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TERRAIN AND COASTAL CONDITIONS ON THE ARCTIC ALASKAN COASTAL PLAIN

ARCTIC ENVIRONMENTAL DATA PACKAGE SUPPLEMENT 1

Paul V. Sellmann, Kevin L. Carey, Charles Keeler and Allan D. Hartwell

March 1972

PREPARED FOR
ADVANCED RESEARCH PROJECTS AGENCY
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BY
CORPS OF ENGINEERS, U.S. ARMY
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This group of four reports describes the characteristics and seasonal variation of prominent relief features on and along the margin of the arctic coastal plain. These relief features include polygonal ground patterns, lake scarps and coastal features. The range of polygonal ground patterns commonly found is illustrated by a number of transects. The influence of the seasonal snow cover on relief is indicated by profiles taken during the summer and the winter. The winter profiles were taken during the period of maximum snow accumulation. The subduing influence of the seasonal snowpack is much more apparent in areas of high relief. Irregularities in the snow surface may approach those found in the more featureless areas of summer relief. A discussion of properties of the snow cover is also included from observations in the Barrow study area. Constant reworking by the wind of small amounts of snow results in a snow surface with high bearing capacity and low (<0.2 m) surface relief. The aerial photo study of the Barrow study area provided statistics concerning the occurrence and amount of relief associated with polygonal ground terrain. Approximately 64% of the area was covered with prominent polygonal ground relief. Polygonal ground patterns with relief >0.5 m and seldom exceeding 1.0 m with 1.5 m being the practical upper limit cover 10.7% of the area. The remainder of the study area can be grouped into two general categories: 1) 53% with polygonal ground relief less than 0.5 m, and 2) 36% containing all other relief categories, including water surfaces. The study of coastal processes and relief features along the northern Alaskan coast was in part based on maps and aerial photos. Mean coastal relief or sea-cliff height was approximately 3.9 m, with about 75% of the coast having 5 m or less relief. Profiles from

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PREFACE

This report was prepared by Paul V. Sellmann, Geologist, and Kevin L. Carey, Research Civil Engineer, of the Experimental Engineering Division; and Dr. Charles M. Keeler, Geologist, and Lt. Allan D. Hartwell, Geologist, of the Research Division, USA CRREL.

The report was prepared as part of the Arctic Surface Effect Vehicle program of the Advanced Research Projects Agency under ARPA Order 1615.

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ABSTRACT

This group of four reports describes the characteristics and seasonal variation of prominent relief features on and along the margin of the arctic coastal plain. These relief features include polygonal ground patterns, lake scarps and coastal features.

The range of polygonal ground patterns commonly found is illustrated by a number of transects. The influence of the seasonal snow cover on relief is indicated by profiles taken during the summer and the winter. The winter profiles were taken during the period of maximum snow accumulation. The subduing influence of the seasonal snowpack is much more apparent in areas of high relief. Irregularities in the snow surface may approach those found in the more featureless areas of summer relief.

A discussion of properties of the snow cover is also included from observations in the Barrow study area. Constant reworking by the wind of small amounts of snow results in a snow surface with high bearing capacity and low ([illegible] 0.2 m) surface relief.

The aerial photo study of the Barrow study area provided statistics concerning the occurrence and amount of relief associated with polygonal ground terrain. Approximately 64% of the area was covered with prominent polygonal ground relief. Polygonal ground patterns with relief [illegible] 0.5 m and seldom exceeding 1.0 m with 1.5 m being the practical upper limit cover 10.7% of the area. The remainder of the study area can be grouped into two general categories: 1) 53% with polygonal ground relief less than 0.5 m, and 2) 36% containing all other relief categories, including water surfaces.

The study of coastal processes and relief features along the northern Alaskan coast was in part based on maps and aerial photos. Mean coastal relief or sea-cliff height was approximately 3.9 m, with about 75% of the coast having 5 m or less relief. Profiles from the Barrow area reveal that the surface geometry of the coast is dramatically altered by the seasonal windblown snow cover which tends to ramp the sea cliffs. The frequency of gullies, streams, embayed rivers and drowned thaw lakes along the coast was examined since they provide "windows" through the scarp and access to inland areas. There are approximately 800 windows along this coast or about 0.4 per km, with a mean width of about 200 m and mean inland extent of .4 km.

TERRAIN AND COASTAL CONDITIONS ON THE ARCTIC ALASKAN COASTAL PLAIN

Introduction

Among the many variables which influence mobility in any particular region of the world, the physical relief of the land surface including variations in relief resulting from seasonal phenomena, is very significant. In areas where vegetation is absent or slight, relief assumes primary importance.

This report considers this topic for the region in Alaska known as the Arctic Coastal Plain (now commonly called the North Slope). Wahrhaftig (1965) describes the Arctic Coastal Plain as "... a smooth plain rising imperceptibly from the Arctic Ocean to a maximum altitude of 600 feet at its southern margin. The coastline makes little break in the profile of the coastal plain and shelf, and the shore is generally only 1-10 feet above the ocean; the highest coastal cliffs are only 50 feet high. The Arctic Coastal Plain is ... [for the most part] ... flat ... [and] ... is very poorly drained and consequently is very marshy in summer. It is crossed by rivers which head in highlands to the south. Rivers west of the Colville River meander sluggishly in valleys incised 50-300 feet; those east of the Colville cross the plain in braided channels and are building deltas into the Arctic Ocean. [Most] ... of the Arctic Coastal Plain province is covered by elongated thaw lakes oriented N 15° W; these range from a few feet to nine miles long, are from two to twenty feet deep, and are oval or rectangular in shape .... The lakes expand about one meter per year in places, and several generations of drained lake basins may be seen. ... A network of ice-wedge polygons covers the coastal plain ...".

While it is not suggested by Wahrhaftig's description, polygonal ground has microrelief associated with it which, due to its ubiquity, is as important to mobility considerations as macrorelief. This is particularly true since macrorelief features, except for the coastline itself, are not overly abundant or widespread on most of the Arctic Coastal Plain. Furthermore, both micro- and macrorelief are subdued by the seasonal snow cover for up to eight months of the year, and thus this moderating effect and the characteristics of the snow cover itself are germane to the subject.

These topics are treated in this report in four separate but related chapters:

1. Relief characteristics and variations due to snow: Barrow, Alaska
2. Classification, mapping and measurement of the distribution of microrelief from airphotos: Barrow, Alaska
3. Properties of the snow cover: Barrow, Alaska
4. Coastal conditions of arctic northern Alaska.

The terrain and climatic characteristics in the vicinity of Barrow are representative of much of the Arctic Coastal Plain. For this reason, but also because of the invaluable logistical support available from the Naval Arctic Research Laboratory at Barrow, concentrated field studies for all four chapters of this report were conducted in that area. Chapter 4, however, deals in detail with coastal conditions from the U.S. – Canadian border westward to Cape Thompson, and includes a portion of the Arctic Foothills in addition to the Arctic Coastal Plain (Wahrhaftig 1965). Much of the information in Chapter 4 was compiled from maps and airphotos.

1. RELIEF CHARACTERISTICS AND VARIATIONS DUE TO SNOW: BARROW, ALASKA

by

Paul V. Sellmann

Study Area

The Barrow area, with its lack of trees, its low vegetation and low regional relief, appears at first to be almost featureless. Closer inspection, however, reveals small but significant local relief. Terrain features include all stages in the evolution of polygonal ground (i.e. low-center through high-center polygons), oriented thaw lakes, natural and artificially drained thaw lake basins, associated lake shore scarps and strands, coastal lagoons and embayments, relatively small streams with associated scarps and swales, coastal scarps, and coastal gravel beaches. For eight months of the year the ground is covered with snow, which greatly subdues the local relief.

The general study area (Fig. 1) is roughly triangular and covers about 100 km². It measures about 10 km in the north-south direction, with its southern boundary at about latitude 71°15'. Coastlines form the eastern and western boundaries, with Elson Lagoon (part of the Beaufort Sea)

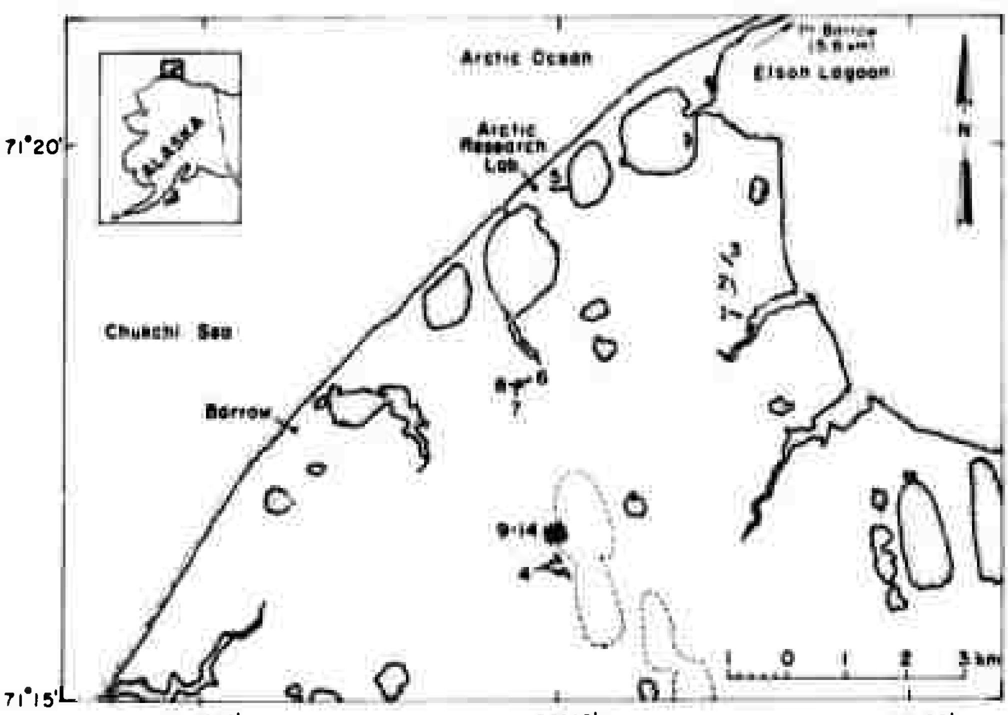

Figure 1. Study area near Barrow. Numbers indicate sites where profile information was obtained.

on the east and the Chukchi Sea on the west. The highest ground surface elevation in the general study area is 15.2 meters, with the average elevation being about five or six meters. A detailed topographic map of the Barrow vicinity with a scale of 1:25,000 and 1-meter contour intervals has been published by Brown and Johnson (1966). This map portrays the topography on a photomosaic base, and coincides with the gen[illegible] study area for this report.

Relief

Based on a ground survey conducted during August 1970 sites were selected to reflect the range of relief common to the area. Emphasis was placed on polygonal ground features, since they represent the dominant source of microrelief. The amount of vertical relief associated with polygonal ground is, in many cases, related to the proximity of macrorelief features, such as streams, lake and coastal scarps and other topographic highs.

Polygonal ground patterns are the surficial expression of large vertical ice wedges that form below the surface in perennially frozen ground. In general, the amount of relief associated with them changes throughout their development. Initially, the trough areas and the polygon centers are low and the ridges surrounding the troughs form the highest microrelief. These forms are known as low-centered polygons. At the time ot maximum development, the centers stand above the troughs and the features are referred to as high-centered polygons. Figure 2 illustrates the range of polygon types commonly found. Surface drainage aids in the development of polygonal forms by accelerating thaw in the troughs, thereby causing settlement and evolution toward high-centered forms. Therefore, areas near major relief features with better drainage have the greatest frequency of high-centered polygons of greater relief. Based on this topographic control, the amount of microrelief associated with polygonal ground can be considered in two categories:

1. Low microrelief polygonal ground in areas with little local macrorelief.
2. High microrelief polygonal ground associated with major local macrorelief, such as stream and lake margins.

Variations in microrelief during the snow-free period were measured at 12 study sites. During the time of maximum snow cover, surface geometry data were acquired in the same study areas. Several additional sites were selected in lake and stream scarp areas.

The surface relief was measured on line transects using conventional surveying techniques. The winter lines were not identical to the summer lines,but were intentionally separated to indicate the local variability within like microrelief categories. Additional surface relief information was obtained by the U.S. Army Waterways Experiment Station. Their data points were obtained by surveying plots having a 1-meter grid spacing. The sites were further documented by using both ground-base stereo and aerial hand-held photography. During the winter study, snow thickness and ground surface profiles were determined by probing along the surveyed lines. A total of 27 profiles were surveyed at the study sites (Fig. 1). The information from these sites also served as ground control for the airphoto interpretation and microrelief mapping study discussed in the following chapter.

The range of relief in the two categories mentioned earlier is illustrated by selected profiles and photos. In Figure 3, profiles 1-3 represent the relief in category 1, which is continuous over a larger area than category 2. Both high-centered and low-centered polygons in category 1 are shown in Figures 4 and 5. Relief in this category varies from essentially featureless surfaces to areas of high-centered polygons with as much as 60 cm of relief in the low trough areas, as illustrated by profiles 4 and 5.

The higher relief common to category 2 is illustrated by profiles 9 and 10, made across the crest of a lake escarpment. Since this microrelief is associated with larger macrorelief features, it is not as widespread as the relief forms in category 1. Reduction in vertical relief of the polygonal patterns away from the larger relief features is noticeable, as can be seen in Figure 6. These profiles were taken parallel to and progressively inland from the scarp at approximately 20-m intervals. This pronounced decrease in microrelief away from the larger relief features can also be seen in the airphoto of a drained lake margin east of Barrow.(Fig. 7). Occasionally pronounced polygonal ground microrelief is not associated with major relief for several reasons: 1) insufficient time for development, 2) unsuitable ground ice conditions, and 3) insufficient surface runoff.

This increase in microrelief near major relief features is also apparent in profiles 6-8.

For vehicle operations, category 2 areas should contain the most difficult obstacles, since they combine high microrelief and high macrorelief. Statistics concerning this can be found in Table II (p. 27). The H_2 mapping class, defined in Chapter 2, would encompass all the features in this category. For the 100-km² Barrow study area this only amounts to 9.2% of the area.

Seasonal Variations

In the Barrow area snow covers the ground for most of the year. The amount of annual precipitation in the form of snow is only a few centimeters but the snow cover is subjected to almost continual drifting and transport by the winds (see Fig. 22), which greatly reduces and subdues the effective relief. This movement causes filling-in of depressions, such as polygon troughs, and increases accumulation from drifting near larger macrorelief features. The properties of the snow cover are covered in Chapter 3.

Snow depths over this irregular terrain range greatly. Topographic highs such as polygon tops, particularly at escarpment margins, are often snow-free, while small stream channels may contain 2 meters or more of snow. Winter profiles 7a and 9a illustrate topographic highs with minimal snow cover. In contrast, winter profiles 4a and 5a illustrate the flat snow surface over two contrasting subsnow relief conditions. In Figure 8 the ground is essentially flat and is mantled with a uniform snow cover of approximately 45 cm. In contrast, Figure 9 shows a trough with a maximum accumulation of approximately 70 cm, thinning to near zero accumulation on the adjacent highs.

Comparison photos from the study site provide an even better record of the surface conditions during the two contrasting seasons. In Figure 10 and 11, high-centered polygon relief is reduced from maximum relief of a meter to only small irregularities in the snow surface. For additional comparison, profiles at site 6 can be compared. Comparative photos (Fig. 12 and 13) show substantial masking of even the largest relief features. The drained lake escarpment in Figure 12 has more than 2 meters of relief. In winter the steep face is ramped, with little noticeable relief. Similar conditions can be seen in Figure 13. Winter profiles 9a-11a and 13a also show the seasonal change in relief in this general area. Figure 14 and profile 7 show the masking of a prominent drainage channel.

The average and range of the accumulation values obtained from measurements along the profiles show several trends. Category 1 relief features (even though they contain a wide range of polygon types and surface relief) have similar average snow accumulation despite differing ranges in accumulation.

In Category 2 naturally the high relief areas such as the scarps have the highest accumulation. The flat areas adjacent to the high relief features have lower accumulation than similar relief areas in Category 1, as can be seen in profiles 7, 8, 9, 10, and 13. The snow depth data are shown in Table 1.

