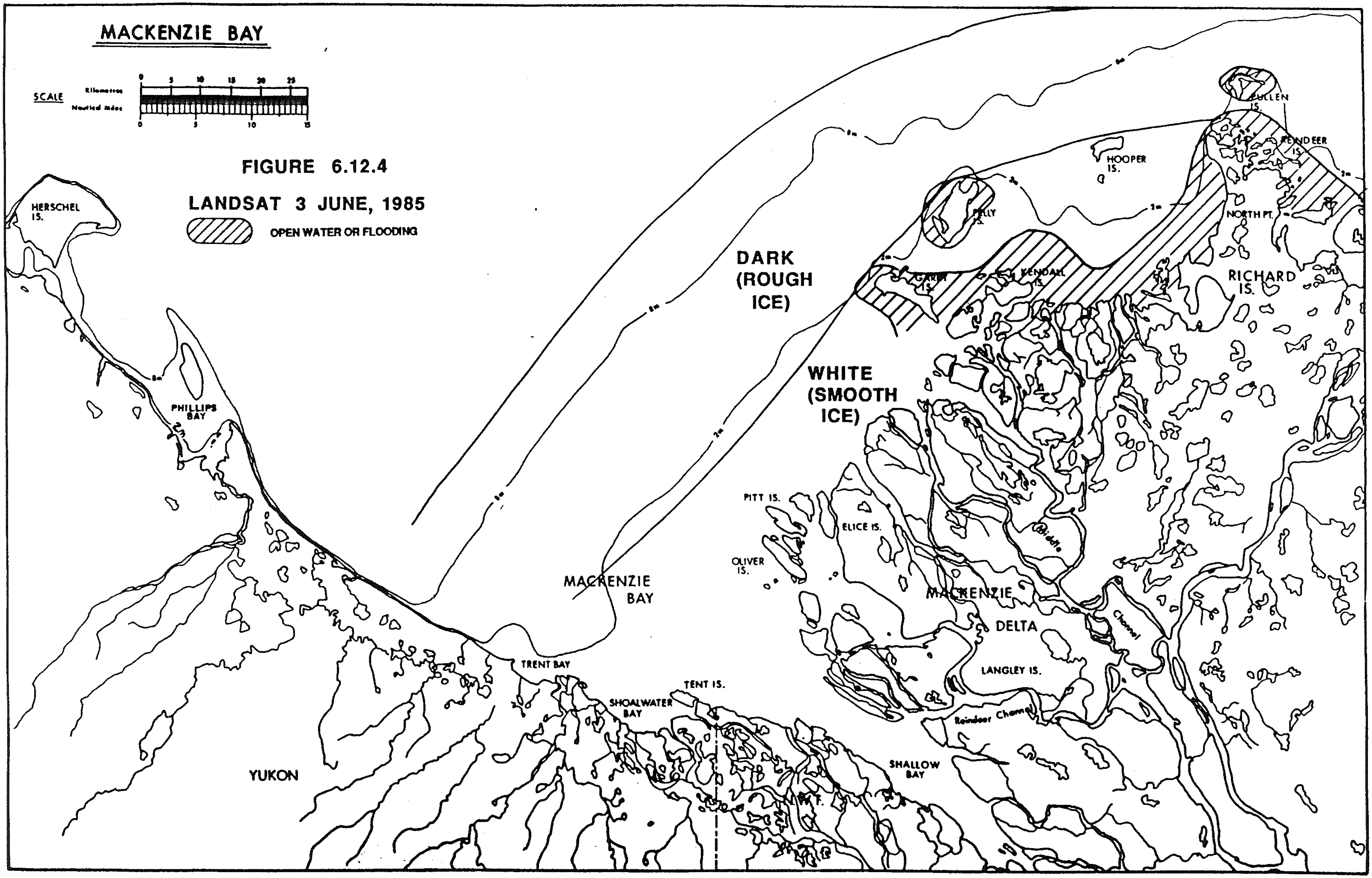


FIGURE 6.12.4

LANDSAT 3 JUNE, 1985

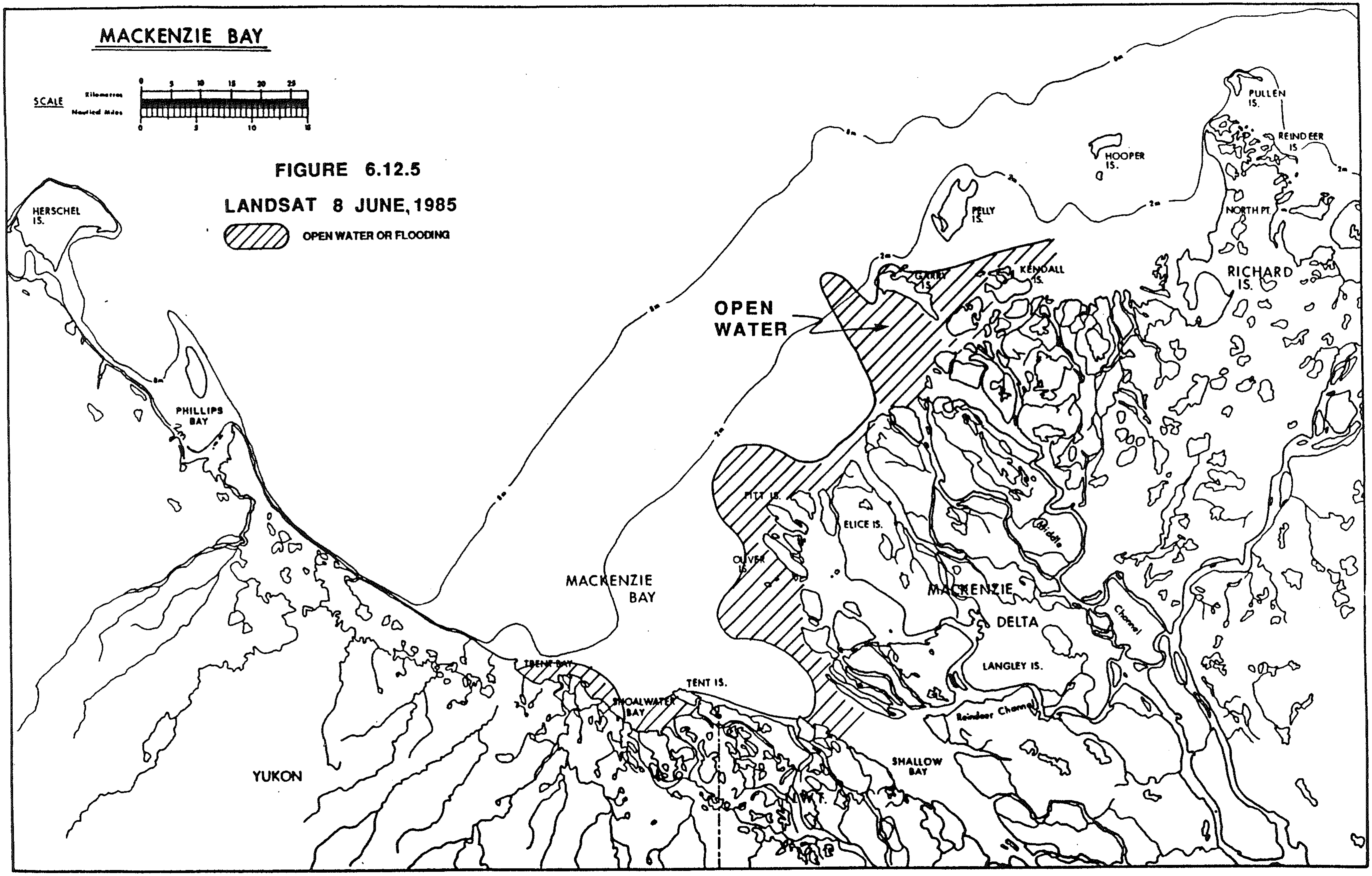
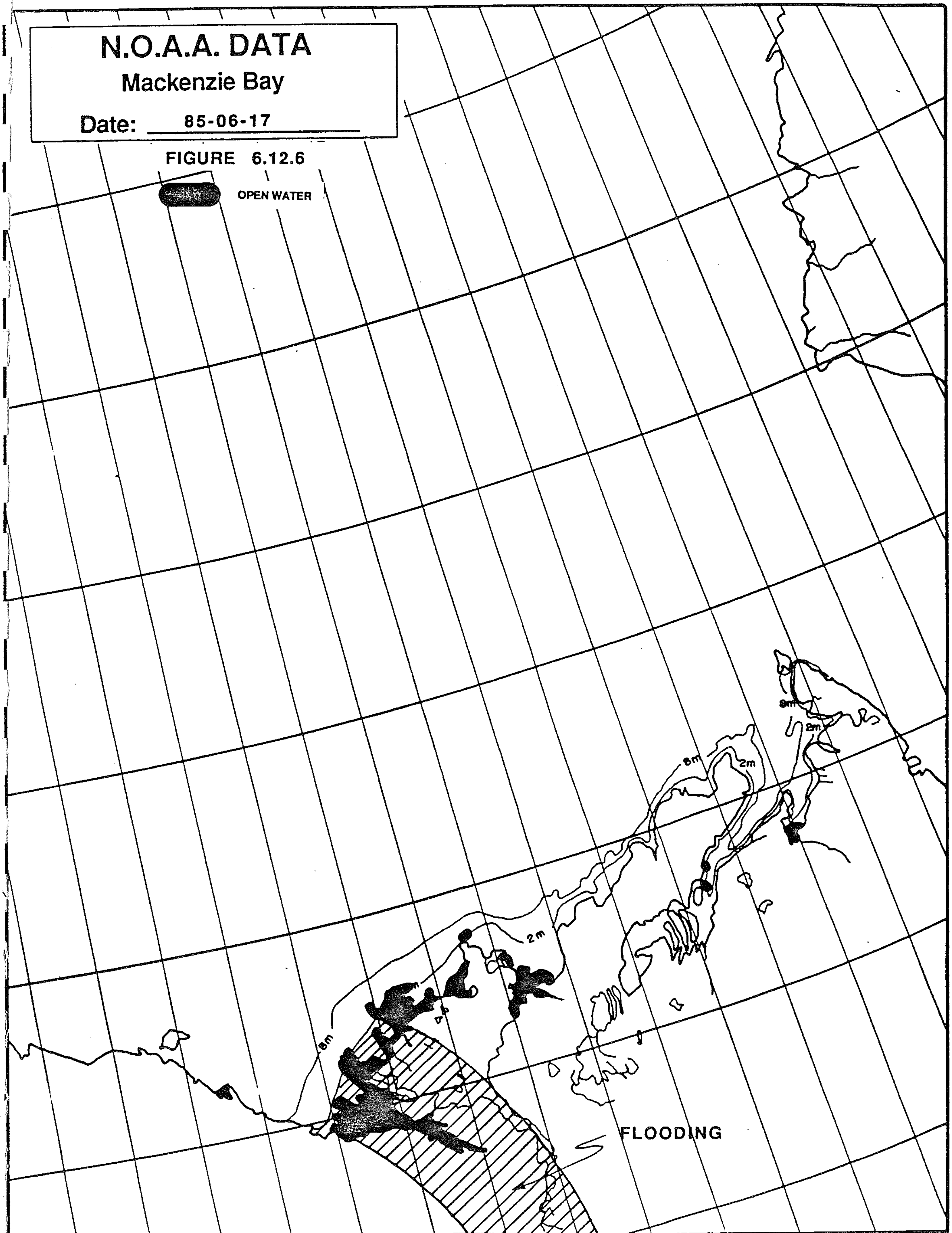


