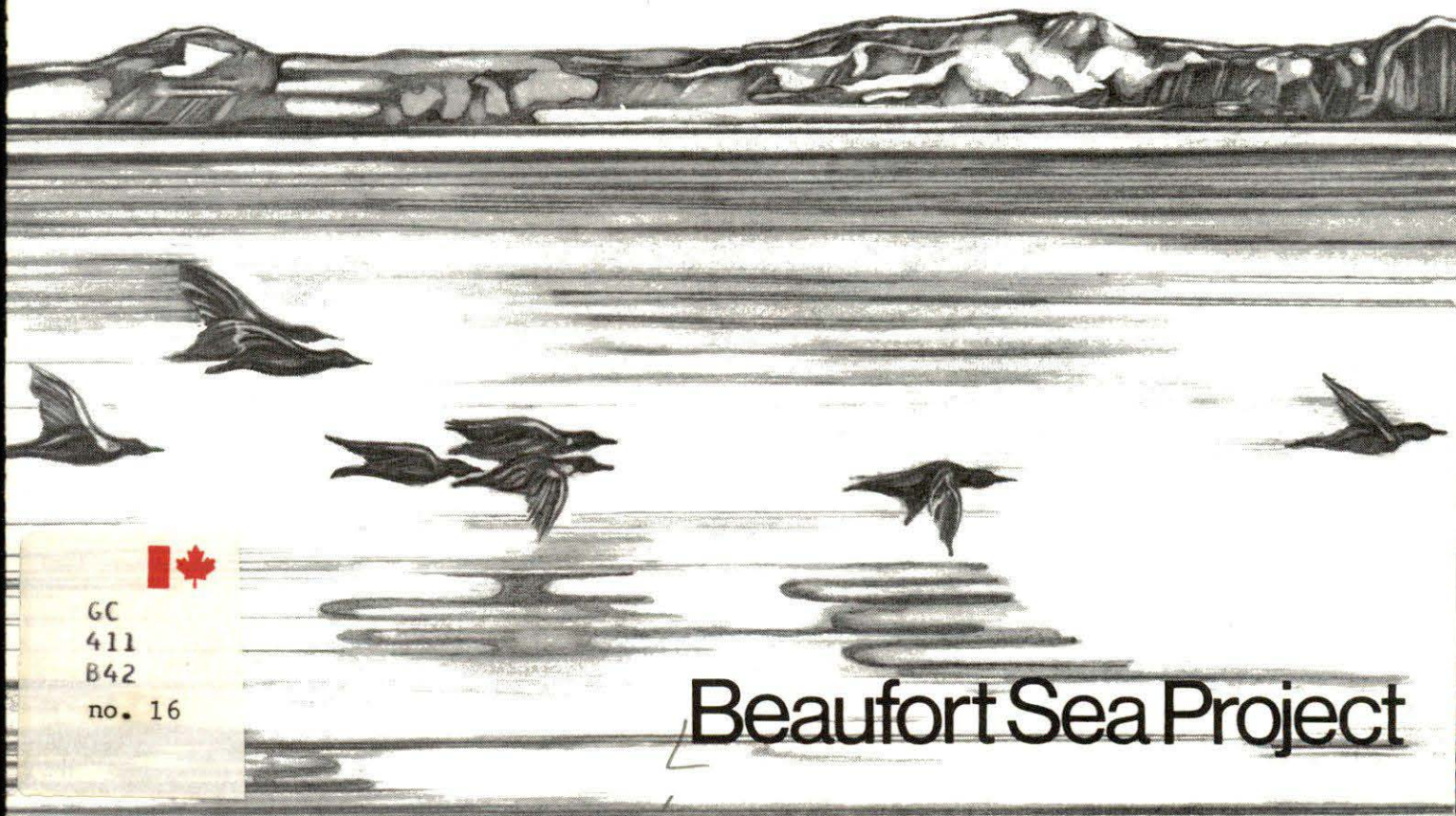


Near Bottom Currents and Offshore Tides

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1. INTRODUCTION

The studies carried out in the Beaufort Sea and described in this report are part of our overall baseline environmental study which will provide background information to the Federal Government. This information could be used to assist in drawing guidelines for offshore drilling.

Our specific objective was to gain some understanding of the bottom currents and offshore tides in the southern Beaufort Sea, their relationship to wind and ice conditions, and to measure storm surges along the coast in the Mackenzie River Delta area. The data obtained in this study, and particularly those on storm surges, are to be used in the fine adjustment of the numerical model described by Henry, (1975).

The Beaufort Sea is the traditional name applied to the waters off the northern coasts of Alaska and Canada. It is an integral part of the Arctic Ocean and cannot be separated oceanographically. The Beaufort Sea extends from the Chukchi Sea on the west, to Banks Island of the Canadian Archipelago. The southern portion of the sea overlies the continental shelf off the northern coasts of Alaska and Canada, which extends northward approximately 150 kilometres and is generally shallower than 65 metres. It then drops off rapidly into the Canadian Basin, reaching a depth of 3940 metres in the Beaufort Deep. (Fairbridge, 1966).

2. HISTORICAL REVIEW

- 2.1. Although some studies have been done in the area, mainly on temperature and salinity distributions, nowhere had bottom current measurements been taken. A few surface current observations had been taken by Healy in 1970 in nearshore waters around the Mackenzie River delta, and he found that the surface waters are strongly influenced by the wind. (Healy, 1970).
- 2.2. The Western Beaufort Sea Ecological Cruise (WEBSEC-71 and 72) surveys conducted by the United States Coast Guard along the Alaskan Coast west of 143°W during the years 1971 and 1972 did measure currents at depth. These were taken on an opportunity basis when the ship was at anchor, and it was found that ".... the 0.058 kts induced by the vessel motion is often equal to or greater than the information recorded on the current meter strip charts." (Hufford, 1974). However, the subsurface currents generally coincided with each other in direction and occasionally in speed, but their relation to the surface current appears to be completely independent, with directions often being 180° out of phase.

Significant changes in current direction were noted about one hour before the predicted times of high and low water for Flaxman Island at stations approximately 75 kilometres (42 nautical miles) from the island. At those stations 306 kilometres (165 nautical miles) to the west of Flaxman Island, the shifts in current direction tended to occur one hour after high or low water.

"The limited data from 1971 suggests a two current system with the primary driving forces determining current velocity being a complex relation between surface winds and the boundary conditions imposed by continuity. The weak mixed tides (range approximately 15 cm) found in this area appear to have some influence on direction of the subsurface (>10 m) currents." (Hufford, 1974).

"A 15 day current record was obtained from a 25 m depth on the Beaufort Sea shelf approximately 83 kilometres northeast of Barrow, Alaska, during August 1972.The current observed at 25 m showed a mean flow to the east but was subject to irregularities and wide day-to-day variations. The local wind, although the major cause of many fluctuations, is not the primary driving force of the eastward flow. The eastward motion of the current appears to be dominated by the momentum present in the flow prior to its entry into the shelf region. There was an intensification of the current during prevailing westerly winds and a suppression of the current during sustained easterly winds." (Hufford, 1975).

In 1973 two current meters were moored in the Barrow Canyon at depths of 96 m and 126 m in 150 m of water for a period of four months (Mountain *et al*, 1975). Rapid flow was recorded along

the canyon, frequently exceeding 50 cm/sec and reaching 100 cm/sec. The average flow was 25 cm/sec toward the northeast (along the canyon). The Barrow Canyon is unusual in that it parallels the coastline. The current recorded is thus strongly correlated with the alongshore flow, the speed of which is amplified by funnelling through the canyon. Little correlation with surface wind was found - possibly due to ice cover. However, a close relationship was shown between the measured currents and the north-south atmospheric pressure gradient.

The tidal signals from the current records were very small, less than 2 cm/sec, and showed only a distinct peak for the O_1^1 constituent. The semi-diurnal components were extremely small relative to the diurnal ones; the M_2^2 being less than one-third as large as the O_1 . In contrast, at Point Barrow, the semi-diurnal tides predominate with the M_2 being over three times as large as the O_1 .

- 2.3. In 1959, a permanent tide gauge was established at Tuktoyaktuk, the first in the western Arctic, to be followed by one at Cambridge Bay in 1961. Prior to this, only one summer's tide readings, in 1956, had been taken, and that was at Tuktoyaktuk. In 1964, 1965 and 1966 observations were taken at Garry Island during the summer months and since 1970 tide gauges have been operated at 17 different locations between Herschel Island and Baillie Island, some on a continuing basis.

1. O_1 - lunisolar diurnal constituent, with K_1 , expresses the effect of the moon's declination. They account for diurnal tides.
2. M_2 - principle lunar semi-diurnal constituent, represents the rotation of the earth with respect to the moon.

3. METHOD

3.1. Instruments

The current meters used in the Beaufort Sea survey were all Aanderaa RCM 4 meters, and were equipped to record either temperature, conductivity or pressure, or some combination of these three, as well as current direction and speed. The offshore tide gauges deployed in 1974 and 1975 were Aanderaa TG1A or TG2A. In 1973, two UBC³ tide gauges were used. All of the above instruments record on magnetic tape, and all were set to record every half hour with the exception of the two UBC gauges, which recorded every five minutes. The shore tide gauges consisted of a combination of Aanderaa TG2A pressure gauges, Stevens bubbler type gauges, Lewis differential pressure gauges, and Ottboro pressure diaphragm gauges. The Ottboro and Stevens gauges give analogue records, while the Aanderaa and Lewis gauges record on magnetic tape, with the former recording every half hour and the latter every 10 minutes.

The acoustic releases used were Interocean models 1000-R and 1002-R and AMF model 395. The latter were used in 1974, with the former used in 1973 and 1975.

3.2. Moorings

The moorings were deployed at three different times, October 1973, May 1974 and April 1975.

3.2.1.

In October 1973, it was decided that an attempt should be made to gather some information from under the ice on currents and offshore tides. To achieve this, three current meters and two tide gauges were moored in positions 12, 13 and 14 (Fig. 2). Positions 13 and 14 had both a tide gauge and current meter while position 12 had a current meter only. Position fixing was by Motorola Range Positioning System (RPS), which limited the distance offshore that the instruments could be moored. The radar scanner for the helicopter was borrowed from the Canada Center for Inland Waters (CCIW), and the two transponders were from Victoria. However, only one transponder functioned, so that the fixes consisted of one range and one bearing from the helicopter's ADF. These moorings were lowered from helicopters through leads in the ice into about 40 m of water. All these moorings had ground lines as well as acoustic releases. Unfortunately, 1974 was such a heavy ice year that only Station 13 became ice free and then only the tide gauge was recovered. The current meter, which was on a separate mooring was lost. The tide gauge had also been turned over by the ice, either by the ice itself rolling the instrument over, or by ice hanging up on the ground line and so dragging it over. In any case, the instrument worked until such time as the oil

surrounding the batteries displaced the battery acid, and 178 days of records were obtained. The other stations were searched for in 1975, but without success.

3.3.2.

In May 1974, ten moorings (Stations 1, 3-11), (Fig. 2), each consisting of a tide gauge and current meter, were put down through holes in ice two to three metres thick. Each hole was made by drilling five holes in the ice (in the shape of a dice 5) and then setting off ten pounds of Geogel in the center hole. The larger pieces of ice were removed prior to lowering the mooring through the hole on a slip line. The Aanderaa current meters were modified to allow them to pass through the holes by hinging the tail assembly. One-half of the current meters were bottom mounted just above the tide gauges on the mooring line, and the other half were about ten metres below the water surface. All moorings had floatation balls within 10 metres of the water surface.

The tide gauges were housed in a stainless steel holder coupled directly to the release mechanisms beneath them (Fig. 3). This method of anchoring the tide gauges was made necessary by the type of anchor used. To make the transport and handling of the 300 pound anchors easier and suitable for movement by helicopter, they were made up of six steel plates (2.5 cm thick, 33 cm square) each with a slot cut out for a hand hold, which were bolted together when used. The amount of ice present in 1974 and the lack of information on blasting holes in ice, convinced us the mooring should be kept as small in diameter and as simple as possible. Positioning of the moorings in 1974 and in 1975 was by Decca Lambda. Again, due to the bad ice year in 1974, only one became ice free and was recovered; Station 4. The tide gauge operated for 52 days, until June 30, when it was presumed struck by ice. The tide gauge had stopped working on June 23 due to a malfunction in the electronics. When recovered in August, the clock on the current meter was still working but the rotor was full of mud. This tide gauge was recovered sometime after it had been searched for by ship. No answering signals were received from the acoustic release, so it is not known for sure whether it was in place when searched for or not. The release code was transmitted, but again no answering signal was received, so either it had been triggered to release by a seismic survey that was being carried out in the vicinity of the mooring, or it had, in fact, released when the release code was transmitted by the ship but was not seen. Fortunately, it was recovered from among ice floes 10 days later after having been spotted from a helicopter.

Several attempts were made to recover the moorings by helicopter, but generally the ice cover was too much to risk setting them off. Station No. 7, with an AMF release, did become free of ice, but no acoustic signals were received from the release instrument.

3.2.3.

In April 1975, a further eight moorings were deployed in positions 3, 5, 8-11, 13 and 15 (Fig. 2). This year all current meters were bottom mounted with the flotation balls (four vinyl plastic balls) placed above them to lessen the chance of interference by ice. All moorings consisted of a current meter, tide gauge and acoustic release (Fig. 3). The ice cover at the end of April had far more open water and leads showing than in the previous year, thus allowing the moorings to be laid without resorting to blasting holes in the ice. Each assembled array was on the ice and was then picked up by the helicopter and lowered through the lead until the floats were in the water. The array was then allowed to free fall to the bottom.