Table I. Snow accumulation along profiles.
Sampled at 1-meter intervals.

Profile	Max cover (m)	Min cover (m)	Average (m)
1	0.82	0.08	0.40
2	0.61	0.19	0.40
3	0.58	0.04	0.35
9 (Scarp)	1.46	0.02	0.86
9 (Flat)	1.12	0.00	0.29
10 (Scarp)	1.47	0.35	0.69
10 (Flat)	0.45	0.00	0.20
11	1.60	0.00	0.52
13	0.60	0.00	0.20
4N	0.68	0.23	0.42
4S	0.60	0.28	0.43
5	0.83	0.00	0.34
6	0.93	0.10	0.50
7 (Valley)	2.23	0.07	0.95
7 (Flat)	0.93	0.00	0.28
8	0.72	0.00	0.22

Figure 2. Airphoto taken in the Barrow area showing the range of polygon types commonly found on the coastal plain. A: little apparent relief. B: low-centered polygons. C: high-centered polygons.

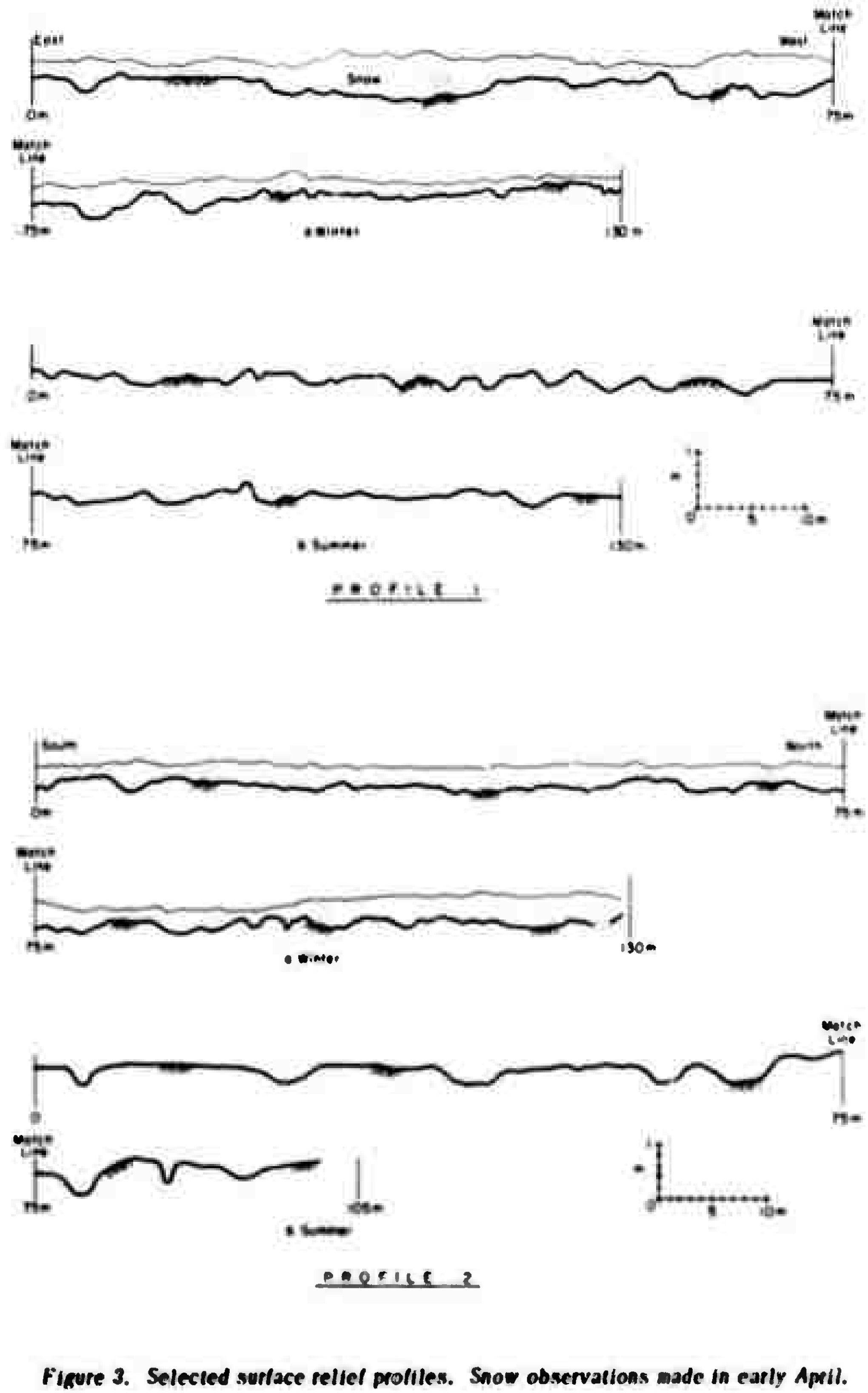

Figure 3. Selected surface relief profiles. Snow observations made in early April.

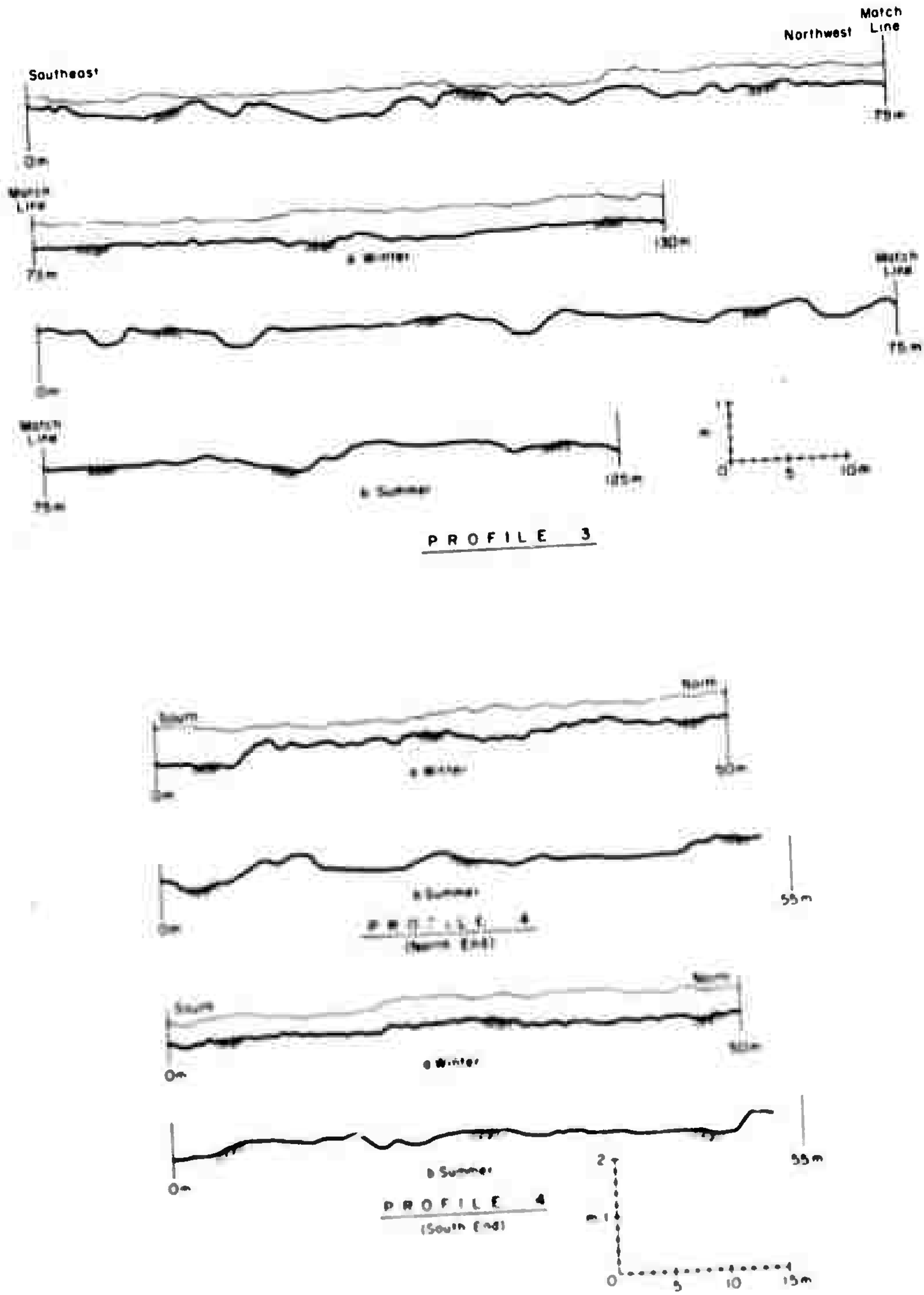

Figure 3 (Cont'd).

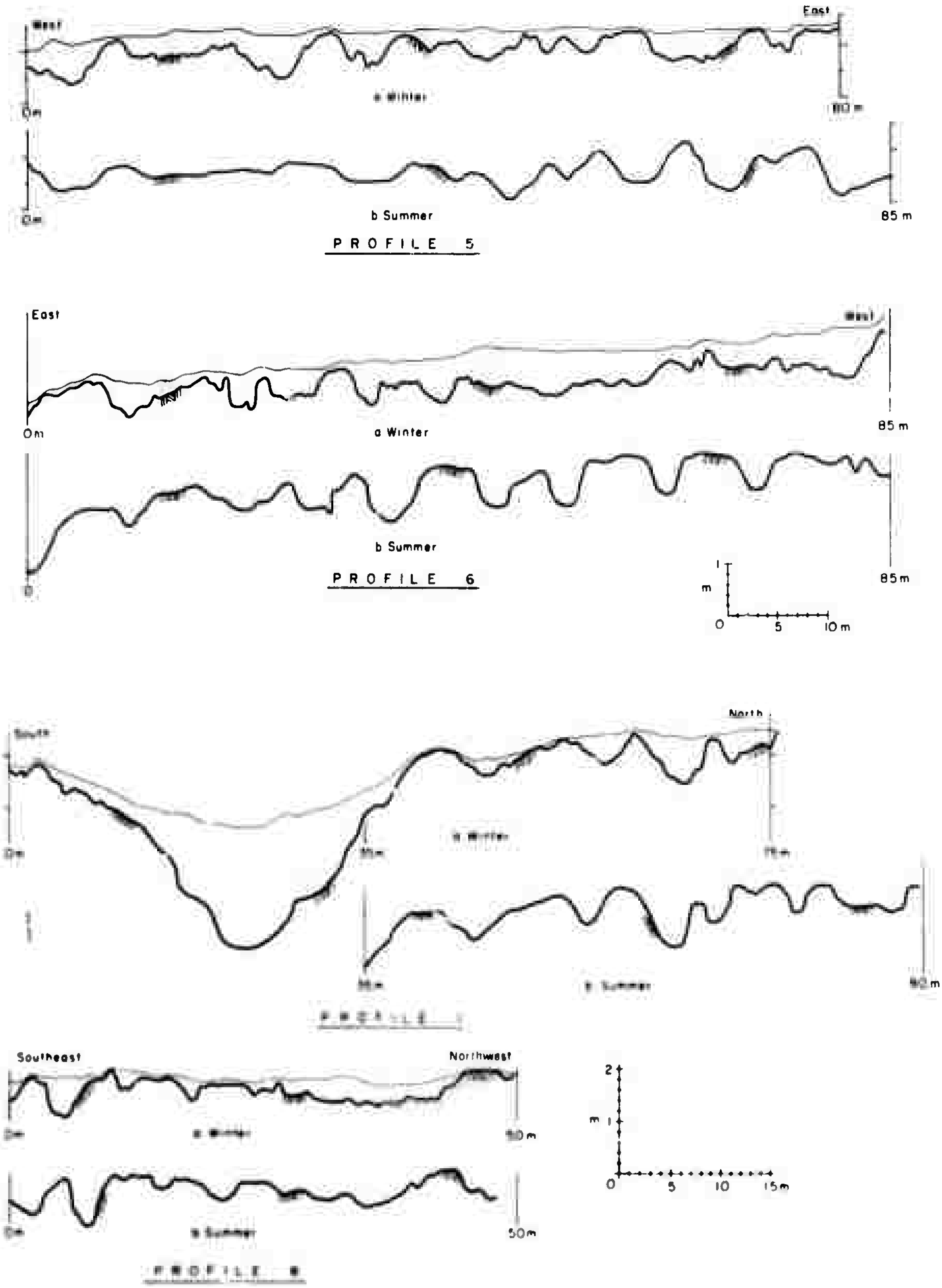

Figure 3 (Cont'd). Selected surface relief profiles.

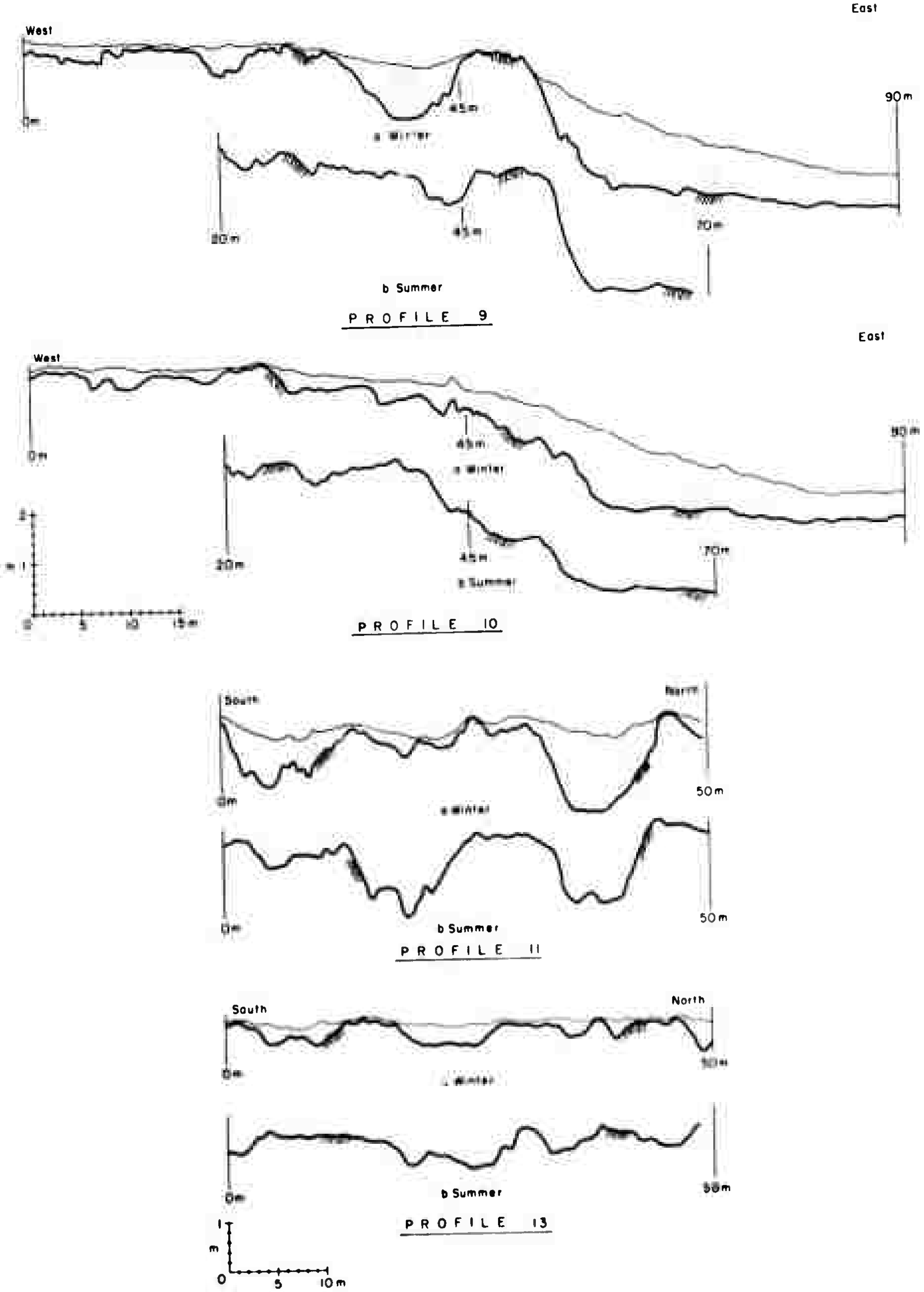

Figure 3 (Cont'd).

