Ice Hazards to Offshore Oil Operations in Arctic Alaskan Waters†

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I. Introduction

Sea ice presents a hazard to offshore drilling structures and associated support activities which can exceed the normal hazards of winds and waves by a considerable margin (Hudson, ?973). Fortunately, along much of the Arctic coastline the ice is grounded during the last half of the winter, exerting only nominal internal stresses (Nelson et. al., 1976). However, under breakup circumstances, this nominally shore-fast ice can acquire velocities of 2 m/sec or more (Sackinger et. al., 1974), and under such circumstances is likely to produce stresses which may be as great as those experienced in the mowing ice pack.

Locations with more extreme ice hazards are found beyond the boundary of the shorefast ice, on the prevailing sides of coasts and islands, and in relatively deep (≥ 20 m) unsheltered water where the ice moves virtually continuously. The proposed Outer Continental Shelf lease sale areas in the Bering, Chukchi, and part of the Beaufort Sea are largely in this latter category. It is obviously important to document the regions of relatively safe, shorefast ice, and a study of LANDSAT (Land Imaging Satellite) imagery is currently in progress to do so. The dynamics of the shorefast breakup events are also being studied using time-

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lapse photography of the screen of the University of Alaska sea ice radar at Barrow, Alaska.

In this paper, we describe the annual cycle of Beaufort Sea near-shore ice events and discuss the possible hazards related to these various ice conditions.

II. Beaufort Sea Hear Shore Ice Conditions

Usually the Beaufort Sea coast is ice-free during August and September. Ice formation begins in October and generally does not form a dependably stable surface until late December or early January. The stable surface, when formed, is usually referred to as "shorefast ice". Although several slightly differing definitions of "shorefast ice" are in common usage, the term generally refers to ice stationary with respect to the shore and bounded by grounded ice features (shear and pressure ridges, floebergs, stamukhi, etc.) (see Kovacs and Mellor, 1974).

The processes at work during the formation of shorefast ice are not well-documented, largely because they have not been at the focus of attention. These processes occur during the dark winter months, when satellites with high resolution visible spectrum sensors are not operative.

However, it is known that the formation of the fast ice usually takes place in stages, often punctuated with episodes of wind-driven ice being piled and compacted into successive bands' parallel to the coast. Many of these features are grounded and serve to anchor the surrounding ice in place. This anchoring effect seems to function to a water depth of approximately 20 m. Hence, the 20 m bathymetric contour is usually taken to be the nominal seaward limit of Beaufort Sea shorefast ice.

Dynamic ice events can and do occur within the "shorefast" zone before the ice becomes sufficiently anchored to be reliably stable. Although these events are presently unobservable by means of imaging satellites, other techniques exist, which although limited in comprehensive geographic coverage, give detailed information, One of these techniques is imaging radar.

Radar has proven to be a valuable tool for the study of the dynamics of shorefast ice during formation and breakup. The University of Alaska sea ice radar facility was established at Point Barrow in March 1973, supported jointly by the Alaska Oil and Gas Associations and the Alaska Sea Grant Program. Using time-lapse photography of a conventional cathode ray tube display, it has recorded the motion of sea ice for over three years.

A particularly severe and unusual breakup event has been analyzed by Shapiro (1975). Until 26 December 1973, the ice was landfast out to beyond the 20 meter water depth contour. An offshore wind in the range 13-24 km/hr prevailed for 15 hours when, at 0545 U.T. on 26 December, the ice broke free and drifted away from the coast at 0.7 km/hr. The windspeed reached 30 km/hr at that time. The time-lapse film shows subsequent ice flow motion parallel to the shoreline at 3.7 km/hr.

Subsequently, on 31 December, the wind velocity increased to 90 km/hr (with gusts to approximately 150 km/hr) parallel to the shoreline, The ice drift velocity increased to 8.3 km/hr, parallel to the shore, and impact of this drifting ice was sufficient to drive out other ice floes which had grounded on shoals earlier. This sequence represents the most severe condition of drifting ice in the shorefast zone which has yet been analyzed.