Of the eight moorings put down in April, seven were recovered by ship in the first week of August. The polar pack had retreated to north of the shelf (Fig. 5), and the meter Stations, 5, 8 and 10, were in about two to three-tenths ice. The instruments from Station 3 were not recovered; no underwater acoustic answering signal was heard from the interrogation signal or from the release code. A box search ranging up to four miles from the station failed to find the instruments thus leaving some doubt whether a faulty release gear existed or whether the mooring had been damaged by ice. At Station 15 no answer was received to the interrogation signal either. However, when the release code was sent it did release, and the mooring was soon found. Station 10 was found six miles from its reported position, but this was (1) because scale errors of .17 and .31 were found to exist between the ship's and the helicopter's Decca decometers on the red and green lanes respectively, and (2) the Decca lane crossing angles are far too acute north of Baillie Island for precise positioning. Once Station 10 was found, and the differences applied to the Decca coordinates of Station 11, the latter station was found immediately. Of the fourteen instruments recovered, only one tide gauge failed to function. This was caused through a short circuit on one of the electronic circuit boards, which drained the battery.

At this time, Stations 5 and 13 were relaid and another mooring was deployed at Station 3. These moorings had a concrete anchor with a tide gauge housed in a hole in the anchor (Fig. 4), otherwise they were identical to those previously deployed. These also were lowered over the ship's side until the flotation balls were in the water, then were allowed to free fall to the bottom. In the first part of September the three stations were to be recovered by ship, but due to heavy ice in the Beaufort Sea, only instruments from Station 13 were recovered.

Instruments from Station 5 were recovered by helicopter in thick fog through nine-tenths ice; this was an exceedingly lucky circumstance. Instruments from Station 3 were not recovered as at the time they were under ten-tenths ice.

The moorings were down for just over three months and no signs of corrosion were evident, although the sacrificial zincs had been consumed. There was no slime on the instruments, but at Stations 13 and 15, a fine layer of silt was found on the flotation balls. The technique of allowing the mooring to free fall to the bottom appears to have no adverse effect on the instruments or the release mechanisms. When such small velocities are present, the tide gauges installed as an integral part of the mooring seems to present no difficulties, as no line tilt was apparent in the gauge records.

3.3. Tide Gauges

3.3.1.

In September 1973, two tide gauges were installed, one at Herschel Island and the other at Cape Bathurst near Baillie Island, to run over the winter months. Unfortunately, the gauge at Cape Bathurst was destroyed by ice movement, but the Lewis gauge at Herschel Island functioned throughout the winter months.

3.3.2.

During the summer months of July, August and September in 1974, five additional tide gauges were installed at: Kay Point, Shingle Point, Rae Island, Atkinson Point and Baillie Island (Fig. 6). All these additional gauges were Ottoboros and produced analogue records. The pressure diaphragms for these gauges were set in one to two metres of water and were serviced every two weeks.

The gauge at Herschel Island was again left in place to record over the winter months, but the kerosene filled tube attached to the gauge corroded through at the gauge, and thus no records were obtained after this time.

3.3.3.

During the summer months of 1975, ten gauges were installed at the following locations: Demarcation Bay, Herschel Island, Kay Point, Shallow Bay, Garry Island, Tununuk, Kittigazuit Bay, Atkinson Point, Baillie Island and Harrowby Bay, (Fig. 6). An Aanderaa TG2A gauge was installed at Demarcation Bay, but it operated only for the two weeks due to dirt on the writing head. All the other gauges ran for the full time.

3.3.4.

The permanent tide gauge at Tuktoyaktuk was out of operation from January 21 to February 9, 1974, and then again from June 3 to June 27, 1974. In 1975, up to October 1, it had only been out of operation for one week in July. This gauge is serviced by Water Survey of Canada with offices at Inuvik.

4. ANALYSIS OF DATA

It is important when interpreting tide and current records from the Beaufort Sea that a predominant feature is their variability. These conditions appeared to differ not only from station to station, and from year to year, but also from day to day. It is also interesting to note that when the instruments were picked up at the beginning of August 1975 from the MV Theta the ice fringe was near the outer Stations 3, 5, 8 and 10; the water at Stations 5, 8 and 10 was exceptionally clear where a white nylon line remained visible to a depth of 30 metres; the sub-surface floats at Stations 13 and 15 had a layer of silt on them; and only around Station 3 and the area to the north and west of Herschel Island was driftwood seen in any quantity.

4.1. Tides

Tides throughout the Beaufort Sea are mixed, but are predominantly semi-diurnal with a range of 0.3 to 0.5 metres. The tide propagates eastward along the continental shelf and the range remains fairly constant, being smaller at the edge of the shelf than in the shallow waters and constricted bays along the coast. There is, however, a noticeable slowing of the magnitude of the diurnal component as it approaches Baillie Island at the Eastern end of the shelf. These features can be seen in the cotidal chart of the principal lunar constituent M_2 (Fig. 7) which approximates the tidal progression along the coast. It should be noted here that the M_2 and K_1 (Fig. 8) cotidal charts are fits to observed data only (K_1 being lunisolar constituent - period 23.93 hours).

As the tide propagates southeast into Mackenzie Bay the range increases from 0.4 metres at Herschel Island to 0.5 metres at Shingle Point. Further south and into Shallow Bay the tidal effects are overshadowed by the effects of wind stress and outflow of the Mackenzie River. The normal tide range is about 30% of that at Herschel Island, but the mean sea level fluctuations, influenced by the two factors mentioned, are much larger than those at Herschel Island. Strong northwest winds produce storm surges here which are larger than anywhere else in the Beaufort Sea study area.

Across the northern end of Mackenzie Bay and seaward of Garry, Pelly, Hooper and Pullen Islands, the tide normally arrives about 15 minutes later than at Herschel Island. In the shallow waters south of these islands, the range decreases to about 0.2 metres but, as in Shallow Bay, water level changes resulting from wind stress often completely dominates the tidal effect.

The tide moves south into Kugmallit Bay and eastward reaching Tuktoyaktuk Peninsula in the vicinity of Point Atkinson about fifteen minutes later than at Herschel Island. The tide now turns and moves along the shelf perpendicular to the Tuktoyaktuk Peninsula, and slows down appreciably as shown in Figure 7. Offshore, the

magnitude of the diurnal component K_1 increases by a factor of 2 to nearly that of the semi-diurnal component M_2 and the tides are quite diurnal at times.

North of Cape Dalhousie the direction of propagation gradually swings from northeast to southeast. Inshore, the tide proceeds into Liverpool Bay, increasing in amplitude, and reaching the entrance to the Eskimo Lakes five hours later than at Tuktoyaktuk. The tide range at this point has increased to 1.0 metres, larger than anywhere else in the Beaufort Sea area. Offshore, the tide swings around Baillie Island into Amundsen Gulf and south along the east side of Cape Bathurst into Franklin Bay.

4.1.1. Storm Surges

The buildup of water along the coast at times of strong onshore winds is of considerable interest in the Beaufort Sea area, for the coastline is very low and susceptible to flooding. During August 1975, two storms occurred which caused water buildup as shown in Figure 9. The water level data has been low-pass filtered with a cut-off period of one day to eliminate the tide. The peak water height is obtained by adding the tidal height to the smoothed height, except in the case of Shallow Bay on August 27 where a very fast rise in level occurred, reaching a height of 1.4 metres above mean sea level. It is interesting to note the increase in the amplitude of the surge of August 27 from the offshore position at Station 5 where the amplitude was 8 cm, to mid-shelf at Station 13 where it was 18 cm, to the coast where it ranged from 28 cm at Herschel Island to 1.4 metres at Shallow Bay.

Disastrous storm surges occurred in 1944 and 1970. In 1944 the wind was estimated at 75 knots which caused a mean sea level change of about 3 metres. Several buildings at Tuktoyaktuk were flooded and most loose articles were washed or blown away. The storm of 1970 generated winds of 70 knots gusting to 85 knots. Water level increases of 2 metres at Tuktoyaktuk, 2 metres at Shingle Point and 1.3 metres at Herschel Island were estimated in a survey by the Department of Public Works (Canada Department of Public Works, 1971). The road at Tuktoyaktuk was flooded; there was considerable erosion of the coastline (14 metres were reported lost in front of the R.C.M.P. office), and buildings 200 to 300 metres from the shore were coated in frozen mud. The return period for such a storm has been estimated to be between 40 and 50 years, using Gumbel's theory of extremes (D.P.W., 1970).

The storm surges of August 1975 were an order of magnitude smaller in amplitude than those of 1944 and 1970, yet the ratio of the surge elevation of 1970 to that of 1975 at Herschel Island and Tuktoyaktuk (Kittigazuit Bay) is the same, for all practical purposes. From this we might conclude that the general pattern of buildup for storm surges is much the same as that shown by the records of August 1975, even for large surges, (Fig. 8). If we use this pattern to extrapolate the amplitude for the 1970 surge at Station 13,

we obtain 1 metre. We note that the mean sea level change offshore caused by such storms is likely to be of little concern compared to the waves, which would have an amplitude of 5 metres or more, thus raising the level of the water by at least 3 1/2 metres.

4.2. Bottom Currents

Currents in the area are the result of a complex of influences: the effects of wind stress, barometric pressure gradients, tidal forces, river discharge, bottom topography, ice cover, and momentum the flow possessed before entering the area. While it is beyond the scope of this report to unravel these interdependent factors, we intend in the following to provide an idea of the nature of the bottom current and to investigate its more obvious features.

As we have seen in the previous section, the amplitudes of the tidal constituents of the offshore water level stations are quite small. The semi-diurnal constituent M_2 is the largest and varies from 4.6 cm at Station 10 to 8.4 cm at Station 13. K_1 , the largest of the diurnal constituents, varies from 2.9 cm at Station 9 to 5.1 cm at Station 11. The associated tidal currents are, naturally, very small indeed. The semi-diurnal constituent M_2 which is also the largest constituent for the tidal currents except at Stations 10 and 11, varies from .7 cm/sec at Stations 10 and 11 to 2.2 cm/sec at Station 13. K_1 is not always the largest of the diurnal constituents for the tidal currents, O_1 being larger at Stations 9 and 11. The amplitude of K_1 varies from 0.2 cm/sec at Station 9 (O_1 is .4 cm/sec) to 1.2 cm/sec at Station 11 (O_1 is 1.4 cm/sec). The above figures are taken from analyses covering the months of May to July inclusive, and do not include data for August 1975 at Stations 5 and 13.

At the three stations along the edge of the shelf, 5, 8 and 10, the direction of the current flow was always northeast, except at Station 5, where there were occasional direction changes during ice-free periods, when the wind stress appeared to have some effect. Associated with these weather disturbances there was often a period when the winds were light and the current at Station 5 flowed in a clockwise gyre. These three stations have about the same velocity during easterly winds, but those at Station 5 have a greater velocity during westerly winds. Ice cover appeared to make little or no difference to current speeds or directions at Stations 8 and 10.

Of the four positions in 30 to 40 metres of water at mid-shelf (Stations 13, 15, 9 and 11), current speeds at Stations 13 and 15 were about the same as those at the outer shelf stations, but had far more variation in the direction of the current. At Station 13 the direction closely followed that of the wind. However the current at Station 15 was southerly when it was westerly at Station 13, perhaps due to the effect of bottom topography in the vicinity of Station 15 (see Fig. 2).

At Station 9 and 11 the current direction was northeast at all times with the speed at Station 9 comparable to that at Stations 13 and 15, but at Station 11 it was nearly double that at Stations 13 and 15.

The root mean square (RMS) speeds (Table 1) for Stations 8, 9, 10, and 13 were all close to 6 cm/sec. At Stations 5 and 15 they were slightly higher at 8 cm/sec, except during the month of August when the RMS speed at Station 5 increased to 13.8 cm/sec, due to two large storms that occurred during this period. Currents at Station 11 had an RMS speed of 10 cm/sec, significantly more than that of the other stations. Currents at Station 4 measured in 1974 had an RMS speed of 3.6 cm/sec which is lower than any of the stations in 1975, but the maximum speed of 23.1 cm/sec is comparable with the 1975 observations.

The maximum speed of the current recorded with ice cover was 38.1 cm/sec at Station 11 on May 29, 1975. At the same time at Stations 9, 13 and 15 speeds of around 20 cm/sec were recorded, but at the outer Stations 5, 8 and 10 no signs of increased speeds were evident. The wind at the time at Tuktoyaktuk had a mean speed of 21.8 knots with the highest hourly wind speed being 30 knots. In August, the highest recorded current reading was 40.9 cm/sec at Station 5 with a mean wind speed of 29 knots and a maximum wind speed of 40 knots. During the same storm, only 22 cm/sec was recorded at Station 13.

4.2.1. Residual Currents⁴

The average bottom current velocities at the stations clearly showed a net northeast flow (Fig. 16). The directions of the average velocities at Stations 4, 5, 8, 9, 10 and 11 all lay between 032°T and 054°T with Stations 8, 9 and 10 having speeds close to 5 cm/sec. At Station 5 the speed was slightly higher and at Station 11 is nearly double that of Stations 8, 9 and 10. The inshore stations in shallow water had current speeds less than half of those at Stations 8, 9 and 10 and had directions of 134°T and 152°T at Stations 15 and 13 respectively.

No logical explanation is readily available to account for the northeast flow over the shelf. We suspect it is part of a large scale circulation which is as yet unknown.

Figure 17 shows the shear zone in the ice field for May 17, 1975, which is taken as representative of that feature (Marko, 1975). The two stations under or close to the shore-fast ice recorded very little residual current, and Station 15, just north of the shear zone, has a small southeasterly current. The other five stations are north of the shear zone and recorded currents of 5 cm/sec or greater in a northeasterly direction. The ice cover north of the shear zone moved to the west with a five day average speed of 14 cm/sec. The

4. Residual current is the observed current less that due to tide.

area between the shear zone shown in Figure 17 and roughly the 500 metre contour is a transition zone. The transition zone normally exists between the land-fast ice and the polar pack ice which moves with the Beaufort Sea gyre. In the transition zone, from March until around the end of July, the ice moves in a southwesterly direction at speeds between 7 km/day (8 cm/sec) to 25 km/day (29 cm/sec). Ice movement may have some bearing on the direction of the bottom currents, but without a more intensive program of measurement of the water column to establish a reason for the apparent horizontal shear, no conclusive explanation can be given at this time.