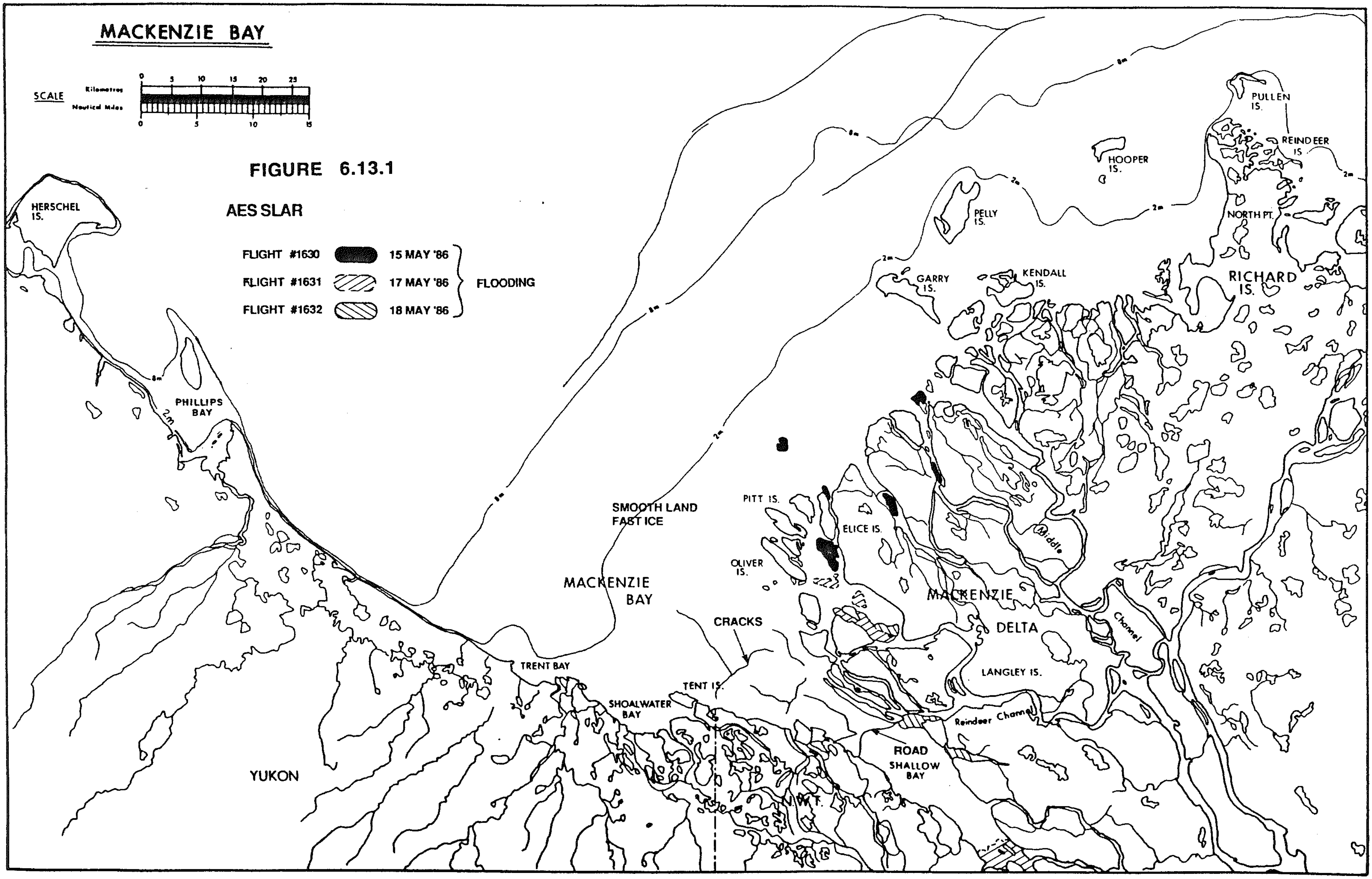
FIGURE 6.12.5

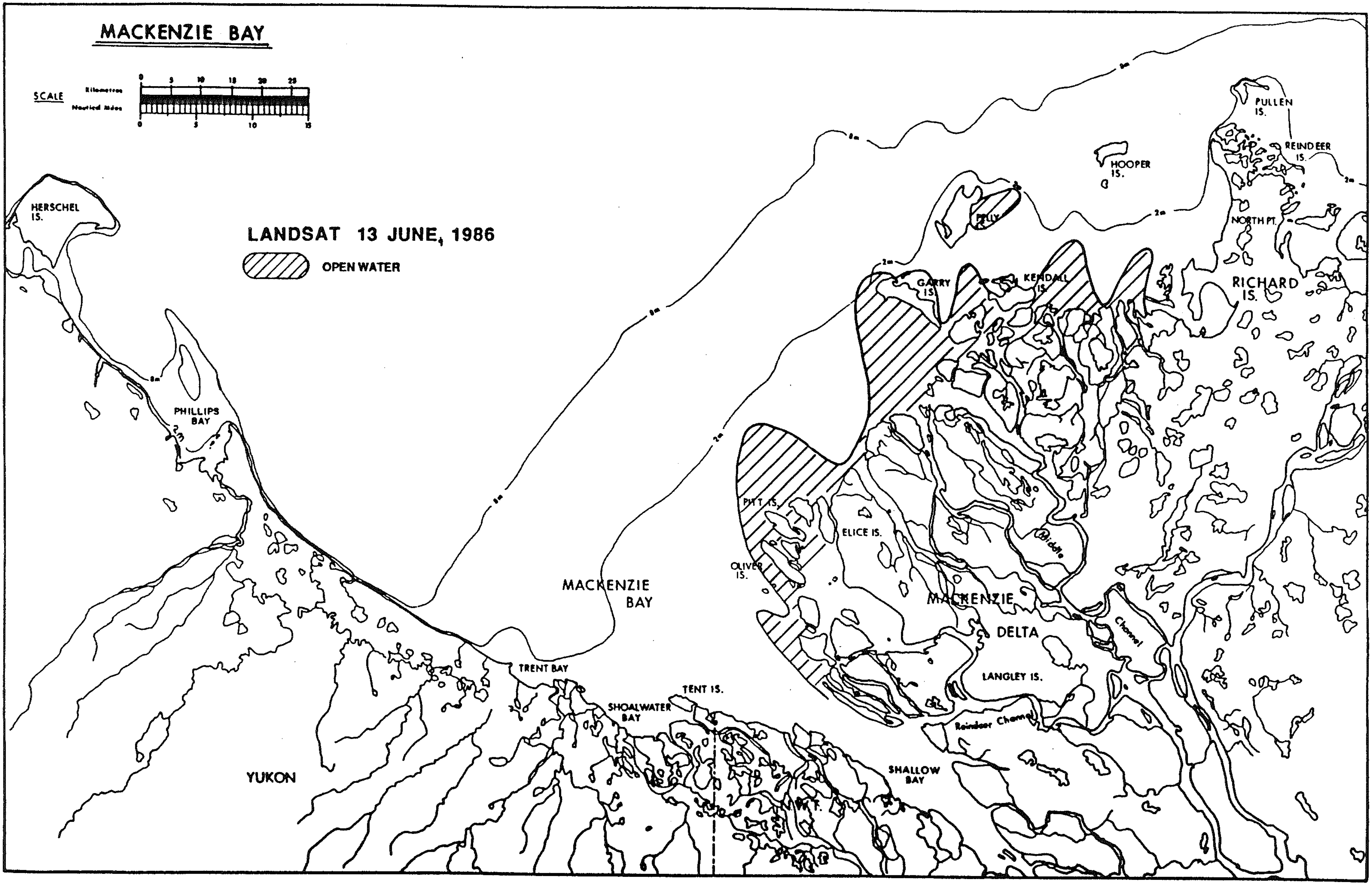
LANDSAT 8 JUNE, 1985


N.O.A.A. DATA
Mackenzie Bay
Date: 85-06-17
FIGURE 6.12.6
OPEN WATER
8m
2m
FLOODING

6.13 1986

SLAR data indicates dark patches on the ice in the channel mouths on May 15 to 18 (Figure 6.13.1). These are interpreted as being areas of flooding.


MACKENZIE BAY
SCALE
Kilometres
Nautical Miles
0 5 10 15 20 25
0 5 10 15
FIGURE 6.13.1
AES SLAR
FLIGHT #1630 15 MAY '86
FLIGHT #1631 17 MAY '86
FLIGHT #1632 18 MAY '86
FLOODING
HERSCHEL IS.
PHILLIPS BAY
2m
8m
PULLEN IS.
REINDEER IS.
HOOPER IS.
NORTH PT.
PELLY IS.
GARRY IS.
KENDALL IS.
RICHARD IS.
PITT IS.
ELICE IS.
OLIVER IS.
SMOOTH LAND FAST ICE
MACKENZIE BAY
CRACKS
MACKENZIE
DELTA
Middle
Channel
LANGLEY IS.
Reindeer Channel
ROAD
SHALLOW BAY
TRENT BAY
TENT IS.
SHOALWATER BAY
YUKON
N.W.T.