In order to illustrate the optically observable portion of the annual cycle of near-shore ice dynamics, a sequence of Landsat scenes showing the vicinity of Prudhoe Bay, Alaska in 1974 will be used. Near-shore ice forms during the dark months when there is insufficient light for Landsat imagery to be obtained. Typically, the earliest Landsat scenes of the Prudhoe Bay area are available in late February or early March. Figure 1, obtained on March 10, shows the already formed "shorefast" ice and evidence of shearing motions in the pack ice beyond. Because no imagery is available from the period of fast ice formation, knowledge of that period must be gleaned from this earliest scene.

Close examination of this Landsat scene shows several discontinuous bands of similarly textured or shaded ice more or less parallel to the coast. These bands represent various stages in the "freeze-up*' of the near-shore ice. The stages represented include freezing in place, compaction, piling and rafting of ice frozen in place, and piling and rafting of newly-formed or multi-year pack ice driven into the near-shore area. The boundaries of each of these bands were each once the seaward edge of the ice, fixed with respect to the shore, and could have been the site of formation of shear or pressure ridges for some period of time.

Each boundary is located in successively deeper water and hence could be subject to more severe ridging conditions. Just seaward of the most pronounced bands a series of large, massive shear ridges can be identified on the imagery. These too, formed during "freeze-up". However, as will be seen, these ridges are well shoreward of the location of shearing conditions-by the date of this image.

The most visible indications of shear are the newly-formed and refrozen lead systems running somewhat parallel to the coast. Examining first the older, now refrozen, 1 ead it can be seen that its formation involved displacement of the pack ice to the east a distance of several kilometers. Further, the pattern exhibited by the other refrozen leads is that of stress relief, showing that the strain release was not limited to the slippage along this lead. The appearance of the outermost of these refrozen leads indicates that after formation of this system of leads, there may have been some westward slippage of the pack ice beyond this lead, thereby opening it up.

Now, on March 10, after this lead system has frozen over, a lead system is forming. This new 7ead system indicates westward displacement along two lines: The outermost" coincides with the outermost of the former lead system and the inner lead runs for some distance within the more shoreward of the refrozen leads, but then strikes off slightly seaward of the former lead.

This image, then, illustrates the concepts of- "shorefast" ice and the active "shear zone".

The next Landsat image available for this area was obtained on March 28, {Figure 2) during the succeeding Landsat cycle. Where formerly the ice exhibited a displacement gradient with westward displacements increasing with distance from shore, it appears that sometime during this eighteen day interval, the ice seaward of the most shoreward of the old lead system has moved several kilometers westward as a block, largely obliterating the old refrozen lead. Presumably during this time a pressure ridge of considerable magnitude was created. Examination of imagery from the summer melt season will show that the ridges formed during this event persisted into that period.

The next Landsat data would have been obtained in mid April but this image is not available - probably due to excessive cloud cover. The May 3 image (Figure 3), obtained on the second Landsat cycle after the late March *scene,* shows that little, if any, change has taken place other than perhaps further compression of the refrozen leads. Hence, during this period of over one month, Beaufort Sea ice off Purdhoe Bay was not subject to conspicuous shear or breakage for at least fifty miles offshore. Apparently this is a somewhat common occurrence, having been observed the previous year also (see Stringer, 1974).

On the west side of this image is an oblong ice feature which, while extant on the earlier images, can be examined for detail for the first time this season on the Landsat image under discussion. This grounded hummock field appears to be a recurring feature and has been reported earlier (Stringer, 1974), based on 1973 observations. An aerial reconnaissance of this feature was performed in July, 1974 which confirmed the nature of this feature. There is reason to believe that this feature and Katie's Floeberg (Stringer and Barrett, 1975) are the result of similar processes and represent essentially the same general type of ice feature. Note that lead systems are strongly deflected around this feature, indicating the major role played by its existence. On subsequent scenes it will be seen that the boundary of shorefast ice was seaward of this feature.