Figure 4. High-centered polygons with approximately 30 cm of relief associated with the troughs. Vehicle tracks crossing the area provide some scale.

Figure 5. Lower-centered polygons near the coast. High water covers the low areas, leaving the ridges adjacent to the troughs more apparent.

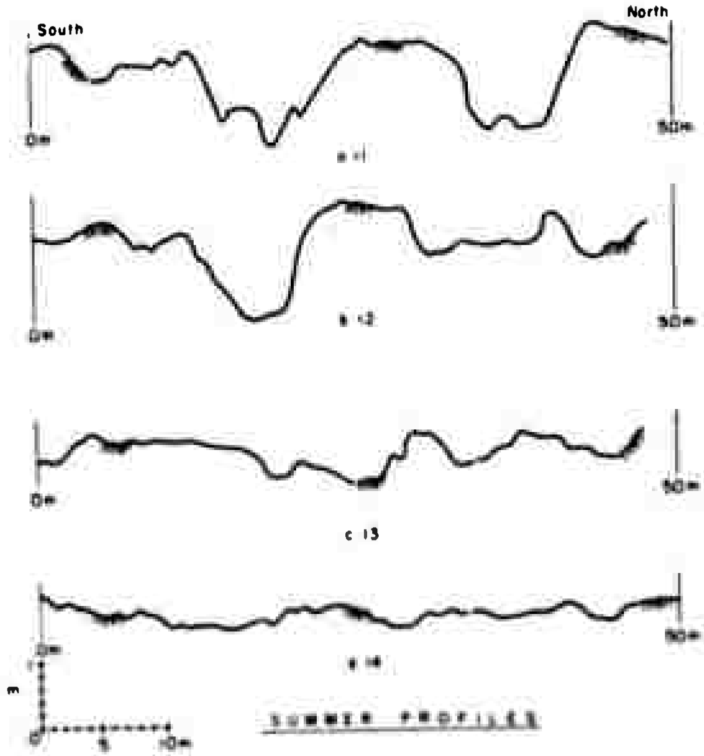

***Figure 6.** Profiles taken parallel to and progressively inland from a lake scarp at approximately 20 meter intervals, illustrating a pronounced decrease in relief.*

***Figure 7.** High polygonal relief associated with the margin of a drained lake.*

Figure 8. Snow accumulation over flat terrain.

Figure 9. Flat snow surface subduing the relief of a deep polygon trough.

Figure 10. Summer view of high-centered polygon near profile 6.

Figure 11. Winter view at same location as Figure 10.

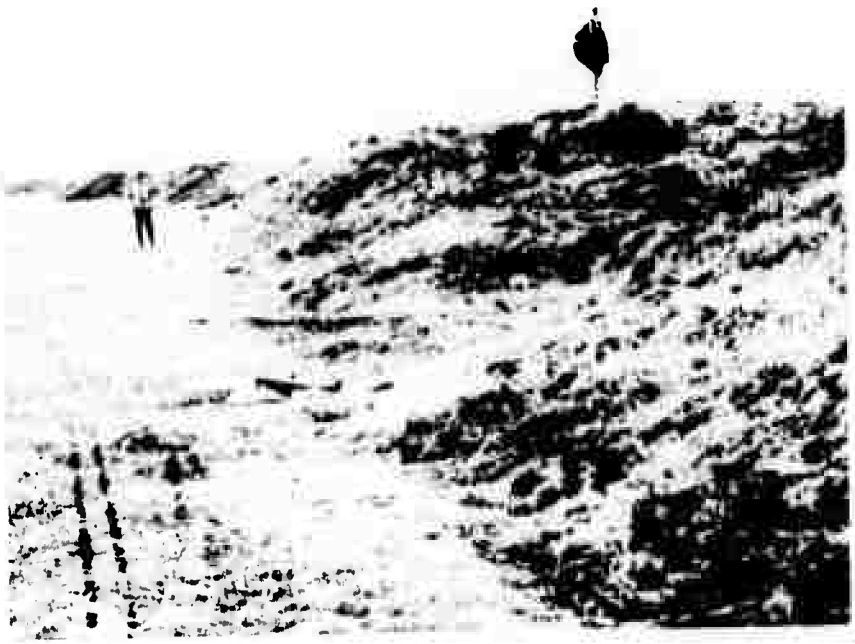

Figure 12. Drained lake escarpment showing ramped winter configuration.

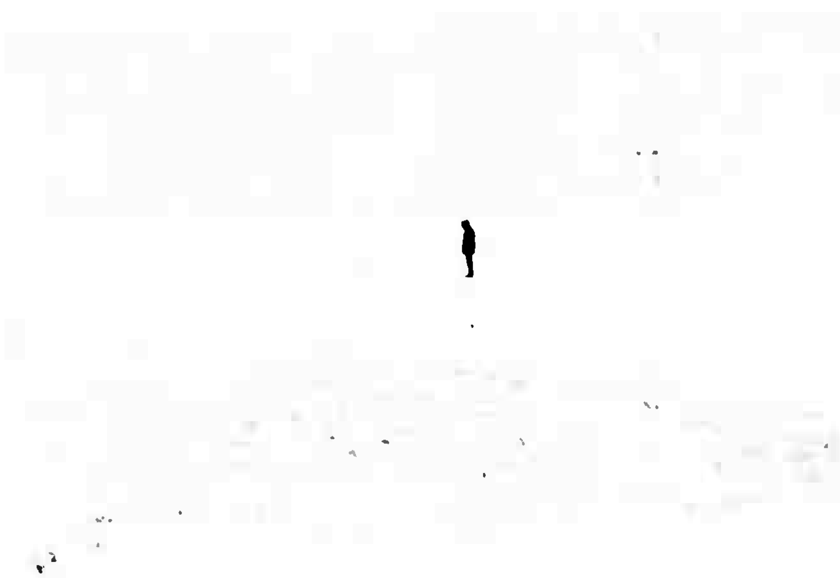

Figure 13. Subduing effect of snow along another lake escarpment.

a.

b.

Figure 14. Noticeable relief differences associated with a small drainage channel.

2. CLASSIFICATION, MAPPING AND MEASUREMENT OF THE DISTRIBUTION OF MICRORELIEF FROM AIRPHOTOS: BARROW, ALASKA

by

Kevin L. Carey

Introduction

In an effort to establish the characteristics, proportion and distribution of various types of microrelief, the Barrow vicinity has been mapped by stereoscopic interpretation of aerial photographs. This mapping effort involved the development of a microrelief classification scheme which was preceded by ground study of the terrain features during the summer of 1970. The study area described in Chapter 1 (Fig. 1) coincides with most of the mapped area; in addition, a small area extending about 3 km to the right (east) of the area in Figure 1 was mapped.

Ground Study

In the summer of 1970, two weeks were spent in the Barrow area examining the various microrelief types in detail. Ground profiles totaling about 1300 meters in length were surveyed in several separate locations. These profiles are discussed in Chapter 1. The profiles, plus about 100 km of reconnaissance travel by tracked vehicle, during which ground-based stereo photography was obtained, provided information that contributed to the development of a microrelief classification scheme.

Aerial Photographs

The aerial photographs used in the photointerpretation of microrelief were obtained for USA CRREL in July 1964. The photo scale is 1:9500, so that each 9 × 9-in. airphoto represents an area on the ground about 2.2 km square. The photography was obtained using black and white infrared film. Due to the high absorptivity of solar infrared radiation by water, open water surfaces and very wet ground appear very dark on prints of this type, compared with conventional panchromatic film. The abundance of moisture at the ground surface in the Barrow area or any tundra region provides a great deal of contrast in the photographic image. This contrast may be useful for photointerpretive studies considering the distribution of surface moisture. However, for the present study, the high contrast is excessive and distracting, and tends to make the stereo relief less-easily perceived. Nonetheless, the large scale of this photography made it the logical choice for this microrelief study.

Earlier uses for this photography include its original purpose, the preparation of the 1:25,000 scale Barrow area topographic map (Brown and Johnson 1966), plus various research studies conducted by USA CRREL in the Barrow vicinity in recent years.

Microrelief Classification System

A microrelief classification scheme was desired which would not only express the characteristics of the ground surface and the height or relief of the terrain features, but also provide an indication of the spacing of the microrelief features. As a result, a three-dimensional microrelief classification scheme was developed. The horizontal dimension desired was the spacing between polygonal ground troughs, rather than an expression of gross ground slopes or the spacing of scarps.

The final formulation of the classification system had to await preliminary examination of the aerial photographs. This examination established the degree of correspondence between field-measured relief and the relief that could be resolved through stereo photointerpretation. As indicated in Chapter 1, the terrain is flat in a gross sense, and therefore the visual stereo model is a subtle one.

The classification system is expressed by mapping classes, which represent the various types of ground surface configuration. The mapping classes are expressed in two ways: 1) For polygonal ground with distinct microrelief, each mapping class is made up of two components, a *terrain-relief class*, and a *feature-spacing class*, which respectively indicate the vertical and horizontal dimensions of the microrelief. 2) For ground without distinct microrelief, or where macrorelief greatly overshadows microrelief, a feature-spacing classification is inapplicable, and therefore the mapping class has only one component, the terrain-relief class alone.

Terrain-relief classes

The terrain-relief classes are based on the character of the ground surface as well as the amount of vertical relief found in the field and recognizable through airphoto interpretation. They are as follows:

High-center polygons covering more than two-thirds of the ground surface:

H_1 = 0.1 to 0.5 m microrelief

H_2 = Greater than 0.5 m microrelief

Low-center polygons covering more than two-thirds of the ground surface:

L_1 = 0.1 to 0.5 m microrelief

L_2 = Greater than 0.5 m microrelief

Transitional polygons: high-center and low-center polygons finely dispersed, each terrain type covering between one-third and two-thirds of the ground surface; or mature low-center polygons with trough depths significantly greater than center depression depths:

T_1 = 0.1 to 0.5 m microrelief

T_2 = Greater than 0.5 m microrelief

Featureless ground: microrelief less than 0.1 m, generally flat to gently sloping ground having 3% ground slope or less:

F_h = Characteristics suggestive of high-center polygons

F_l = Characteristics suggestive of low-center polygons

F = Neither high-center nor low-center polygon characteristics

Sloping or steep ground: microrelief undefined and generally insignificant compared with macrorelief, ground slope greater than 3%, generally much greater and approaching near-vertical scarps in some localities.

S_g – Stream valley sides

S_b – Lake, dry lake or lagoon basin scarps and strands

S_o – Ocean scarps

Feature-spacing classes

The classification of the horizontal spacing of relief is based on the spacing, or frequency per fixed linear distance, of polygonal-ground troughs. As such, this classification is meaningful and applicable only in the H, L and T terrain-relief classes. The feature-spacing classes are as follows:

A – Less than 5 troughs/100 m
B – Between 5 and 7 troughs/100 m
C – Between 7 and 9 troughs/100 m
D – More than 9 troughs/100 m

To establish this classification scheme 15 sites were selected (from the aerial photographs), with each site measuring about 200 m square. Each site was chosen for its relative uniformity of polygonal ground pattern, but together the 15 sites represent a considerable range in polygon sizes. Eight equally spaced radiating transects were drawn from the center of each site on the airphotos. Trough encounters along the photo transects were counted, and each site became characterized by an average number of troughs per 100 meters. The range in trough frequency in the 15 samples was found to be from 3.8 troughs/100 m to 10.1 troughs/100 m. These values led to the adoption of the feature-spacing classes given above.

Mapping classes

Mapping classes including the H, L and T terrain-relief classes are signified by a symbol which is a combination of a terrain-relief class as a numerator and a feature-spacing class as a denominator. For example, the mapping class H_3/D indicates high-center polygonal ground with an average microrelief in excess of 0.5 m, and a trough frequency on a linear path greater than 9 troughs/100 m. The mapping class L_2/A is low-center polygonal ground with 0.1 to 0.5 m microrelief, and with large polygons so that the trough frequency is less than 5 troughs/100 m.

As indicated earlier, the F and S terrain-relief classes have the status of mapping classes by themselves.

As an aid to visualizing the various mapping classes, idealized profiles of selected mapping classes are shown in Figure 15, and Figures 16-19 show some of the mapping classes as photographed in July and August 1970. In addition, figures elsewhere in this report depict various mapping classes as follows:

Figure	*Mapping class*	*Figure*	*Mapping class*
11a	H_3/D	14	S_g
12a	S_b, F_b on left	60	S_o
13	S_b, F_b on right, H_1/C on left above S_b and in foreground	66	S_o

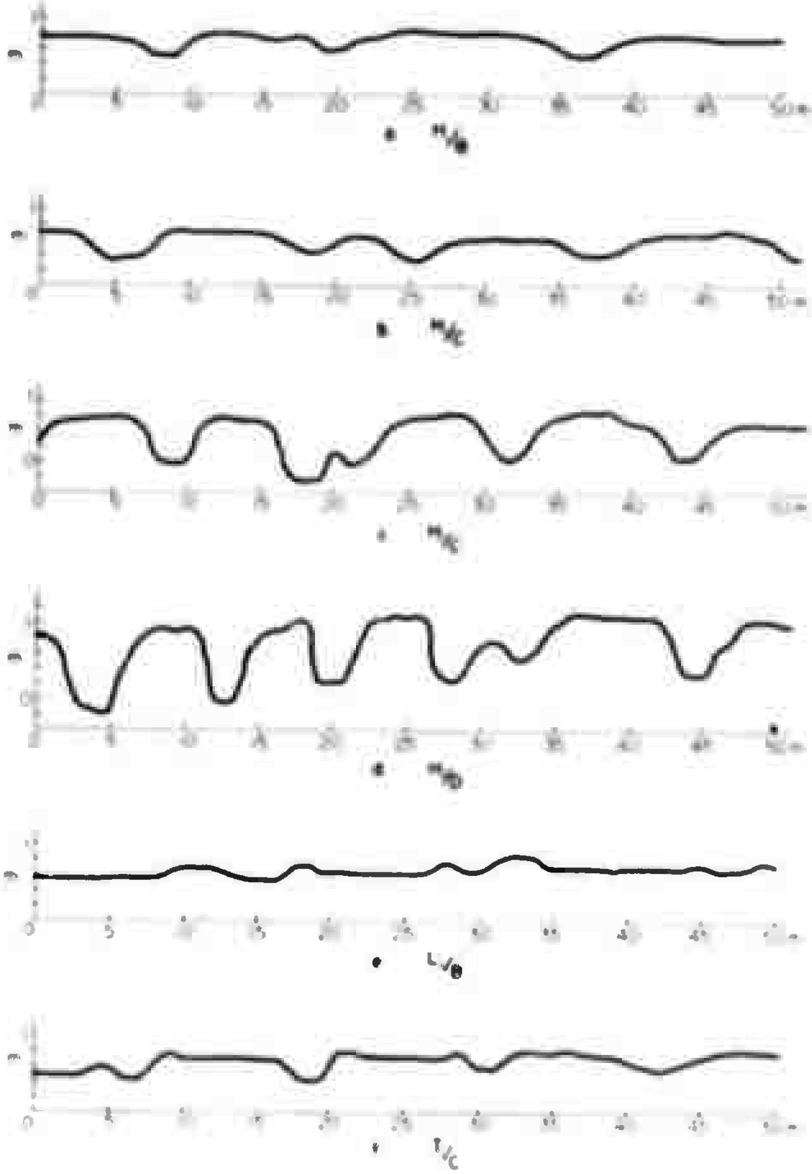

Figure 15. Idealized profiles of selected mapping classes.

Mapping and Statistical Results

Aerial photographs were arranged in an uncontrolled mosaic on a 4 × 8-ft mounting board. The amount of overlap in the photography allowed every other photo to be removed without loss of coverage. The photos that had been removed were used for stereoscopic examination of any point on the

Figure 16. Class H_1/B.

Figure 17. Class L_1/B.

Figure 18. Class E, B.

Figure 19. Class T, C.

a. Central Marsh is a drained lake basin.