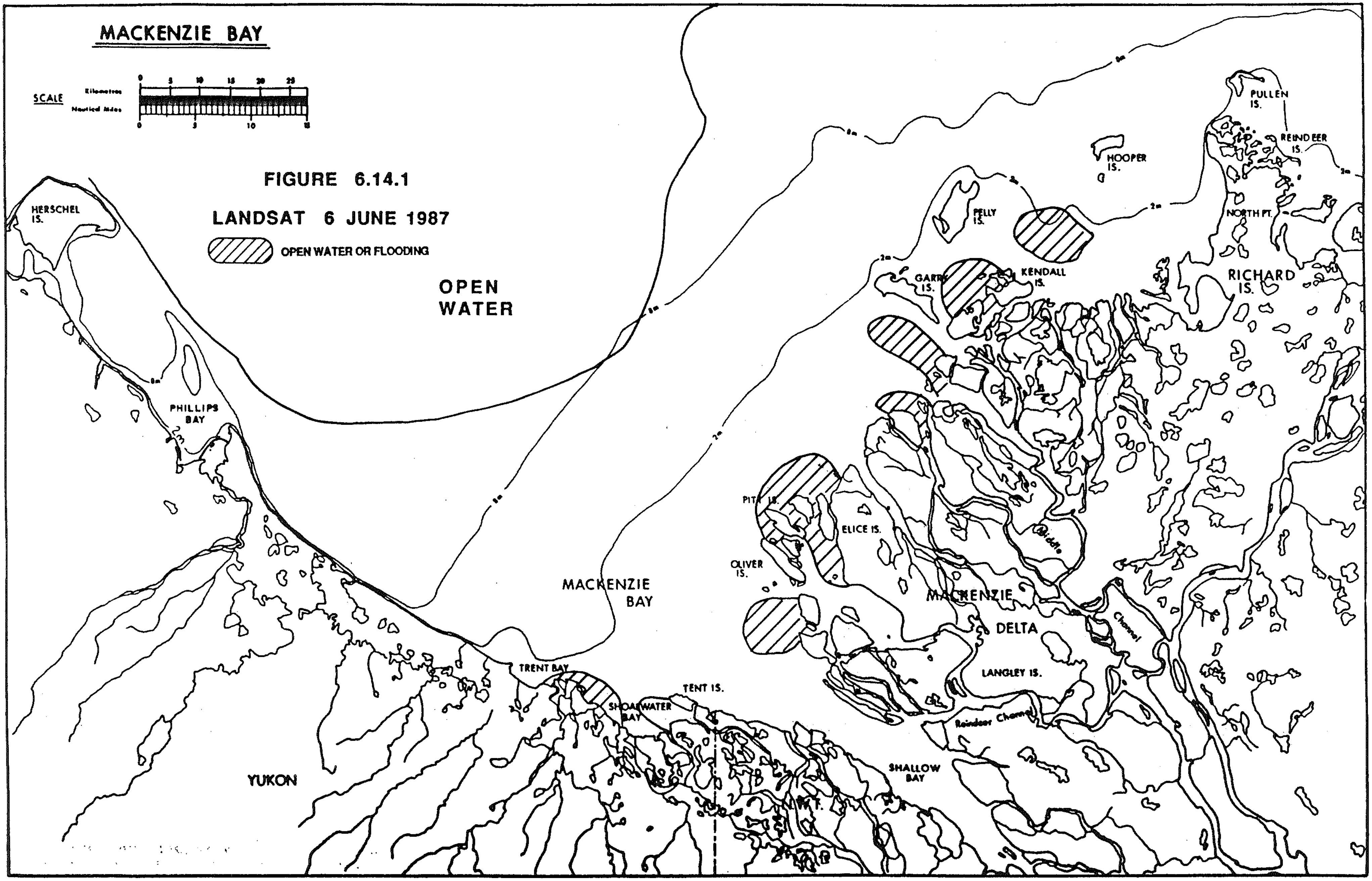


MACKENZIE BAY
SCALE
Kilometres
Nautical Miles
0 5 10 15 20 25
0 5 10 15
LANDSAT 13 JUNE, 1986
OPEN WATER
HERSCHEL IS.
PHILLIPS BAY
YUKON
TRENT BAY
MACKENZIE BAY
SHOALWATER BAY
TENT IS.
N.W.T.
SHALLOW BAY
PITT IS.
OLIVER IS.
ELICE IS.
MACKENZIE DELTA
LANGLEY IS.
Reindeer Channel
Middle
Channel
GARRY IS.
KENDALL IS.
PELLY
HOOPER IS.
PULLEN IS.
REINDEER IS.
NORTH PT.
RICHARD IS.
2m
8m

6.14 1987

On June 6, both LANDSAT and SLAR data show flooding or open water around Olivier and Pitt Islands, and adjacent to Middle and Harry Channels and near Kendall Island.

SLAR data for June 6 and 7 show flooding in Liverpool Bay adjacent to the Anderson and Mason Rivers. The black areas in the SLAR (Fig. 6.14.3) are interpreted as open water and the grey, speckled areas as flooding; the speckled appearance being caused by the rough ice surface penetrating in places above the flood water. Note the dry areas adjacent to major drainage channels, and also black dots in the flooded areas which might be strudel holes.



MACKENZIE BAY
SCALE
Kilometres
Nautical Miles
0
5
10
15
20
25
FIGURE 6.14.1
LANDSAT 6 JUNE 1987
OPEN WATER OR FLOODING
OPEN WATER
HERSCHEL IS.
PHILLIPS BAY
YUKON
TRENT BAY
SHOALWATER BAY
TENT IS.
N.W.T.
SHALLOW BAY
MACKENZIE BAY
OLIVER IS.
PITT IS.
ELICE IS.
MACKENZIE DELTA
LANGLEY IS.
Reindeer Channel
Channel
Middle
GARRY IS.
KENDALL IS.
PELLY IS.
HOOPER IS.
PULLEN IS.
REINDEER IS.
NORTH PT.
RICHARD IS.
2m
8m