One other surprising aspect of this survey was the correlation between increased speeds of the bottom currents and the force of the wind. No matter from which direction the wind blew, the currents always ran to the northeast at the offshore stations with increased speeds. Changes in ice concentration over the area made no difference to the increases in speeds of the bottom currents, in fact, from the records one cannot tell when the area became ice-free. It is possible that a relationship existed between the low pressure area associated with the periods of stronger wind and the increased speed of the northeast currents. This could explain the insensitivity of bottom currents to the ice cover.

4.2.2. The Effects of Wind and Barometric Pressure

The effects of wind and barometric pressure gradients on bottom currents on the continental shelf are only discernible in extreme cases. When the wind speed was less than 15 knots, no correlation was found between the surface winds and the bottom currents. For winds with speeds between 15 and 25 knots there were periods when the influence of the wind was noticeable, particularly at Stations 13 and 15. However, even for these relatively high wind speeds, no consistent or reliable relationship between wind velocities and bottom currents was found due to the presence of strong surges of current of unknown origin.

The storms that occurred on the 10th and 27th of August 1975, gave a good indication of the relationship between wind and bottom currents during strong winds. At Station 5 on August 10 (Fig. 10), the current reached a maximum of 35 cm/sec when the wind speed was 35 knots. The fluctuations in the wind velocity match fairly well the fluctuations in the current velocity. The wind direction plotted is the direction of flow of the wind, contrary to normal convention. At Station 13 (Fig. 11) for the same period, the bottom current velocity matches fairly well the wind velocities, but the maximum current speed recorded was only 22.5 cm/sec. In both the above cases the wind was that recorded at Immerk Island (Lat. 69° 37.4'N, Long. 135° 9.7'W), and was plotted with a lag of 8 hours and 6 hours respectively at Stations 5 and 13. On August 27 at Station 5 (Fig. 12) the fluctuations in current velocities again match quite well those of the wind. The current attained a maximum speed of 40.9 cm/sec after a sustained wind speed in excess of 30 knots. However, the peak wind speed occurred some two days previous

to the peak currents. It would appear that the duration of the wind from any one quarter is more likely to generate high current velocities than stronger winds over a short period (<12 hr.). For example, at Station 13, for the same period (Fig. 13), the current speed and direction follows that of the wind closely, with the highest speeds occurring 30 hours after the strongest winds, but only seven hours after those with a much longer duration. From these observations we may conclude that: at Station 5 for strong winds, the current speed increased by nearly 1 cm/sec for every knot increase in wind speed and increase by a little more than 0.5 cm/sec at Station 13 for every knot increase in wind speed.

The barometric pressure gradient associated with the storm of August 8, 1975, is plotted with the corresponding currents at Stations 13 and 5 (Fig. 14 and 15). It is seen from these and the previous diagrams of the wind and current, that the wind stress is the more direct cause of the current. The direction plotted for the gradient is that toward the lower pressure. The gradient was calculated from observed pressures at Barter Island, Cape Parry, Tuktoyaktuk, and Inuvik. Separation of the effects of barometric pressure gradient and wind stress was not attempted as the wind is probably a more accurate indication of the local pressure gradient than that derived from the available observed pressures.

4.2.3. Tidal Streams

The tidal streams in the Beaufort Sea have low speeds, in the range 2-3 cm/sec (.05 knots), and consequently are for the most part masked by currents due to other causes. They are also mainly semi-diurnal, the ratio of M_2/K_1 being around 3.5 for all stations except the two north of Baillie Island, where the ratio is 0.6. This result is in close agreement with observed tides, which become mostly diurnal as they round Baillie Island and enter Amundsen Gulf.

Over the shelf north of Tuktoyaktuk Peninsula the tidal streams are mixed, being semi-diurnal with the M_2 constituent (see Fig. 18) being the dominant factor. The amplitude of M_2 increases towards the west, with Station 13 having the largest amplitude of 2.2 cm/sec. The amplitudes of M_2 at Stations 10 and 11, however, drop off sharply to 0.7 cm/sec while the amplitude of K_1 (see Fig. 19) rises to 1.0 cm/sec from about 0.3 cm/sec on the shelf.

The phase angles of the M_2 tidal stream constituent are completely different from those of the tidal constituent. In this case the time of maximum flow advances from east to west, and takes 9 hours to traverse the distance from Baillie Island to McKenzie Bay, whereas the time of high water takes 2 1/2 hours to cover the same distance, but in the opposite direction. Why this should be is not clearly understood at present, and the area will have to be studied in greater detail before the mechanics of the tidal processes are known.

The phase angles of K_1 (Fig. 19) behave the same way as for

the tide (Fig. 8), with the co-phase lines running parallel to the coast. The phase of the tidal stream is 90° out of phase with that of the tide, which makes slack water occur at the time of high and low water for the diurnal constituents.

4.2.4. Inertial Oscillations

Inertial oscillations occur when the water is disturbed by external influences, for example, by rapid wind and atmospheric changes. Under the influence of the coriolis effect (the deflecting force of the earth's rotation), the water displacement is transferred into an inertial oscillation with a period of half a pendulum day. For Latitude 70° this period is 12.7 hours, which falls among the periods of the semi-diurnal tidal components, and is very close in period to the N_2 component.

The two storms that occurred in August 1975, imparted considerable energy to the bottom currents; several surges with considerable rotary motion were recorded. The current data records were divided into seven-day intervals and harmonic analysis was performed upon each of these seven-day intervals to obtain the current ellipses. Major and minor axis of these ellipses are listed in Table 2. We see that for the week centred on August 7 there is a marked increase in the magnitudes of M_2 and a large deviation in the phases. This disruption of M_2 is not due to the tidal effect, which is quite predictable, but is caused by inertial oscillations dominating the semi-diurnal frequencies. (Note that with a seven day record length the semi-diurnal components are not separable.) If for Station 5 we subtract the M_2 component for the whole record from that obtained for the week of August 7, we obtain a major axis of 4.1 cm/sec, a minor axis of 3.7 cm/sec and a clockwise direction of rotation, which gives a very nearly circular inertial current. At Station 13, for the same week, there is a noticeable increase in M_2 and a tendency towards circular motion, but not as strong as that for Station 5, as the motion is damped by friction in the shallow depths. Similar effects are seen for the week centred on August 28.

Weak manifestations of the inertial oscillations seem to have appeared at Stations 5 and 13 during May, June and July, but these are not well defined. Stations 8, 9, 10 and 11 showed no evidence of this effect during May, June or July. The surges, mentioned above that occurred during the August storms, occurred when the sea was relatively ice free. During May, June and July the area was covered by ice, accounting for the reduced amplitudes of the inertial oscillations, and indicating that these oscillations were mostly wind-driven.

5. CONCLUSIONS

The tide propagates from west to east along the southern edge of the Beaufort Sea, and as it rounds Baillie Island to enter Amundsen Gulf it slows down considerably. The tidal characteristics are mixed, being predominantly semi-diurnal over most of the Mackenzie Basin shelf, but becoming predominantly diurnal as the wave rounds Baillie Island. The tidal streams associated with the tide are very weak, in the order of 2-3 cm/sec and are semi-diurnal. However, the time of maximum flow progresses from east to west across the shelf, and the reason for this is not understood at this time.

Changes in mean sea level are often larger than the tide, and are closely related to the wind speed and direction. The storm surge heights shown in Figure 9 appear to be representative of the general pattern of storm surge heights for the area, but Shallow Bay has a far greater surge height than elsewhere, and this height may not be as predictable as the water level heights elsewhere on the coast.

Another prominent feature of the continental shelf of the southeastern Beaufort Sea is the prevalence of a northeast current during the months of May to September along the outer regions of the shelf. This current is quite sensitive to wind speeds but not to wind directions, the current maintaining a steady northeast direction but varying in speed according to the wind speeds. The mechanisms driving this current are unknown, and studies must be carried out over a wider area before any light can be shed on this problem.

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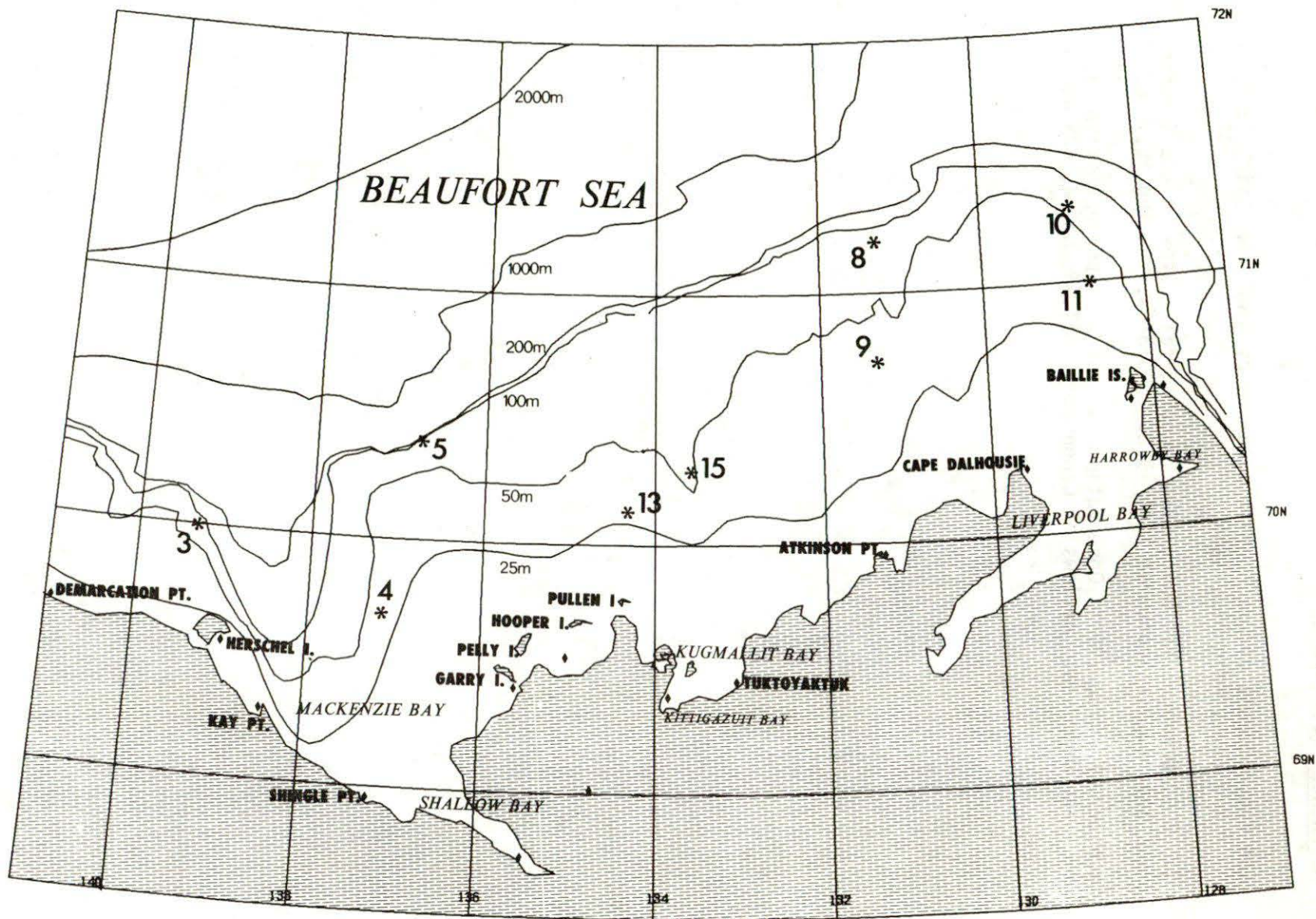


