Movement and Deformation of the Landfast Ice of the Southern Beaufort Sea

P.F. COOPER, JR.

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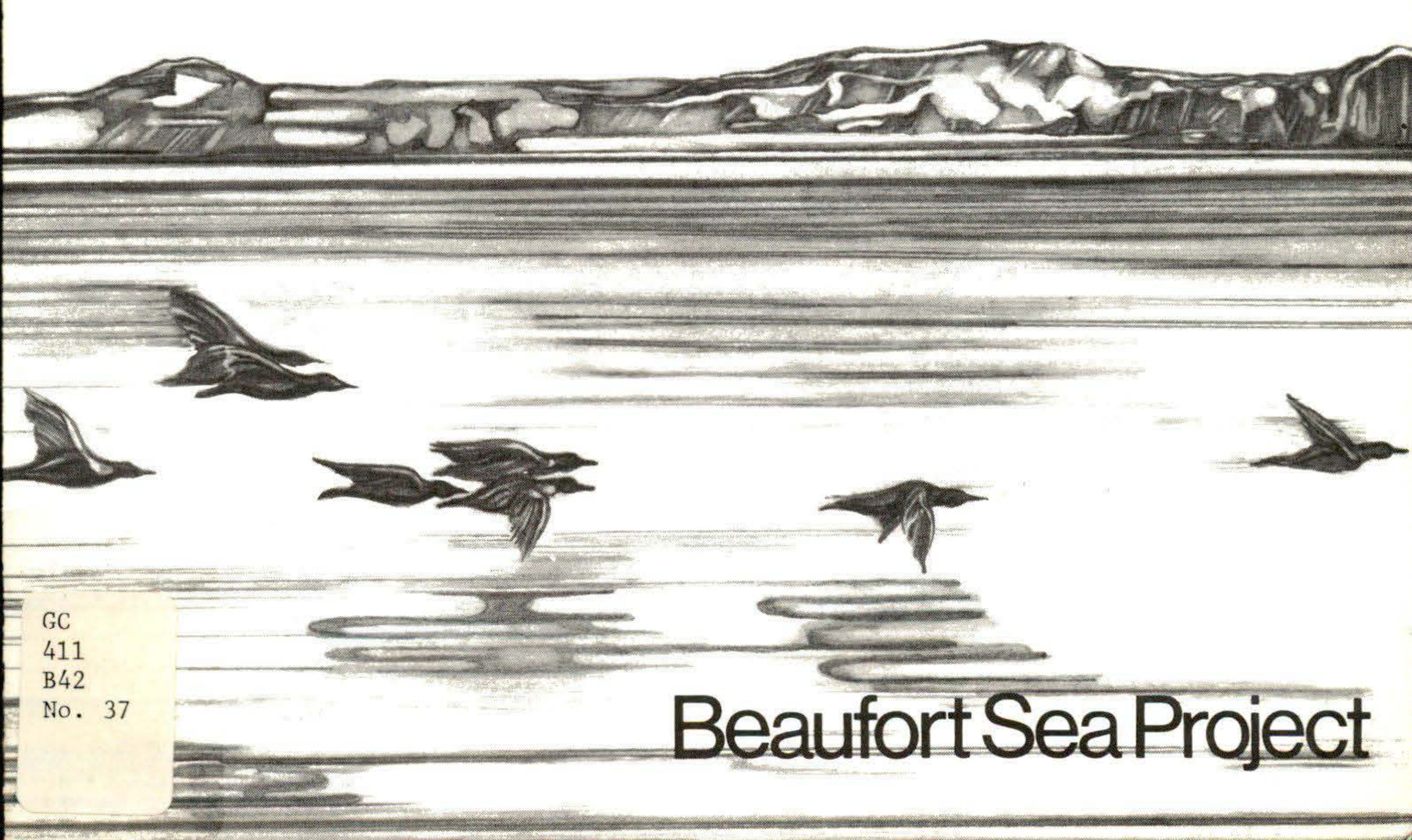

Beaufort Sea Project

MOVEMENT AND DEFORMATION OF THE LANDFAST ICE OF THE SOUTHERN BEAUFORT SEA

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1. SUMMARY

Every year extensive landfast ice develops along the southern coast of the Beaufort Sea. This formation is considerably more stable north and east of the Mackenzie River Delta and southeast of Herschel Island than it is in between these two areas. Yet even in these apparently stable regions observations indicate that the ice surface moves a considerable distance during a typical winter.

Measurements carried out in the winter of 1969 indicate that ice in the centre of the mouth of Kugmallit Bay, north of Tuktoyaktuk, can move as much as 17 m northward over the period mid-January to mid-May. Results from succeeding years confirm the occurrence of similar movements in the landfast ice of that region. More recently a strain gauge has been developed to observe strains in the ice surface of the order of one part in 10^{-5} or more. Such gauges have detected strain, presumably elastic, on the landfast ice in the open ocean north of Tuktoyaktuk.
In two winters, 1972-73 and 1974-75, they have been applied to look for small-scale deformation southeast of Herschel Island. In 1973, crude observations there indicated the presence of changes on a time scale of several months. More satisfactory measurements, made in the winter of 1975 show; a) an apparent overall contraction of the ice surface south of Herschel over the period from early April to late May, as well as, b) an expansion in a direction roughly parallel to the prevailing winds which is coupled with a contraction in the perpendicular direction. These effects were observed on scales of both 30 metres and 1 to 2 kilometres. In all cases the strains were of the order of a few parts in 10^{-4}, of comparable magnitude to those found earlier in Kugmallit Bay.