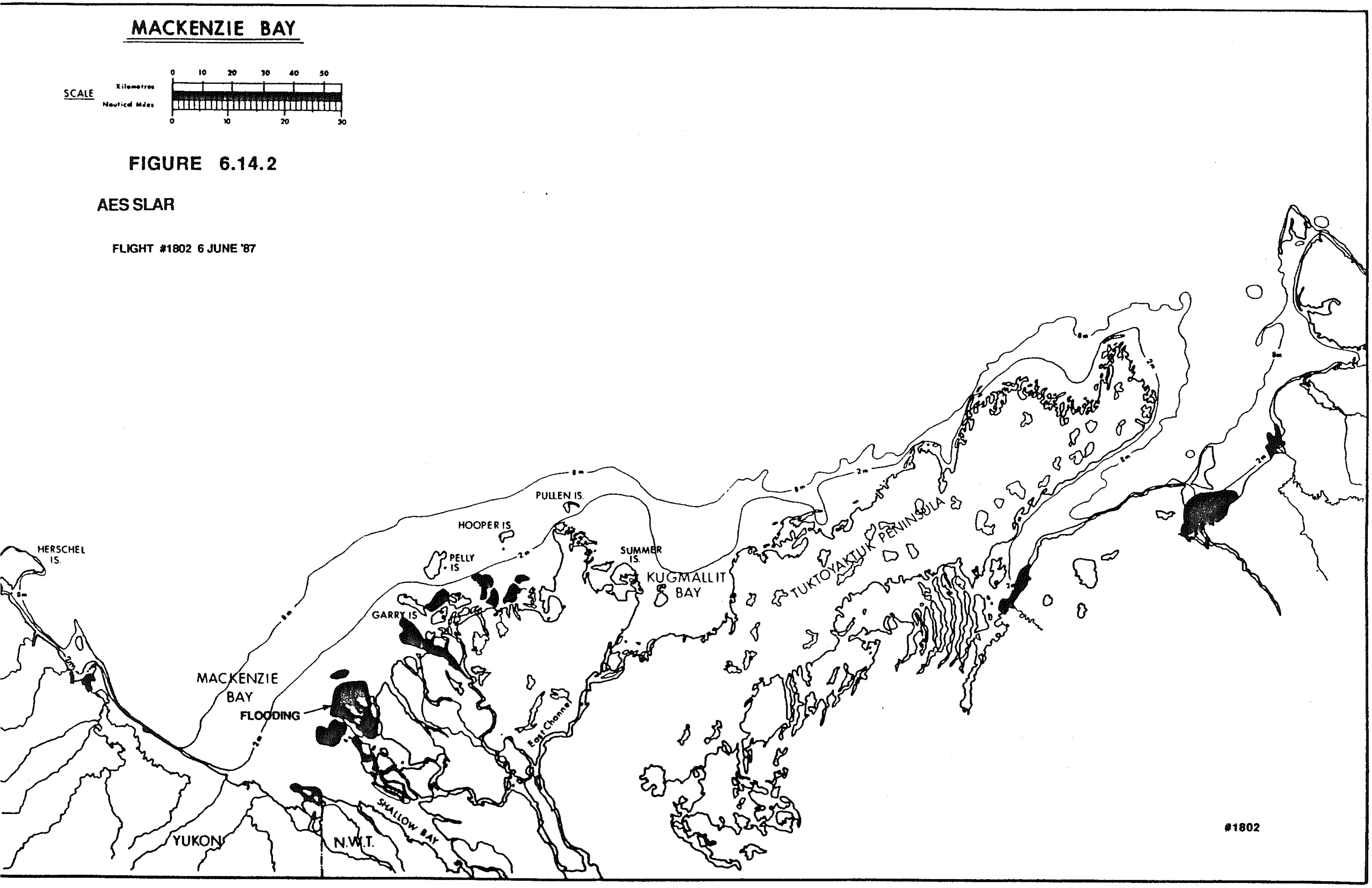


FIGURE 6.14.2

AES SLAR

FLIGHT #1802 6 JUNE '87

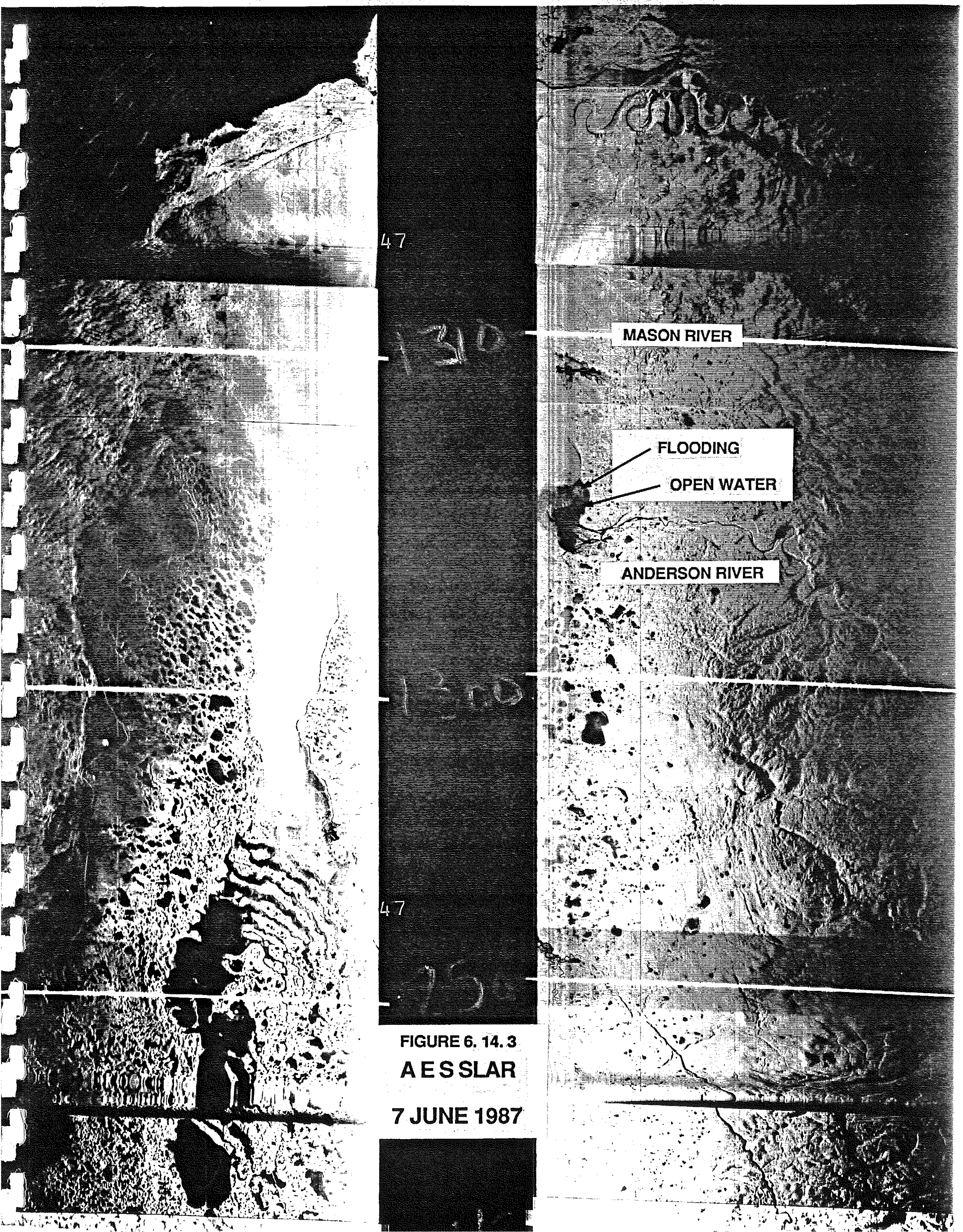


FIGURE 6. 14. 3
A E S SLAR
7 JUNE 1987

CHAPTER 7: IDENTIFICATION OF STRUDELS

Identifying actual strudel holes in the data used is very difficult due to the scale of the data as indicated below.

Data Type	Typical Scale	1km =	Size of Strudel Hole (30 m max)	Size of Drainage Channels (300m)
NOAA	$1:3 \times 10^6$	.3 mm	.07 mm	.1 mm
LANDSAT	$1:10^6$	1 mm	.03 mm	.3 mm
AES SLAR	$1:10^6$	1 mm	.03 mm	.3 mm
	$1:5 \times 10^5$	2 mm	.06 mm	.6 mm
Gulf/Dome SAR	$1:250 \times 10^3$	4 mm	.12 mm	1.2 mm

Only the large scale AES SLAR or Gulf/Dome SAR data would allow identification of strudel drainage channels.

Reference 1 indicates that strudels and drainage channels are best identified after the ice has drained, i.e., late May, very early June. There after, drainage holes and channels are most likely caused by the melting ice surface and snow, which would not have enough of a head to generate a vigorous strudel flow and the resulting scour in the seabed.

Figure 7.1 shows a section of Gulf/Dome STAR 001 data for the area between Olivier Islands and Beluga Bay. There is extensive open water along the coastline of Richards Island, particularly adjacent to the various river channels. Of particular interest are the black dots which may be strudel holes on the ice, although at this late date they could be surface melt holes from the melting ice and snow. A similar example was found for Phillips Bay for June 8, 1984, and Fig. 6.14.3 shows flooding and possible strudel holes by Anderson River in Liverpool Bay.

Of all the data examined, these were the only examples found showing "black dots" - possible strudels - on the ice cover; the SLAR data had marginal resolution for this project. Unfortunately one cannot say categorically that the black dots are indeed strudel holes.

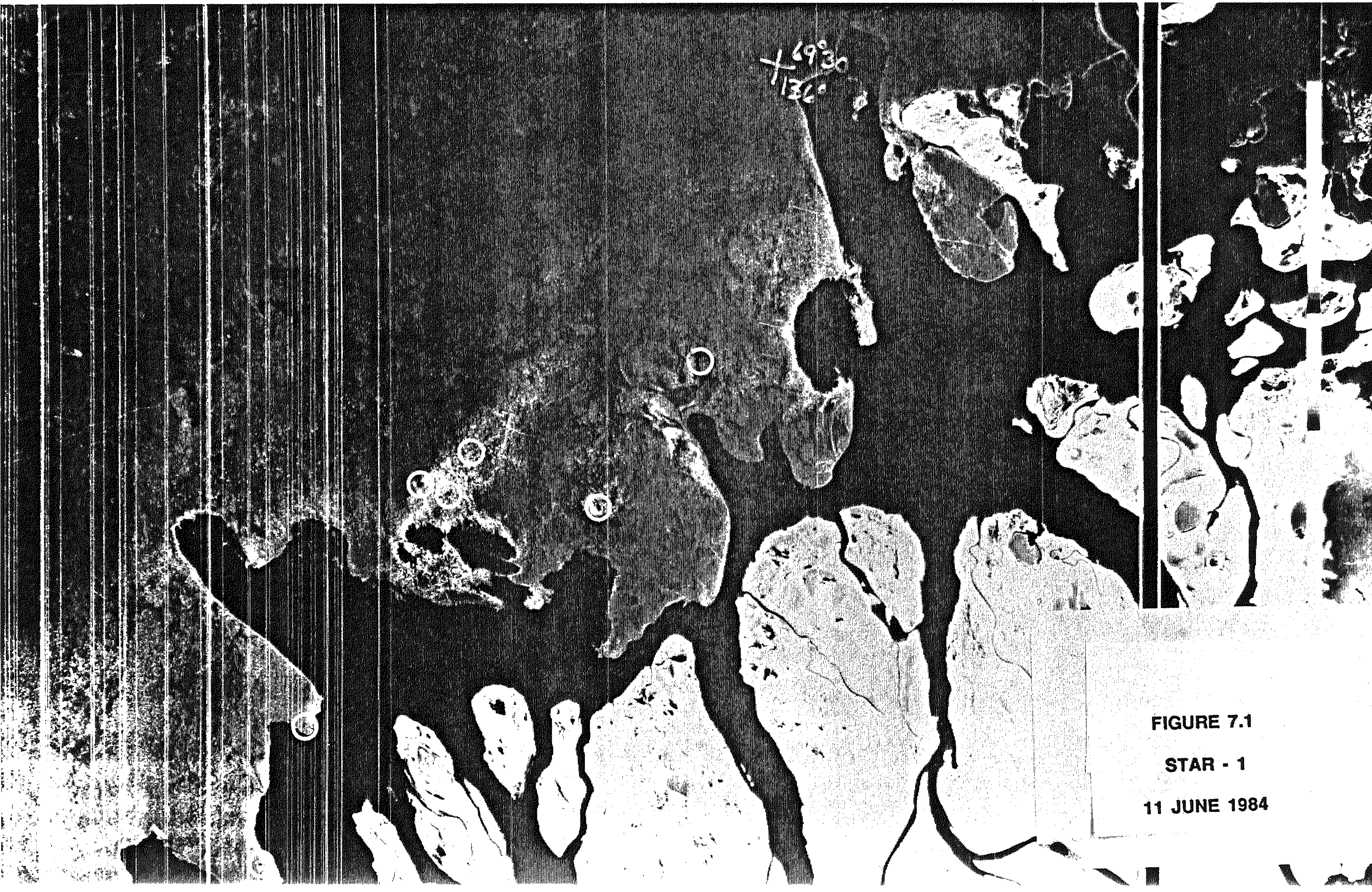


FIGURE 7.1

STAR - 1

11 JUNE 1984

CHAPTER 8: DISCUSSION

8.1 Chronology

The data examined shows extensive areas of water on the ice in the mouths of the river channels in early May. Based on the observations here and the Esso references, the following sequence of events is expected.

- Based on the 13 years of data reviewed, flooding is first noted in early May. The earliest evidence of on-ice flooding was noted on 6 April, 1974 in the various channels (Figure 6.2.1).

- As seen in Figure 8.1, flooding first occurs when the Mackenzie River is just starting to rise.

- The river water appears to flow down narrow deep water channels to specific regions along the shore. Generally flooding occurs out of the north exits of Reindeer Channel in the Olivier Islands, the west exit into Shallow Bay, Middle Channel and the 2 exits of Harry Channel.

- The water flowing down the deep (5 to 9 m deep) river channels is inhibited by the grounded and/or near-grounded shore fast ice in water depths of less than 2 m. The water possibly raises the ice and finds a crack which allows it to flow onto the ice surface. This flood water then weighs down the ice and so further restricts under-ice flow. According to Ref. 10, the flood water advances at rates of 0.6 to 5 km/day with an average of 2.2 km/day.

- Flooding occurs from the mouths of the river channels <u>normal</u> to the shoreline. No flooding (or open water) is observed <u>along</u> the coastline in mid to late May.

- From references and the data reviewed here, the spread of flood water is sometimes limited by the tidal crack. In fact for most of the years and areas analyzed, flooding appears to stop at about the 1.6 to 1.8 m water depth contour, which is where the tidal crack is expected to be.

- Five examples were found (9 June 1977, 15 May 1979, 10 June 1980, 21 May 1982, 25 May 1983) in which flooding extended beyond 2 m water depths. Other cases may have occurred but were not evident in the data reviewed. However, flooding beyond the 2 m water depth appears to be the exception rather than the rule in this area.

- Mid May to early June, lagoons are melted out to the 1.5 to 2 m water depths, giving the river water direct access to the ocean under the ice. The flood water drains off the ice by late May or early June.

- In early June there was evidence of flooding at the Anderson and Mason Rivers in Liverpool Bay.

- By early June there is extensive open water <u>along</u> the coast of Richards Island. This open water region extends rapidly, mainly adjacent to river channels, until by about the third week of June, only a narrow ice bridge of landfast ice exists. The river flow eventually cuts through the bridge and the remaining landfast ice drifts away with offshore winds.

8.2 Extent of Flooding

Reference 10 and one example shown here indicates that the flooding sometimes went as far as the tidal crack on the edge of the grounded ice, being dammed to the north of this crack by a small shear ridge. Water poured down the tidal crack like "Niagara Falls" (G. Spedding-private communications). It is not known whether this water fall would have the potential to scour the seabed, however, it is worth investigating. Note that the water would probably not form a vortex or strudel as it flowed down the tidal crack, so this would not be a "strudel scour". However, any scouring at the tidal crack would be of importance because of its' lateral extent (from Shallow Bay to Harry Channel) as it would certainly cross any pipeline running to shore.

It would appear that the flooding in the Mackenzie Bay rarely extends beyond the 2 m water depth and out to 30 km as appears to occur off Alaska; note only 2 or 3 reports of flooding extending out to this distance are presented in the literature for Alaska. Extensive offshore flooding, when it occurs, is adjacent to the north channel of Reindeer Channel seaward of Olivier Islands and Middle Channel. Flooding around Harry Channel never extended far offshore in the examples reviewed, presumably due to limited river water in this channel.