The next available Landsat image was obtained on May 21 (Figure 4). Here, the ice exhibits a marked change over the previous image. Whereas before this date the polar ice off Prudhoe Bay formed mainly a sheet continuous with the shorefast ice, now the polar ice is breaking up. This general behavior has been observed on imagery from other years at this date. However, it may be unusual for the pack ice to be broken up with such large voids between individual pans. Obviously at this time the "shear zone" begins at the boundary of the ice continuous with the shore and the open water. On the west side of the image, the shear boundary nearly coincides with the boundary defined by much earlier ice activity but it is still actually somewhat seaward of this location. The grounded hummock field mentioned earlier is located at this point and it is worthwhile to note that this feature remained within the shear boundary. Our contention is that this feature was a factor in determining the shear boundary.

The shear boundary runs nearly eastward across the image, increasing its distance from shore and the edge of the shorefast ice toward the east. It is not uncommon for the shear boundary to coincide with the edge of shorefast ice at this time, however (see Stringer, 1974).

The next Landsat imagery of Beaufort Sea ice off Prudhoe Bay is available for June 25 and 26 (Figures 5 and 6). By this time, the Beaufort Sea pack ice is well broken up and moving. Examination of the Landsat images for these dates shows that there is a definite boundary between moving and non-moving ice. Further, this boundary coincides with the shear and pressure ridges observed under construction in late March. The late June images are especially useful for examination of the make-up of the ice within the boundary mentioned. Many authors consider this ice "shorefast ice" but this definition is not held universally. Melting conditions have removed most of the snow cover from the ice, showing for the first time the detailed structure of the ice which was obscured on previous imagery: Here, the successive bands of ice within the shorefast zone can be examined for clues about their origin and alterations. It can be seen that some bands appear to consist of uniform sheets of ice which probably formed in-situ, while" others consist of compacted blocks of ice which were formed elsewhere and driven into their present location. Hence the "freeze-up" of the shorefast zone was a dynamic event bringing highly variable ice conditions. We have seen that radar observations of shorefast ice formation at Barrow generally corroborate this behavior.

By July 14 when the next Landsat image is" available, Figure 7, considerable deterioration of the shorefast ice has taken place. Near shore - particularly near river mouths - it has melted completely, while seaward, particular pans and areas of pans have melted. Hummock field, shear and pressure ridges become more distinct due to their persistence.

The last Landsat image for the Prudhoe Bay area in this year was obtained on September 6 (Figure 8). It shows the near-shore areas free of ice and the polar ice pack far beyond. Between the coast and the pack ice are several groups of floes which appear to be stranded at locations far offshore. Evidence supporting the contention that these groups of floes are stranded can be found in that other floes are passing around them toward the west exhibiting typical slip-stream patterns. This is not an uncommon occurrence (Reimnitz, 1976) and results when a few pieces of ice of deep draft become grounded (or remain from the previous ice season). Currents and winds cause other ice floes to pile up against them. Brooks, (1974), studied one occurrence of this phenomena and remarked on the relatively small number of grounded obstructions required to produce this effect. Presumably ice of this nature can persist into the next year's ice season. However, this is not always the case, as demonstrated by the October 4, 1972 image.

The October 1972 image (Figure 9), although not related to the sequence described above, demonstrated early freeze-up conditions. From this image, it can be seen how the near-shore ice forms in successive bands. Although young ice may be formed over quite an extensive area, only the most protected ice remains fixed in location. Portions of new ice are broken off and drift under the influence of wind and currents. This mechanism repeats successively during the freeze-up period, accounting for the many bands of differently textured ice in the near-shore areas.

III. Discussion

It can be seen that throughout the year there are a series of-ice conditions representing hazards to operations related to offshore petroleum exploration and extraction activities. These will be discussed in terms of each season.

Freeze-up: (October - January} During this time there is not a clear distinction between a shorefast zone and pack ice. Hummock fields, shear and pressure ridges form in all near-shore areas, providing load-bearing surfaces with large cross-sectional areas. Consequently large forces may be impressed on obstructions to ice motion regardless of their location. It would be extremely difficult, for example, to maintain a barge or drill ship in a desired location during this time. Modes of travel to offshore locations would be restricted to airborne methods. Bottom-fast structures may be subjected to rather large lateral forces.