In the absence of further data, in particular on the presence of apparent short-term changes in the sheltered regions southeast of Herschel Island, it is pointless to try to speculate on the causes of these effects. Measurements are planned for the future, which it is hoped, will cast light on the problem.

2. INTRODUCTION

Landfast ice occurs every winter along the coast of the Beaufort Sea between Herschel Island and Baillie Island. The extent of this surface and its varying stability are discussed elsewhere (Cooper 1974). Here I need only remind the reader that each winter stable landfast ice extends north of the Mackenzie River delta and the Tuktoyaktuk Peninsula to, approximately, the 20 m isobath. West of the delta a similar formation is found east of Shingle Point and in the sheltered region between Herschel Island and Kay Point, while in between these places a much less stable surface occurs.

It is obvious that even the more stable parts of this ice cover are not completely static throughout the winter; for example, pressure ridges commonly form near Tuktoyaktuk in mid-winter. More quantitative observations of such movement have been made since 1969. These are discussed briefly in an earlier paper; in this report they are presented in detail on the basis of a complete re-working of the original data. They show that the ice at the mouth of Kugmallit Bay can exhibit considerable movement in the course of a winter. Observations are inadequate to show the extent of such movement further north and east of Tuktoyaktuk, though what data are available show that it also occurs.

In more recent years, instead of measuring movement with respect to fixed points on land, strain gauges have been developed to study deformations of the ice surface on a smaller scale. Observations southeast of Herschel Island in 1973 showed that in the course of the winter changes took place there, while in 1974 similar changes on a time scale of a few hours were detected north of Tuktoyaktuk. More sensitive strain gauges were used in 1975, again southeast of Herschel Island. At that time long-term deformations were measured on scales of both 60 m and 2 km.

This is a continuing project, and accordingly the data to be presented are incomplete in many respects. They show the presence of distortions of the ice cover which can be of substantial size. Though the equipment used in the winter of 1975 was suitable for long-term measurements, it was only marginally sensitive to short-term deformations in the comparatively sheltered environment studied that season. Refinements are being incorporated this winter of 1975-76 in an attempt to improve the precision of measurements.

More extensive measurements of landfast ice movement found near Herschel Island will, it is hoped, cast light on their causes. In the longer term, efforts are being directed toward developing equipment suitable for use in more exposed and more remote locations. It is desirable to observe small-scale changes in movement which, for example, could be related to large-scale movements found north of Tuktoyaktuk. It is also important to gain a better understanding of those factors which determine the areal extent of landfast ice.

These objectives have arisen as a result of continuing curiosity about the detailed nature of the landfast ice off the Mackenzie River Delta. An understanding of the movement of landfast ice might eventually be of practical use in designing equipment for offshore drilling and in estimating the risks involved in the use of landfast ice as a platform for a specific project in a specific location.

3. STUDY AREAS

3.1 Location

The work described in this report has been carried out in two locations: the first around the mouth of Kugmallit Bay, between 20 and 30 km from Tuktoyaktuk; and the second in Ptarmigan Bay, a few kilometres southeast of Pauline Cove, Herschel Island.

3.2 Nature of the Ice Cover

In most years both areas studied are characterized by a fairly smooth ice cover, which develops about October and lasts until late June. In some years — though not in ones covered by this report — large amounts of old polar ice occur southeast of Herschel Island.

Also there are patches of rough ice, perhaps a metre or so high, which are formed during autumn storms. The ice of Kugmallit Bay is generally smoother, and, apart from isolated pressure ridges there is often little or no rough ice within several kilometres of the mouth of the bay.

The fresh water from the Mackenzie River produces an ice cover on the southern part of Kugmallit Bay with a particularly low salt content. Ptarmigan Bay, southeast of Herschel Island, is further removed from the influence of river water, but has atypical landfast ice for other reasons. The area of continuous stable ice is much smaller, being limited at times to the area bounded by the southeast coast of Herschel Island, the mainland coast as far as Kay Point, and a line connecting the latter with Collinson Head at the eastern end of Herschel Island. (This area comprises 1100 square kilometres, compared with the area of more than 14,000 square kilometres commonly covered by landfast ice north of the Tuktoyaktuk Peninsula.) In addition to the proximity of the flaw lead, Ptarmigan Bay is generally sheltered by Herschel Island from prevailing northwest winds; there is no large reach across which the wind can blow.

4. EXPERIMENTAL METHODS

4.1 Large-scale measurements

All the measurements on scales of more than 100 metres to be discussed herein have been done by my personal observation using optical surveying techniques and snowmobile for travel. The survey line laid out in 1969 at the mouth of Kugmallit Bay (Figure 1) was a simple traverse, which enabled only ice movements perpendicular to the survey line to be measured. In later years, triangulation nets were laid out north of Tuktoyaktuk (Figure 3), and, in 1975, a quadrilateral was set out southeast of Pauline Cove at Herschel Island (Figure 4).

4.2 Small-scale measurements

The strain gauges set out near Pauline Cove in 1973 and 1975 made use of Invar steel tapes 100 ft (30.48 m) long. In the configuration used in the winter of 1975, a gauge consisted of an Invar Tape which could be used with three lines laid out from a common centre at 120° angular azimuthal intervals. The termination of each line was marked by fiducial fixtures on the ice which consisted of iron tripods about 60 cm high with aluminum plates carrying steel machinists' scales bolted to their tops. The Invar tape could be supported at both ends and its midpoint and anchored at one end by an independent support also fixed to the ice. This was done to avoid errors arising from ice's poor qualities as an anchoring medium. Tension was provided by a steel weight and checked by a spring scale. Readings consisted of comparing marks on the steel tape with those on the steel scales attached to the tripods and were estimated to be accurate to within 0.3 to 0.4 mm.