Figure 20. Examples of microrelief mapping.

mosaic by juxtaposing them with the corresponding mounted photos. The mosaic was overlain by a sheet of clear acetate, on which mapping was inscribed. Mapping progressed by marking the overlay with the boundaries and outlines of each representative map unit of the terrain-relief classes, through stereoscopic photointerpretation. Subsequently, these map units were further subdivided according to feature-spacing classes, by drawing additional boundaries where appropriate. This latter interpretive technique was accomplished by visual comparison of the particular map units with a "comparison scale," a device which contains 15 actual aerial photograph segments (2 cm square), in proper scale, showing each of the 15 sites used to develop the feature-spacing classification system.

Selected examples of the terrain mapping are shown in Figure 20. Unfortunately, presentation of the entire terrain map in this report is not practical. The original photomosaic and map overlay are retained at USA CRREL.

b. The large map unit marked F_1 is a drained lake basin which is much older than Central Marsh in a.

Figure 20 (Cont'd).

In an attempt to determine quantitative measures which would characterize the various types of terrain in the Barrow area, the following parameters were established for each mapping class.

1. Percentage of the total map area occupied by the sum of all map units of the particular mapping class.
2. Average frequency with which a map unit of the mapping class is encountered along a random linear path.
3. Average length of the path segment over a map unit of the mapping class.

c. The central area is a subtle upland compared to the drained lake basins at the right, left and top.

Figure 20 (Cont'd).

The quantitative parameters were determined from measurements made along a grid of transects which blanketed the mapping area on a second acetate overlay. The transects totaled 145 km in length over the 100-km² study area. With this degree of transect coverage, the "length percentage" of transect segments over map units of a given mapping class is an excellent approximation of the "area percentage" of that particular mapping class. Moreover, the transect procedure permitted evaluation of the frequency of encounters and the average path segment length for the map units of the various mapping classes. Table II presents these data. It can be seen that high-center polygonal ground is the largest single ground type (34% of the area), and that all polygonal ground with microrelief greater than 0.1 m accounts for nearly two-thirds of the total mapping area. Polygonal

d. Tributary streams to Elson Lagoon flow northward, beyond the top of the photo.

Figure 20 (Cont'd).

ground in the microrelief range of 0.1 to 0.5 m is much more common than such ground with an average microrelief in excess of 0.5 m. Water, in the form of streams, stream mouths (locally termed sloughs), lakes and lagoons, covers only 7.2% of the mapped area.

The frequency of encounters ranged from 0.007 encounter/km (i.e. 1 in the 145 km of transects) to 0.955 encounter/km (or 139 encounters in the total length of all transects). If all the map units of each mapping class were the same size, the encounter frequencies would vary directly with the area percentages. But since the sizes (as well as the shapes) of the map units are quite variable, such a correspondence is not found. For example, compare the H_1/A class with the S_b class. Each covers about 1% of the total area, but a map unit of S_b is encountered an average of 0.309 time/km, or about once every 3 km, while a map unit of H_1/A may be expected to be encountered only

0.055 time/km, or about once every 18 km. The reason for this difference is that map units of H_1/A, though less numerous than map units of S_b, have much greater areal dimensions, as indicated by the average path segment length of 173 m, compared to an average of 33 m for map units of S_b.

Table II. Quantitative summary of microrelief, Barrow, Alaska vicinity.

Microrelief as percentage of area				Frequency of encounters (encounters/km)	Average path length over a typical map unit (m)
H: 33.8%	H_1: 24.6%	H_1/A	1.0%	0.055	173
		H_1/B	8.7%	0.708	123
		H_1/C	14.3%	0.955	158
		H_1/D	0.6%	0.082	79
	H_2: 9.2%	H_2/A	–	–	–
		H_2/B	0.9%	0.103	89
		H_2/C	6.9%	0.584	118
		H_2/D	1.4%	0.206	66
L: 20.9%	L_1: 20.3%	L_1/A	4.1%	0.282	145
		L_1/B	12.4%	0.577	215
		L_1/C	3.8%	0.234	164
		L_1/D	<0.1%	0.007	38
	L_2: 0.6%	L_2/A	–	–	–
		L_2/B	0.5%	0.028	190
		L_2/C	0.1%	0.007	133
		L_2/D	–	–	–
T: 8.9%	T_1: 8.0%	T_1/A	0.7%	0.048	157
		T_1/B	3.5%	0.371	94
		T_1/C	3.7%	0.343	107
		T_1/D	0.1%	0.028	50
	T_2: 0.9%	T_2/A	–	–	–
		T_2/B	0.1%	0.007	152
		T_2/C	0.6%	0.041	154
		T_2/D	0.2%	0.014	128
All F: 24.0%	F_h: 7.4%			0.426	172
	F_1: 5.9%			0.275	216
	F: 10.7%			0.474	225
All S: 5.2%	S_s: 3.5%			0.371	93
	S_b: 1.0%			0.309	33
	S_o: 0.7%			0.206	34
Water: 7.2%				0.261	274

3. PROPERTIES OF THE SNOW COVER: BARROW, ALASKA

by

Charles Keeler

Microrelief

As has amply been demonstrated, the seasonal snow cover in the Barrow area effectively smooths all but the largest natural relief features. However, there is a microrelief on the snow surface itself which is, by and large, independent of the underlying terrain. This microrelief is generated by erosion and deposition of the snow by wind. It may consist of such features as barchanoids (Fig. 21) which are formed by erosion at a windward face and deposition to leeward. Other features such as sastrugi (elongate ridges), dunes and pits are formed by wind sculpturing and snow deposition (Fig. 22). In general, in arctic Alaska, these features remain small in scale (less than 0.20 m in height) and would not be expected to impair the ride characteristics of any SEV of the SK-5 class or larger.

A potential use of these features is for navigation in the absence of other aids. These features are aligned in the direction of the prevailing winds, which at Barrow have a strong easterly component (see Fig. 23). Consequently, the direction of alignment can be used as a compass needle. Naturally, storm winds can disturb this pattern.

Mechanical Properties

In general, the snow surface of arctic coastal Alaska presents a firm bearing surface for men on foot and low ground pressure tracked vehicles. Figure 24 shows the track left by an M29C Weasel (GVW 1100 kg, track pressure 15×10^3 N m^{-2}. The surface is so hard in some areas that the grousers do not even register.

As a measure of the variability of surface hardness, a traverse of Canadian hardness (an index of hardness measured with a hand-held, circular plate penetrometer) was made at winter profile 8a (Fig. 25). The values are spread over two orders of magnitude; however, all values are high relative to those for snow in the continental United States. The cause of this is, of course, the effect of the wind continually reworking a rather sparse snow cover.

Three representative vertical sections of the snow cover are shown in Figure 26. Pits A and B show the common succession over the tundra of a hard, wind-packed layer overlying a coarse, granular layer with little to no cohesion. This layer, referred to as "depth hoar," is created by the mass transport of water vapor along the temperature gradient (and consequently a vapor pressure gradient) which exists between the ground surface and the atmosphere. Pit C shows a somewhat different situation in which a deep snow cover overlies a streambed (Voth Creek, profile 7, Fig. 3). In this case the water in the creek, before fully freezing, indurated the lower snow layers, making them extremely compact and coherent. Benson (1969) describes the genesis of the features much more fully and also presents profiles further inland from the Barrow area. Profiles over sea ice may or may not have a depth hoar layer, depending on the snow thickness and exposure to wind action. In all cases the lowest surface snow density exceeded 280 kg m^{-3}.

Figure 21. Barchanoids formed by wind erosion of the snowpack. Prevailing wind direction indicated by arrow.

Figure 22. Wind transport of snow across the surface creates a varied microrelief. The arrow indicates the direction of movement. Note erosion by undercutting on the windward side of the microfeatures.(for example to the left of the pencil).

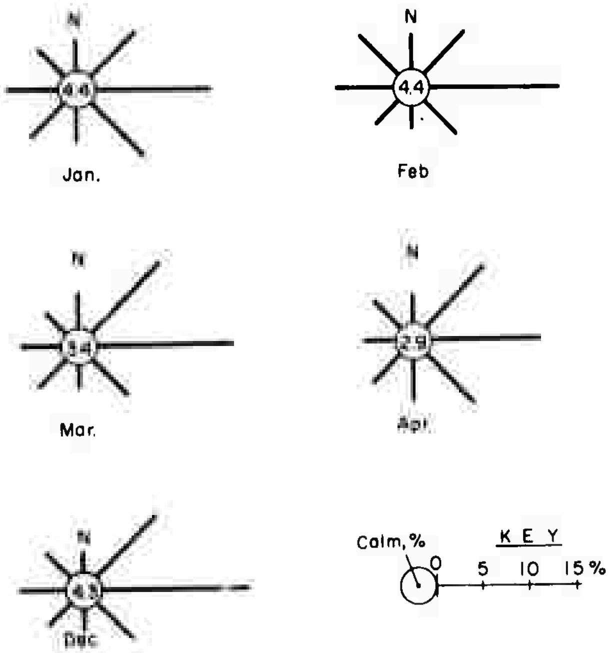

Figure 23. Wind direction data from the Barrow area. Wind roses show the percent frequency of direction for the winter months.

Figure 24. Vehicle tracks made by an M29C Weasel, indicating the limited depth of track penetration in the hard, high density snow. Arrow indicates prevailing wind direction.

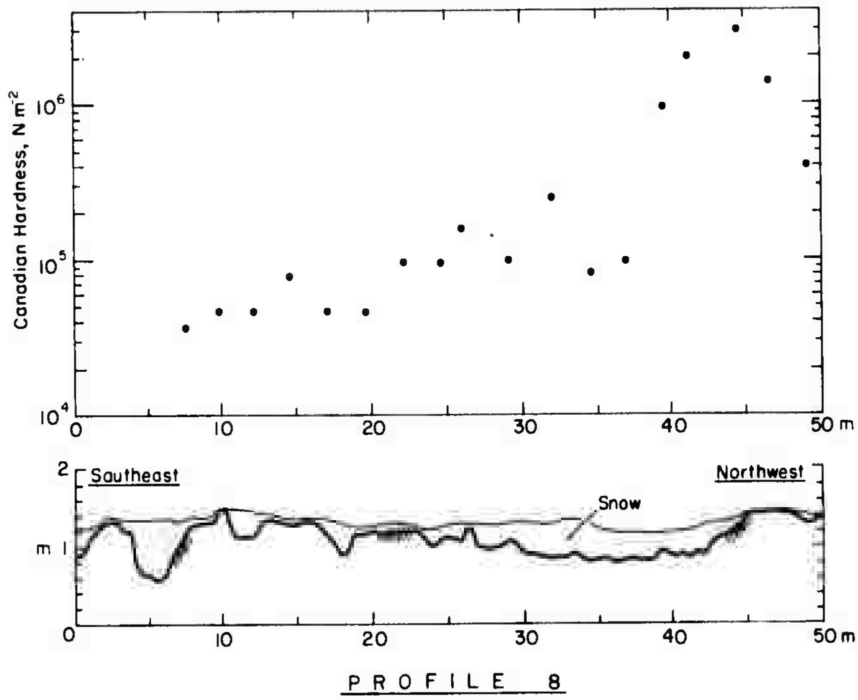

Figure 25. Canadian hardness values shown above the winter snow surface profile from which they were obtained.

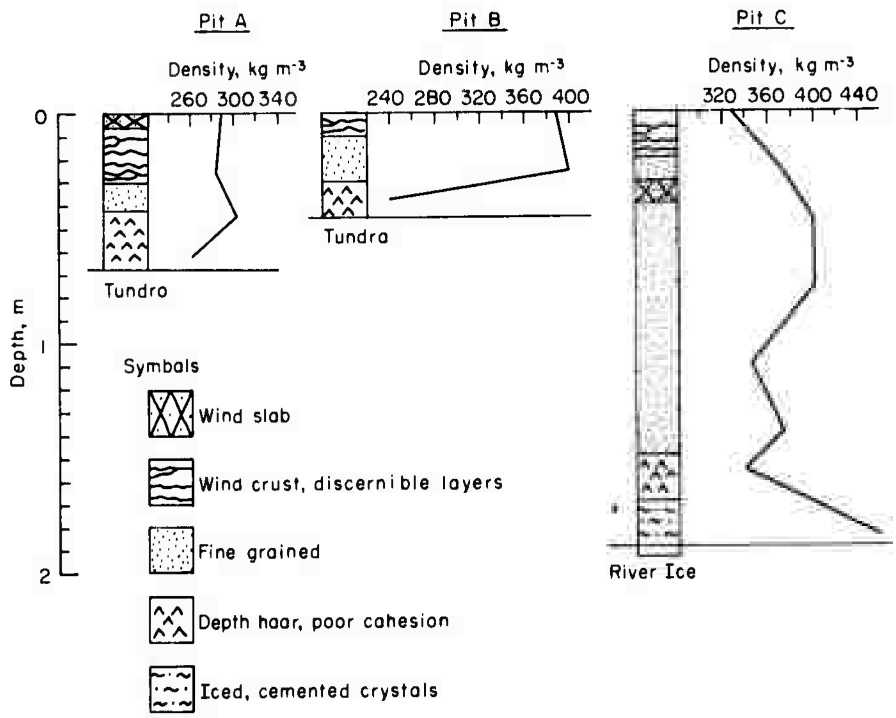

Figure 26. Snow stratigraphy data from the Barrow study area (early April).

4. COASTAL CONDITIONS OF ARCTIC NORTHERN ALASKA

by

Allan D. Hartwell

Introduction

This chapter summarizes general coastal processes and terrain features of more than 2150 km of coastline along the large part of northern Alaska referred to as the Arctic Slope (Payne et al. 1951). This study was undertaken in order to obtain quantitative data on the coastal environment of arctic Alaska for use in technological development of surface effect vehicles (SEV's) capable of arctic operation. This coast, which extends from Cape Thompson eastward along the Chukchi and Beaufort Seas to the U.S.-Canadian border near Demarcation Bay (Fig. 27), is part of two physiographic provinces: the Arctic Foothills and the Arctic Coastal Plain (Payne et al. 1951, Williams 1958, Wahrhaftig 1965). The foothills to the south, which are geologically old, have high relief that is controlled largely by the underlying folded bedrock. The coastal plain is geologically younger, with lower relief, and has been formed primarily by marine and fluvial sedimentation.

The coast of this extensive tundra area is a generally narrow transition zone between the land surface and the sea, ranging from steep, nearly continuous sea cliffs with gullies and narrow valleys, to low gentle slopes. Other coastal landforms common to the region include beaches, barrier islands, spits, dunes and river deltas. Despite this variety of landforms, the processes which shape this coast are about the same from place to place. Breaks in the coastal scarp which would permit inland access to surface transportation such as large SEV's are called " windows." They occur where streams, rivers and lakes have been intersected by the sea.

This coastal environment has several unique features. For up to nine months of the year sea ice is frozen fast to the coast, protecting it from the normal processes of erosion and sediment transport. Unconsolidated material is bonded by ice (permafrost) to depths as great as 500 m. During the summer months the ground surface and near-shore sea ice melt, allowing thermal erosion and wave attack of exposed sections. These processes result in features such as steep sea cliffs and marked annual retreat of shorelines.

Methods of Study

This report is primarily the result of a map and photo study which was substantiated by limited field studies in the Barrow area. A literature survey was undertaken to obtain all available information pertinent to the coastal processes and morphology of this region. Portions of the following topographic map series were used to classify geographic regions and coastal types and to acquire quantitative information on relief and morphology of sea cliffs and windows: Army Map Service 1:50,000 series (1955); U.S. Geological Survey 1:63,360 series (1955) and 1:24,000 series of Beechey Point area (1970); and U.S. Coast and Geodetic Survey 1:50,000 bathymetric series (1968).