The one clear example presented here which shows the flooding terminating at the tidal crack, also shows flooding simultaneously extending beyond the tidal crack to considerable distances in the form of narrow fingers of water. Although several good examples of flooding were evident in the LANDSAT data provided, this is only one example of flooding terminating at the tidal crack as far as one can see. However, in most cases, flooding appears to stop at the 1.6 to 1.8 m water depth, which is where the tidal crack would be expected to be.

G. Spedding (private communications) indicated that he has never seen strudel holes on the ice similar to those reported off the north coast of Alaska. This was felt to be partly due to the fact that most if not all of the flooded area is on grounded ice (less than 2 m contour), and also the warm river water melts out under the ice much faster than does the cold water off the north coast of Alaska and Phillips Bay, with the result that flooding does not last as long in the Mackenzie Bay area. It is also possible that Spedding never observed the flooding in water depths beyond the tidal crack due to the limited extent of this flooding and its' infrequent occurrence.

8.3 Area of Potential Strudel Scouring

Whether strudel scours occur or not, they only occur in regions where the river floods onto the ice in the spring. The data in Chapter 6 shows areas of flooding prior to the end of May for most years. After this time the dark areas around the coast are believed to be open water. As shown, flooding occurs along most of the NW shore of Richard Island out to about 15 km from shore from Shallow Bay to south of Hooper Island. No flooding is evident around North Point or along the Tuk Peninsula because of the lack of rivers in these areas. Some flooding occurs in Kugmallit Bay, but this tends not to be too significant. Also flooding is evident in Liverpool Bay (Anderson and Mason Rivers) and Phillips Bay. In fact, Phillips Bay is the only location where a strudel and strudel scour have been observed (Ref. 6).

Most years the flooding does not extend beyond 2 m water depths and hence is over grounded ice. No strudels would be expected in grounded ice due to the restriction to under-ice water flow. Occasionally (about 30% of years based on the analysis here) flooding extends out about 30 km seaward of the Reindeer and Middle Channels into water depths beyond 2 m. These restricted areas would be areas of potential strudel scouring. As the flood waters subside, the grounded ice lifts off the seabed and it appears that at this time strudels are observed in water depths down to 1.4 m off the Alaska Coast. Thus one should look for strudels in the Mackenzie Bay area in late May as the flood water is subsiding in water depths down to about 1.4 m.

8.4 Implication for Pipelines

If a strudel scour occurred over a pipeline on the sea floor, it could result in a loss of foundation of the pipeline and possible pipeline failure. As indicated above, the potential zones of scouring are limited in the Mackenzie Bay areas seaward of the major river channels; any pipeline to the area west of Beluga Bay would not be affected.

Using the scour dimensions and frequencies given for the US Beaufort, we can calculate the approximate probability of a strudel scour occurring over a pipeline. Assuming 2.5 strudels per square km (Ref 3), and that the average scour diameter is 10 m, then the probability of a scour hitting a pipeline is

$$2.5 * 10 / 1000 = .025 \text{ per km of pipeline per year.}$$

If the zone of scouring is 10 km wide, the probability of a scour occurring over the pipe is 22 % or once in 4.5 years. This is an unacceptable level of risk.

Assuming, as we must, that strudel scours do occur in the Mackenzie Bay, and that the pipeline passes though the strudel region, then remedial action must be taken. Some possible solutions are:-

- checking to see if the standard pipeline or a thicker walled pipe will span the maximum probable scour.
- rerouting the pipeline away from the strudel zones; this is unlikely to be a viable solution.
- covering the pipeline with several metres of gravel (it is assumed that the pipe will be in a trench to avoid ice scours.

The three possible solutions suggested are all expensive and so further work in this area is warranted.

CHAPTER 9: CONCLUSIONS

Based on a review of references and remote sensing data the following summary and conclusions are presented.

i) In late April or early May the Mackenzie River starts to rise, lifting the ice in the channels.

ii) The river water cannot flow under the grounded, or near grounded coastal ice so the water floods over the ice surface at the mouths of the Mackenzie River channels in early May (sometimes in late April), presumably depressing the ice and further restricting under-ice flow. Flooding generally occurs first at the mouths of the Middle and Reindeer Channels and in Shallow Bay, and these flooded areas are generally normal to the shoreline.

iii) By mid-May flooding extends 15 to 20 km from shore adjacent to the main channels, particularly around the Middle channel, Olivier Islands, in Shallow Bay, and Harry channel. The flood water appears to be limited by and flow down tidal cracks. Small Shear ridges at the tidal cracks appear to inhibit the flood water's further outward progress (Ref. 16). There are five examples in the 14 years of data reveived here which show evidence of the flood water progressing well beyond the tidal crack.

iv) The flood water on the ice has been measured up to 90 cm deep off the Alaska coast; similar depths have been observed in the Mackenzie Bay (Ref. 16).

v) By late May, the ice has melted lagoons out to the 1.5 to 2 m water depths, allowing the river water direct access to the ocean under the ice. By this time considerable melting is also evident along the coast.

vi) During the last week of May, or early June, once the melt lagoons have become established, the flood water drains off the ice and by early to mid June the ice has generally drained.

vii) The lagoons rapidly melt longer and wider, and eventually by mid-June there is open water along the entire coast of Richards Island.

viii) There is minimal flooding in Kugmallit Bay probably for 2 reasons. Firstly there is a deep channel which allows the flood water access to the sea below the coastal fast ice and secondly, less water flows down the Kittigazuit Channel.

ix) Flooding occurs at the mouths of the Anderson and Mason rivers in Liverpool Bay in mid to late May and in Phillips Bay in early June.

x) Melting of the coastal ice continues out to about the 4.5 to 6 m water depth by late June. This thawing of the fast ice from shore due to river water and the slow breaking away of the seaward edge of the fast ice, leaves a narrow strip of landfast ice along the coast. In early July, the river water cuts a channel through the ice strip causing the rest of the ice to drift offshore.

xi) Observers (L.G. Spedding and D.F. Dickins - private communications) report that they have not seen well formed strudel holes in the ice off Richards Island, as reported by the U.S. observers off Alaska. Dickins reported a strudel in Phillips Bay and verified that it did in fact cause a scour.

xii) Spedding has been suggested (Ref. 16) that warm Mackenzie river water may cause a more rapid undercutting of the ice than occurs off Alaska and in Phillips Bay. However, even in the Mackenzie Bay, the flood water appears to reside on the ice for about 2 weeks.

xiii) The majority of the flooding off Richards Island is over grounded or near grounded ice in water depths of less than 2 m. Strudels would not be expected in grounded ice, due to the restriction to water flow away from the strudel hole below the ice. However, strudels have been observed off the Alaska coast down to water depths of 1.4 m as the flood waters are subsiding and the ice lifts off the sea bed. Thus one should look for strudels in the Mackenzie Bay area in late May in water depths down to 1.4 m.

xiv) In some years, the flooding extends out to about 30 km from shore adjacent to the north arm of the Reindeer and the Middle channel (see figure 6.10.3 for example). The area of this flooding beyond the 2m water depth is a likely area of strudels and strudel scouring.

xv) An attempt has been made to identify strudels in the remotely sensed data after the flooding has drained. Due to the scale of the data, only the SLAR and SAR could be used for this purpose and even here the resolution is marginal. However, numerous black dots and lines have been identified on the ice surface, but whether these are remnant strudels or simply melt holes from melting snow and ice is not known.

xvi) There is no flooding and hence no potential for strudel scouring at North Point or along the Tuktoyaktuk Peninsula as there are no rivers in these areas.

xvii) Sediments on the seafloor of the Mackenzie Bay would scour easily in some areas (of loose to very loose silt or soft clays), or not at all (firm clays, sands and gravels). Also the loose silts would fill in very rapidly from wave action and river sediment transport in the shallow waters.

xviii) In water depths of less than 2 m the ice freezes to the seafloor causing ice to form in the seafloor sediments. Observations (Ref. 18) indicate that the ground is not solidly frozen but contains occasional ice crystals. This would not be a significant impediment to strudel scouring. Beyond the 2m water depth, no freezing of the seabed is expected.

ACKNOWLEDGEMENTS

We would like to acknowledge the assistance provided by numerous individuals and organizations.

Dave Mudry and Phil Cody provided guidance and assistance at AES in Ottawa while we were reviewing the AES SLAR data.

The Satellite Receiving Station in Prince Albert provided invaluable assistance when we reviewed the LANDSAT data.

Gulf Canada kindly allowed us to review their SLAR/SAR aerial photographs and NOAA data. Dome Petroleum allowed us to review and copy SAR and Landsat data.

Esso (Geoff Spedding) allowed us to review and abstract a number of reports in their library. Geoff Spedding also provided useful advice and discussions.

Chris Hill kindly provided his collection of 1980 and 1981 NOAA data for review.

The scientific Authority, Phil Hill, provided extremely valuable comments and suggestions.

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APPENDIX A

Literature Review

1. **River Discharge into an Ice-Covered Ocean and Related Sediment Dispersal, Beaufort Sea, Coast of Alaska.**
Erle Reimnitz and Karl F. Bruder
Geological Society of America Bulletin, V.83, p.861-866, March 1972.

Reconnaissance observations were made along the Beaufort Sea Coast of Alaska in 1970 during a 4 week period after initiation of river flow into the ice covered ocean (May 29 to June 23). Main points are as follows:

1. during first few days following river breakup, the fast ice was inundated by fresh water overflow,
2. water flooded up to 10km from shore,
3. water drained through widely distributed drain holes in ice, which created scour depressions in the sea bottom,
4. when ice had thawed out to beyond the 2m water depth, the river water flowed directly into the open water area under the ice,
5 the fast ice extending down to or near to the seabed greatly restricts river outflow, causing the water to flood onto the ice.
6. major part of the river flooding occurred during a 13 day period in June,
7. the advancing water moved at 2 to 3m per second.
8. water depths on the ice were between 0.5 and 1m,
9. overflooding only lasted a few days,
10. the drain holes are up to 30m wide with well developed radial feeder patterns,
11. after draining the ice appears dry except for puddles lying within the sastrugi (snow drift) patterns,
12. strudels easily identifiable by drainage channels about 300m long,
13. strudels lie up to 5km from shore in 5m water. Some strudels in water less than 1m deep.
14. strudels were "semicircular"(probably mean "roughly circular") with diameters of about 15m; other were elongated with long axes up to 30m.
15. spacing of strudels varied from 100m, to several km.

16. strudels were aligned along cracks in the ice.

2. **Strudel Scour: A Unique Arctic Marine Geologic Phenomenon.**
Erle Reimnitz, C.A. Roderick and S.C. Wolf
Journal of Sedimentary Petrology, Vol 44, No.2., p 409 - 420, June 1974.