It can be objected that this system has several obvious shortcomings. In particular, the method of setting the tension of the tape was crude, but it was estimated that errors from this source corresponded to an error in indicated length of up to 0.5 mm. This error was small compared to the observed changes (in several instances of 2 to 5 mm). Even though the anchor point was separated from the fiducial marks, any movement of the anchor during the course of a set of measurements could be detected by arranging readings in such an order as to check routinely against this possibility. No anchor drifts were observed on the time scale involved. Finally, no attempt was made to measure and correct for thermal changes in the length of the tape; Invar steel has a coefficient of thermal expansion of 5×10^{-7}. With all their imperfections the strain gauge system described provided unequivocal evidence of long-term landfast ice deformation and of the magnitude of this deformation.

4.3 Miscellaneous measurements

In 1969 some measurements were made with pegs and a steel tape across features such as cracks and pressure ridges where movement would most naturally be expected.

In the winters of 1971-72 and 1972-73, considerable effort was spent in attempts to measure ice movement more directly than by using survey networks. The method tried consisted of dropping anchors through the ice to the seabed and then seeing how much the ice moved relative to the ocean bed by measuring how much line each anchor pulled through an "insulated" hole in the ice (one such hole was constructed by freezing a pipe in place and filling it with oil). To determine such motion unambiguously, it is necessary to have three anchors, each offset from the hole in a different direction and by a known distance. Though an analogous method using hydrophones has been used successfully (Wetzel et al, 1974), the approach outlined has proved too crude for successful, reliable measurements. As will be seen later, the results can at best be used as an indication that significant movement has taken place and to provide a guide as to its magnitude.

4.4 Treatment of data

4.4.1 Results from optical surveying

The results from optical surveying were reduced by standard arithmetic methods. In 1975 it proved impossible to establish adequate ground control and, correspondingly, to obtain changes in distances by this method.

4.4.2 Results from strain gauge measurements

The strain gauges were conventional in that they provided measurements at one time of three distances laid out in different directions from a common centre on the landfast ice. These data were used to calculate the distortion of a circular area into an elliptical area, in analogy with theories of strain. Three parameters are needed to define such an ellipse. For present purposes it seemed convenient to choose them to be ϕ, the angle the ellipse's semi-major axis makes with some prime direction, e, the eccentricity of the ellipse, and Δ, the dilatation, or the ratio of the area of the final ellipse to that of the original circle.

As will be discussed below, not only were measurements over the full length of the survey tapes analyzed in this way, but use made of the fact that the tapes also had a mark at their midpoints to enable an analysis to be made from the inner and outer parts of the same area. In addition, since all proportional changes in length were small enough that their products and higher powers could be neglected, the data from optical surveying could also be used to provide values for ϕ and e (though not, of course, Δ).

5. RESULTS

5.1 Results from Kugmallit Bay in 1969 and the following year

Figure 1 shows the location of the 1969 survey line across the northern part of Kugmallit Bay and also the position of several features of the ice surface during that winter. Figure 2 shows measured movements perpendicular to this survey line. The first traverse, made on January 19 through 21, is represented schematically in Figure 2 by a straight line; the other lines show deviations from the January survey found during the periods March 21 to 26 and May 13 to 14.

It is difficult to estimate the errors inherent in this type of survey. Some idea of the reliability of the numbers can be obtained from the fact that the first and last segments were on land. Accordingly the azimuth of the last segment, as calculated from that of the first one, should remain constant. In fact such a calculation showed an overall angular error of 14", between the January, the March and the May surveys. These errors corresponded to displacements of 2.5 m and 3.9 m respectively, which were small compared with the measured excursions.

These measurements can most simply be visualized as an expansion of the ice cover of Kugmallit Bay during the course of the winter. Such an interpretation appears to be too simple, as indicated by the behaviour of the crack observed in the same year and also shown in Figure 2. This crack steadily grew in width during the winter and was measured as follows. A pair of markers were set out, at position A (Figure 1), on either side of a crack measured to be 3.6 m wide on January 2. Additional growth in width of 2.6 m was observed on March 21 and another expansion of 0.9 m was observed on May 14. A second set of markers on this crack, at position B, showed similar increase of width of 0.9 m between March 21 and May 14, 1969.
It is unfortunate that logistic problems, combined with periods of poor weather, made it impossible to complete the surveying programs attempted in the following two years.

In December 1969 a triangulation net was laid out on the ice about 16 km northwest of Toker Point, as shown in Figure 3. A resurvey of the net in March 1970 showed movements listed in Table I. As with the results of the preceding winter, the magnitude of expected errors is important, and, again, is difficult to determine. Between two sets of readings, however, several of the angles changed by between 30" and 1' 35", while the largest angular corrections needed to complete the net ranged between 10" and 12". Accordingly, the movements appeared to be real.

TABLE I

Movement of Ice Surface, Northeastern Kugmallit Bay, between December 1969 and March 1970.

Point	Movement (m)	Direction °T
A	1.6	83°
B	5.3	297°
C	5.7	295°
D	2.6	94°
E	2.5	53°

Again, these observations indicate considerable movement of the landfast ice. In this season the measurements are most easily interpreted as being uniform movements of comparatively large areas of ice; the ice around James Shoal, as might be expected, remained comparatively stable, while an area covering several tens of square kilometres west and northwest of Toker Point moved in a general northwesterly direction.