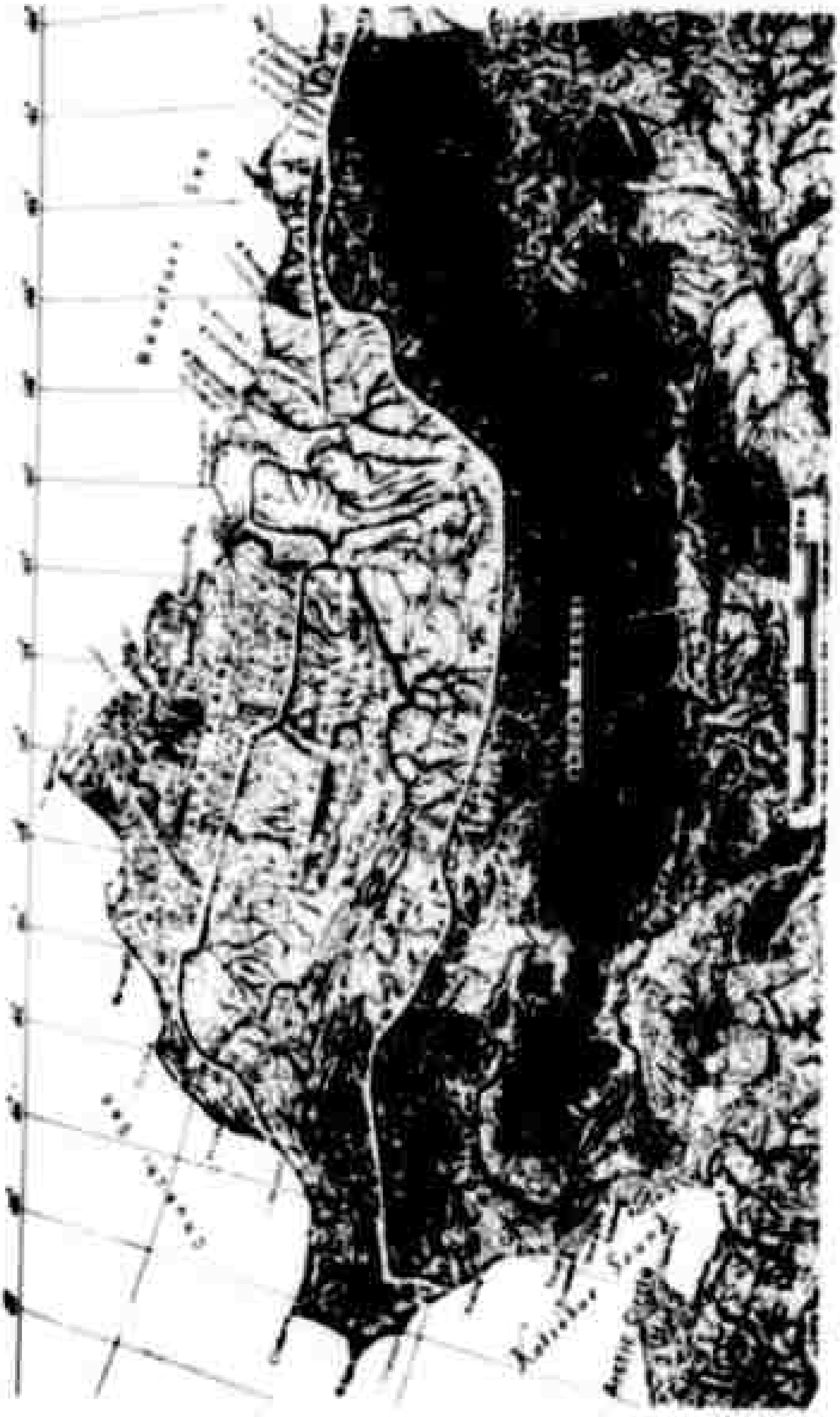

Figure 27. Map of northern Alaska showing both general relief and physiographic subdivisions (from Raisz 1968).

Linear measurements of terrain features were made from maps using a wheel-type map measuring device, with a precision of about 0.5% for nearly straight coastlines, and about 4.0% for very irregular coastlines. Because of the anticipated size of the proposed SEV's, coastal relief or sea cliff height along the coast was estimated in the following height categories: 0-1, 1-2, 2-3, 3-4, 4-5, 5-8 and > 8 m. Vertical aerial photographs taken in 1955 (scale about 1:50,000) were used to confirm the configuration of the coastline at a number of selected locations; however, these estimates of coastal relief are believed accurate only to within about one meter, due to the generally low, flat character of the coast and the paucity of spot elevations in coastal areas. In high relief areas the 25-foot contour interval on the maps was also utilized. In view of the objectives of this study, these levels of reliability were considered adequate.

Field studies were undertaken in the Barrow study area described in Chapter 1. During the winter investigations (March 1971) profiles were made at 12 sites which included beaches, sea cliffs and estuary banks. The profiles were used for the same purpose as those acquired for the relief study in Chapter 1: to determine the morphology of coastal features and to determine variations in relief caused by the seasonal snowpack.

Coastal Processes

The coastal environment of the Chukchi and Beaufort Seas is unique in many ways. The basic processes of sediment transport and deposition are controlled primarily by waves and currents; however, the effectiveness of these processes is severely limited during the long winter season (about eight months) when the coast is frozen fast with pack ice. The ice itself is responsible for several unique processes of coastal modification: scouring of the near-shore sea floor, ice push, and rafting of sediments. The outstanding unique feature of this coast is the prevalence of perennially frozen ground or permafrost. The ice-bonded sediments are very susceptible to erosion, and retreat of escarpments as much as 10 m a year is not uncommon (Lewellen 1970). However, during summer months surface thaw of the permafrost can make the escarpments unstable, and slumping frequently occurs. Wave and current action at the base of sea cliffs may destroy the ice bonding in the permafrost and form a "thermo-erosional niche" or thermal undercutting of the bluff face. These processes acting in ice-indurated material can form unique morphologic features such as steep sea cliffs, tilted blocks of slumped tundra, and windows.

Sea ice

First-year ice is found adjacent to the coast all along the Chukchi and Beaufort Seas. This ice, which attains a thickness of about 1.5 m during the winter, appears to be protective rather than destructive. Commencing in late fall, the ice freezes fast to the beach and sea floor along the coast, and in bays and lagoons, for a distance of several tens of meters offshore (Fig. 28), and remains there for about eight months of the year. (The actual dates of freeze-up and breakup are summarized in Table III.) During this period the ice is firmly frozen to the shore and no wave or current action is possible. Thus, near-shore erosion, sediment transport and coastal modification are essentially halted until spring.

Shearing may occur offshore between the fast ice and the floating ice to produce large pressure ridges and jumbled rubble fields. Offshore of Point Barrow, pack ice forms a major pressure ridge nine years out of ten (MacGinitie 1955) and grounds on the sea floor between depths of 18 and 30 m. From shore to a depth of over 30 m, the sea floor is rubbed and gouged by the deep keels of pressure ridges which extend beneath the floating sea ice, causing considerable alteration of submarine topography (Carsola 1954, MacGinitie 1955, Rex 1955). Ice which is grounded near shore is usually uplifted and contains considerable sediment (Fig. 29).

Figure 28. Winter view of the Chukchi Sea showing snow-covered frozen beach near Barrow and near-shore zone with large ice blocks. Note Eskimos with sled for scale.

Figure 29. Grounded sea ice which has been uplifted. Note sediments trapped in ice.

Table III. Dates of ice breakup and freeze-up at selected locations along the northern Alaskan coast.*

Location	Ice breakup			Ice freeze-up			Avg yrs of record
	Average	Earliest	Latest	Average	Earliest	Latest	
Point Hope	20 June	30 May 27	8 Jul 46	11 Nov	6 Oct 42	19 Dec 47	8
Point Lay	24 June	1 Jun 43	10 Jul 53	4 Nov	12 Oct 43	27 Nov 48	4
Wainwright	29 June	7 Jun 44	26 Jul 48	2 Oct	26 Sep 48	9 Oct 45	7
Point Barrow	22 July	15 Jun 44	22 Aug 31	3 Oct	31 Aug 27	19 Dec 47	31
Barter Island		late July	early Aug		mid Sept	early Oct	

*Data from U.S. Department of Commerce, Coast and Geodetic Survey, United States Coast Pilot No. 9, 1964. Dates for Barter Island not available.

Figure 30. Ice-push ridges about 1 m high at Barrow.

During the breakup period, the shelf of fast ice tends to protect the beach and shoreline from possible disturbances by the ice floes. When the pack ice is moved strongly toward the land by currents and wind action, it may override this protective belt of fast ice, but only rarely impinges against actual beach material. As this belt thaws, the sea ice may be driven ashore to modify shorelines locally and produce push ridges up to several meters high (Fig. 30). Major ice shoves, which occur in the vicinity of Point Barrow at least once in every four or five years, may build up the beach, bringing considerable quantities of sand and gravel landward where it is deposited on the beach when the ice melts (MacCarthy 1953). At many locations the fast ice and drifted snow also form a toe at the base of coastal sea cliffs which is retained well into the thaw season, protecting the beach and lower slope from waves, currents and permafrost thawing.

After breakup, the concentration of ice in coastal waters depends mostly on wind direction. Offshore winds tend to hold the ice away from shore, whereas landward winds carry it in. Near Point Barrow, easterly and southerly winds tend to hold the main ice pack offshore, whereas the northerly and westerly winds force the ice onshore. However, near-shore ice floes and grounded ice may be present even when the pack ice retreats. Moving eastward from Point Hope, the amount of open water progressively decreases while the influence of pack ice increases. At Point Barrow the ice pack usually retreats from shore in mid-July and returns in late October (see Table III). On a few occasions there has been as much as 320 km of open ocean off Barrow (Hume and Schalk 1967) and in some years the pack ice has remained against the shore for the entire summer (Rex 1961). Safe ship movement in these waters requires many years of experience in navigating through ice, and often requires the support of reconnaissance aircraft.

Waves

In general, the size of waves is controlled by wind velocity and fetch (amount of open water that the wind can blow across). Because of the pack ice, wave action along this coast is much reduced in comparison with more southern latitudes. The floating ice, which is present even during the warmer months, helps to protect the beaches from direct wave action and has a strong inhibiting effect on wave development. The waves expend a large proportion of their energy on the floating ice offshore and are greatly reduced before reaching the beaches. Even when no floating ice is visible from the shore, the edge of the polar pack may be only a few kilometers beyond the horizon, allowing a relatively small fetch of open water for wave development. At Point Barrow these factors tend to minimize effective wave action and only several times a summer is wave development sufficient to produce much active surf (MacCarthy 1953).

Since the region is dominated by the polar high-pressure system, the prevailing wind is northeast for every month of the year (Stettler 1952). The most severe wave conditions occur during rapidly moving storms, provided ice conditions permit an appreciable fetch across open water. The largest waves ever recorded offshore of this coast were greater than 9 m (Lewellen 1969). Near Point Barrow waves of 6-m height were observed during a storm in late August 1951 (Carsola 1952) and waves 3 m high occurred during the greatest storm of record, 30 October 1963 (Hume and Schalk 1967). However, such waves may be quickly eliminated when the pack ice is blown onshore. A tabulation of sea height versus direction for the vicinity of Point Barrow shows that about 90% of the time sea height is less than 1 m, and that the dominant winds are from the northeast (Table IV).

Waves are also partially responsible for the formation of "kaimoos" or ice and gravel ramparts, a unique feature of many arctic beaches (Moore and Scholl 1961). This feature, which is especially common on beaches near Cape Thompson, begins to form in mid-October when air temperatures fall below freezing. Because sea ice has not yet started to form, waves continue to break on the beach, freezing and leaving a thin layer of ice. Frozen spray frequently coats the beach with a glaze that may extend more than 35 m inland (Rex 1961). Gradually a bed of ice up to 1.5 m thick, commonly interbedded with sediments, is built up on the beach. The upper surface becomes very flat and continuing wave action only affects the resistant outer face of the kaimoo, marking the end of effective wave action on the beach for the season. Occasionally, a heavy fall storm may undermine the kaimoo but the near-shore sea ice soon forms and surf activity is terminated for the year (Moore 1966).

Table IV. Observations of sea height versus wave direction for near-shore areas between Point Barrow and Lonely, Alaska (data taken July to November).

Wave direction	Sea height, m <1	1	1-2	2-3	>3*	Total obs	% of total
NNE-NE	146	25	2	2	1	176	7.3
ENE-E	317	57	7	2	2	385	15.9
ESE-SE	68	6		1		75	3.1
SSE-S	22	3				25	1.0
SSW-SW	23	7				30	1.2
WSW-W	102	20	7	4		133	5.5
WNW-NW	63	29	28	12	1	133	5.7
NNW-N	68	20				88	3.6
CALM	1370					1370	56.7
Total	2178	168	44	21	4	2415	
%	90.2	7.0	1.8	.9	.1		

*Actual observations were: 3.4 m, 4.3 m, and 2 of >9 m.

Currents

The currents along the coast are generally weak due to the dominance of pack ice, limited wave action, and small tidal range. Three main currents are present: the Northern Alaska Littoral Current which flows along the Chukchi Sea from the southwest, a longshore current from Cape Simpson eastward into Canadian waters, and the Pacific Gyral of the Arctic Ocean which meets the coast near Point Barrow, creating a weak longshore current from the southeast (Fig. 31). These currents are generally weak (less than 1.9 km/hr or 1 knot), but west of Point Barrow velocities up to 5.5-7.4 km/hr or 3-4 knots have been measured (Lewellen 1969).

Tides

The astronomical tides along the coast are weak and somewhat unpredictable (Fig. 31). At Point Barrow the tide is only about 15 cm (Fig. 32), ranging from 7.6 cm during neap tide to 15.2 cm during spring tide (Don Schell 1971, personal communication). Tidal conditions are about the same west of Point Barrow, but become less predictable to the east (Fig. 31). Near Herschel Island in Canada the tides are about 61 cm (Lewellen 1969).

In addition to these astronomical variations, storms cause longer period changes in sea level of up to 1 m. This storm surge or storm tide is the result of two factors: a rise in sea level under an atmospheric low-pressure area, and a rise in sea level caused by wind blowing onshore (Hume and Schalk 1967). For example, at Barrow Village winds from the west blow water against the coast and raise the sea level, whereas winds from the east tend to lower the sea level. Under certain conditions of ice breakup, surging oscillations in sea level have been observed, apparently due to the impinging of a strong current on the shore-fast ice (Rex 1964).

The largest sea-level fluctuations are storm surges which occur during the polar storms in the fall. On 30 October 1963, the greatest storm on record attacked the coast with winds up to 88.5 km/hr (55 mph) and gusts up to 120 km/hr (75 mph) which blew over an ice-free ocean (fetch about 100 km). Waves estimated at 3 m, combined with a storm surge of about 3.6 m, caused coastal flooding and over $3.3 million damage at Barrow (Hume and Schalk 1967). The area of strongest attack was between Wainwright and Point Barrow, with decreasing effects in both directions from this zone. From Point Barrow eastward to Cape Simpson the offshore barrier islands were

Figure 31. Currents and tides along the coast of northern Alaska.

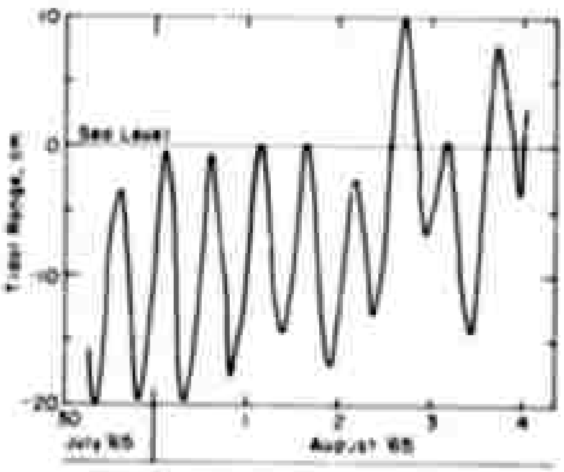

Figure 32. Tidal record from Elson Lagoon near Point Barrow, 30 July to 4 August 1965 (from Lewellen 1965).

drastically altered by erosion and breaching. Near Cape Simpson, sea level rose about 2.4 m but little damage occurred because sea ice in the area had dampened the waves. The storm surge decreased further to the east with the greatest beach changes noted along western exposures. The storm surge at Barter Island was about 1.7 m. Beyond Wainwright to the southwest a surge of about 2.7 m occurred near Point Lay. The magnitude of this storm suggests that it was a "two hundred year storm" for the area (Hume and Schalk 1967). Other recent storm tides at Barrow were 2.7 m (October 1954) and 1.2 m (6-7 October 1956; Schalk 1963).