FIG. 1

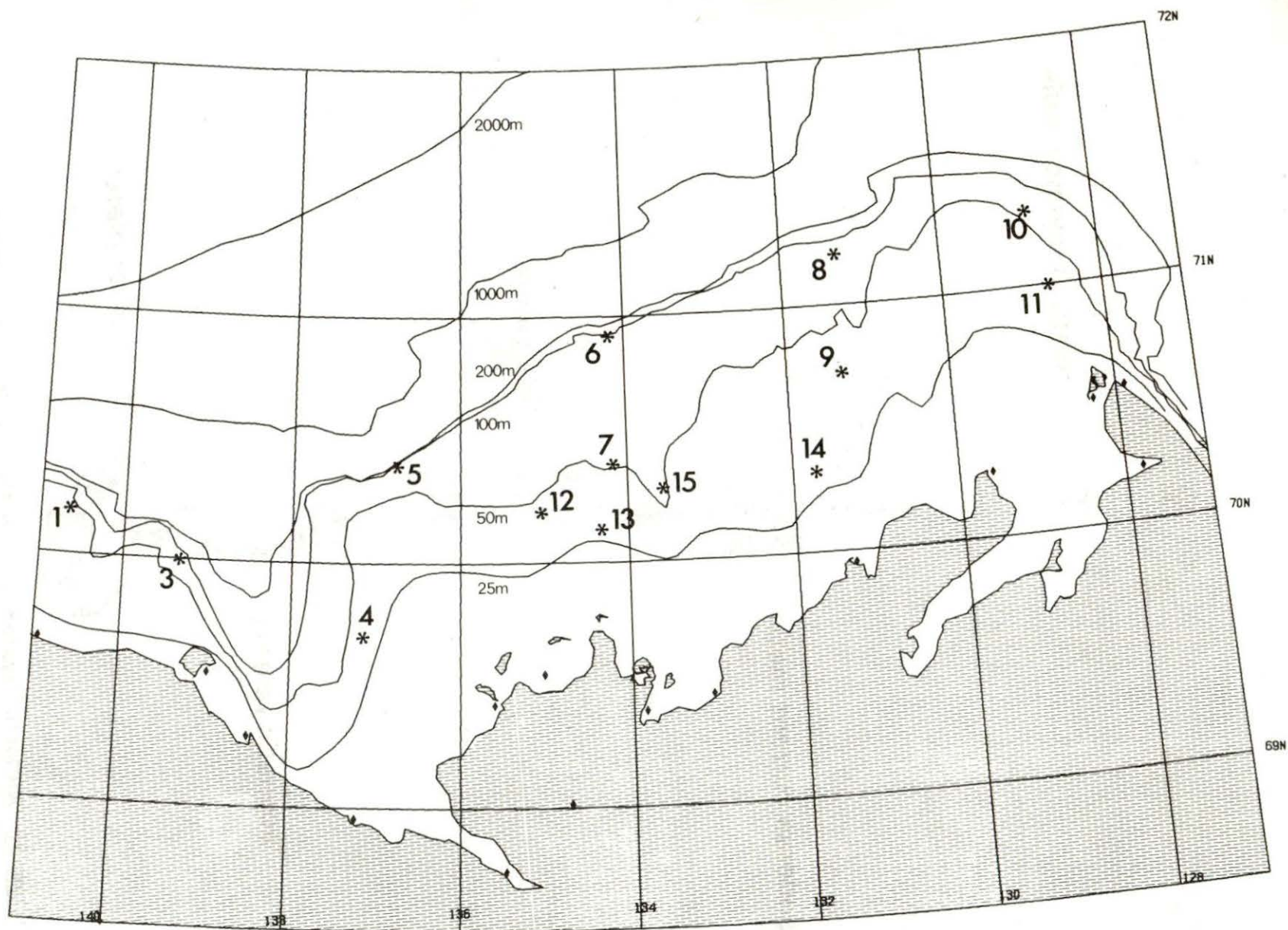


Fig. 2 POSITIONS OF OFFSHORE MOORINGS AND
SHORE TIDE GAUGE STATIONS

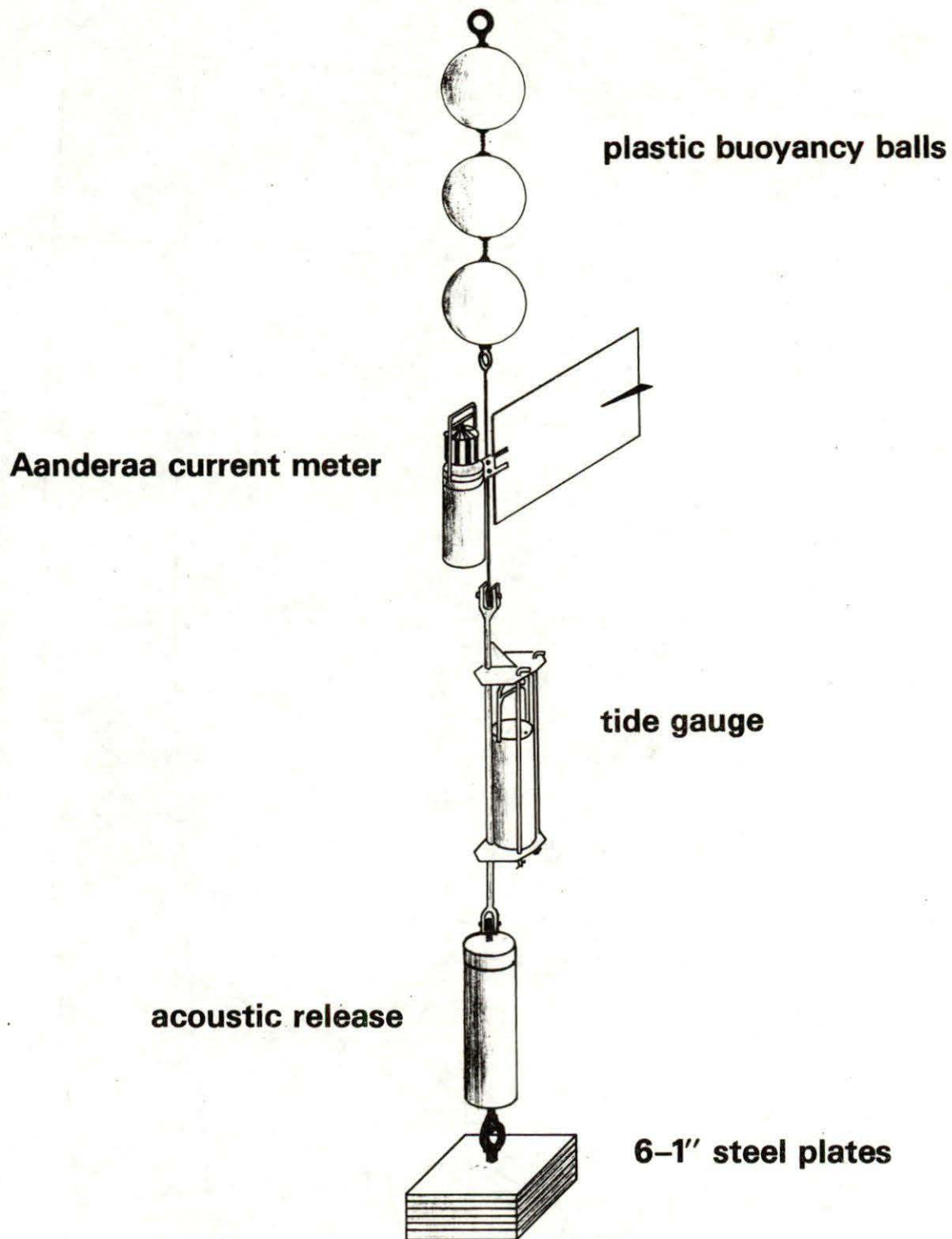


Figure 3: Anchoring system used in the Beaufort Sea under ice cover. (Unit moored on bottom by lowering through hole in ice).

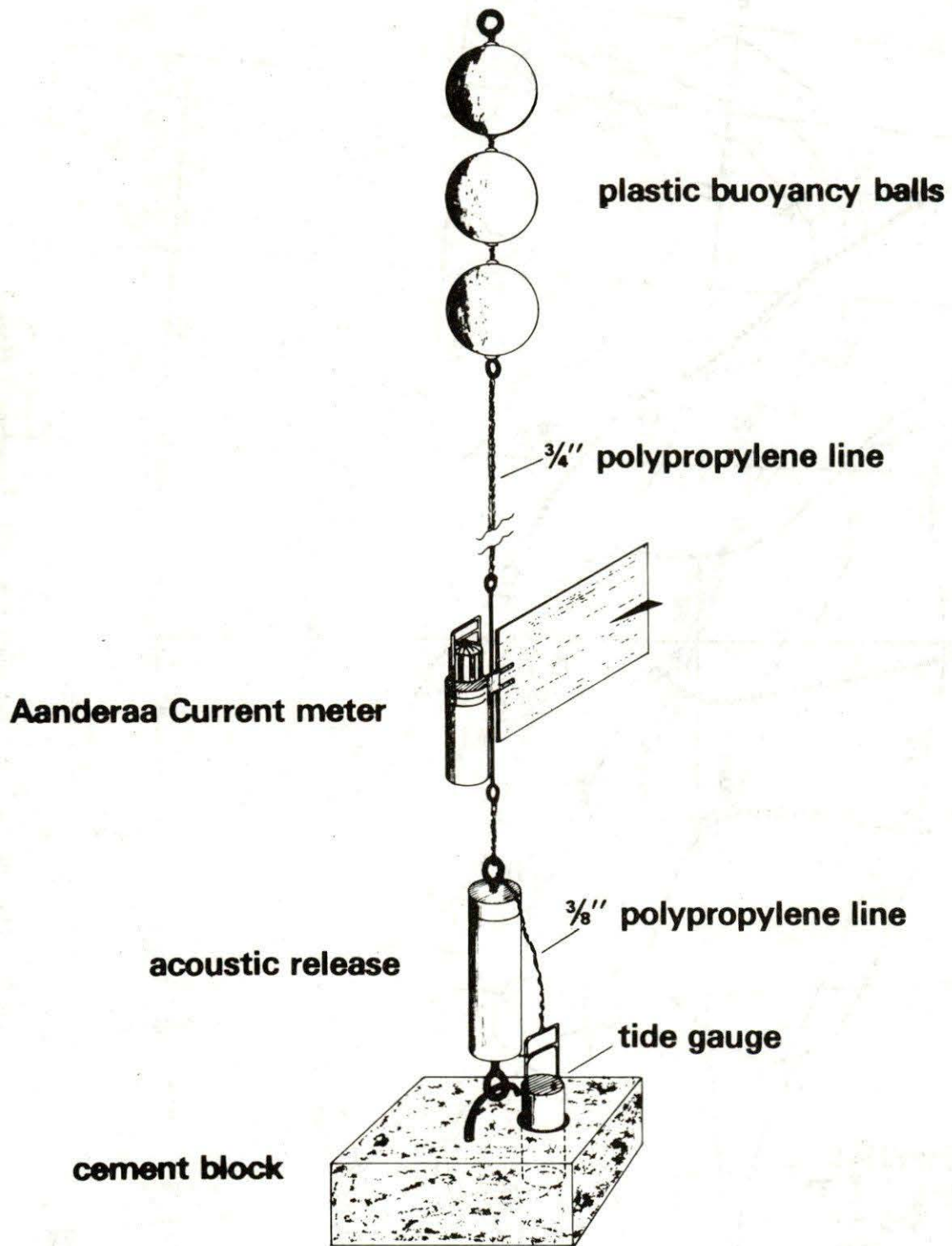


Figure 4. Anchoring system used in the Beaufort Sea when ice free.

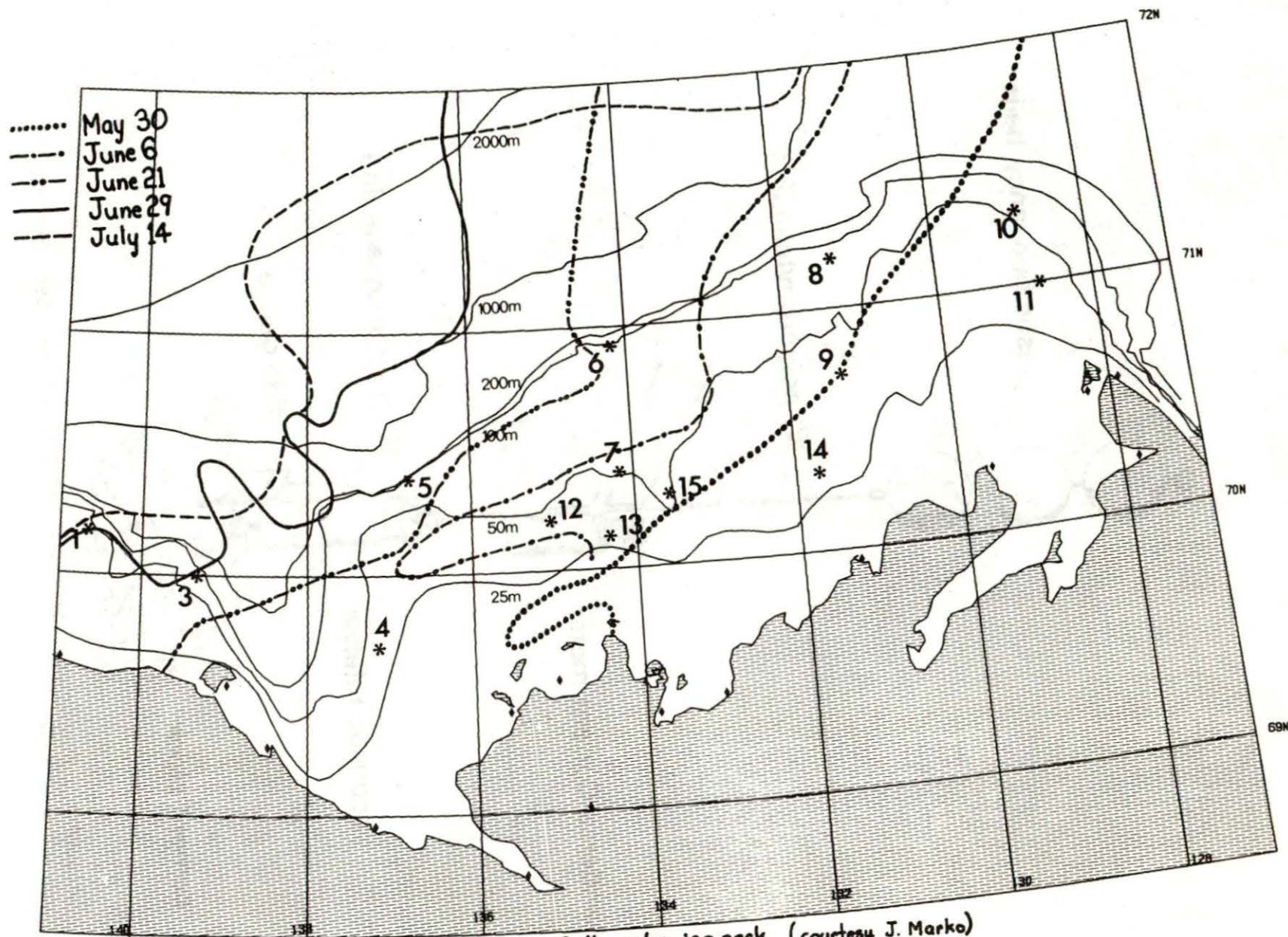


Fig.5 The retreat of the polar ice pack (courtesy J. Marko)

BEAUFORT SEA TIDE GAUGES

STATION - NUMBER LAT. LONG	1973	1974				1975			
	Sept-June	July	Aug	Sept	Oct-June	July	Aug	Sept	
DEMARCATON BAY 6530 69° 41' 141° 14'							28/8	14/9	
HERSCHEL ISLAND 6525 69° 34' 138° 55'	25/9				16/11	13/7	30/8		
KAY POINT 6515 69° 17' 138° 26'		14/7	19/7	6/8	3/9	9/9	22/9	23/6	12/9
SHINGLE POINT 6505 68° 56' 137° 12'		14/7	28/7	2/8	20/8				
SHALLOW BAY 6503 68° 45' 135° 36'						31/7	14/9		
GARRY ISLAND (75) 6499 69° 27' 135° 36'						15/7	24/8		
RAE ISLAND 6492 69° 32' 135° 07'		28/7			26/9				
TUNUNUK POINT 6490 69° 00' 134° 39'						18/7	28/8		
KITTIGAZUIT BAY 6488 69° 25' 133° 52'						31/7	14/9		
TUKTOYAKTUK 6485 69° 27' 133° 03'						8/7			
ATKINSON POINT 6476 69° 57' 131° 25'		27/7			27/9	10/7	13/9		
BAILLIE ISLAND (S.S.) 6443 70° 31' 128° 21'		27/7			27/9	15/7	18/8	1/9	13/9
HARROWBY BAY 6447 70° 14' 127° 39'						10/7	13/9		

Figure 6. Operating times of Beaufort Sea Coastal Tide Gauges.