A further study of this net in May, 1970, could not be completed, though a few fragmetnary results indicated a more extensive ice movement occurred during the period March to May than was observed between December and March. Again, a program was attempted during the winter of 1971 but its result provided little more than confirmatory evidence for the existence of the large-scale movement observed in the previous years. In April, 1971, a triangulation net was run several kilometres westward from North Peak (Figure 1). Unfortunately in late May of that year it proved impossible to resurvey more than one-third of the stations. These once again show systematic changes in angles, similar in magnitude to those found in 1969, but in the opposite direction. It is impossible to tell from the data whether the entire ice surface moved southwards, rather than northward as observed in the earlier year, or whether it merely shows that the ice near the east side of the bay behaved in an irregular manner, as can also be seen in the region of Points 6 through 9 in Figure 2.

The information from the systems of anchors described in subsection 4.3 was inconclusive. The most provocative result they provided was several kilometres north of Warren Point (located about 25 km NW of

Toker Summit), where a set of two anchors indicated essentially no movement for the period 23 December 1971 to 14 January 1972, but followed by an apparent movement of the ice cover roughly 1 m westward between 14 and 18 January. As I have already mentioned the sources of error in these measurements are probably large so that this result can be regarded as little more than an indication that movements of the same type as those observed in Kugmallit Bay also occur in more exposed offshore areas of landfast ice.

5.2 Results from Ptarmigan Bay

5.2.1 Strain Gauges

Since 1972 the measurement of deformation of the ice surface has been attacked on a smaller scale. Preliminary measurements southeast of Herschel Island, made in the winter of 1973, showed deformations of the ice cover of the order of one part in 10^4 over distances of 60 m (Cooper 1974). These observations indicated that extension of the surface if the ice was in a direction perpendicular to the prevailing wind. Later results do not confirm this observation, though it is still open to question whether the earlier readings were inadequate or whether conditions differ from year to year.

In the winter of 1974-75, an irregular quadrilateral, with sides ranging between 1 and 1.5 km long, was laid out south of Pauline Cove, Herschel Island (Figure 4). Strain gauges were set up at two corners of the quadrilateral at points I and II.

In late March and early April, repeated strain readings were taken to look for short-term, presumably elastic, changes in the ice cover. Indications were that these might be taking place on a scale of a few parts in 10^{-5}, even in such a sheltered spot on Site 1, but these strains were too close to the sensitivity of the gauges to permit obtaining positive evidence of their occurrence. Long-term changes, however, were readily measurable, and consistent readings were obtained during each of the three periods, April 4 to 7, on May 10, and on May 26. The data were used to calculate deformations over the two intervening intervals, and the results are given in Table II. It is apparent that the results from Sites 1 and 2 are in broad agreement. Contrary to what might have been expected from the results in Kugmallit Bay (and in contrast to the sketchy 1973 results, also from Ptarmigan Bay), this data shows that a continuing decrease in surface area occurred combined with a deformation in which the ice surface expanded in a direction roughly parallel to the prevailing winds (northwest or east, as determined by observations at Herschel Island) and contacts perpendicular to the wind direction.

A simple model could be used to represent the data in Table II. Only very small changes were observed in the length of lines laid out more or less parallel to the prevailing winds. Within

TABLE II

Deformation of the Ice Surface, Ptarmigan Bay, 1975

	Site I	Site II
April 7	$\phi = 83.4^\circ$	$\phi = 70.0^\circ$
to	$e = 0.023$	$e = 0.010$
May 10	$\Delta = -1.734 \times 10^{-4}$	$\Delta = -6.861 \times 10^{-5}$
May 10	$\phi = 115.2^\circ$	$\phi = 106.3^\circ$
to	$e = 0.016$	$e = 0.010$
May 26	$\Delta = -8.357 \times 10^{-5}$	$\Delta = -6.861 \times 10^{-5}$

experimental errors, almost all of the observations would have resulted from the compression of an original circular area into an elliptic area with its major axis parallel to the winds and equal in length to the diameter of the original circle. Two further systematic effects seemed to be present; all changes at Site II (the one further to sea) were less than at Site I, and, the azimuths characterizing the orientation of the ellipses were more southerly in May than in April.

It seems unlikely that these results could have been solely due to observational errors. I have already discussed errors due to changing tension and movement of anchor points. Earlier in the year it had been found that winds could result in large and spurious errors with the equipment as it was set up in the 1975 season. Measurements were accordingly attempted only during calm weather.

More seriously, no corrections were made for thermal expansion and contraction of the Invar tapes, but if it is assumed that air temperatures did not change abruptly in the 30 to 45 minute time interval required for a set of observations, thermal effects would appear to be relatively small. Between early April and early May, daytime temperatures rose by about 15°C (of course on a sunny, calm day the tape temperature could be several degrees above the air temperature) and this change could contribute at most about 1.5×10^{-5} to the dilatation, or less than one-third of the observed change at Site II, and less than one-tenth that at Site I. The change in air temperature between the two sets of May readings was about 5°C, which would lead to an error of less than 10% in the measurements.