Sedimentation

Sediment transport and deposition along the coast are primarily due to waves, currents and sea ice. In late spring after the pack ice has broken up along the shore, waves and currents begin to rework the coastal material and transport it in two primary directions: normal to the shoreline and along the shore. Near Cape Thompson, studies over several seasons revealed that the former direction is more important in terms of the volume of material transported (millions of kilograms during a single storm) but that sediments carried offshore are soon returned to the beach in response to changing surf conditions (Moore 1966). Thus in this area, offshore and onshore movements tend to balance each other during the year, causing little permanent alteration to the position of the shoreline. Further northeast along the coastal plain, the coast is slowly retreating landward due to wave attack and thermal erosion. Longshore transport, which is caused by wave attack at an angle, with some assistance from weak longshore currents (Moore and Scholl 1961), carries material along the shore and has built beaches, spits, barrier islands and offshore submarine bars along much of the coast. In addition, sea ice can bring considerable quantities of sediment ashore, either by ice push along the sea floor or through sediment being frozen into the ice, rafted onshore and released during melting.

The beaches along the coast are quite variable, largely due to differences in quantity of sediment supply, lithology of source material, and dominant coastal processes. In general, the beaches are narrow, steep and coarse-grained and commonly abut the mainland at the base of sea cliffs. Beaches in the vicinity of Point Barrow which are similar to those along much of this coast are of two types. Where sea cliffs are high, such as a few kilometers southwest of the point, beaches are narrow with a well-developed foreshore. Here a backshore develops only where the beach truncates the mouths of estuaries. Waves reach the base of the cliffs only during severe storms. In contrast, beaches on the Point Barrow spit have a moderately steep foreshore and a gently sloping backshore which reaches to Elson Lagoon. The underwater portion of the backshore is steep and the beach sands and gravels form a sharp contact with the grey mud on the lagoon bottom. Beach sediments in the Point Barrow area are coarse-grained with coarse and medium gravel in the surf zone that grades into fine gravel and sand on the foreshore of the beach. (Sample means of foreshore material 1.0 to 2.5 mm and standard deviation about 1.0; Rex 1964.) Backshore areas usually consist of laminated sand and fine gravel. Under favorable wind conditions convex ridges of coarse sand and fine gravel may develop on the foreshore. In the Point Barrow area, beach gravels are generally hard and abrasive with lithologies dominated by chert, quartz, sandstone and limestone (Rex 1964, Moore 1966).

Figure 33. Vertical aerial view of Cooper Island near Cape Simpson showing how sea ice is held offshore by the barrier islands.

In the west at Point Hope, the coastal sediments have been deposited as a complex pointed projection of spits and barrier islands called a cuspate foreland (Shepard 1963). Further east the sediments have formed narrow spits that extend out parallel to the coast, shallow offshore bars, and nearly continuous barrier islands, giving the coast a smooth shoreline with shallow inland lagoons and river deltas (see Fig. 43 and 47). These islands have very low relief (0 to 2 m) but form an effective obstacle to offshore pack ice and the direct effects of the open ocean. At the same time they keep large portions of the landward lagoons clear of ice and provide open water where waves can form and attack the coast (Fig. 33).

The 1963 storm which attacked the coast demonstrated the unsteady rate at which sediment transport and other geologic processes operate over short time spans. At Point Barrow this storm moved more sediment in a few hours than would normally be transported in 20 years (about 152,920 m^3; Hume and Schalk 1967). Thus, the shoreline is changing constantly but one sudden storm can cause tens of meters of erosion and deposit sediments many kilometers away from their original location.

Erosion

Along most of the coastal plain the cliffs are retreating rapidly, even where sheltered from direct wave action, and losses of up to 10 m/year have been recorded (Lewellen 1970). Cliff erosion occurs primarily due to thawing of permafrost and physical attack by waves and currents. During the summer months the surface of permafrost thaws, making the ice-bonded materials unstable and highly susceptible to slumping. Along the base of the sea cliff and inland along the

Figure 34. Closeup view of a thermo-erosional niche near Barrow (from Lewellen 1965). Scale in centimeters.

banks of estuaries and rivers, water can thermally undercut the permafrost, forming a "thermo-erosional niche" (Walker and Arnborg 1963). These niches can form rapidly and may extend several meters under the bank (Fig. 34). This niching makes the overhanging bank unstable and it can collapse easily, especially where ice wedges are intersected (Lewellen 1965). Thawing along the ice wedges which underlie the troughs of polygonal ground features frequently causes the cliff to slump as large tundra blocks (Fig. 35, 36). At many locations microrelief along the margins of polygons is accentuated by erosion in the polygonal troughs at the edge of the main sea cliffs (see Fig. 40). Frequently vegetation hangs together as a thin mat draped over the edge of the cliff (Fig. 37).

Temporary protection from coastal retreat is provided by material which accumulates at the base of the main coastal slope. In the summer slumped soil and tundra vegetation material protect the slope from direct wave attack (Fig. 38). The ramp of snow and ice which forms along the sea cliffs during the winter (Fig. 39) tends to insulate the slope from thermal erosion well into the summer melt season (Fig. 40). Large ramps which usually develop along higher sea cliffs are retained later than small ones. In general the areas of low cliffs have less protection than those with higher cliffs (relief greater than about 5 m) and seem to be retreating more rapidly. The net effect of continual cliff retreat is to form smooth, straight or gently curved coasts with narrow beaches above which gullies are left hanging on the steep cliff faces as they retreat (Fig. 40, 44).

Bathymetry

West of Point Barrow the continental shelf is broad and shallow (averaging about 42 m in depth) and the 11-m (6-fathom) bottom contour is very close to shore (5 to 8 km; Fig. 31). East of Point Barrow the 11-m contour is further offshore (about 15 to 32 km) but shortly beyond (about 70 to 100 km offshore) there is a very sharp break in slope from the continental shelf into the oceanic deep of the Arctic Basin.

Figure 35. Tilted blocks of tundra near Cape Simpson, caused by thermal erosion along the margin of polygons.

Figure 36. Aerial view showing slumping of tundra blocks along the coast near Drew Point.

Figure 37. Steep erosional scarp near Cape Simpson. Note draped vegetation mats and massive appearance of permafrost.

Figure 38. Closeup view of same scarp as Figure 35. Note slumped material at base of slope.

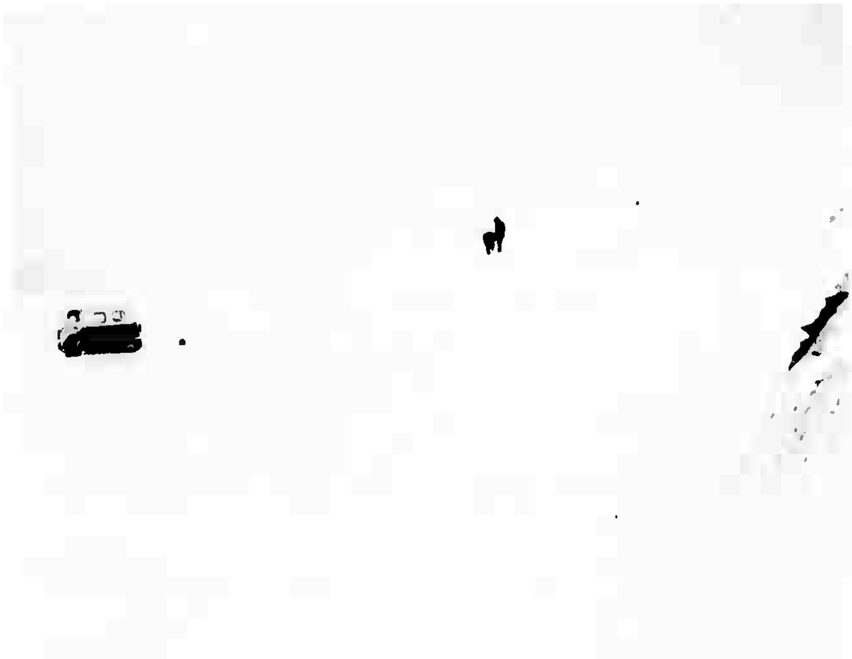

Figure 39. View of snow ramp at profile 23. Weasel is parked on the snow-covered beach.

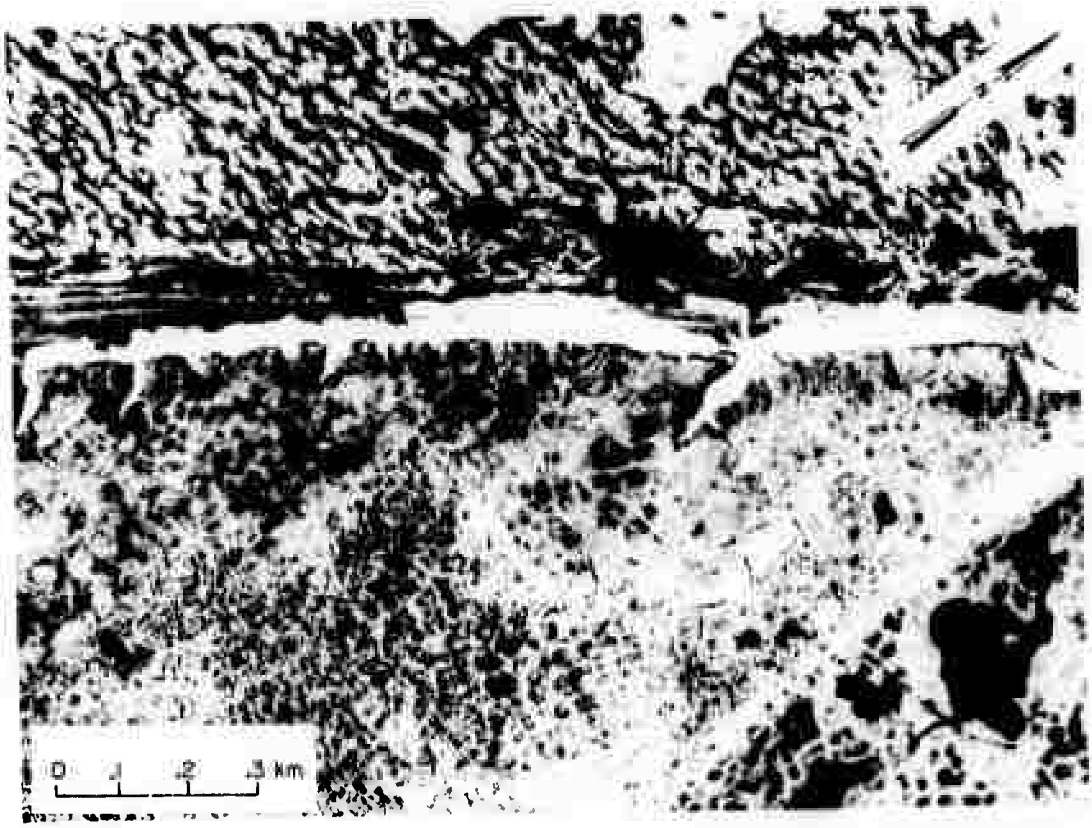

Figure 40. Vertical aerial view of coastal scarp with residual snow ramp at profile 24, 30 June 1971.

Coastal Classification

In order to meaningfully describe the terrain conditions of the northern Alaskan coast and develop a classification scheme for relief features that would be useful to the purposes of this report, it was first deemed necessary to evolve a genetic classification of coastal types based on an understanding of the dominant geologic processes acting on this environment. Four main types of coast are recognized (after Shepard 1963):

1. Primary coasts – configuration due to the sea coming to rest against a landform shaped by terrestrial rather than marine agencies.

a. Land erosion coasts – shaped by subaerial erosion and partly drowned by rise in sea level; characterized by a nearly straight shoreline with steep, sheer sea cliffs and bluffs formed in bedrock (Fig. 41); the cliffs are in a general erosional state but at some locations are fronted by near-shore sedimentary deposits (barriers) which provide some protection from the open ocean; relief is high to very high (about 10 m to several tens or hundreds of meters).

b. River deposition coasts – largely due to deposition by rivers extending the shoreline; fluvial deltaic deposits consisting of multiple braided and branching river channels separated by sedimentary lobes (Fig. 42); dune fields are present on some deltas where loose sediments are not vegetated; channel banks are frequently steeply eroded by thermo-erosional niching and active slumping (Walker and Arnborg 1963); some sections are fronted by near-shore barrier islands (Fig. 43); generally low to very low relief (about 0 to 4 m).

2. Secondary coasts – coastlines shaped primarily by marine agencies but which may have originally been primary coasts.

a. Wave erosion coasts – coastlines which are exposed directly to the open ocean and along which marine deposition is negligible; characterized by sea cliffs in bedrock or poorly consolidated frozen material (permafrost) which are either undergoing marked erosion or in a near-equilibrium condition; cliffs are wave-straightened and have a generally sheer and nearly continuous appearance (Fig. 44); may have a narrow beach at the base of the slope (Fig. 45); moderate to low relief (less than about 11 m).

b. Marine deposition coasts – coastlines prograded by waves and currents and along which marine deposition is active; fronted by near-shore sedimentary deposits (barrier islands and spits) that extend roughly parallel to the general coastal trend but are separated from the mainland by a relatively narrow body of water (usually less than about 5 km wide; Fig. 46); these barriers tend to straighten the coastline and provide some coastal protection from the pack ice, waves and currents of the open ocean (Fig. 47); spits may also extend across river valleys and partially close them (Fig. 48 and left-hand portion of Fig. 44); relief generally low (less than about 4 m).

The distribution of coastal types is shown in Figure 49 and tabulated in Table V. About 30% of the coast is considered primary (dominated by terrestrial processes) whereas 70% is marine-dominated (secondary).

Geographic Regions

In order to describe the geographic distribution of these different genetic coastal types, the northern Alaskan coast was subdivided into six distinct geographic regions on the basis of geology, physiography and recent marine processes (Fig. 49).

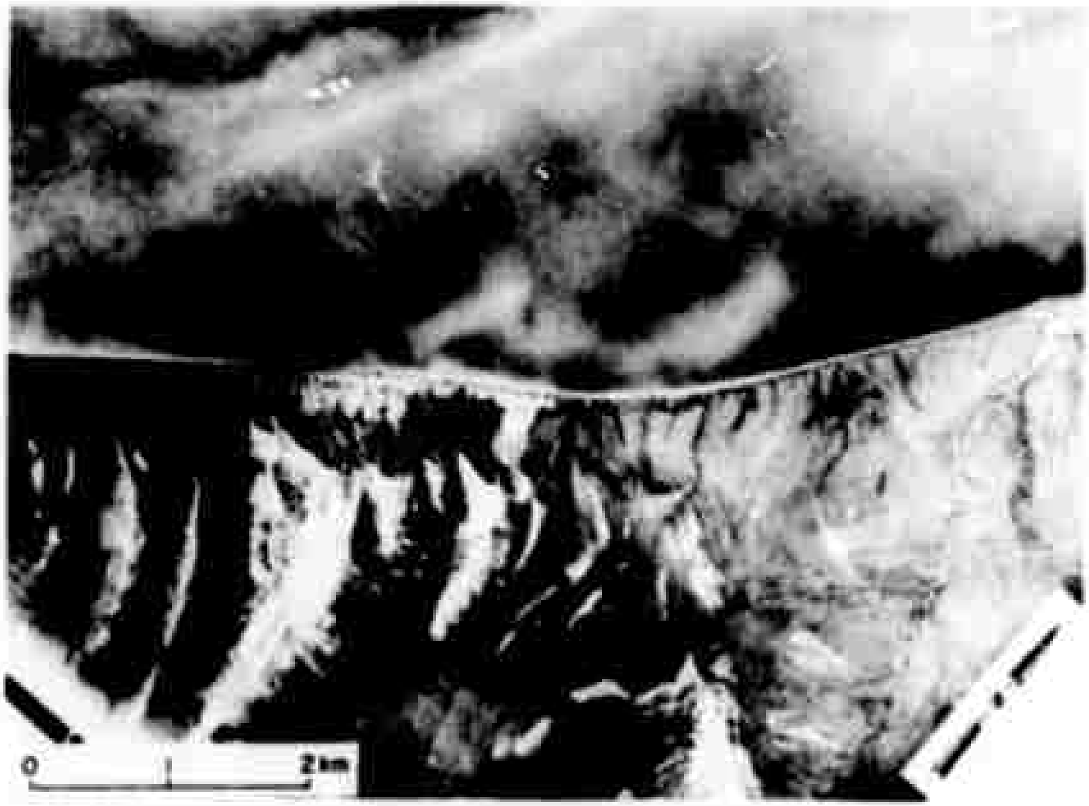

Figure 41. Vertical aerial view of land erosion coast with exposures of tilted bedrock near Cape Beaufort.