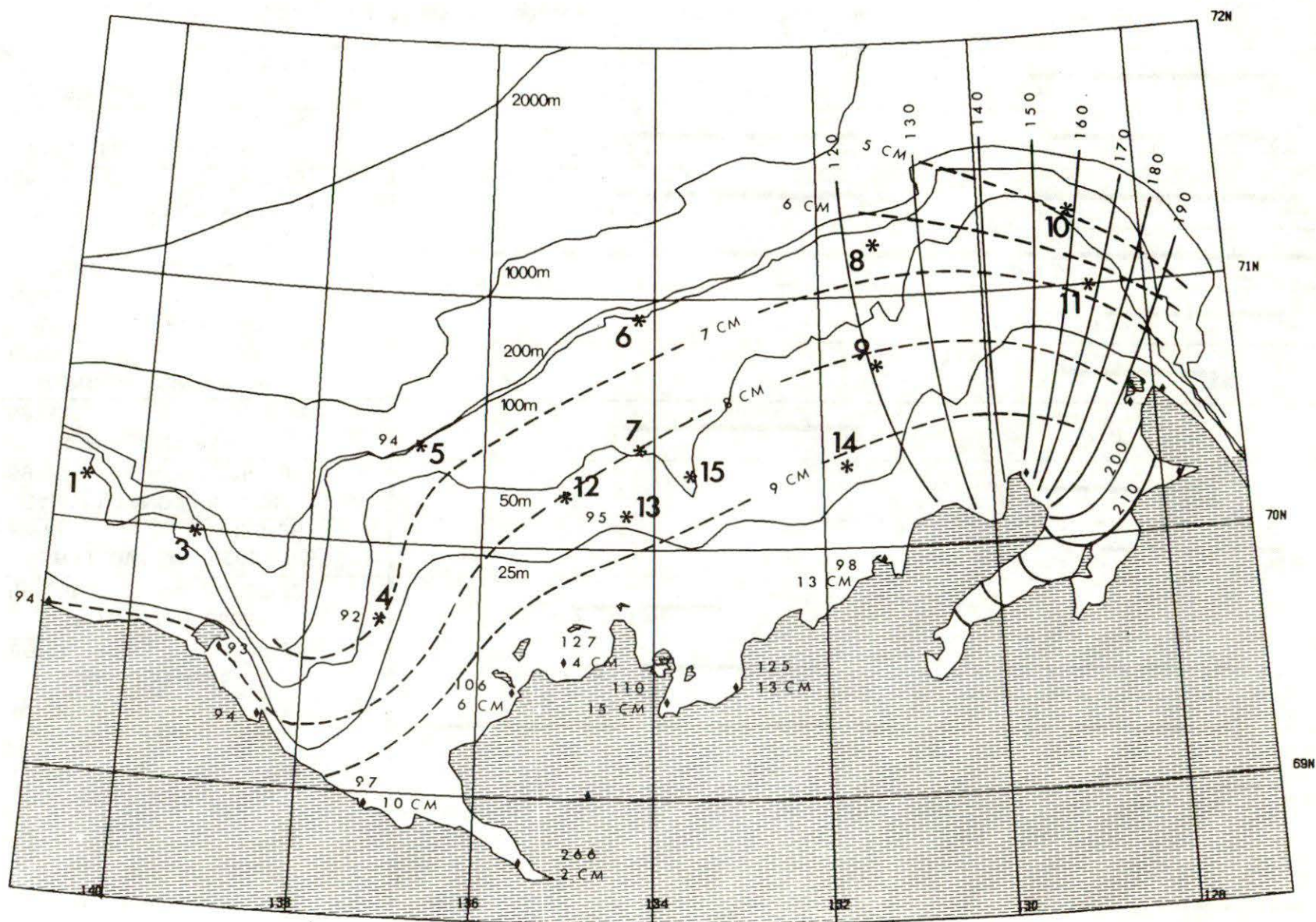


FIG.7 M₂ COTIDAL CHART - WATER LEVELS (Z+6)

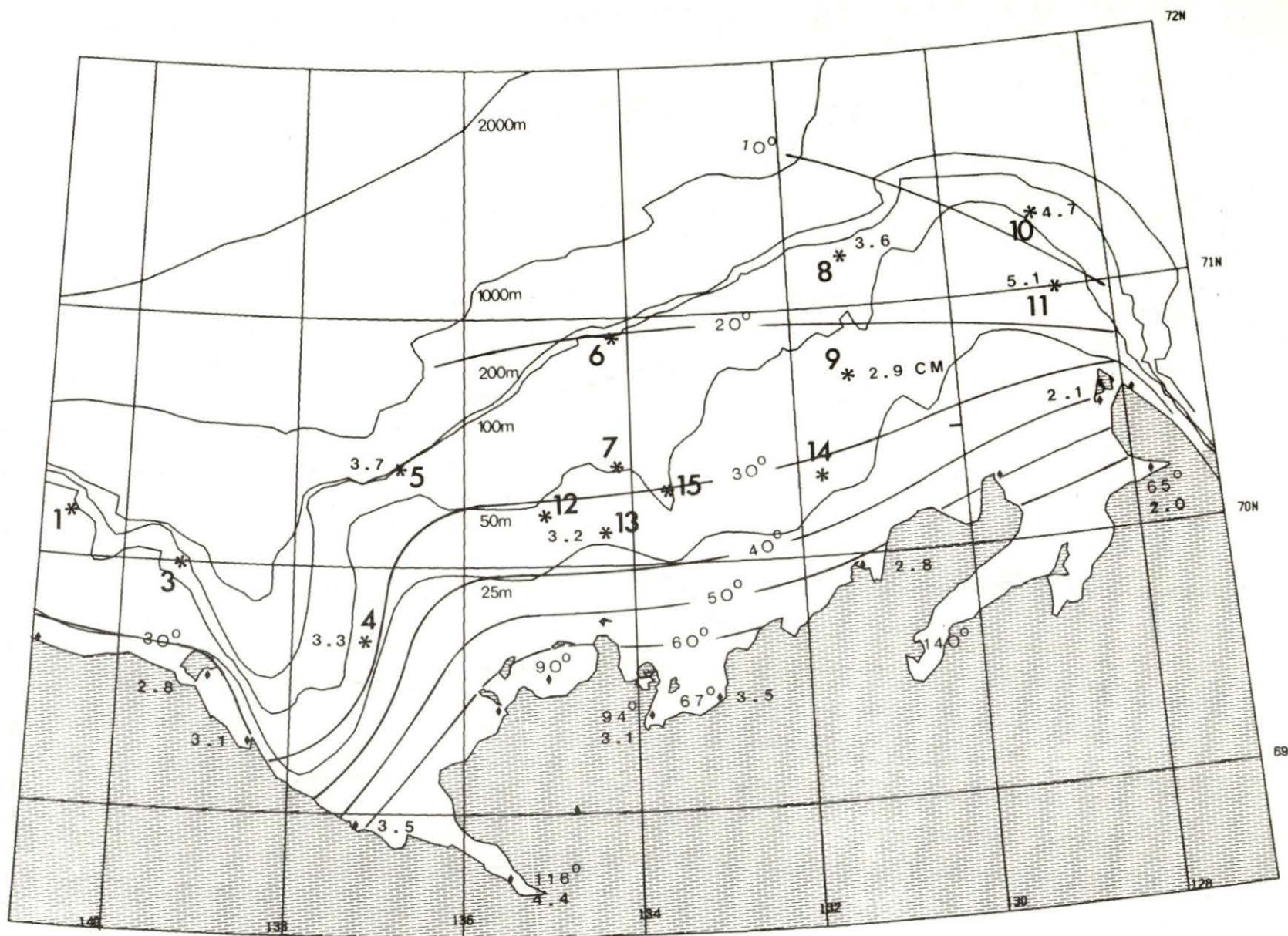


FIG. 8

K₁ COTIDAL CHART - WATER LEVELS (Z+6)

AMPLITUDES IN CM

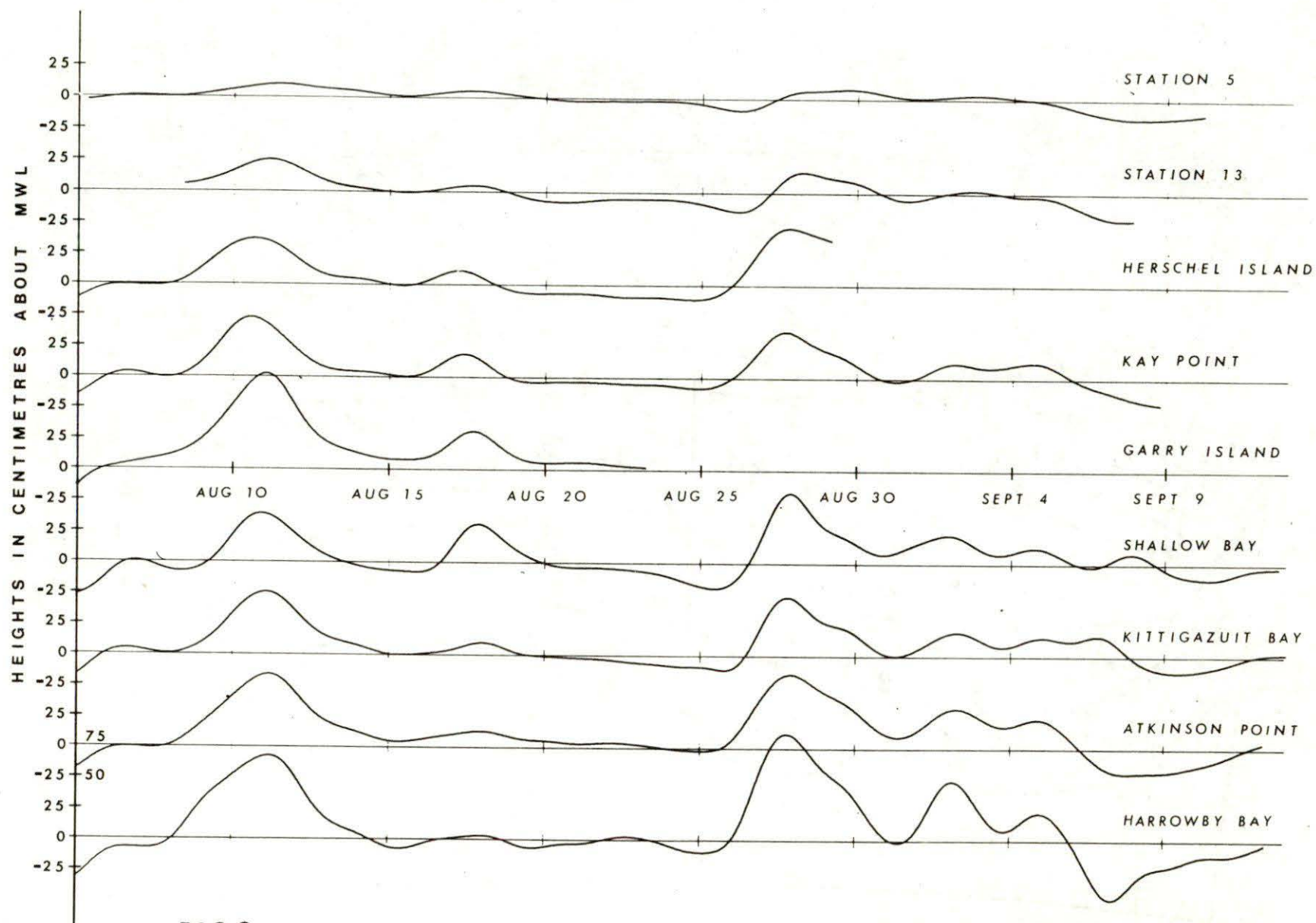
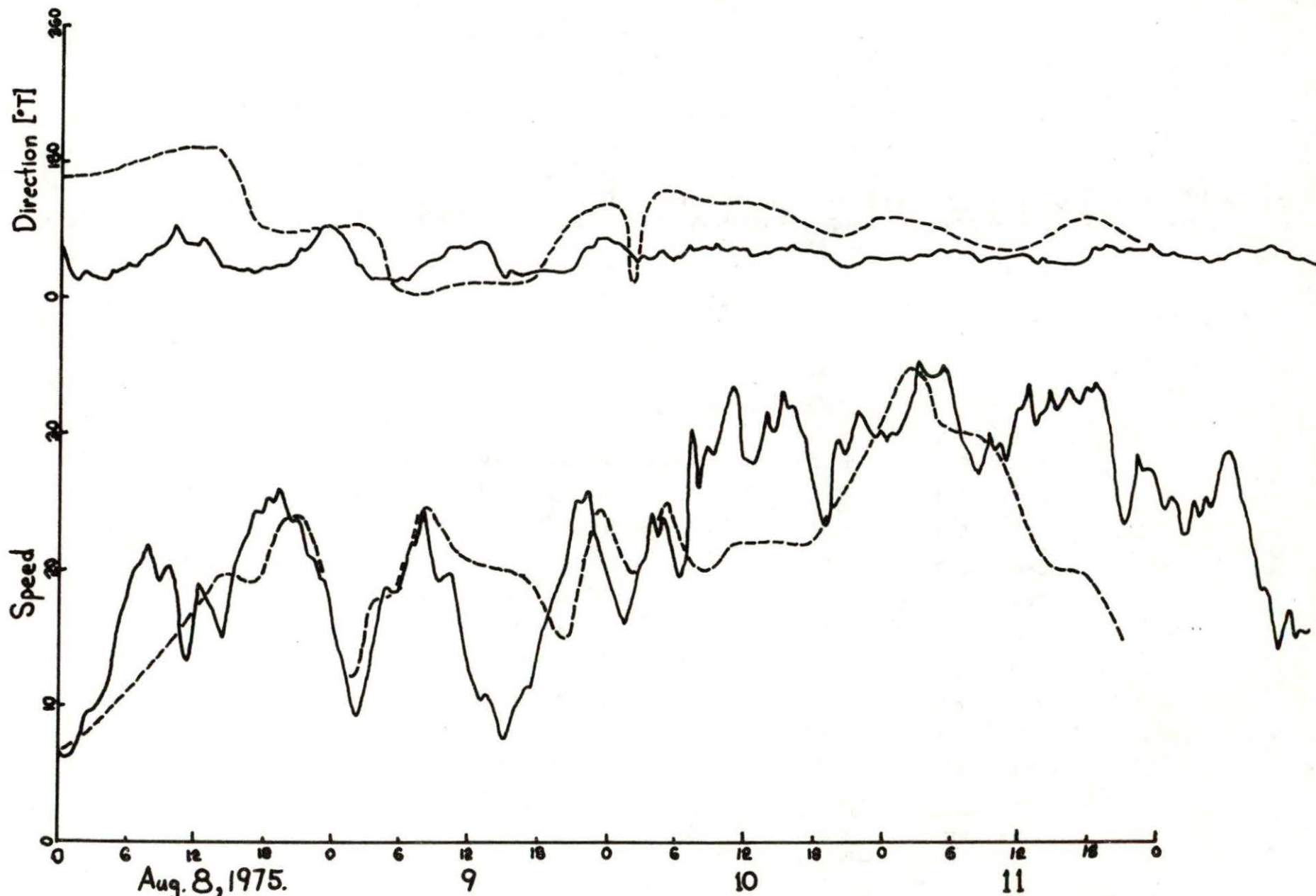