Apart from possible sources of error in the equipment, there remains the problem of choosing a suitable horizontal scale for this type of observations. Early in the winter a crack had developed across the observing Site at location I, but it seemed to have become inactive by the time the measurements described were made. Fiducial markers had been set not only at the ends of the tapes but also at their midpoints and measurements from the midpoints were also examined. No signs of recent activity across the old crack was evident. These readings were then analyzed to give the same parameters as displayed in Table II, but deduced separately for the inner and outer 15.24 m (50 ft) or the original 30.48 m (100 ft) radius circle. These are given in Table III.

Table III

Comparisons of Results from Inner and Outer Readings, Site I, Ptarmigan Bay, 1975

	Overall	Inner 15.24 m	Outer 15.24 m
April 7	$\phi = 83.4°$	$\phi = 98.8°$	$\phi = 59.1°$
to	$e = 0.0228$	$e = 0.0282$	$e = 0.0232$
May 10	$\Delta = - 1.734 \times 10^{-4}$	$\Delta = - 7.791 \times 10^{-5}$	$\Delta = - 2.689 \times 10^{-4}$
May 10	$\phi = 115.2°$	$\phi = 133.2°$	$\phi = 84.1°$
to	$e = 0.0159$	$e = 0.0200$	$e = 0.0173$
May 26	$\Delta = - 8.357 \times 10^{-5}$	$\Delta = - 9.441 \times 10^{-5}$	$\Delta = - 7.273 \times 10^{-5}$

It is apparent that this type of deformation can vary significantly over distances of a few tens of metres.

5.2.2 Optical Surveying

The quadrilateral shown in Figure 4 was surveyed on March 30, 1975, and again on May 12 and May 13. Unfortunately, at neither time was the weather good enough for sufficient control linkage to the shore to be established, so a precise scale of distance cannot be given. The angles, however, changed in a regular manner by up to 18". Since the largest correction needed to adjust the angles was 6.6" for the March readings and 2.4" for the May readings, it is judged that the changes are real. They corresponded to proportional changes of length of the order of 10^{-4} to 10^{-5}, comparable to those observed with the steel tapes on a scale of 30 m. Table IV gives calculated changes in centimetres for the distance from Site I to Site II of 2.096 km, under the hypothesis that this distance did not change during the two-month period. In view of the preceding discussion, this was clearly unrealistic, and so the same quantities are also given for a second, equally hypothetical case, in which the overall area of the rectangle diminished during this time by an amount proportional to the average of the changes in dilatation found at Sites I and II. It is curious that this assumption, no matter how shaky its foundation, leads to measurements which show that in directions parallel to the prevailing winds, dilatations were quite small, while perpendicular to the wind, shrinkage was marked.

Table IV

Side	Hypothesis A Distance I-II Constant	Hypothesis B Area diminished by 1.868 x 10^{-4}
I - a	7.55 cm	- 3.93 cm
II - A	-9.35	-24.45
II - B	6.45	- 3.93
1 - B	-15.02	-30.92

Further, these results can be analyzed in terms of two of the three parameters (ϕ and e) used in the presentation of the strain gauge results. This leads to the numbers in Table V.

Table V

Deformation from April 13 to May 13 as Deduced from Survey Data; Ptarmigan Bay, 1975.

	Site I	Site II
ϕ	64.1°	97.2°
e	0.0205	0.0152

These are comparable with those derived from the small-scale measurements. It is interesting to see that the eccentricity at Site II, as found in this way, is still less than at Site I and also that the values of this quantity as found by large-scale measurements lie in between those found on a small scale. All this is most easily explained by a real change in this parameter over a distance of 2 km.

6. DISCUSSION

The results both from Kugmallit Bay and Ptarmigan Bay show that changes of length of the order of several parts in 10^{-4} over the course of a winter occur in landfast ice in every year of observation. In different years these changes have been observed on a variety of scales; from tens of kilometres to tens of metres.

Several points can be adduced further to characterize these changes. First, these long-term changes seem to be irreversible, at least for the period January through May. Further, the 1975 results do not fit the criteria for any simple elastic relationship; for plane stresses, for example, the observed deformations would lead us to expect the stress parallel to the wind direction to be equal to Poisson's ratio times the stress perpendicular to that direction. The fact that the stress perpendicular to the wind direction was always greater than that parallel to the wind does not appeal to common sense.

Second, the 1975 data indicate that similar changes take place on scales of up to at least a few kilometres. In addition, the magnitude of these changes seems to vary over distances of this magnitude. This presents a problem in choosing suitable distances over which to take measurements, since, as we have seen, the available data indicate that the process is random on a small scale, and that measurements over short distances of 15 or 30 metres appear to be inadequate to characterize large-scale strains with adequate precision.

Third, there is as yet no indication of the time scale on which these processes take place, although an observed lack of any measurable long-term change during the two-week period from March 25 to April 7, 1975, might be used as negative evidence for their happening abruptly.

Fourth, there is the question of short-term change in strain. As noted above, these have not as yet been detected with any confidence. But one hypothesis that might explain the long-term changes and also provide a mechanism for their occurring suddenly is that they are the result of plastic flow during periods of storm. If so, during conditions when travel is practicable (with winds of no more than 9 m/sec) one might hope to find short-term changes of perhaps one-tenth the magnitude of long-term ones. It is hoped that improvements now made to the equipment will resolve this particular question in the near future.

Beyond these general statements it seems fruitless to discuss strain mechanisms on the basis of the available data. The only clues are variations over short distances and systematic changes in reference angle between the April and May 1975 observations, as shown in Table II. This last is highly suggestive of a wind-related effect. Wind records from Herschel for the winter of 1974-75 show that prevailing wind directions are east and northwest. The 1975 data only show a contraction perpendicular to the wind direction and little or no change in that parallel to the wind.