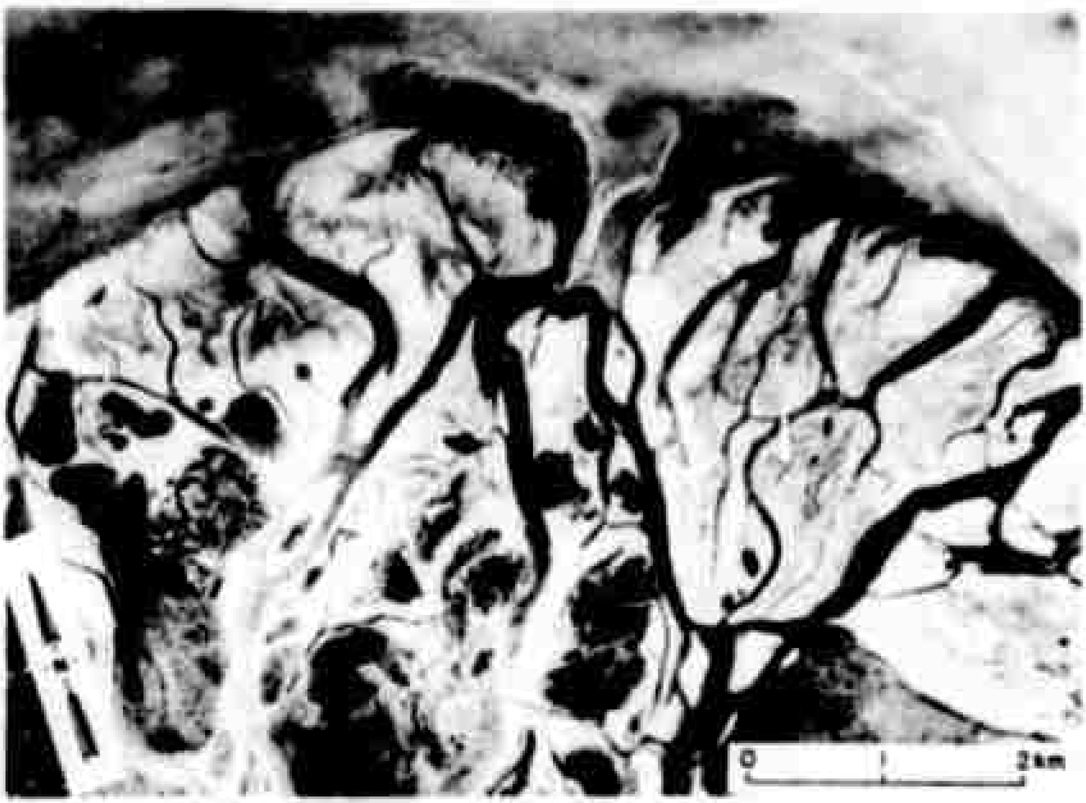

Figure 42. Vertical aerial view of river deposition coast showing braided channels and delta of the Ikpikpuk River southeast of Cape Simpson.

Figure 43. Vertical aerial view of river deposition coast fronted by barrier islands located near Demarcation Bay.

Figure 44. Vertical aerial view of wave erosion coast several kilometers southwest of Barrow.

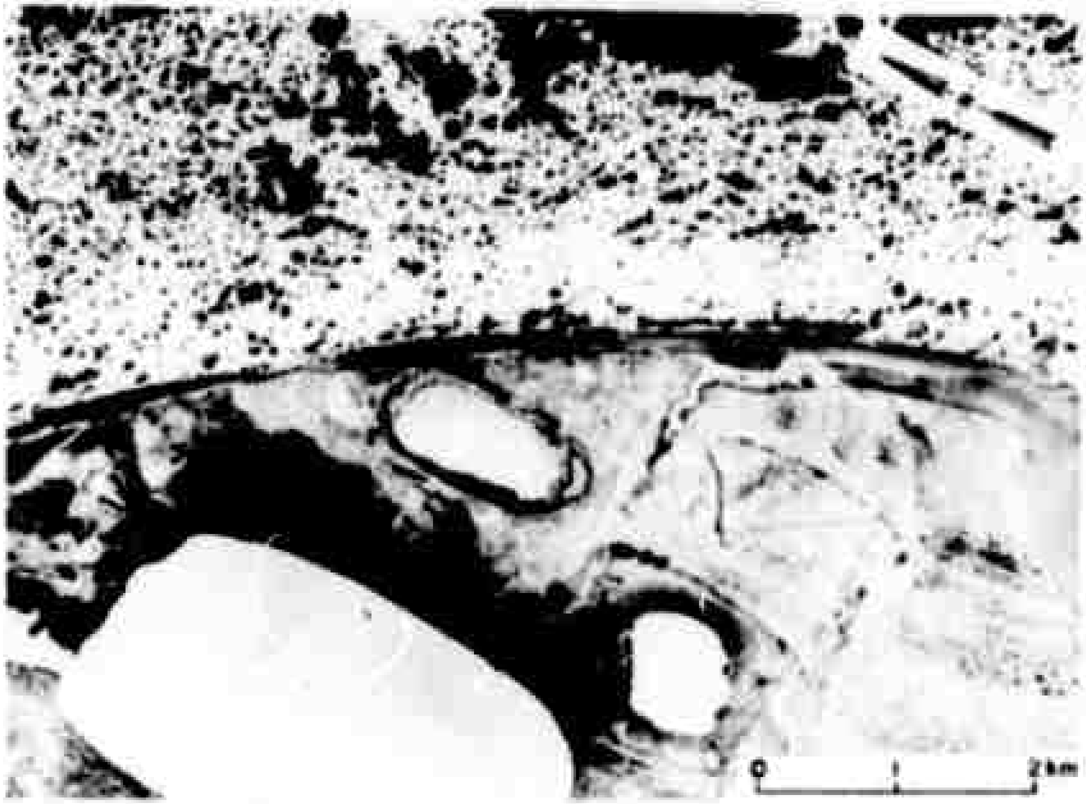

Figure 45. Vertical aerial view of wave erosion coast near Cape Simpson.

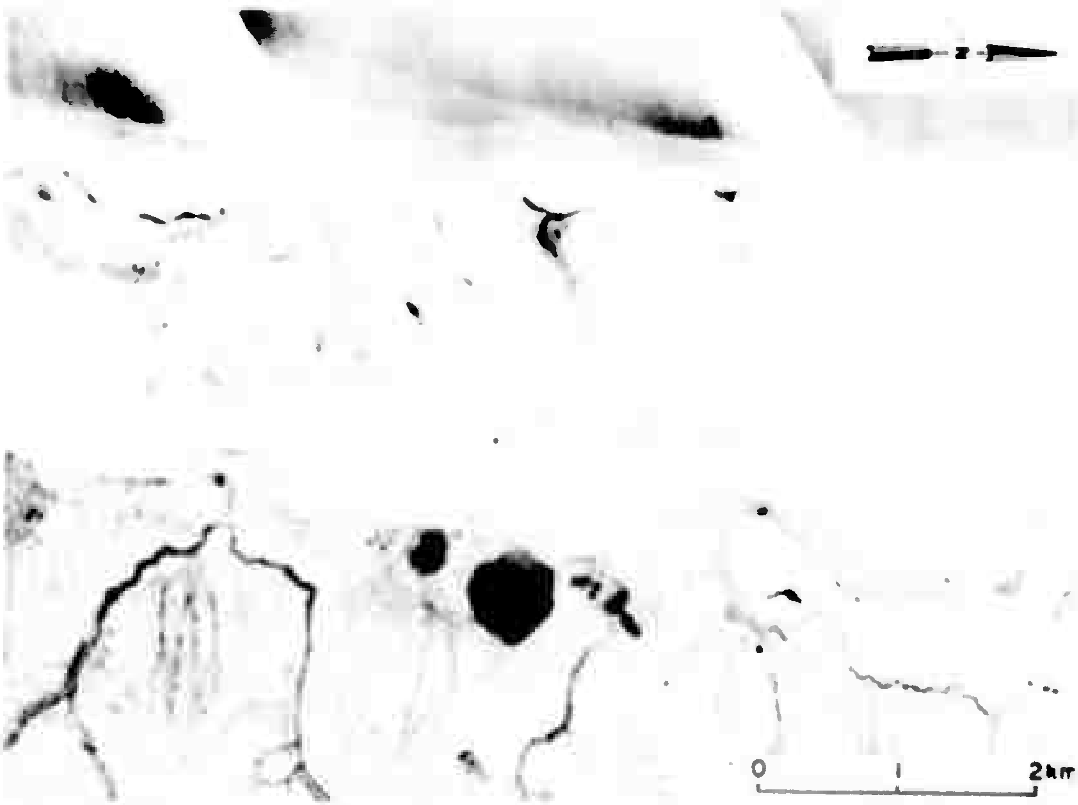

Figure 46. Vertical aerial view of marine deposition coast near Point Lay. Note lobate appearance of barrier islands caused by storm washovers.

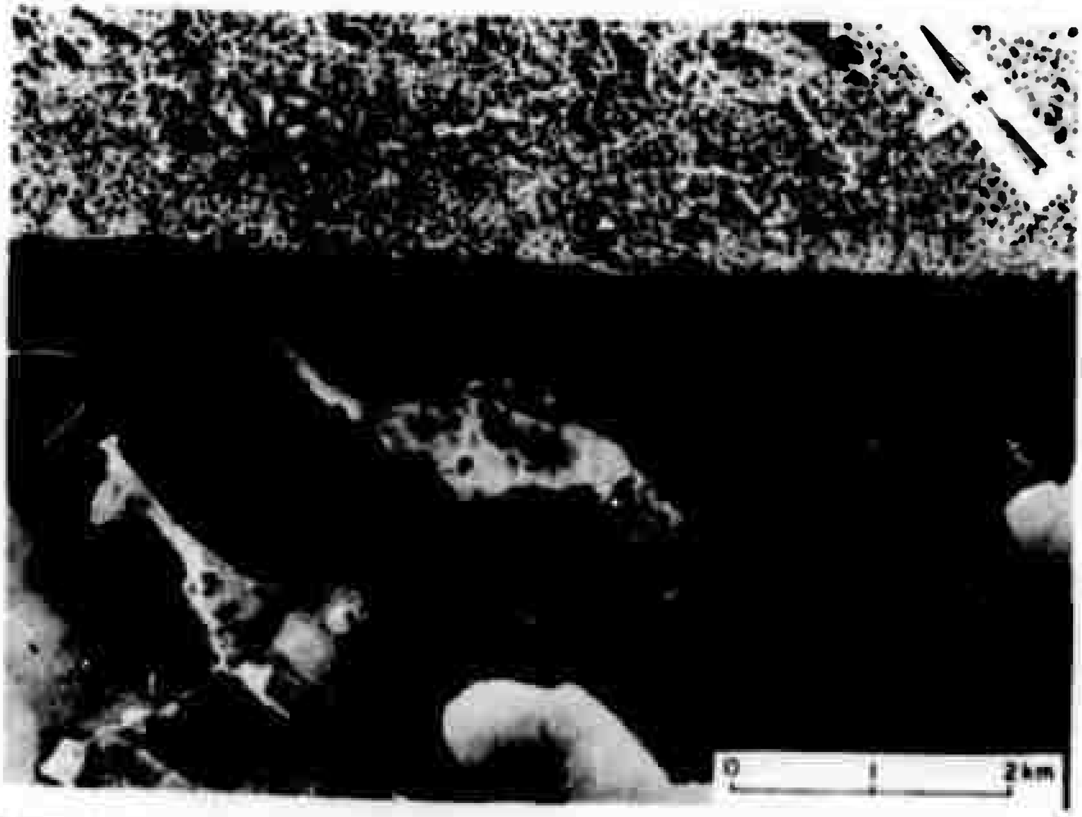

Figure 47. Vertical aerial view of marine deposition coast near Cape Simpson. Note how barrier islands hold the sea ice offshore.

Figure 48. Aerial view of an embayed-river-type window with mouth nearly blocked by a sedimentary barrier located southwest of Point Barrow. Note tents for scale.

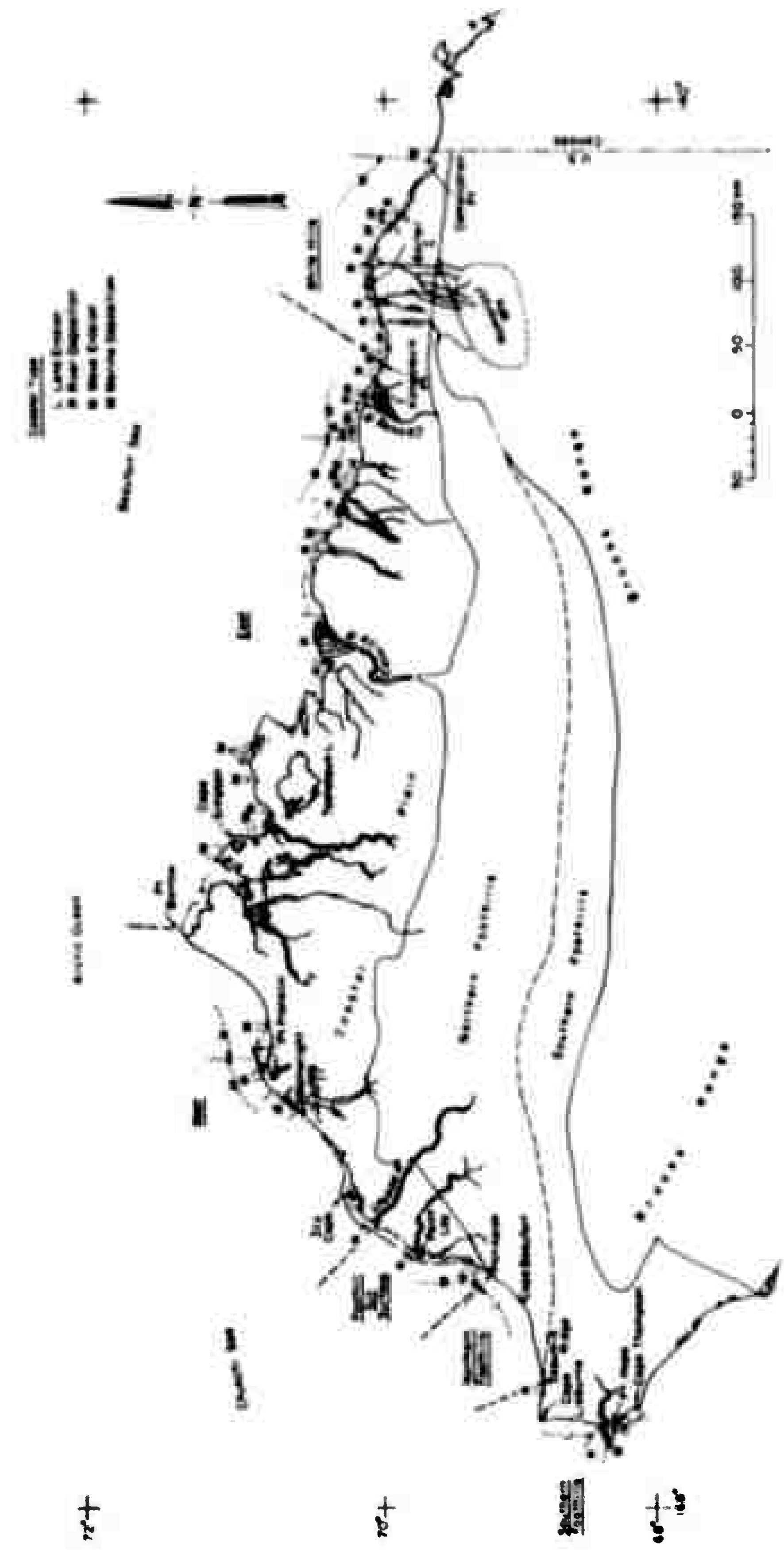

Figure 49. Distribution of geographic regions and coastal types in northern Alaska.