FIG.9 LOW PASS FILTERED WATER LEVELS AUG 05 - SEPT 13 1975

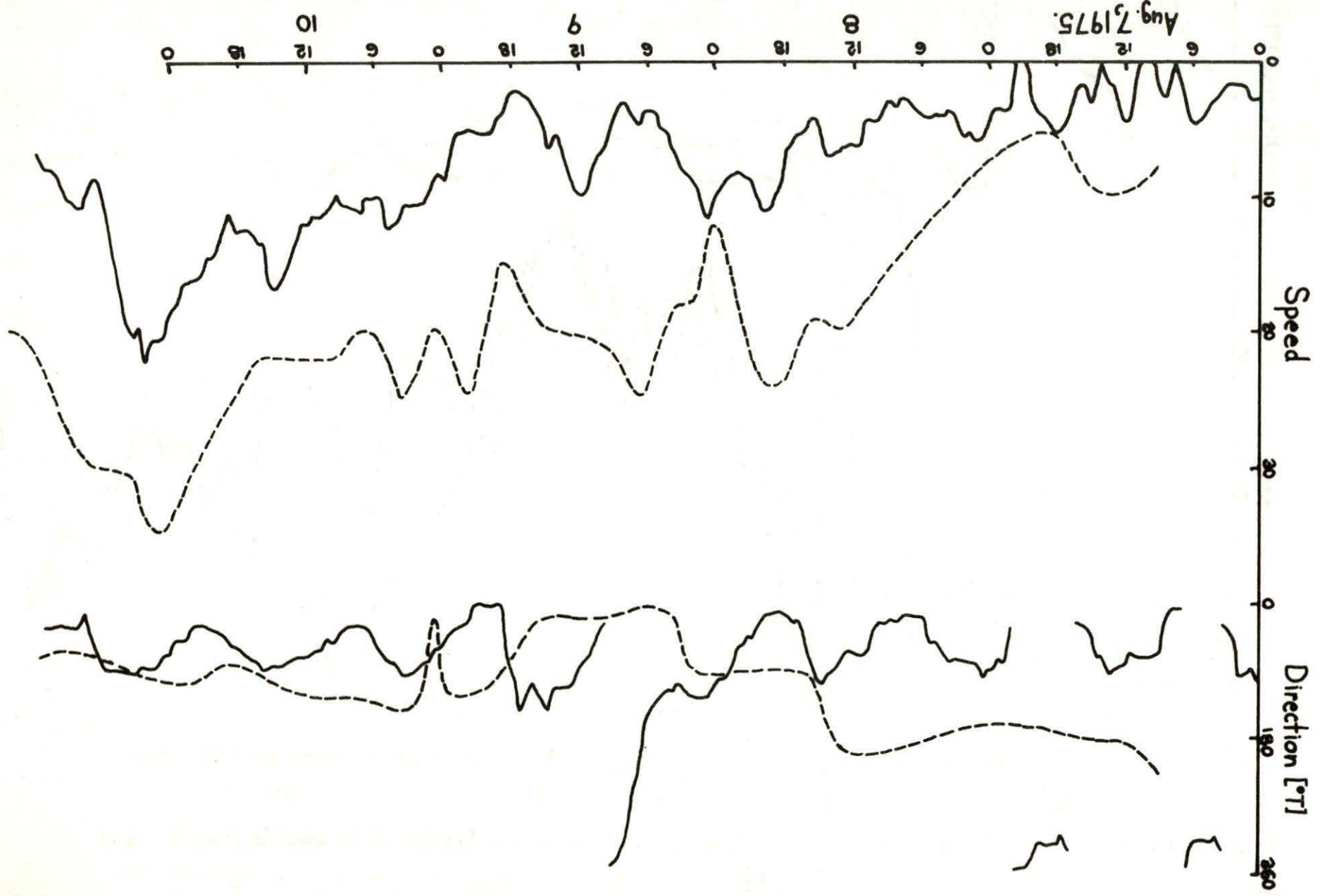
Station	Date		R.M.S. Speed cm/sec	Maximum Speed cm/sec	Average Velocity cm/sec	θ_T
4	9/5-30/6	74	3.6	23.1	2.4	143
13	26/4-29/7	75	5.6	20.2	0.5	159
15	28/4-5/8	75	7.5	21.6	2.2	134
9	26/4-5/8	75	6.0	21.0	4.4	054
11	25/4-4/8	75	9.9	38.1	8.2	040
5	29/4-2/8	75	8.0	23.1	6.0	047
8	26/4-4/8	75	6.2	16.3	4.9	032
10	25/4-4/8	75	5.8	16.4	4.9	035
13	6/8-8/9	75	6.4	23.8	0.9	110
5	3/8-10/9	75	13.8	40.9	8.3	051

Table 1: R.M.S. speed, maximum speed and average velocity at each station. Direction of average velocity is in degrees true.

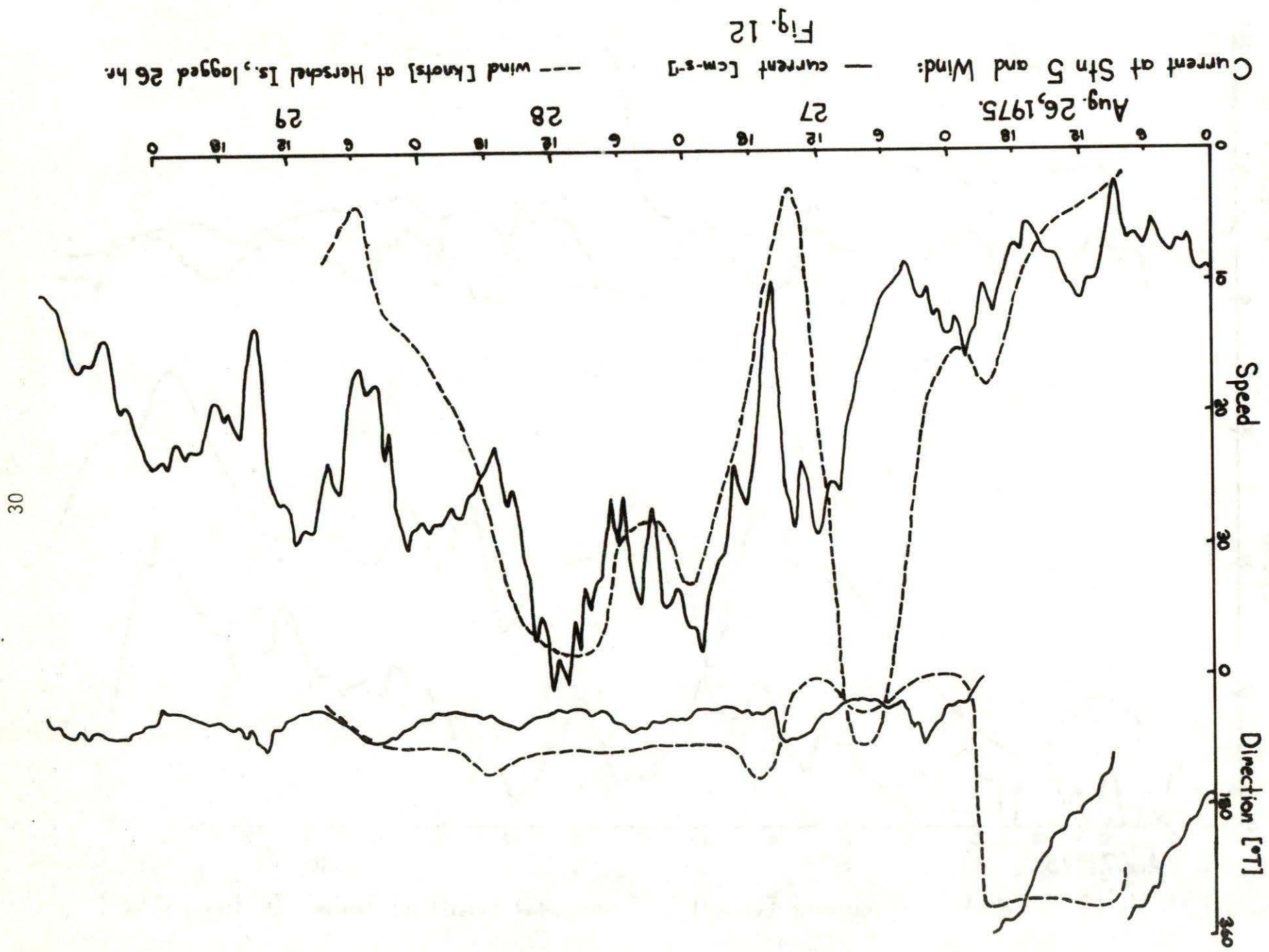


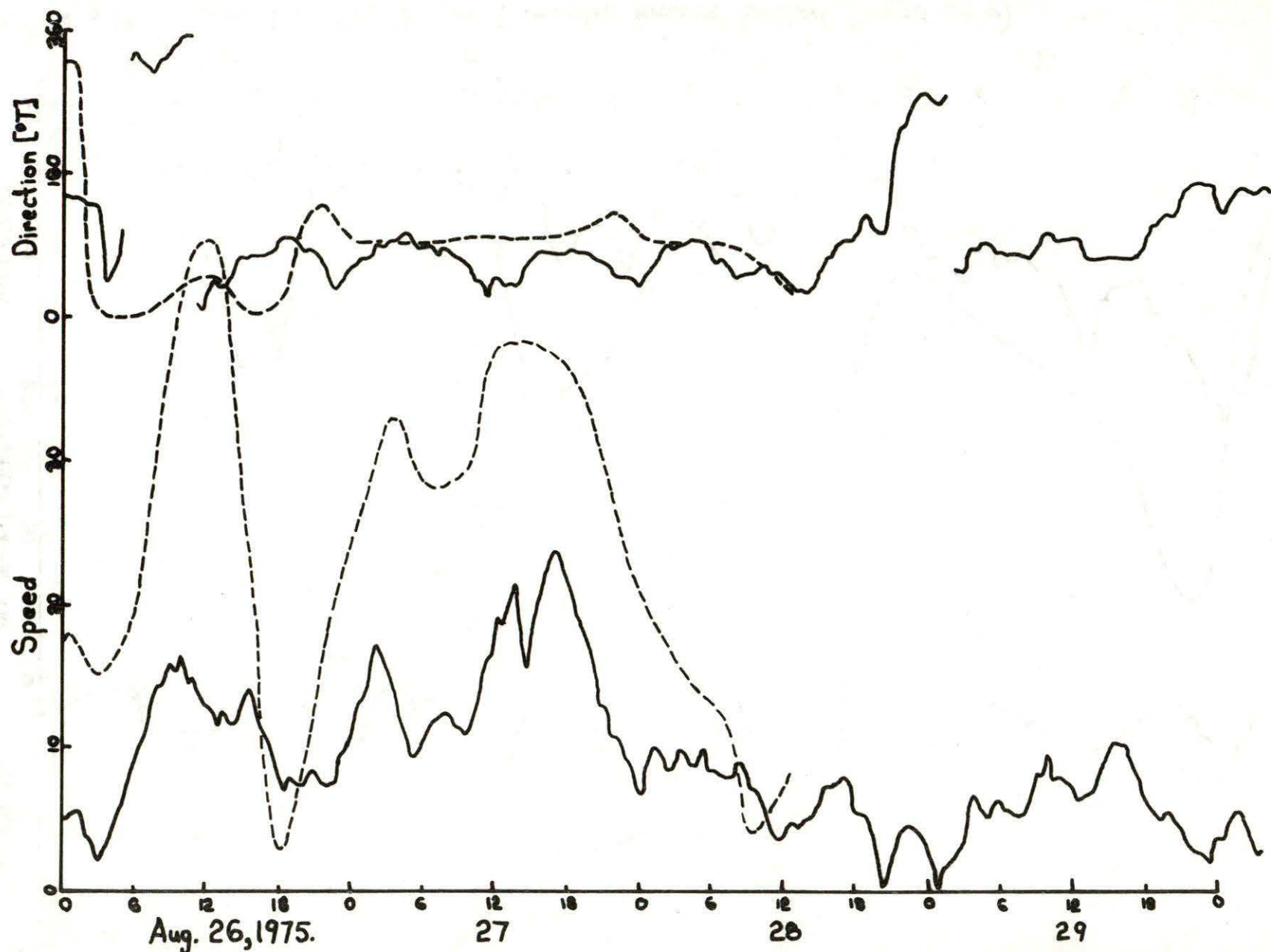
Current at Stn 5 and Wind: — current [cm-s⁻¹] --- wind [knots] at Immerk Is. lagged 8 hr.