If we reverse the point from which we view the 1969 survey line across Kugmallit Bay, we could interpret the ice field motion to be the result of a general contraction of the landfast ice north of the bay causing the ice cover on the bay to be pulled to the north. Since observations were made in the latter part of the winter and during a time of rising temperatures, this would be in agreement with thermal effects in the ice, since salt water ice has a negative coefficient of thermal expansion. If the ice in the southern part of the bay had sufficiently low salt content, it would have a positive coefficient of thermal expansion, which again would act in the proper direction. Such an explanation would also explain the presence, north of the bay, of the crack which also grew in width during the winter. But further work is clearly needed; and perhaps rather than looking for a multiplicity of causes related to wind-induced stress and thermal changes we should instead be hunting for explanations for the loss of volume in a preferred direction.

7. CONCLUSIONS

It is premature to assign definite mechanisms to explain the measured landfast ice movements described above. Two points, however, are clear:

1. Points on landfast ice around the mouth of Kugmallit Bay can move by distances of up to several tens of metres in the course of a winter.

2. Smaller-scale measurements southeast of Herschel Island show deformations of the ice cover there of comparable magnitude (up to a few parts in 10^4), on scales of both 30 m and a few km. These indicate that whatever process is at work around Kugmallit Bay is of more general occurrence and that movement of the ice cover can be expected anywhere in the landfast ice between Herschel Island and Cape Bathurst.

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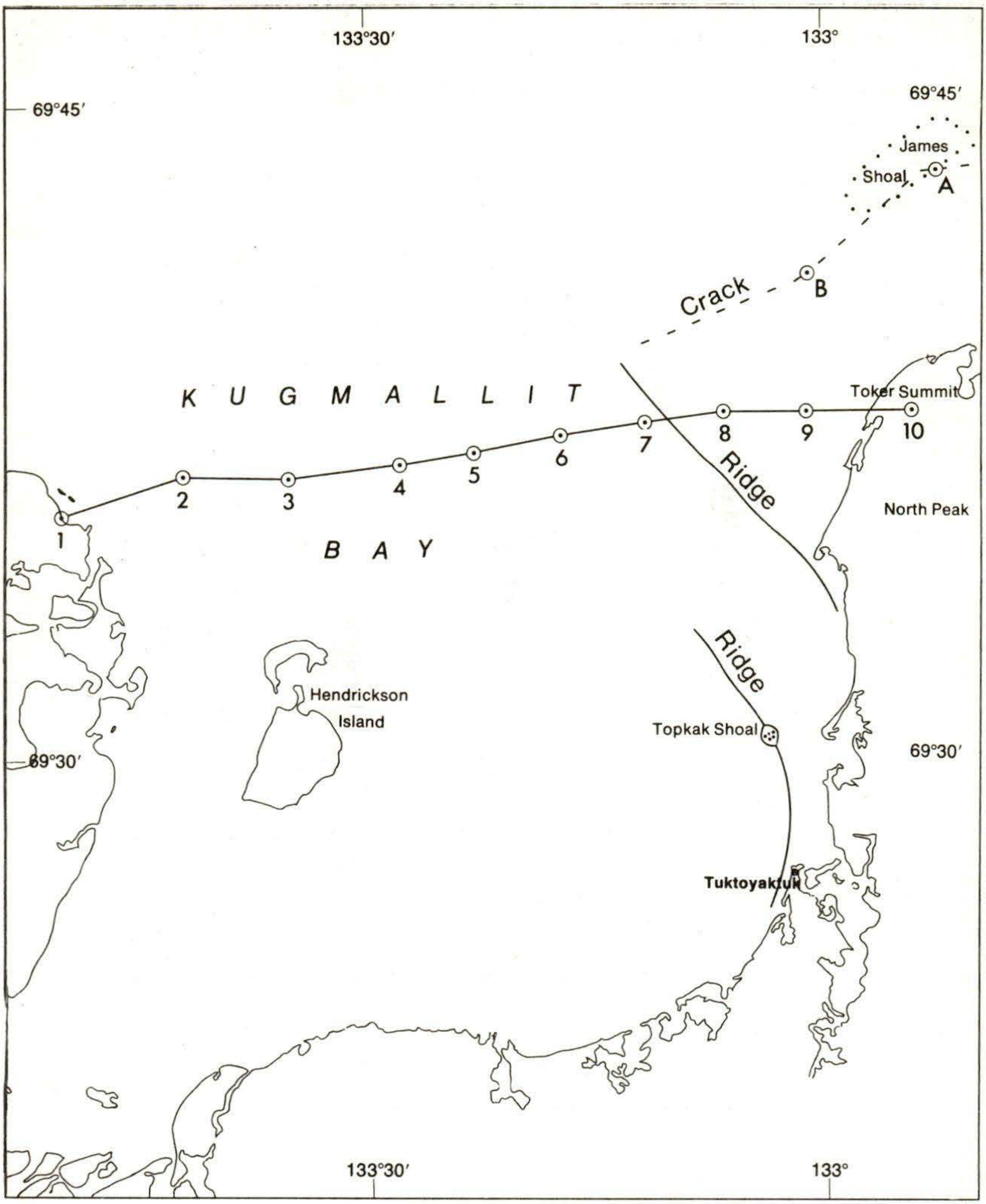

Figure 1. Kugmallit Bay, showing line surveyed in winter 1969 and certain features of the ice cover of that year. Scale: 1:250,000.