Post Freeze-up: (February -April) The most stable ice conditions are found during this time. Once the grounded features which define the shorefast zone are established, that area becomes-suitable for surface travel. Further, bottom-fast structures within this area could be protected from large forces even -if they did develop *in* that zone by means of a number of artifical strain-release mechanisms. (For instance, explosives could be used to eliminate physical continuity of the ice.) During this period there is also the greatest likelihood of stability of ice beyond the shorefast ice .,. perhaps affording a temporary platform for seismic exploration.

Spring: (April - May) Shear becomes active along the edge of the shorefast ice. There is some danger of transmission of forces to points within the shorefast ice and consequent strain release within this zone (Stringer, 1974). Beyond the shorefast ice, great lateral forces can be exerted by moving pack ice.

Melt season: (June - July) Shear continues beyond the shorefast ice. Within the shorefast zone, ice movement takes place by non-grounded ice. Although such an occurrence has not been observed on the satellite data, it has been observed by radar (Sackinger et, al., 1974). Severe ice conditions may develop within the shorefast zone resulting from summer storms. -

Ice-Free Season: (August - September) This period is generally . the span of time that the coastal area is ice free. However, this condition is not entirely dependable as was demonstrated by the September 6, 1974 image (Figure 8). During this time the entire coastal area is prone to severe ice conditions resulting from storms. The well-known Beaufort Sea storm surge beach ridges offer testimony that these events do occur.

It is interesting to speculate on the effect of a number of man-made structures placed in the near-shore areas. If placed within the present shorefast zone, the effect could be "that of increased hummocking in their vicinity and greatly' increased stability of the ice sheet within the perimeter defined by the structures. In the extreme case there might be a tendency for the ice within this perimeter to become permanent. If placed beyond the present boundary of shorefast ice, man-made structures could very likely move the edge of shorefast ice out to that location. In either case, in the ice-free season the structures would serve the same purpose as the grounded ice fragments during that period and result in large groups of ice floes forming a barrier to seaward.

IV. Implications: Effects of Ice on Offshore Operations

If petroleum exploration is initiated from floating drillships, as is planned for the Canadian Beaufort Sea in the summer of 1976, drilling can proceed only during the ice-free (less than 10% ice cover) periods. Based upon the limited number of years of satellite and aircraft observation data available, this can range from approximately 8 months in the St. George Basin of the Bering Sea to a mean of 28 days in the Prudhoe Bay area of the Beaufort Sea. Anomalous weather conditions can shorten or segment these ice-free periods, as occurred in the summer of 1975 in the Beaufort Sea. Ice-reinforced drilling and resupply vessels would permit an extension of the drilling time and should be seriously considered. Exploration from gravity structures which could resist ice pressure would result' in longer working periods, but platform service and" resupply access would be primarily by helicopter, hovercraft, or in the case of shorefast ice - by wheeled vehicles over the ice after mid-winter. The shorefast ice zone is the safest region for winter drilling operations. On the prevailing side of coasts and islands, or indeed beyond the shorefast ice in water deeper than 20 meters, ice pressures are more severe and virtually continuous.

Eventual production would require the development of subsea production equipment which can withstand occasional ice scour. 'Continuous petroleum production throughout the year from the western coast of Alaska will be likely to require a fleet of ice-reinforced tankers, as well as an ice-resistant deepwater loading terminal offshore. For the annual ice encountered in the Bering Sea, this appears to be within the capabilities of present technology, although the existence of sufficient reserves, together with the economics of the situation, remain to be determined. The relationship between ice motion and meteorological variables would be operationally important, so that accurate ice forecasts could be made.