Paper covers observations of strudel scours off the Alaskan coast using side-scan sonar, echo sounder, high resolution seismic gear, diving observations, and sediment sampling during the summer of 1972. The conclusions are:

1. strudel scours may be over 4m deep, and over 20m diameter,
2. they occur within 30km of river mouths
3. the shapes and distribution patterns of strudel scours on the seafloor correspond to those of strudel seen in the ice canopy,
4. strudel scours are most numerous in the inner areas of river overflow and as many as 25 per km of track,
5. one scour investigated by diving was surrounded by a ridge up to 40 cm high, had vertical walls exposing a tundra horizon and terminated at a gravel layer 4m below a lagoon floor. Another one terminated at a semiconsolidated layer of silty clay.
6. seismic records show that virtually all of the Holocene deposits and significant parts of underlying older sediments around river mouths have been reworked by strudel scours,
7. river flow advances rapidly, reaching a maximum extent in about 3 days
8. water depressed floating ice (i.e., beyond 2m water depth contour); strudels formed initially at cracks and beyond the 2m depth contour,
9. later as ice lifts off bottom, strudels are formed inside 2m contour,
10. the density of scours varied from more than 6/km around the larger river mouths out to about 10 to 15 km, 1 to 6 in the next 5 km beyond, and none beyond this. Immediately adjacent to the mouths of major rivers there can be as many as 25 scours per km, in water depths down to 1.4m (limited by vessel draft),
11. strudel scours appear to fill slowly with sediment, and hence are

preserved for several years,

12. strudel scours have been found in water depths to 8m. It is postulated that at this depth the effectiveness of the cutting action of water vortex is not very efficient.

3. **High Rates of Bedload Transport Measured from Infilling Rate of Large Strudel Scour Craters in the Beaufort Sea, Alaska.**
E. Reimnitz and E.W. Kempema
Continental Shelf Research, Vol 1, No 3, pp 237-251, 1983

The paper contains data and observations on the infilling rate of two strudel scours in diverse environments of the shallow Beaufort Sea Shelf near Prudhoe Bay, Alaska. Both scours were similar in size in 2.5m of water, but one was sheltered by a nearby barrier island, whereas the other was located on an exposed prodelta.

The conclusions relevant to this project are as follows:

1. strudel scours can be as much as 25m wide and 6m deep,
2. strudel scours form at a rate of about 2.5 km^{-2} yr^{-1},
3. the strudel scours observed filled in within 2 to 3 years, - hence observations record only the most recent events
4. with westward sediment transport, the sand layers dipped at the angle of repose westward into the scour crater, whereas the west wall remained steep,
5. the scour bottom trapped almost all bedload,
6. over a 20m wide sector, an exposed strudel scour trapped 360m^3 of sediment during 2 seasons,
7. one strudel scour discovered, surrounded by barrier islands or shallow water areas, decreased in depth from 5.5m (possibly 6.5m) in 1978, to 4.4m in 1980. This indicates 1.1 to 2.1m of infill over 2 years, equivalent to 15 to 25cm per month.
8. the second strudel scour investigated was in 2.5m of water and exposed to the predominant wind and current direction. It was 16 to 25m diameter and 3.5m deep with 10 to 50cm high scarp cut into bedded sandy silt. The infill at the time of first observation occurred each year for the next 2 years by which time the scour was nearly filled. Infilling rates varied from 35 to 60cm per month,
9. authors felt that strudel scour rate of 25 scours km^{-1} from Reimnitz et al (1974) was too high, as the "strudels" identified

were not verified properly.

10. channels feeding a particular strudel did not extend beyond 100m.
11. strudel scours are efficient sediment traps
12. strudel scour B was infilled mainly by bedload transport
13. based on above, every square km of seabottom would be reworked to
2m every 2300 years out to 5m water depths.
14. aerial photos were felt to be the most reliable way of identifying and counting strudel scours.

4. **Strudel Scour: An Arctic Seafloor Scouring Process**
Thomas L. Johnson
Arctic Offshore Engineering Conference, San Francisco, 1985

The paper describes model tests conducted to simulate the strudel scour process in the laboratory. Ponded fresh water over the strudel hole in the ice, and water having a horizontal velocity were tested. The strudel hole sizes varied from 0.5 to 2 inches. The results provide preliminary insights into the relationship between head of water, thickness of ice, velocity of flow, strudel hole size etc.

5. **Orbital Sensing of MacKenzie Bay Ice Dynamics**

B. Dey

Arctic, Volume 33, No. 2, June 1980, pp 280-291

This was a study of satellite images (Landsat and NOAA, 1970-77) of the MacKenzie Bay to determine ice breakup and freeze up patterns. Conclusions relevant to the current study are:

1. break up in the MacKenzie Bay proceeds from the south and the north, the southern melt rate is faster because of an influx of warm water from the MacKenzie River,
2. snowmelt starts in the southeastern part of the basin and proceeds towards the north and northwest. The lower basin is snow free by the end of May or early June. The lower MacKenzie River is normally ice free by the end of May or early June,
3. runoff from the river flows out over the bay, flooding a very large area,
4. the large heat transport of warm MacKenzie water is an important factor in ice disintegration along the delta perimeter,
5. sediments carried by the river are deposited onto the ice during the flooding period,
6. once the water drains through the strudel holes the ice lifts vertically,
7. sediments on the ice and water draining through the ice contribute to deterioration of the bay causing the open water area to expand out from the river mouth,

6. **Aerial Reconnaissance Survey of Ice Breakup Process in the Canadian Beaufort Sea Coastal Zone.**
D.F. Dickins and Associates

The report presents visual, photographic and satellite data pertinent to breakup of the ice in MacKenzie Bay during a field survey program May 31 to June 21, 1987. Relevant conclusions are:

1. Noted flooding and strudel hole in ice in Phillips Bay due to flooding of the Bay by the Babbage river. Maximum pit depth was 2m. Water depth 2.5 to 3.5m. Pit depth documented by drill holes and plumb line soundings. This is the first documented strudel scour in the Canadian Beaufort Sea.

2. Flooding of ice first noted at Arvoknar and Reindeer Channels in satellite photos of May 19, 1987. By May 26 flooding had expanded to North of Garry Island.

3. All areas except Phillips Bay drained without evidence of well developed strudel scour. However, in 1987 the river discharge was relatively low, and so may not be typical of other years.

4. Due to resolution of satellite (30 - 100m) and scale (1mm equal 3km), it is not possible to see strudel holes (20 to 30m across) or drainage channels (300m long) in these data.

7. **The Extent and Growth Patterns of Land Fast Ice in the Southern Beaufort Sea Winter 1972-1973.**
IPRT-2ME-74; April 1974
L.G. Spedding (Esso)

This was a study of satellite photos and visual observations of the Landfast ice, in particular its decay in the spring of 1973. Relevant observations are:

1. Near shore flooding of ice was noted at mouth of middle channel by May 10, and by May 18 in other channels.

2. North of Hogren Island, ice thawed back to 2.5 miles (4 km) between May 26 and June 10.

3. Landfast ice broke away completely July 5.

8. **Spring Break Up in the MacKenzie Delta and Southern Beaufort Sea 1973**
IPRT-7ME-74
L.G. Spedding (Esso)

Report covers analysis of a series of aerial photo flights from May 01 to July 29, 1973. Relevant conclusions are:

1. First week of May, isolated flooding was noted on the Mackenzie River and some side channels up to 20 miles north of Inuvik.

2. Flooding of ice occurred first at the mouth of the middle channel on May 08, 1973. Flooding was occurring at channel mouths to the east and in Kugmallit Bay by May 17.

3. By May 14, flooding of river ice along main channels and backup of the water into side channels and adjoining lakes was occurring almost to the coast. Flooding had reached 6 miles (10 km) from land at middle channel but less severe to north. River rising 6 in (15 cm) per day at Bar C in Mackenzie Delta but no flooding yet at mouths of other channels.

4. May 17, flooding now extended to 10 miles (16 km) from shore on middle channel. Some flooded areas in mouths of other channels.

5. May 24, large area of flooding and/or open water now around Richards Island. Snow starting to melt and layer of slush and water lies under snow on ice.

6. May 26, flooding to within 4 miles (6.4 km) of Garry Island. Flooding out to beyond Roe Island dammed by ridge to north. Photos from May 30 show water has pulled back, leaving area to east and north of Roe Island no longer flooded.

7. In Shallow Bay area of flooding increases.

8. May 29, area south of Roe Island has melted through forming a lagoon for the river water to pass directly into the sea and causing the flood water to drain off the ice.

9. May 30, ice has drained. Deterioration of ice is accelerating. Thaw holes visible along edges of old flooded areas on June 6.

9. **The Extent and Growth Patterns of Landfast Ice in the Southern Beaufort Sea, Winter 1973-74**
IPRT-10ME-75, April 1975
L.G. Spedding (Esso)

Report covers a review of satellite photos and visual observations for the winter of 1973-74. Relevant conclusions are:

1. Some evidence of flooding or open water in channels by April 06, 1974. First flooding noted in Shallow Bay, May 12. Flooding patterns in early May were similar to previous years with greatest flooding in Shallow Bay and off Langley Island.

2. By May 18, flooding noted to 2 miles past Adgo Island (11 km from shore), and at this time water and slush was 18 to 36 inch (45 to 90 cm) deep.

3. Flood water started to retreat May 21, when the restricting ice melted at the channel mouths through to the ocean.

4. Water drained through the tidal crack between the grounded and floating ice.

10. **Spring Break-up in Mackenzie Delta and Southern Beaufort Sea in 1974**
IPRT-3ME-76
L.G. Spedding, Esso

This report covers a review of break up in 1974 and some conclusions reached to date. Relevant conclusions are:

1. Flooding of ice due to the rising river water being restricted by ice grounded (frozen) to the seabed occurs in the first and second week of May.

2. Flooding occurs around the middle channel first as this channel carries 2/3 of the river water volume.

3. May 18 water drains off the ice at the shear/tidal crack on the edge of the bottom frozen ice.

4. May 20-22, river flow melts the landfast ice out to the sea, and starts to discharge directly into sea.

5. Mid June, river continues to melt back fast ice.

6. Middle channel is distribution channel - it carries most of the river water and feeds the other channels. Around Hooper Island (Harry Channel), breakup is much slower.

7. Ice-water interface advances between .6 and 5 miles (.96 to 8 km) per day (2.2 miles/day, 3.5 km, average).

8. There is little or no flooding in Kugmallit Bay - probably because the channel is deeper, and there is always a channel under the ice for the water to flow into the sea; also, water volumes are lower.

9. By May 25, flood water has drained off the ice.

10. May 28 - 31 flooding occurs in Phillips Bay.

11. **Break Up Pattern of Landfast Ice in MacKenzie Delta Region for the Spring of 1975.**
IPRT-19 ME-77
L.G. Spedding, Esso

This report reviews satellite photos and visual observations. Relevant conclusions are:

1. Breakup in 1975 was similar to 1974, except that it was about 2 to 3 weeks earlier.

2. May 3 lifting of ice and commencement of flooding at mouth of middle channel of river.

3. May 7 flooding noted around Kendall and Garry Islands.

4. May 12 - 15 flooding 6 miles (10 km) from shore at mouth of middle channel between Langley and Ellice Islands.

12. **Landfast Ice Breakup Patterns in the Mackenzie Delta Region for 1976, 1977 & 1978**

L.G. Spedding

Relevant conclusions are:

1. Early May river starts to rise and water, restricted by grounded ice, floods the ice surface. This occurs first at the mouth of the middle channel due to its high volume flow. Flooding occurs at other river mouths over the next 2 to 3 weeks.