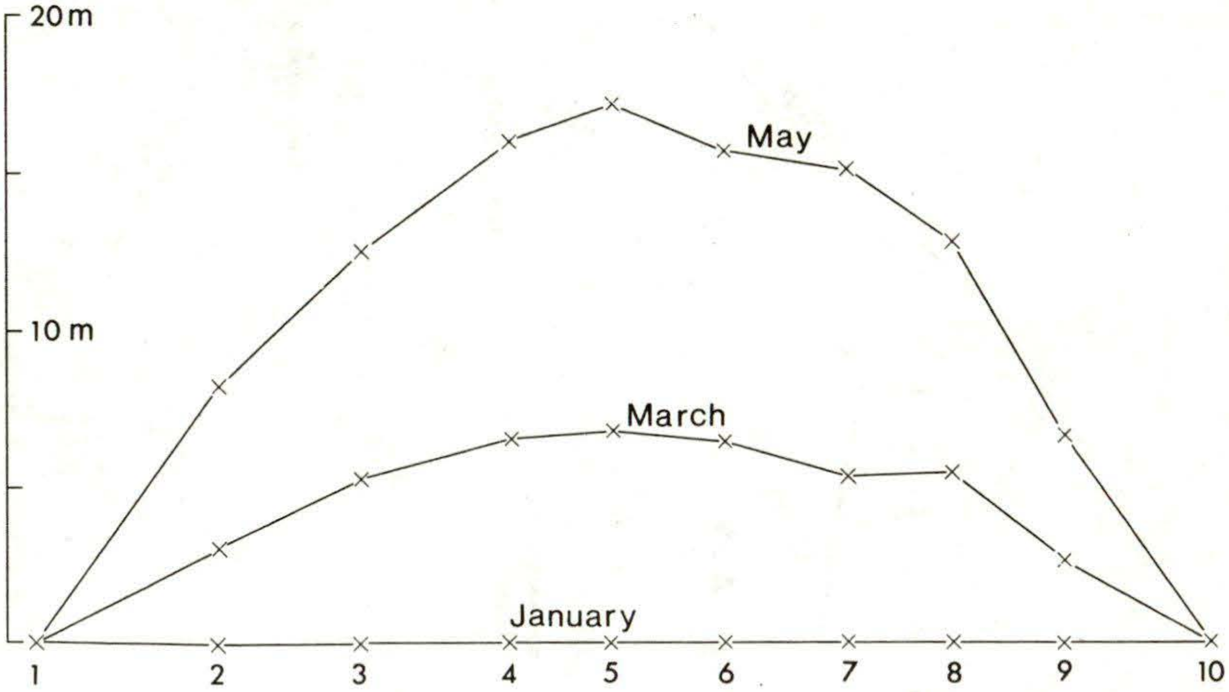

Figure 2. Movement of the ice cover of the northern part of Kugmallit Bay, Winter 1969. Movement is shown relative to the January survey, and displacement of the positive y-direction corresponds to motion northwards. The points correspond to the survey stations shown in Figure 1.