Fig. 10



Current at Sta 13 and Wind: — current [cm-s⁻¹] --- wind [knots] at 1mmark Is. lagged 6 hr.
Aug. 7, 1975.
Fig. 11





Current at Stn 13 and Wind: — current [cm-s^{-1}] --- wind [knots] at Herschel Is. lagged 7 hr.

Fig. 13

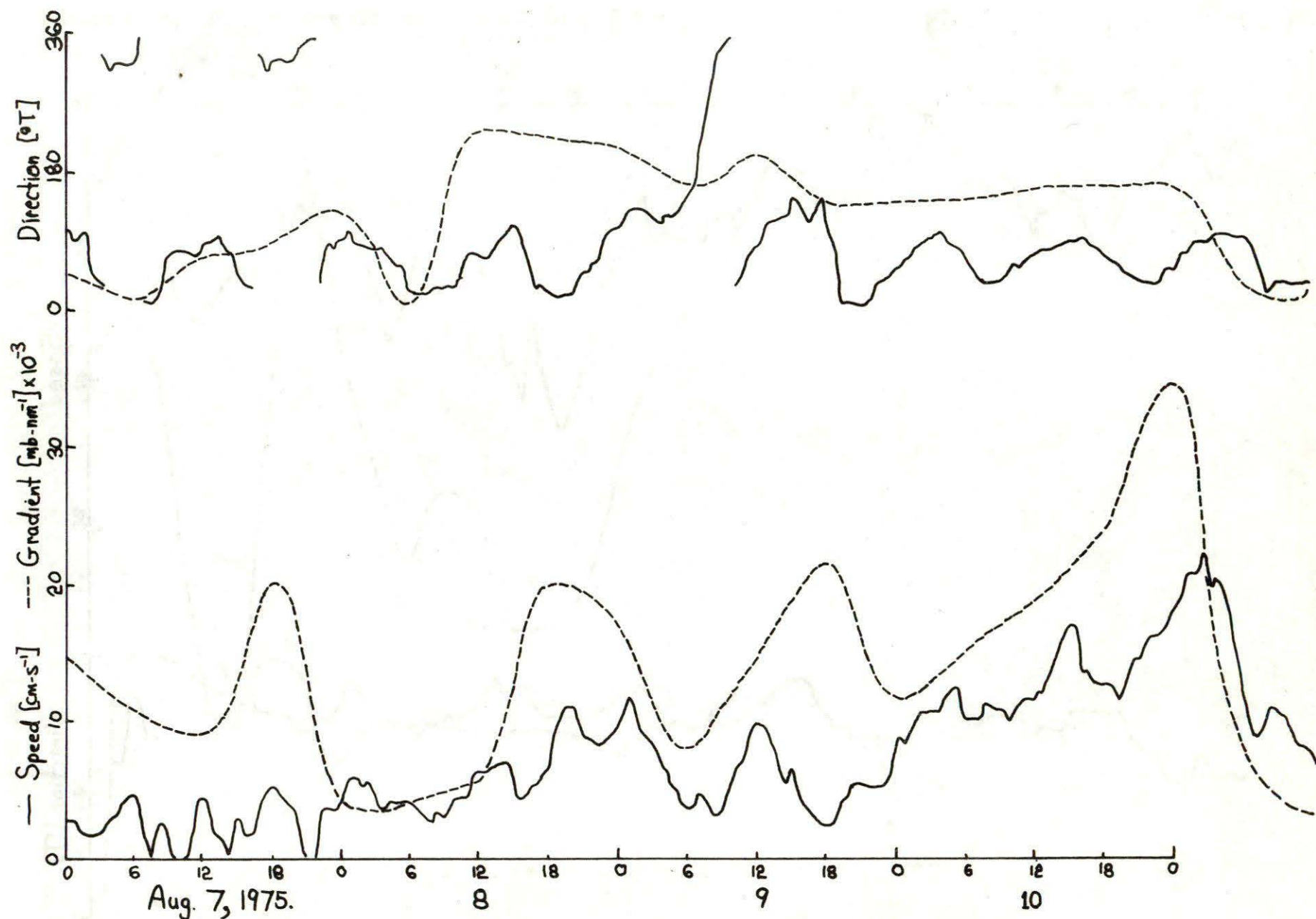


Fig.14 Current at Stn. 13 and Barometric Pressure Gradient (lagged 24 hr)

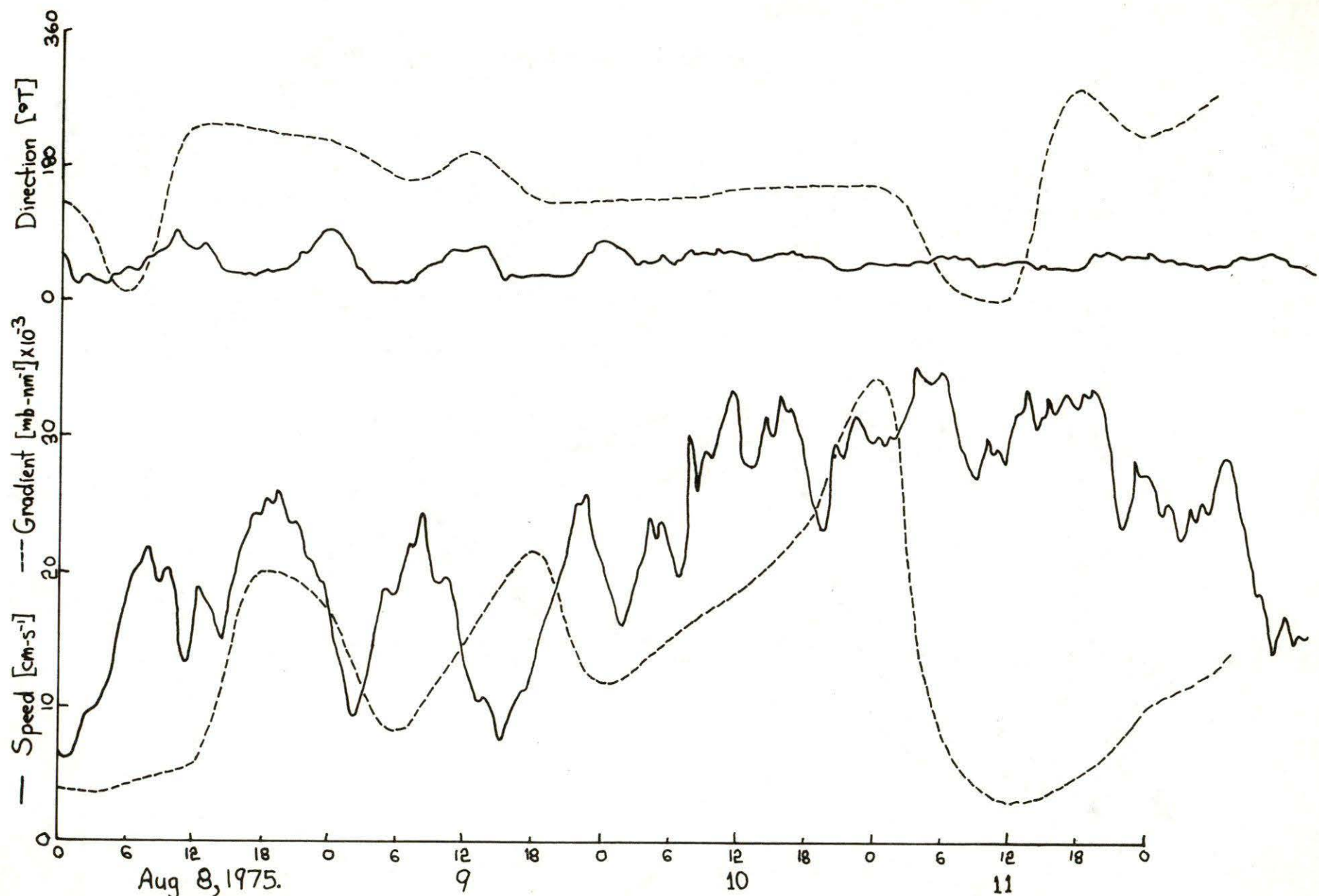


Fig. 15 Current at Stn 5 and Barometric Pressure Gradient (lagged 24 hr)

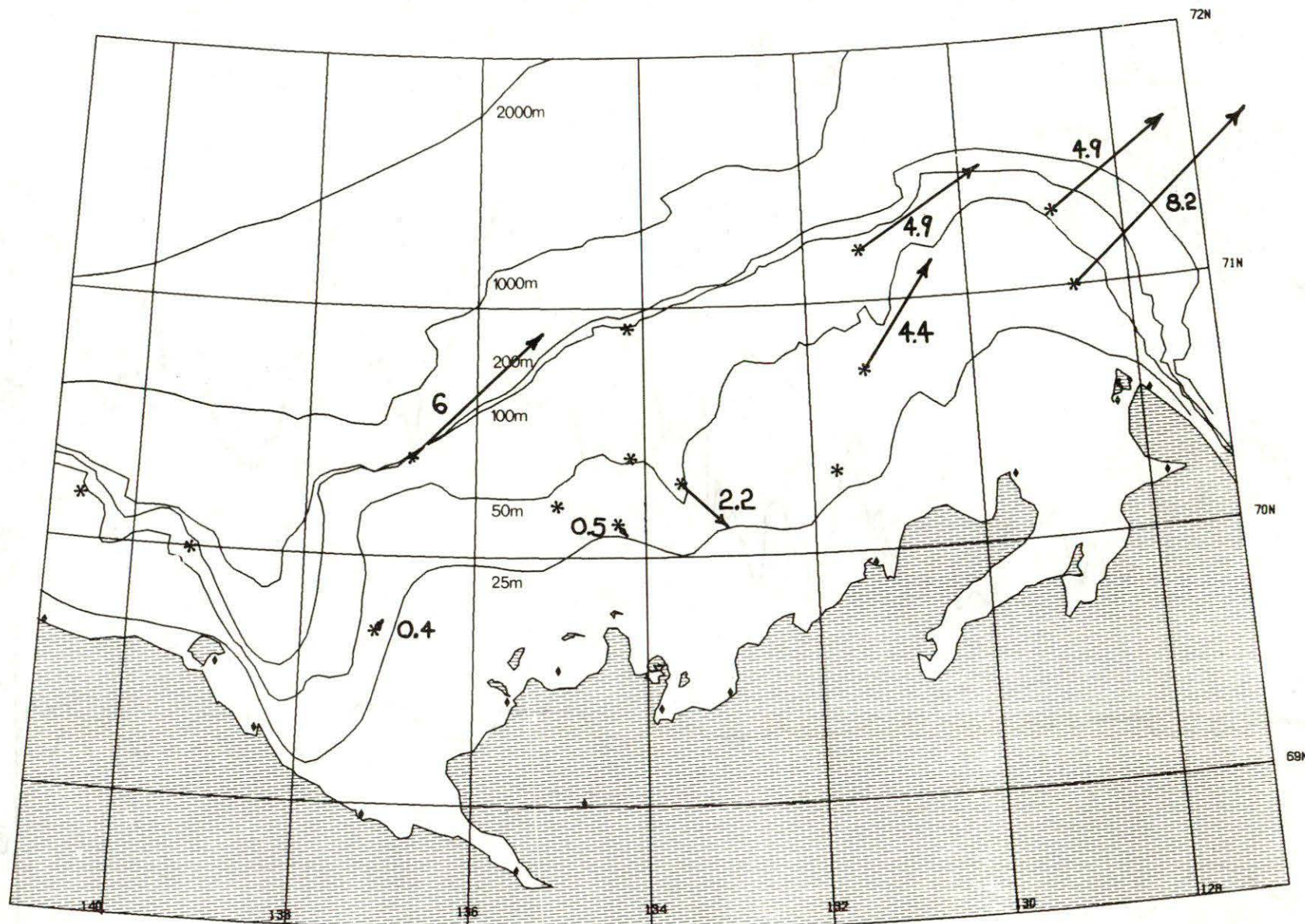
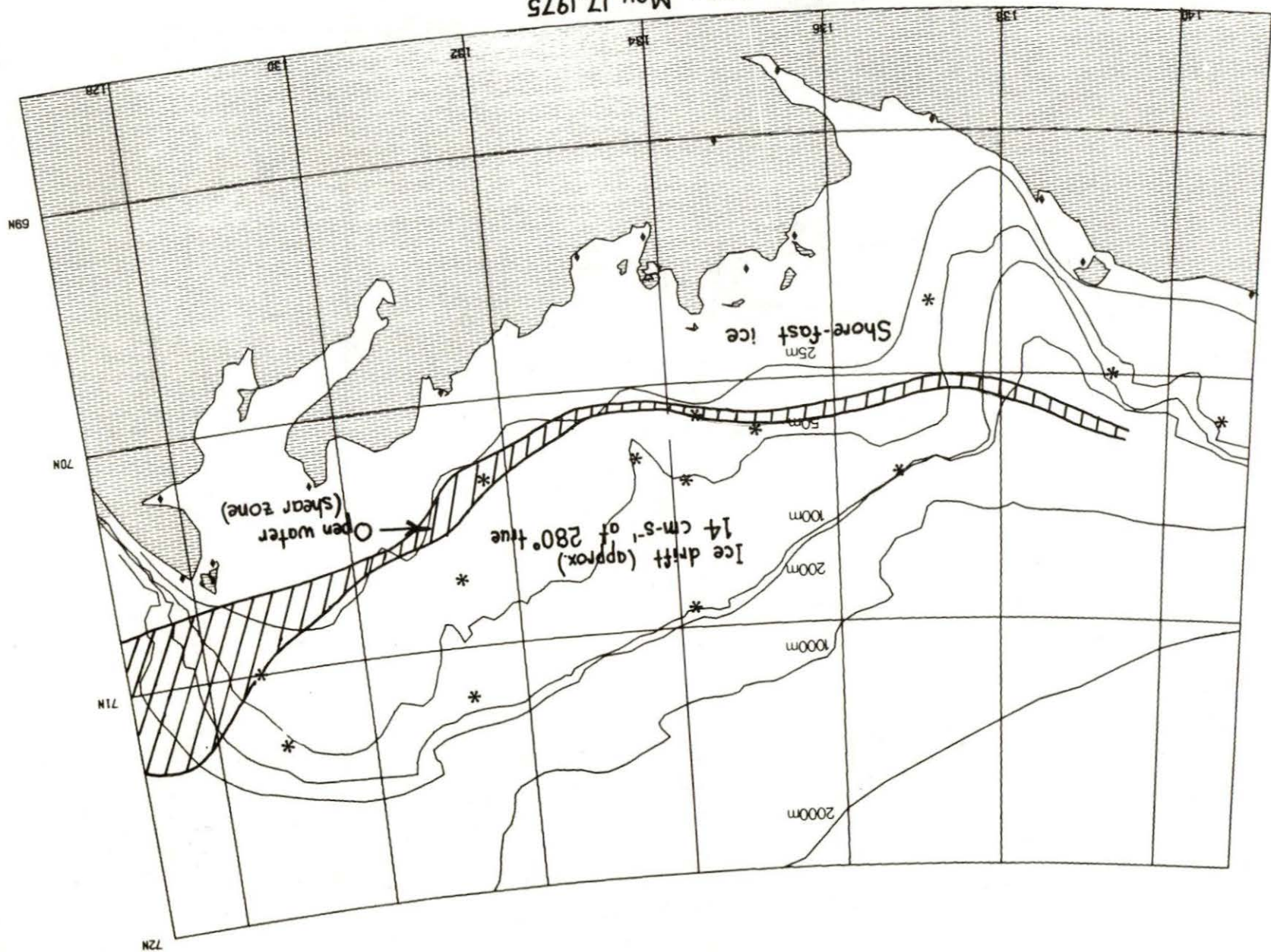