ACKNOWLEDGEMENTS

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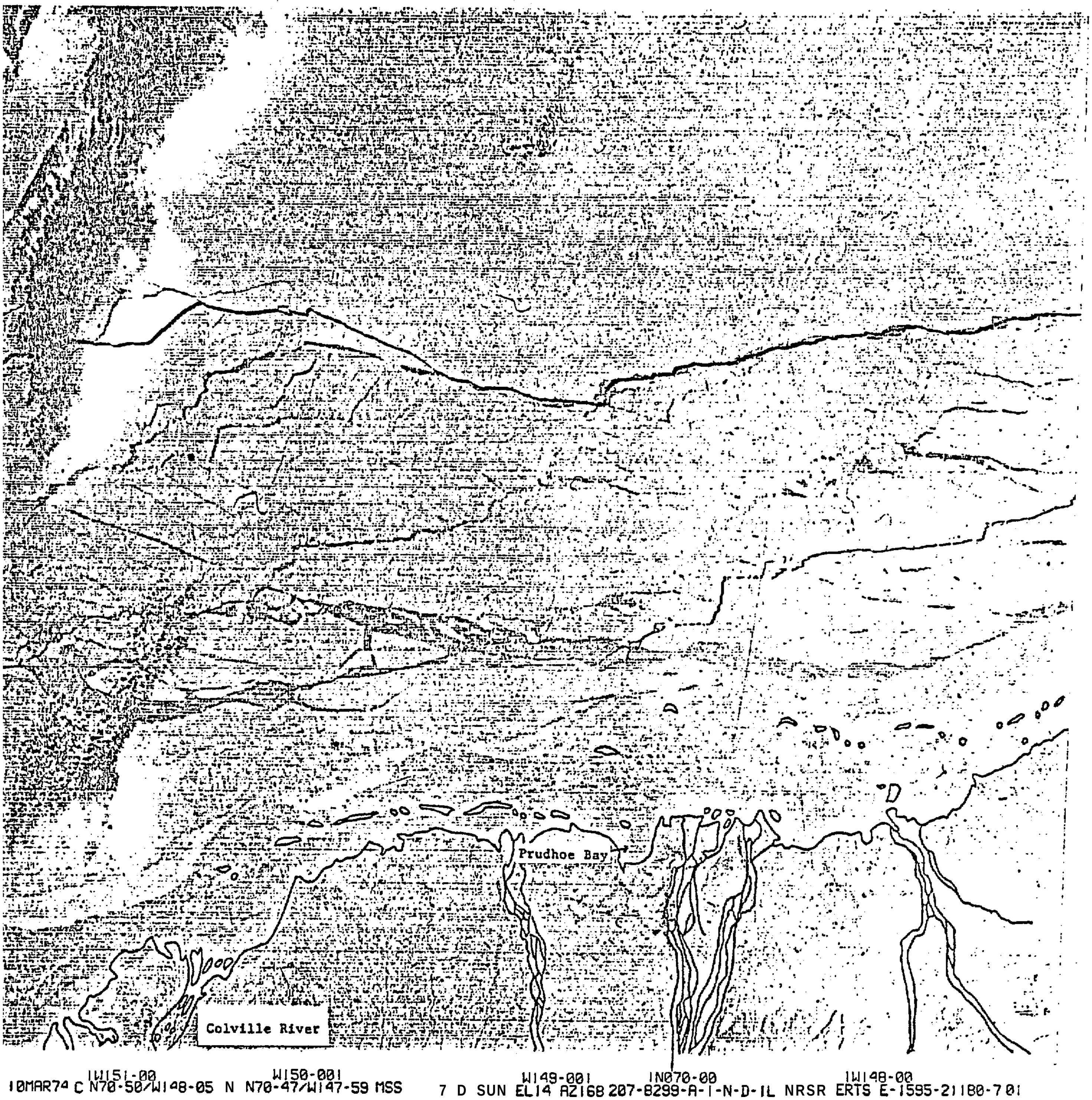


Figure 1: Landsat image 1595-21180 obtained 10 March,1974 showing near-shore ice from the Colville River eastward to the vicinity of Flaxman Island.

Figure 2: Landsat image 1613-21174 obtained 28 March,1974 showing near-shore ice from the Colville River eastward to the vicinity of Flaxman Island.

Figure 3: Landsat image 1649-21165 obtained 3 May, 1974 showing near-shore ice from the Colville River eastward to the vicinity of Flaxman Island.

Figure 4: Landsat image 1667-21162 obtained 21 May,1974 showing near-shore ice from the Colville River eastward to the vicinity of Flaxman Island.