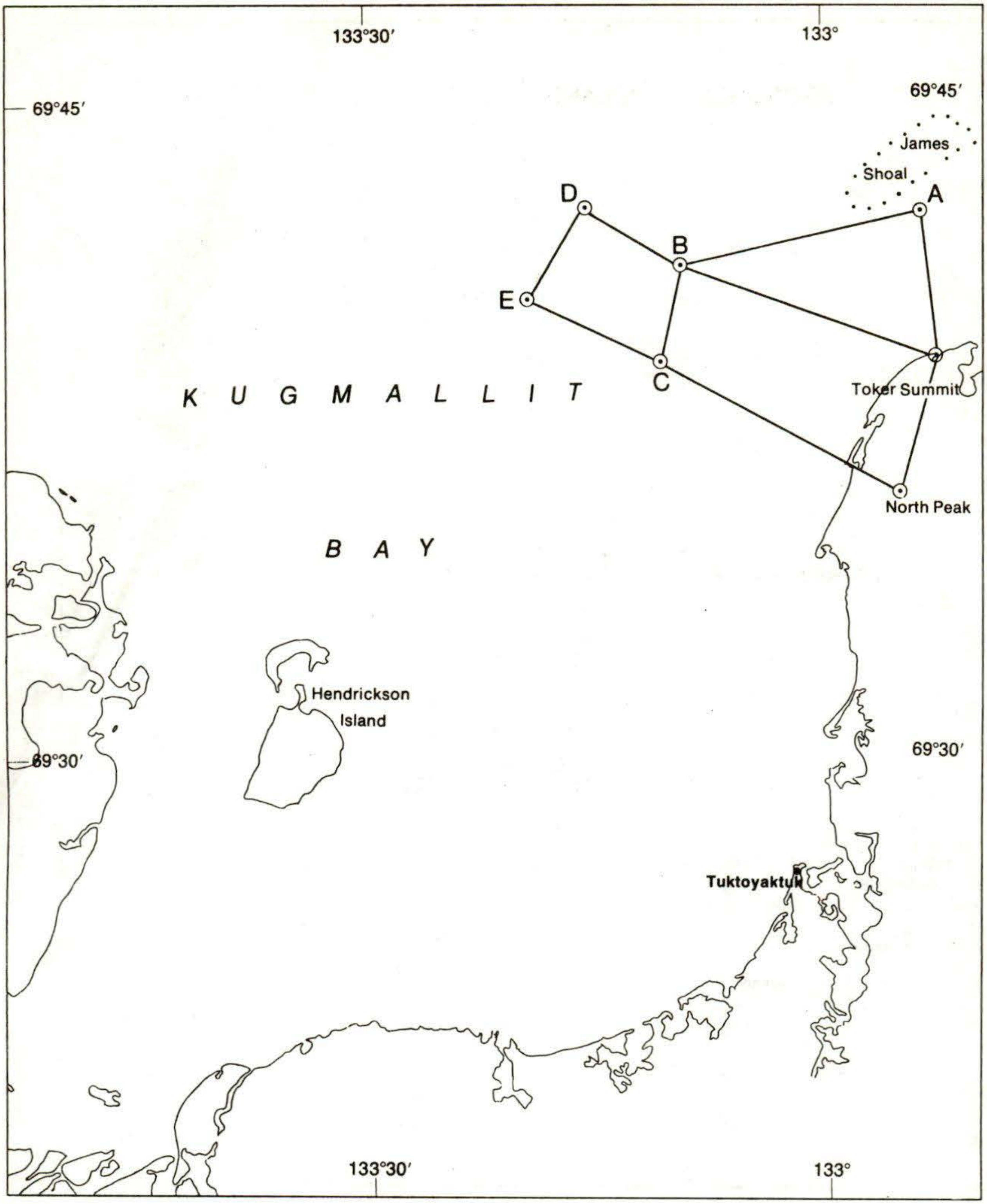

Figure 3. Triangulation Network, Winter 1969-70. Scale: 1:250,000.

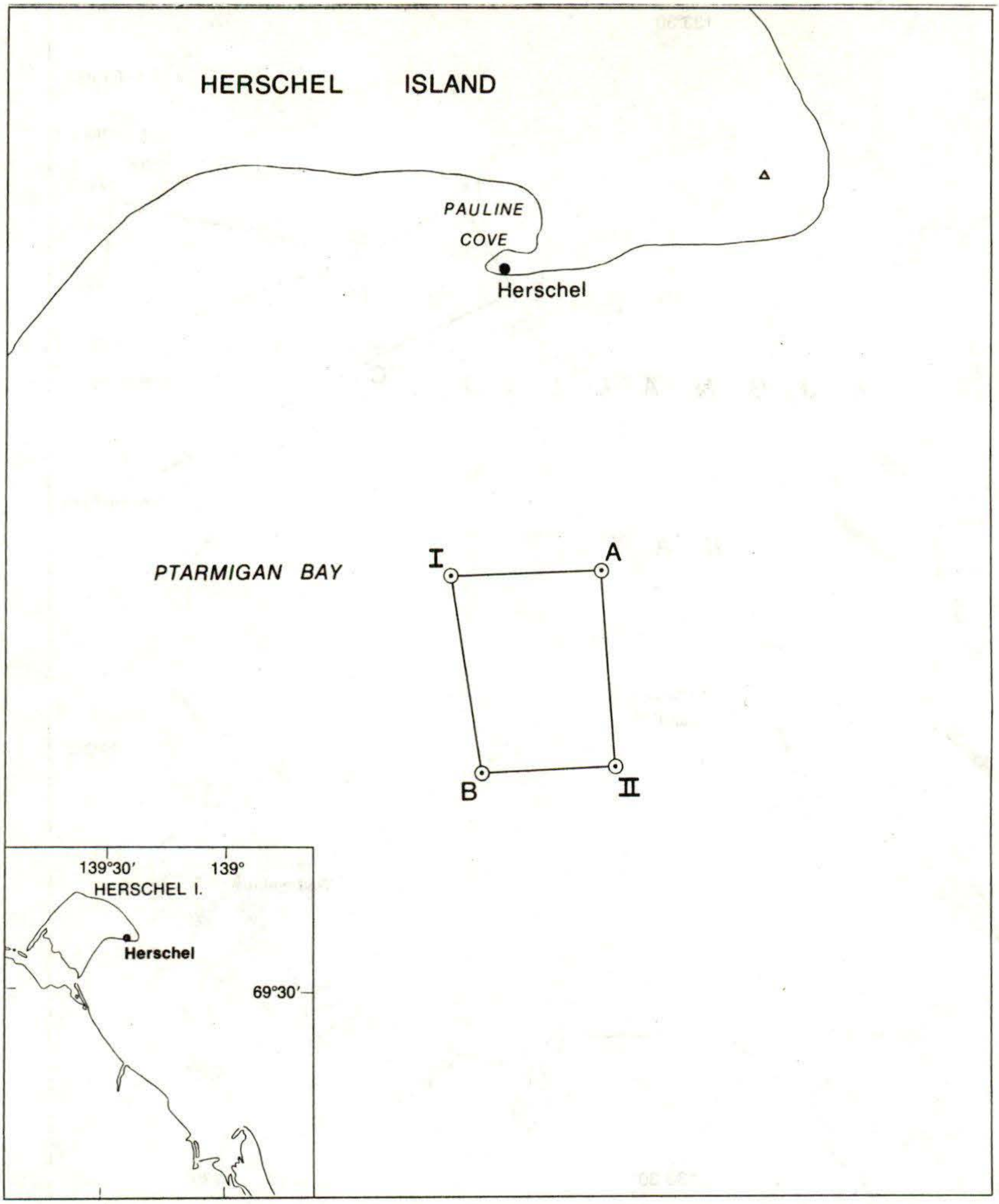

Figure 4. Quadrilateral studies in 1975. Scale: 1:50,000. (Inset: Location Map, Scale: 1:1,000,000.)