2. By mid to late May, the warm water eventually melts the ice at the river mouths such that the water has direct access to the sea and the ice drains.

3. The river water continues to widen and extend the lagoons, out to about the 4.5 to 6m water depth, which marks the extent of the insitu melting of the ice.

4. Beyond the above depth, solar radiation and warm air temperatures rot and melt the ice and large floes break off and drift away with off shore winds.

5. By early July only a narrow barrier of landfast ice remains, which is generally cut through by the river water, and moves away as large floes.

6. Flooding was first observed on May 5, May 3 and April 21 in 1976, 77 and 78, respectively.

13. **Southern Beaufort Sea Ice Conditions in the Vicinity of Issungnak O-61 Winter 1978/79**
IPRT-ME-80-14
L.G. Spedding

The report covers a review of satellite data and aerial photos. Relevant conclusions are:

1. In spring of 1979, flooding was first evident May 2 at the mouth of the middle channel.

2. Flooding in Shallow Bay and around Oliver Islands was visible May 4, but it was May 11 before flooding was evident in the mouth of Harry Channel south of Hooper Island. Flooding probably started earlier in most locations.

3. May 25 before flooding was evident in Kugmallit Bay.

19. Effect of Sea Ice on Beaufort Sea Coastal Processes
Arctec Newfoundland Ltd, 1987

This report investigates the significance of sea ice for Beaufort sea shoreline processes and identifies the critical information gaps to guide the planning of future research effort. The study reviewed available data on coastal morphology, sediment transport and sea ice to develop conceptual models for shore/ice interaction processes.

Included in this report are excerpts from a paper by Rajaratnam (1981) which provides a theoretical understanding of strudel scour action. The study indicates that water velocity at the seabed is a function of the head of water on the ice, water depth and size of the strudel hole. The study indicated a good agreement with a strudel scour depth found in nature. For example, it indicated that for a jet diameter (strudel hole diameter) of .3 m, a water head of .6 m over normal water level, a strudel scour depth of 4.5 m will be generated in 2.5 m of water for fine grained seabed material (0.1 mm diam). The model does not include strudel (vortex) action and also field values for critical model parameters are not available. It is also noted that in the model the strudel scour depth increases continuously with water depth, whereas in nature there appears to be an upper limit water depth (of something less than 8 m) for strudel scours to occur. The scour depth estimated above is the static depth determined after the strudel flow has stopped. The dynamic scour depth which occurs when the jet is impinging on the seabed maybe 2 to 3 times deeper than the static scour depth.

Based on the above, the Arctec report suggests that 1.3 to 2m of gravel above the pipe would be needed to isolate it from any strudel scouring. Arctec describe a more sophisticated theory that takes strudel action into account which increases the flow of water through the hole. Also, they point out that the head of water on the ice depresses the ice resulting in a much reduced head.

Arctec review other papers which are also reviewed here.

APPENDIX B

AES SLAR Data

AES SLAR DATA

This Appendix covers the AES SLAR data reviewed.

Table 1 gives the flight numbers and dates. NDZ, NAY and CFR are the three SLAR aircraft designations.

This is followed by a brief summary of the conditions observed in each SLAR photograph. A line drawing is provided for flights of interest and photos of the more interesting data.

SLAR FLIGHTS OVER MCKENZIE BAY

Flight No.	Date
NDZ 060	26 June, 1978
NDZ 061	27 June, 1978
NDZ 252	14 May, 1979
NDZ 253	15 May, 1979
NDZ 266	18 June, 1979
NDZ 273	29 June, 1979
NDZ 444	16 May, 1980
NDZ 445	17 May, 1980
NDZ 450	20 June, 1980
NDZ 453	25 June, 1980
NDZ 454	27 June, 1980
NDZ 650	14 May, 1981
NDZ 651	15 May, 1981
NDZ 657	21 June, 1981
NDZ 658	23 June, 1981
NDZ 853	20 May, 1982
NDZ 854	21 May, 198
NDZ 855	22 May, 1982
NDZ 865	30 June, 1982
NDZ 866	01 July, 1982
NDZ 867	02 July, 1982
NDZ 1263	15 May, 1984
NDZ 1264	16 May, 1984
NDZ 1459	16 May, 1985
NDZ 1460	17 May, 1985
NDZ 1464	19 June, 1985
NDZ 1465	21 June, 1985
NDZ 1463	17 June, 1985
NDZ 1471	01 July, 1985
NDZ 1630	15 May, 1986
NDZ 1631	17 May, 1986
NDZ 1632	18 May, 1986
CFR 0008	27 June, 1986
CFR 0009	28 June, 1986
CFR 0010	30 June, 1986
NDZ 1801	06 June, 1987
NDZ 1802	07 June, 1987
CFR 148	26 June, 1987
CFR 149	28 June, 1987
CFR 150	29 June, 1987

Review of SLAR Flights

NDZ 60	Flight out over Richards island, possible evidence of old flooding to north of islands. Melting well progressed.
NDZ 61	Nothing
NDZ 252	Evidence of flooding near Hooper Island
NDZ 253	Landfast ice area is white (clear film) to 30km from shore. Cracks visible in ice. Pack ice shows individual floes.
NDZ 266	Shows islands (Hooper, Garry, Pelly) and ice. Lots of white dots on ice. Ice around islands is indistinct, no obvious drainage channels, but then if channels 300m long, they would be only 0.3mm! Poor image
NDZ 443	No good
NDZ 444	Lots of cracks in ice, some flooding evident in shallow bay.
NDZ 445	Too far to E of Tuk. No river mouth
NDZ 450	Starts at river mouth SW exit, at 25 km scale, changed to 1 in 10^6 scale. Shows melting around mouth of river out to beyond the 2 islands. Several strudels and drainage channels visible. (Photo for 25km -> 1453) Light-dark texture possibly due to flooding Also 2234 to end. Lots of white dots and drainage channels. Open water around shore and in some lakes.
NDZ 650	May 14: Road still evident near shore no evidence of thawing in Kugmallit Bay.
NDZ 651	Same problem as 650
NDZ 657	Wrong area
NDZ 658	Over shallow bay to W. Open water over shallow bay to beyond Herschel Island to west. Ice still in Thetis bay with evidence of open water and flooding on SE end in Phillips Bay. Water is white (transparent on film), ice is dark, mud flats are dark.
NDZ 854 seeing ice	Landfast ice and water give clear film Dark edge around edge of land fast ice (LFI) Radar edge. Exposure of film probably adjusted to give best image

LFI is very light, but nearby rough ice is dark also.

NDZ 865	Good 1 in 500,000 of Richards island (Print 2053 -> end). Lots of holes - drainage channels in ice near Hooper Island and around islands (Pelly and Garry). Small floes give strong returns due to edges Area between floes filled with small floes -> strong return - dark
NDZ 866	Good one of Thetis Bay, open water or flooding in Phillips Bay, lots of drainage channels and holes in Thetis Bay SE end. Ice still in mouth of Liverpool Bay. Lots of white dots and channels.
NDZ 867	Good run along Tuk peninsular at $1:10^6$ Major distortion at 1524 (Print 1523 -> 1601) Note holes and drainage channels of Kugmallit Bay
NDZ 1263	Shallow bay still ice covered; some OW patches in bay and on river (Print beginning 1540 -> 1620)
NDZ 1264	Not useful
NDZ 1465	Not useful
NDZ 1469	No obvious signs of ice flooding or melt. Good of Tuk peninsula. Cracks in Kug Bay. Scale changes over Richards island. Could be signs of flooding
NDZ 1460	nothing useful
NDZ 1465	Print beginning to 1444 Useful sections Open water forming in Phillips Bay
NDZ 1464	As above but not as good
NDZ 1630	1 in $5x10^5$ Excellent shots of Richards Island and area just off shore at 1 in $5x10^5$
NDZ 1631	Print 2208 (?) to 2220 of roll 1631
CFR 008	Print last 11" at end of film Open water in all channels and out to ice bridge across McK. Bay. OW in Kug Bay.
CFR 009	2 passes over Richards Island and Kugmallit Bay. Very rotten ice south of Hooper and in ice tongues close to

	shore W. of Garry (Print last 11" approx 1940 to end)
CFR 10	Begins in Liverpool Bay. Shows open water (or flooded areas) at various river mouths. (Print from beginning, miss 2" print next 11 1/2")
CFR 11	(Print 1946 to end)
NDZ 1801	Print beginning -> 1620 I think that OW areas are areas of flooding, because they are mottled and edges are indistinct.
NDZ 1802	Goes over Liverpool Bay. Evidence of OW and flooding at River mouths. (Print 1242 -> 1315)
NDZ 1800	Nothing useful
CFR 149	1 in $5x10^5$ of Richards Island and McK Bay, see drawing. Too late to see flooding
CFR 148	No use
CFR 150	Similar to 149 but not as good
CFR 149	Shows lots of melt holes but rotten as late in season

APPENDIX C

Dome Petroleum Ltd.
SLAR and SAR Data

Dome SLAR and SAR Data

The following SLAR and SAR data were reviewed

Prior to 1981:
No May or early June data

1982:
June 18: North Point some evidence of drainage holes near shore; poor image
June 24: Nothing

1983:
June 09: Possibly evidence of drainage holes; very poor image
June 14: Good picture; lots of dots on ice

1984:
May 03: Possibly areas of flooding around Garry and Pelly Islands.
May 14: Black and gray areas in image near North Point and island; possibly evidence of holes through ice and flooding, respectively.
May 17/19/21/25/31 SLAR: No useful data.
June 08: STAR - too far to North
June 11: Good image (see Figure 7.2)
June 16: Too far North

APPENDIX D

Dome/Gulf SAR Data

Dome/Gulf SAR Data

Gulf Canada Resources Ltd. started operating in the Beaufort Sea in August 1983. In 1984, 85 and 86 they ran SAR flights in the May-June period. A review of these data show the following:

<u>1984</u>

25 May SLAR 60: Open water or flooding in Phillips Bay and possibly to the east of Garry Island (photo very dark - darker area to east of Garry).

6 June SAR 56: Flooding or open water in Phillips Bay north to a line off the tip of Kay Point west to shore.

8 June SAR 58: Ice in Phillips Bay has drained leaving ice visible. Flooding also possibly evident in strips between Garry and Pelly islands. These areas are evident as dark areas on May 25 and June 6 and had lightened June 8.

Open water or flooding developing to SW of Hooper Island in strips extending to South. Flooding or open water around Pelly Island.

14 June: Open water to 2 m contour in Kugmullit Bay and in shallower areas north of Richard Island.

<u>1985</u>

15 May (SAR): Nothing evident in Beluga Bay and to west.

Darkening of ice in Phillips Bay but features still quite visible. Possibly some holes or flooding close to Richard Island around Kendall Island.