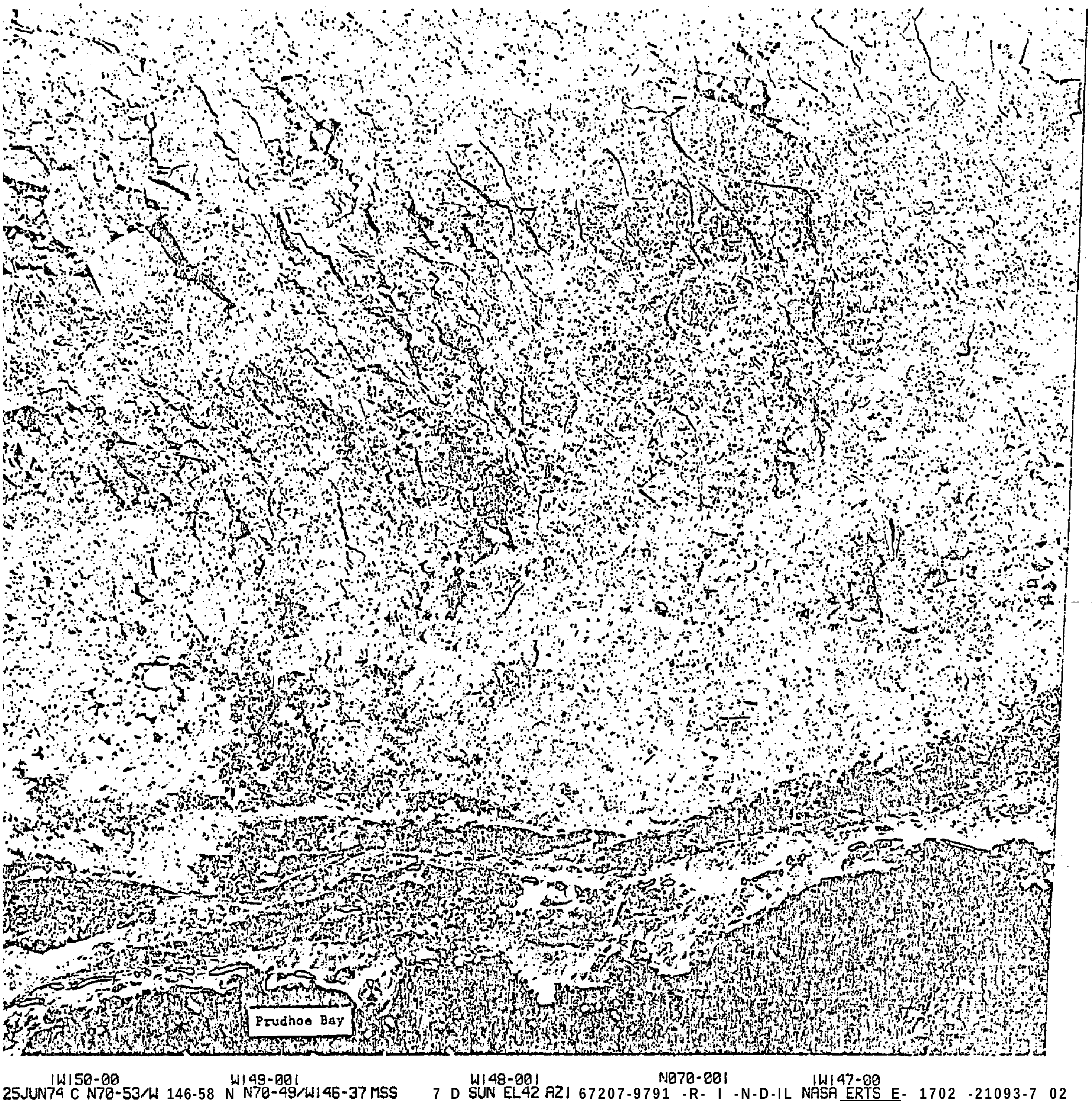