Fig.16 The residual current velocity 1975

Fig. 17 The shear zone - May 17, 1975



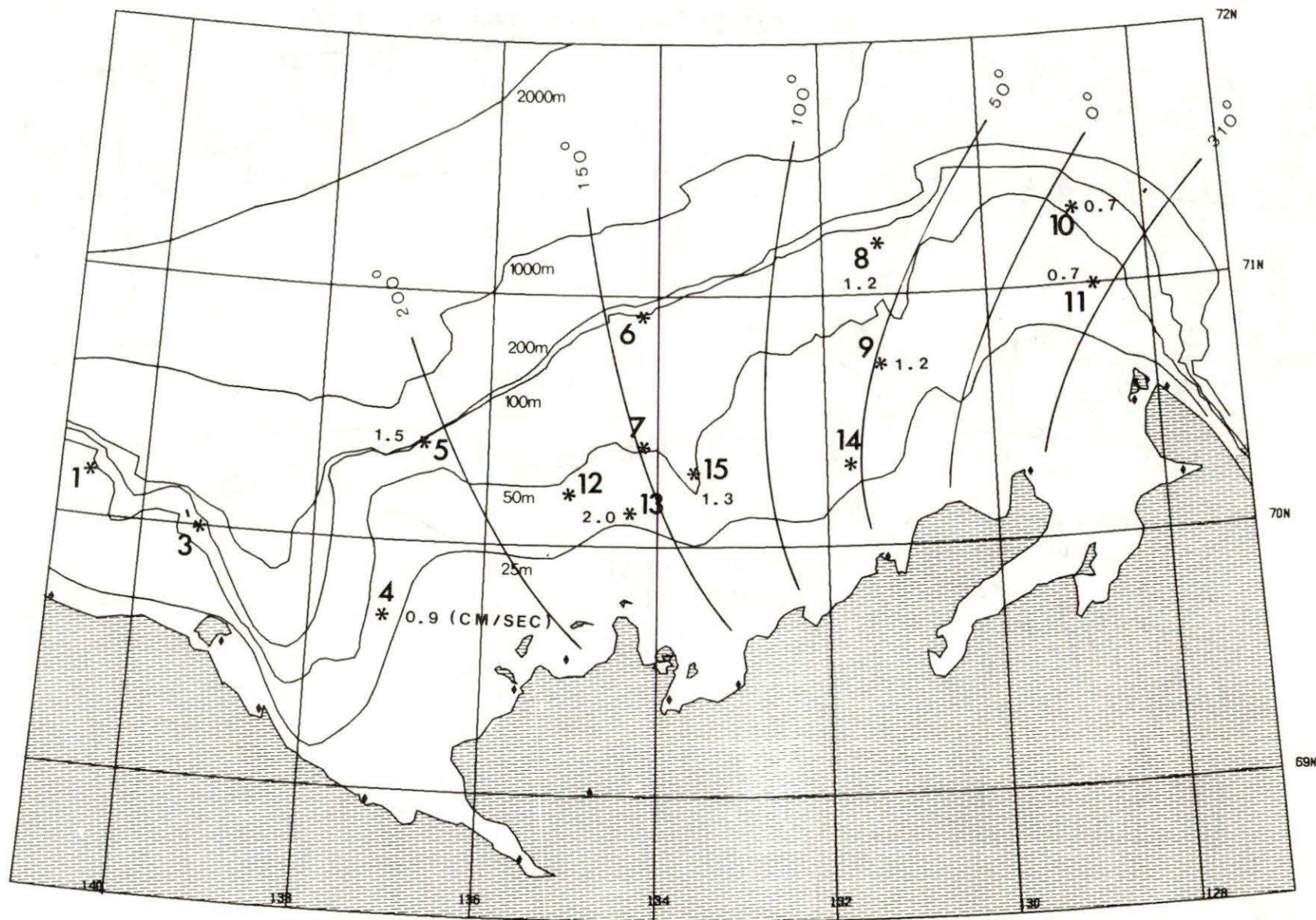


FIG 18 M₂ COTIDAL CHART - TIDAL CURRENTS (Z+6)

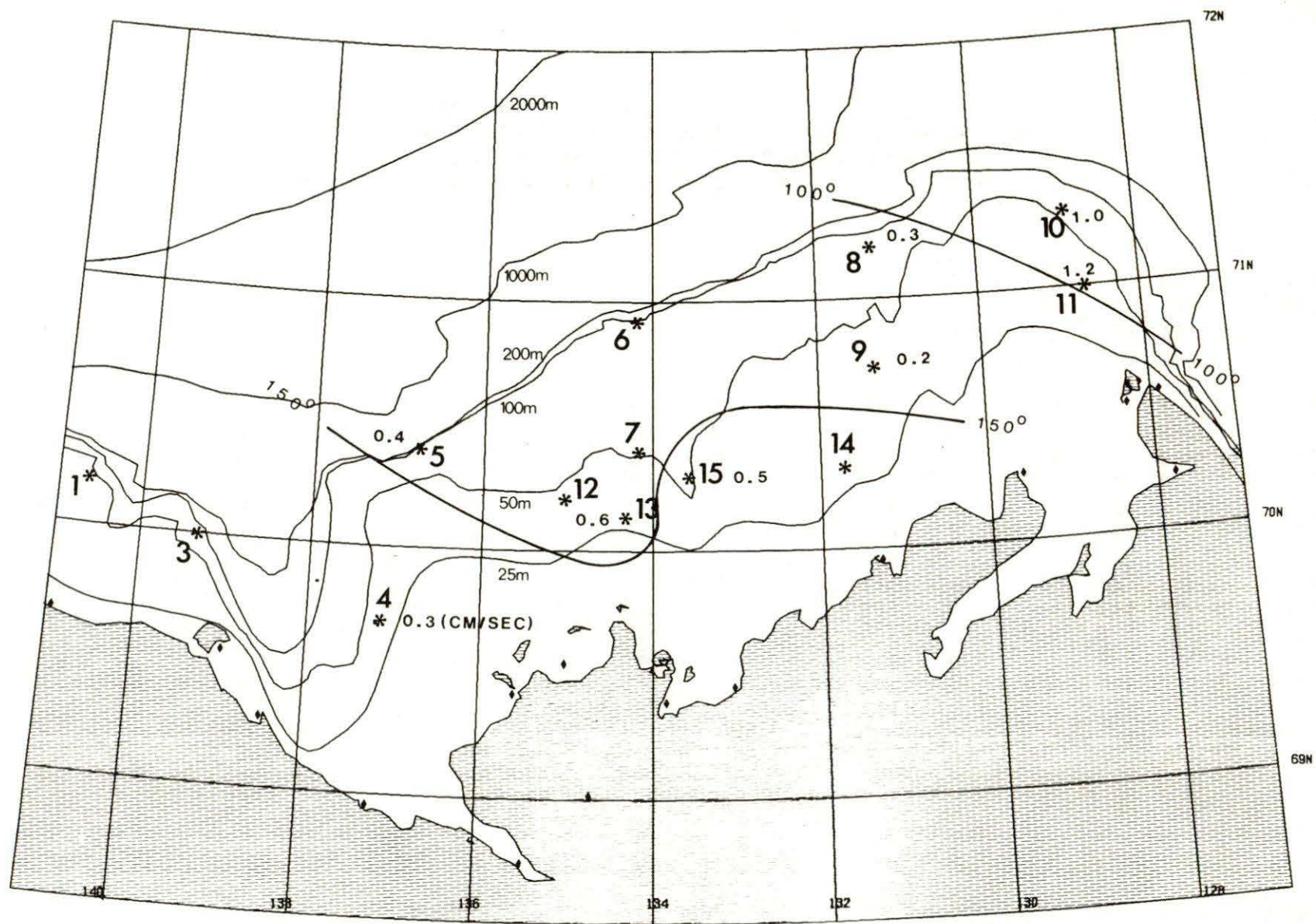


FIG 19 K₁ COTIDAL CHART - TIDAL CURRENTS (Z+6)

	Station 5			Station 10			Station 11			Station 13				
	Major	Minor	G	Major	Minor	G	Major	Minor	G	Major	Minor	G		
Entire Record	1.5	-0.4	203	0.7	0.0	340	0.7	0.3	316	2.2	0.5	162		
Central Day of the Week													Predominant Features of the Wind	
30/4/75	1.5	-0.8	245	1.7	-0.5	129	0.9	-0.4	394	2.2	0.0	144	E→NW→E	7(10)
7/5	2.7	-1.8	278	0.5	-0.1	185	0.8	0.6	310	1.8	0.1	184	E→NW→E	10(16)
14	1.7	.4	222	0.8	-0.6	339	1.3	0.0	291	2.8	-0.2	168	N→E	10(24)
21	1.6	-0.8	246	0.7	-0.2	375	0.9	0.1	306	2.4	0.3	179	W→E→NW	10(19)
28	0.7	-0.4	95	1.5	0.3	322	1.8	-0.3	329	2.8	0.5	173	N→E→NE	15(30)
4/6	1.1	-0.5	219	0.6	0.2	313	2.2	0.3	329	1.5	0.4	172	NE	10(18)
11	1.7	-0.3	204	1.0	0.1	337	1.8	0.3	153	3.7	1.4	172	NE	10(18)
18	1.3	-0.4	191	1.4	0.2	155	0.9	0.2	325	2.4	0.3	164	N→NW→NE	10(21)
25	3.3	-0.2	194	1.1	0.1	312	1.8	0.3	295	2.2	0.5	146	E→SE→N	10(17)
2/7	2.2	-1.4	251	0.9	0.3	397	0.8	0.1	312	2.1	0.4	139	E→NW→E	10(20)
9	2.3	-0.6	130	1.6	-0.1	154	1.6	0.0	157	1.9	0.8	162	NW	12(28)
16	2.4	-0.1	201	1.4	0.6	300	2.6	-0.2	313	3.2	0.3	163	E	15(24)
7/8	5.7	-4.1	112							4.1	-1.2	147	NW	20(35)
14	3.1	-1.7	62							1.4	0.2	29	Variable	
21	2.9	-1.0	104							3.3	0.0	175	NW	10
28	5.8	-3.5	138							1.6	-0.3	320	SW	10(50)
4/9	4.5	-3.0	198											

Table 2: M_2 current ellipses for Stations 5, 10, 11 and 13.
Amplitudes are in cm/sec, phases in degrees.
The speed of the predominant wind is in knots, the
peak wind bracketed.