13 June: Open water or flooding west of Phillips Bay.

16 June: Lots of open water near shore. Rotten looking ice.

1986

June 11 SLAR: Open water or flooding in Phillips Bay and to south of Pelly Island. Flight too far north to see edge of Richard's Island.

June 13: Open water SE of Pelly Island.

June 15: Open water fingers melting through ice adjacent to river mouths.

June 18: Good image over Richard's Island. Lots of open water. Large rotten area of ice with lots of holes and drainage channels. Rotten ice in Shallow Bay.

APPENDIX E
NOAA Data

NOAA Data

1986:	06-18	Earliest photos - too late for flooding
1985:	05-10	
	05-16	Flooding just starting at mouths of Kitti and middle channels
	05-17	Flooding more extensive
	05-30	Difficult to see
	05-31	Extensive flooding or Open water, possible flooding in Kittigazuit Bay
	06-01	Difficult to see
	06-17	Whole of Mackenzie Delta is flooded. Extensive open water in Bay. Phillips Bay opening up.
	06-18	Whole of Mackenzie Delta is flooded. Extensive open water in Bay. Phillips Bay opening up.
1984:	05-09	Nothing
	05-16	Small areas flooded off Richard Island Some flooding noted in Liverpool Bay
	05-17	Much more extensive flooding in channels and off the Anderson River in Liverpool Bay.
	05-19	Flooding more extensive
	05-21	Flooding more extensive
	05-22	Flooding more extensive
	05-24	Flooding less extensive. Flooding evident in Phillips Bay
	05-30	Flooding less extensive
	06-18	Extensive open water
1983:	05-02	Flooding off Richard Island
	05-06	More flooding

	05-10	Open water or flooding
	05-12	More extensive
	05-18	More extensive flooding, open water off Richard Island
	05-29	More extensive flooding, open water off Richard Island
	05-31	Extensive open water or flooding
	06-02	Extensive open water or flooding off Richard Island, Phillips Bay, Liverpool Bay and Kittigazuit Bay.
1982:	05-10	Evidence of water on ice in small area off middle channel and east channel. Clouds over Shallow Bay.
	05-13	Evidence of water on ice (Bad Picture)
	06-07	Areas of open water
	06-10	Flooding in delta
	06-11	Open water in Kittigazuit Bay and off Richard Island
	06-12	Open water in Kittigazuit Bay and off Richard Island
	06-20	Only narrow ice bridge is left
1981:		Nothing useful
1980:		Nothing useful
1979:		Nothing useful

MACKENZIE BAY

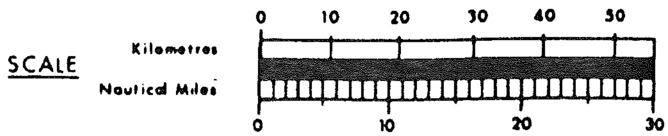
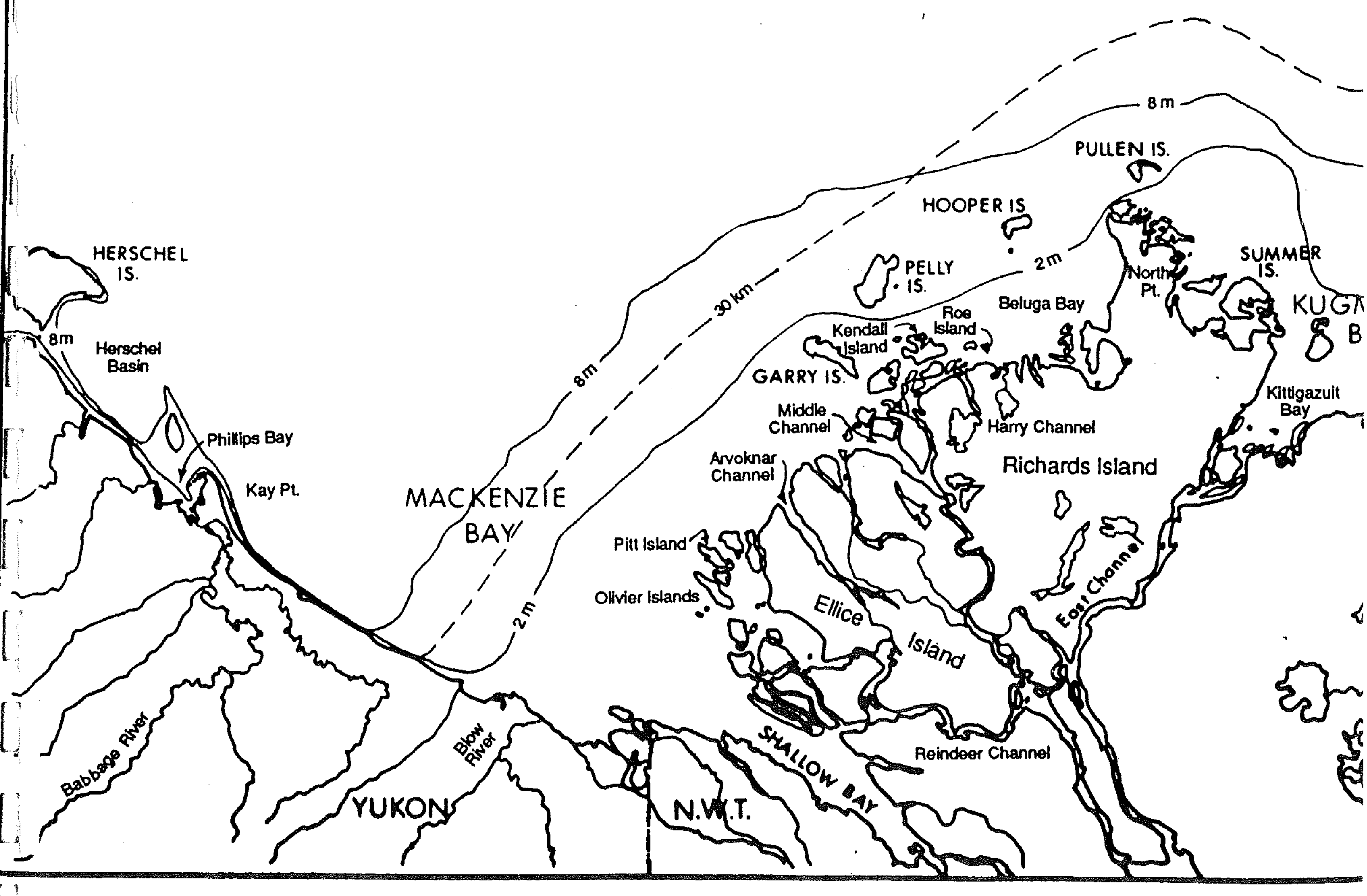
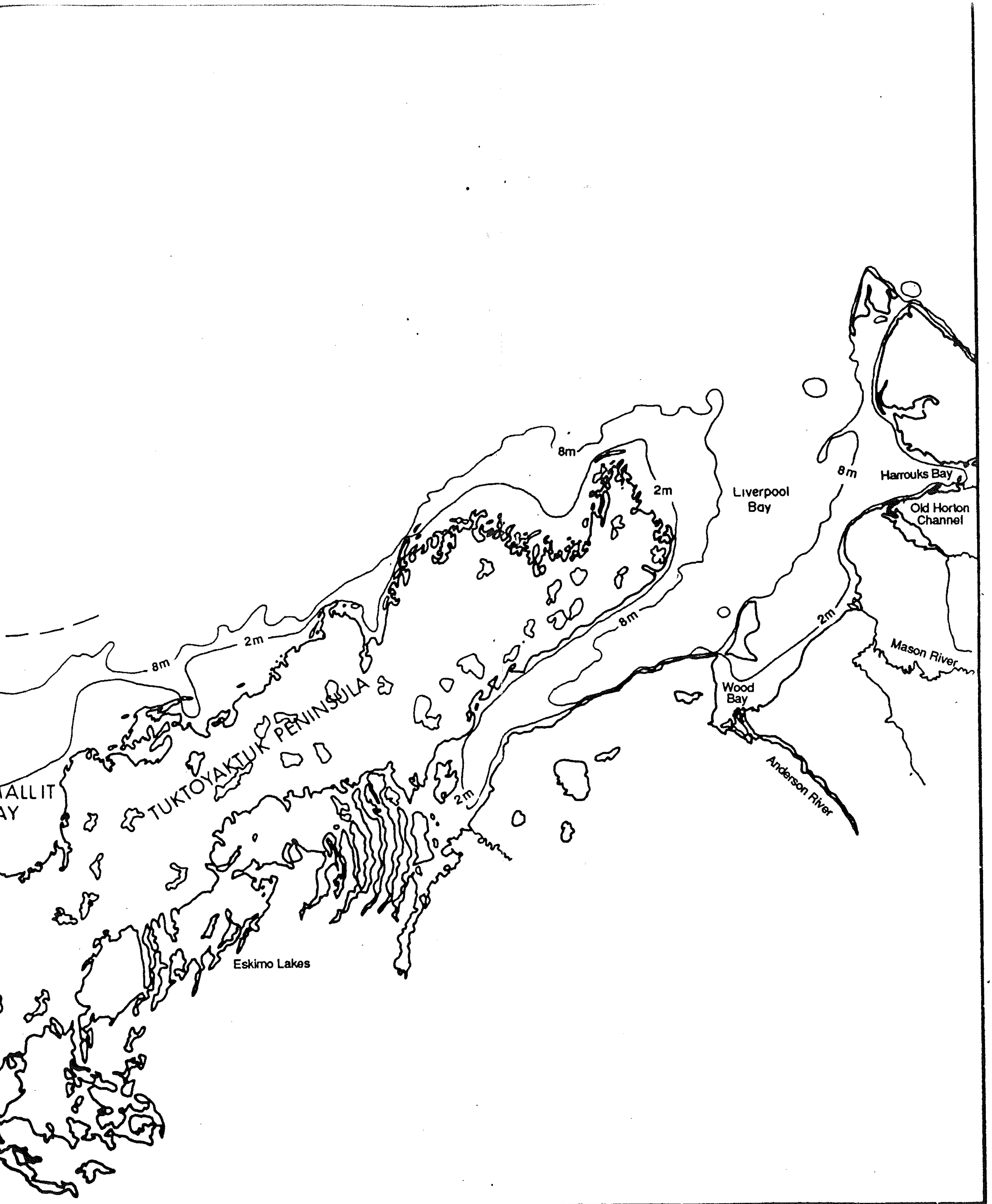


FIGURE 3.2

MAP SHOWING LOCATION NAMES, 2 m AND 8 m CONTOUR AND 30 km DISTANCE FROM SHORE





Harrouks Bay
Old Horton
Channel
Liverpool
Bay
Mason River
Wood
Bay
Anderson River
TUKTOYAKTUK PENINSULA
Eskimo Lakes
8m
2m