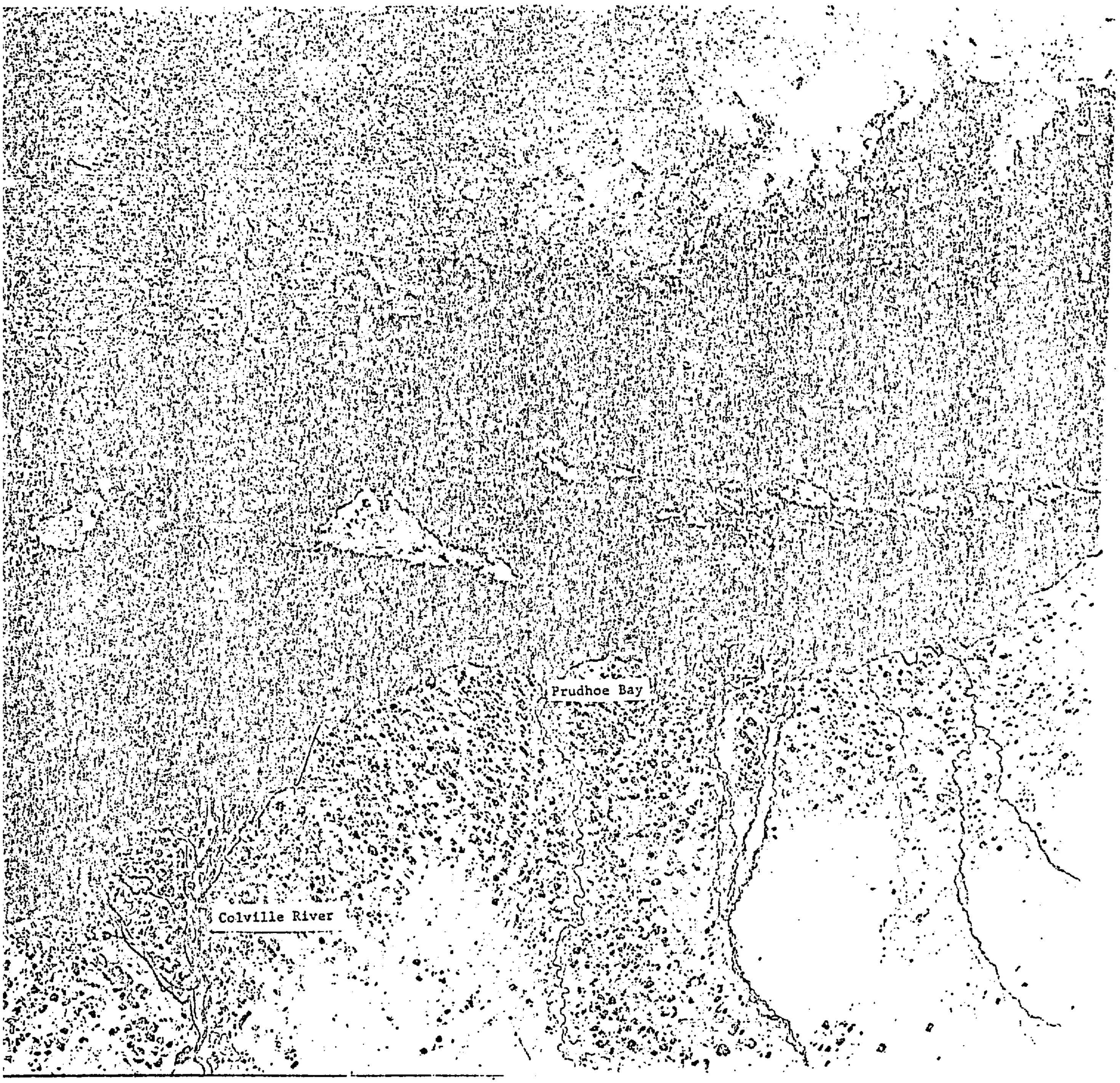


Figure 5: Landsat image 1702-21093 obtained 25 June,1974 showing near-shore ice" from the Colville River eastward to the vicinity of Flaxman Island.

Figure 6: Landsat image 1703-21151 obtained 26 June,1974 showing near-shore ice from the Colville River eastward to the vicinity of Flaxman Island.

Figure 7: Landsat image 1721 -21143′ obtained 14 July,1974 showing near-shore ice from the Colville River eastward to the vicinity of Flaxman Island.



igure 8: Landsat image 1775-21124 obtained 6 September,1974 showing near-shore ice from the Colville River eastward to the vicinity of Flaxman Island.

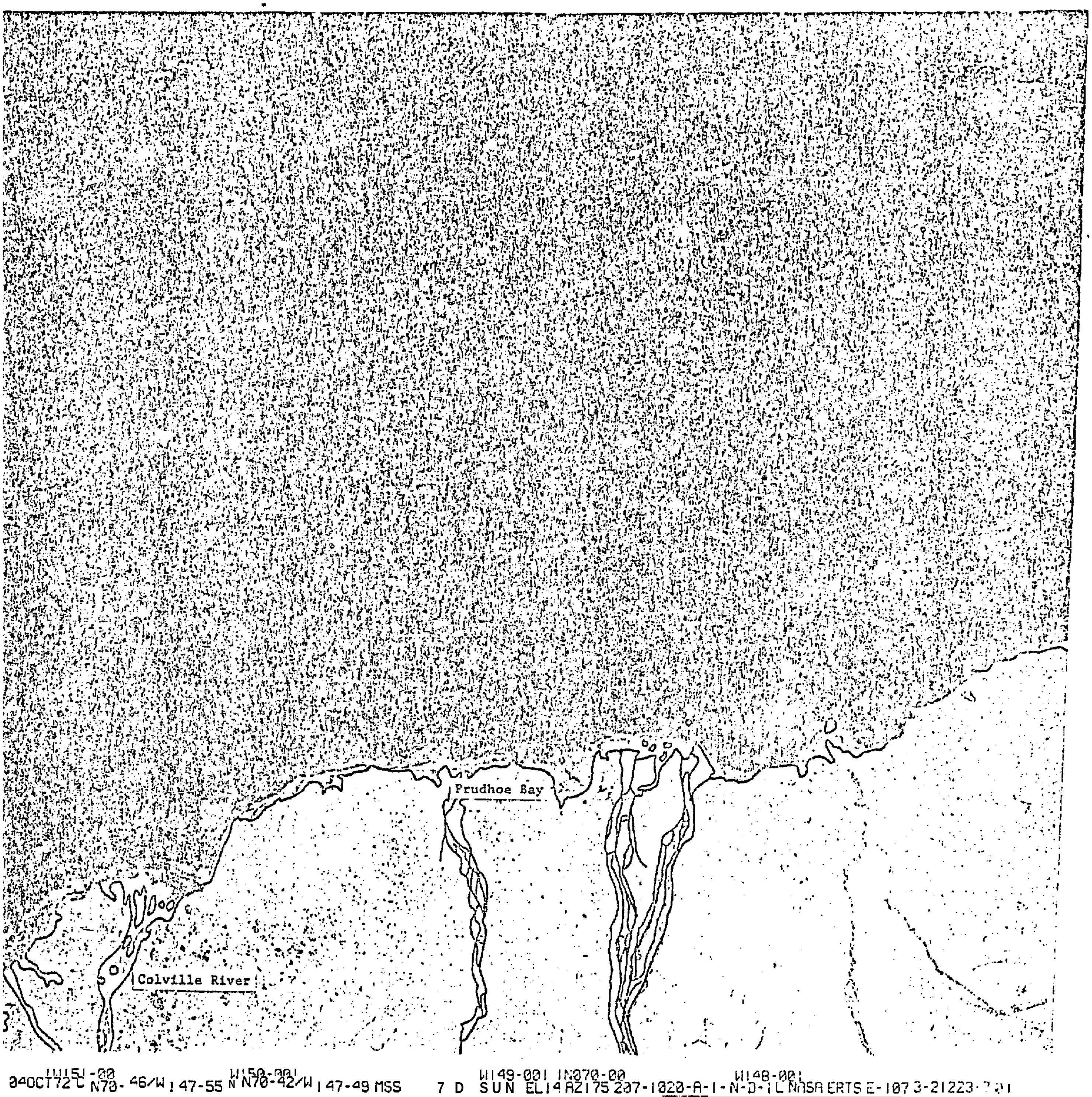


Figure 9: Landsat image 1073-21223 obtained 4 October,1972 showing near-shore ice . from the Colville River eastward to the vicinity of Flaxman Island.