Table V. Distribution of coastal types in northern Alaska from Cape Thompson to U.S.-Canadian border.*

Coastal type	Length of coast (km)		% of total coast	
Primary	621.1		28.8	
a. Land erosion		191.9		8.9
b. River deposition		429.2		19.9
Secondary	1534.5		71.2	
a. Wave erosion		807.6		37.5
b. Marine deposition		726.9		33.7
Total	2155.6		100.0	

*Compiled from U.S. Geological Survey topographic maps of scale 1:63,360.

Southern foothills

This region is the southern portion of the Arctic Foothills province and extends about 192 km from Cape Thompson north and northeastward along the Chukchi Sea to Sapumik Ridge. It is a hilly region which has the structural complexity of the Brooks Range province to the south but is composed of less resistant rocks (late Paleozoic and Mesozoic marine sedimentary rocks; Payne et al. 1951). The coast is primarily the land erosion type, exposed directly to the open ocean except at Point Hope where waves and currents have built a pointed cuspate foreland of barrier islands which project offshore. The mainland is characterized by nearly continuous steep sea cliffs and bluffs, up to 260 m high at Cape Lisburne. Beaches, common along the base of the cliff, are generally narrow, steep and coarse-grained. Windows, or breaks in the cliffs that permit inland access by surface transport such as SEV's occur where stream valleys meet the coast. These valleys generally have floors at or slightly above sea level. Coastal relief is generally high to very high (about 10 to 260 m).

Northern foothills

This region is the northern portion of the Arctic Foothills province and extends about 82 km from Sapumik Ridge northeastward along the Chukchi Sea to the Eskimo village of Pankpiak near Cape Beaufort. It is primarily a belt of folded rocks which form parallel ridges, mesas and hills (Payne et al. 1951). The topography is much more regular than in areas to the south. The coast is primarily the land erosion type and is characterized by nearly continuous steep sea cliffs exposing Cretaceous marine sedimentary rocks (see Fig. 41). Narrow beaches and sedimentary barriers across windows of the stream-valley type are present but provide little protection from the open ocean. Relief along the coast is high (about 10 to 75 m) but is lower than that of the southern foothills.

Foothill silt surface

This region is the westernmost part of the Teshekpuk Lake section of the Arctic Coastal Plain province and extends about 172 km from near Cape Beaufort to the Utukok River near Icy Cape. This region is primarily a low rolling topographic extension of the northern foothills which has been buried by up to 45 m of Quaternary silt (O'Sullivan 1961). The mainland is characterized by nearly continuous moderate to high relief sea cliffs (about 4 to 14 m). The southernmost section is wave erosion coast, exposed directly to the open ocean. The northern portion is marine depositional coast, fronted by a nearly continuous chain of low-relief (less than 3 m) offshore barrier islands which inclose a shallow lagoon (see Fig. 46). Behind the barrier islands rivers have formed numerous small deltas which project out into the shallow lagoon.

Coastal Plain west of Point Barrow

This region is also part of the Teshekpuk Lake section of the Coastal Plain and extends about 365 km from the Utukok River northeastward along the Chukchi Sea to Point Barrow. The Coastal Plain is low and smooth, sloping gently from the foothills to the Arctic Ocean. It is characterized by wet tundra and abundant lakes, meandering streams and swamp areas. The general wetness is due to slow evaporation and poor drainage as well as permafrost at shallow depths below the surface vegetation (Payne et al. 1951). The region is underlain by 3 to 46 m of unconsolidated Quaternary marine sediments resting on nearly flat Cretaceous sedimentary rocks containing coal (Wahrhaftig 1965). The mainland is characterized by nearly continuous sea cliffs which are either exposed directly to the open ocean (wave erosion coast, such as Fig. 44) or fronted by nearshore sedimentary barriers (marine depositional coast). Narrow beaches abut much of the sea cliff (Fig. 50). Although the ocean has intersected numerous rivers along this coast, none have formed deltas of any significance (for example, see Fig. 48). Coastal relief is generally moderate to low (less than about 12 m) and is a function of the elevation of the adjacent flat land surface with respect to sea level.

Waves and longshore drift from the southwest have produced nearly continuous chains of barrier islands (Point Lay and Ice Cape) and large spits (Point Franklin and Point Barrow). At Point Barrow two systems of longshore transport converge (from the southwest and southeast) but they have not produced bars and spits as extensive as might be expected (Rex 1961). Instead, this is actually an area of large scale erosion, about 4 to 6 m per year (Leffingwell 1919, MacCarthy 1953). Apparently the sediments transported into and eroded within the area are being carried offshore and into the Arctic Ocean basin through the Barrow Sea Valley (Carsola 1952) which passes approximately 8 km to the northwest of Point Barrow (Rex 1964).

Figure 50. Moderate-relief coast with narrow beach abutting sea cliffs about 5 m high located southwest of Point Barrow.

Coastal Plain east of Point Barrow

This region is also part of the Teshekpuk Lake section of the Coastal Plain and extends about 1054 km from Point Barrow southeastward along the Beaufort Sea to Konganevik Point near the mouth of the Canning River. It is a continuation of the Coastal Plain region to the west, except that sea ice influences the shoreline more strongly. The pack ice rarely moves far offshore and in many areas has helped carry sediments in landward from the wide, shallow sea floor and build them into low-relief barrier islands. The coast is characterized by nearly continuous, moderate to low relief sea cliffs (less than about 8 m) which are either wave erosion coast (exposed directly to the open ocean, as in Figure 45) or marine depositional (fronted by nearshore barrier islands, as in Figure 47). Much of the coast has an irregular appearance due to the drowning of old lakes and river valleys by the general rise in sea level during the last 20,000 years (Creager and McManus 1967). Rivers have built numerous large, low-relief deltas (less than 3 m high) which extend many kilometers offshore (see Fig. 42 and 43). Narrow beaches and spits also abut much of the mainland.

White hills

This region is the easternmost section of the Coastal Plain and extends 290 km from Konganevik Point southeast along the Beaufort Sea to the U.S.-Canadian border. This portion of the Coastal Plain is characterized by scattered groups of low hills and a wide, broad alluvial fan which slopes gently northward from the Romanzof Mountains. This region has a nearly continuous, moderate to low relief sea cliff (less than 8 m) which is either wave erosion coast or marine depositional. A number of small, low-relief deltas are present, many of which are fronted by near-shore barrier islands. This region also has an irregular appearance due to drowning of old terrain features by the ocean. Because of its position with respect to the main arctic ice pack, the region is dominated by sea ice more than any other portion of the coast, and coastal retreat seems to be proceeding at a slower rate.

Coastal Relief Features

Although much of northern Alaska is flat coastal plain, the extensive lengths of nearly continuous sea cliffs offer a formidable obstacle to surface transportation such as SEV's. The previous discussion on coastal types and geographic regions permits the identification of three categories of coastal relief, based on snow-free conditions. Note that because of the generally flat terrain and the unique process of coastal retreat in this region, maximum coastal relief is primarily a function of the elevation of the adjacent land surface with respect to sea level.

Low relief (less than about 2 m; 568 km or 26% of the total coast)

Relief of this type is primarily associated with depositional features such as barrier islands and barrier spits along marine deposition coasts and across river valley entrances (see Fig. 33, 43 and 48), deltas of river deposition coasts (see Fig. 42 and 43), and beaches which abut most of the coastline (see Fig. 30 and 50). This category also includes sections of sea cliffs along low points in the tundra surface (wave erosion coasts). The lateral variations in morphology along the coast are generally minor because of the low heights. Typical profiles in the low relief category from the vicinity of Point Barrow (location map, Fig. 51) are shown in Figure 52. Profile 15 is a gently sloping featureless beach with no scarp or ice-push ridges. Profiles 16 and 17 are low erosional scarps which form a sharp break in the tundra along Elson Lagoon. Profiles 18 and 19 are gentler slopes along the banks of estuaries some distance inland from the open ocean.

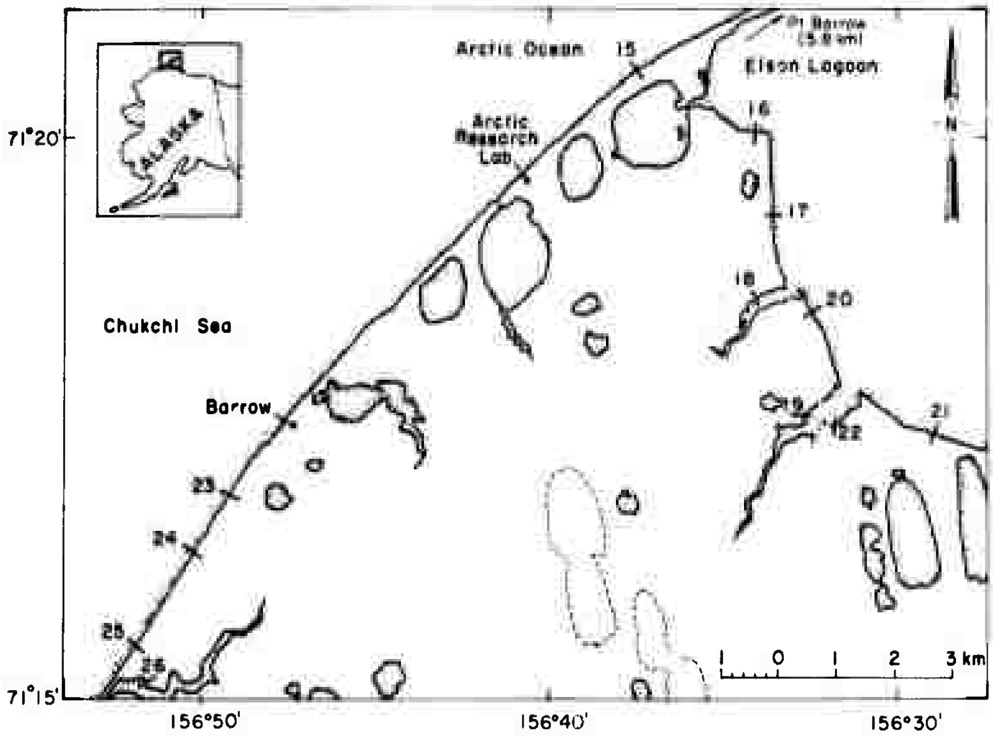

Figure 51. Location map for coastal profiles 15-26 near Barrow.

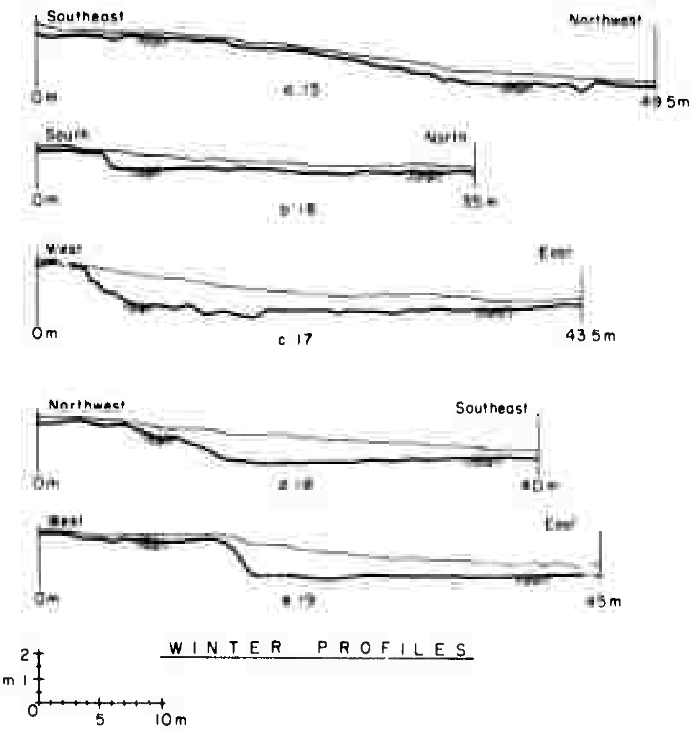

Figure 52. Low-relief coastal profiles from near Point Barrow.

Moderate relief (about 2 to 5 m; 939 km or 44% of total coast)

Relief of this type is primarily associated with sea cliffs or scarps along wave erosion coasts and the mainland of marine deposition coasts (see Fig. 35-38, 50). These cliffs are undergoing some degree of erosion and form a generally sharp break along the edge of the flat tundra surface. Slopes and lateral characteristics are variable. Some cliffs are steep with nearly uniform slopes across long distances (see Fig. 45 and 47). Others are more irregular due to differential erosion along polygonal ground features and thawing of permafrost (see Fig. 37, 38, 53). Typical moderate relief profiles from the vicinity of Point Barrow are shown in Figure 54. Profiles 20 and 21, along the shore of Elson Lagoon, have sharp erosional breaks in slope. Profile 22 is located about 1 km inland along a large estuary where slumped material forms gentler slopes (located in same area as Fig. 62 and 63).

Figure 53. Aerial view of eroding and slumped moderate-relief coast southwest of Point Barrow.

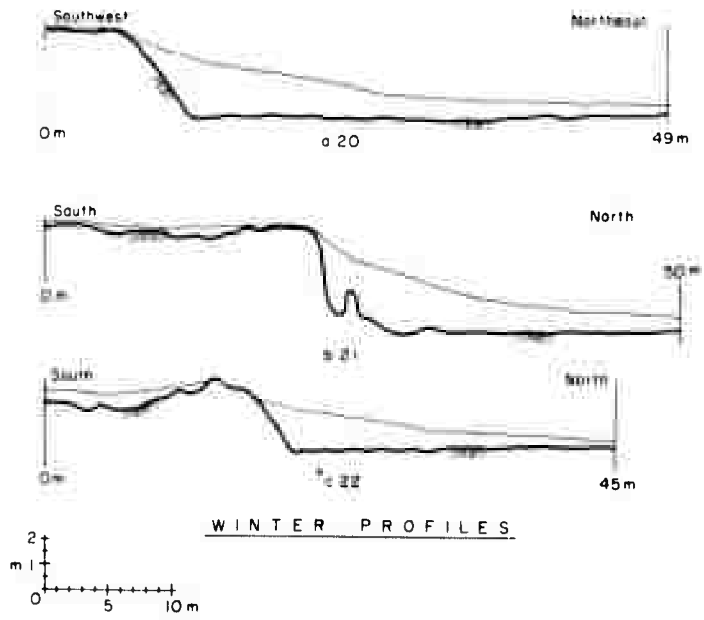

Figure 54. Moderate-relief coastal profiles from near Point Barrow.

High relief (greater than about 5 m; 566 km or 26% of total coast)

Relief of this type is found along the sea cliffs of land erosion coasts and wave erosion coasts. Because of bedrock control and protection by the large ramps of snow and ice which form in the winter, these cliffs are undergoing much more gradual erosion and slope retreat than moderate-relief areas. The cliffs are generally steep, sheer, and nearly uniform across long distances (see Fig. 40, 41, 44, 55). Typical high-relief profiles from the Point Barrow area are shown in Figure 56. Profiles 23 and 24 have steep slopes and form a sharp break between the tundra surface and the sea. Profile 25 is along the coast in an area where the slope has eroded back less steeply, much as in Figure 53. Profile 26 is inland along Nunavak Bay where slopes are gently and steep scarps rarely develop.

An additional 82 km or 4% of the coast is open water where streams, rivers and lakes are intersected by the ocean.

Distribution of coastal relief

As noted previously, the total coastal relief (or height of the sea cliff where present) was estimated from topographic maps and tabulated in increments of 0-1, 1-2, 2-3, 3-4, 4-5, 5-8 and >8 m for each of the six geographic regions (Table VI). Mean scarp heights were calculated by a weighting process, using mid-point values in the relief increments, and a value of 10.5 for the >8 m increments. These data revealed that about 1590 km or 74% of the coast has a scarp height of 5 m or less and that mean scarp heights decreased to the east along the coastal plain (Fig. 57). Mean scarp height for the entire coast is about 4 m.

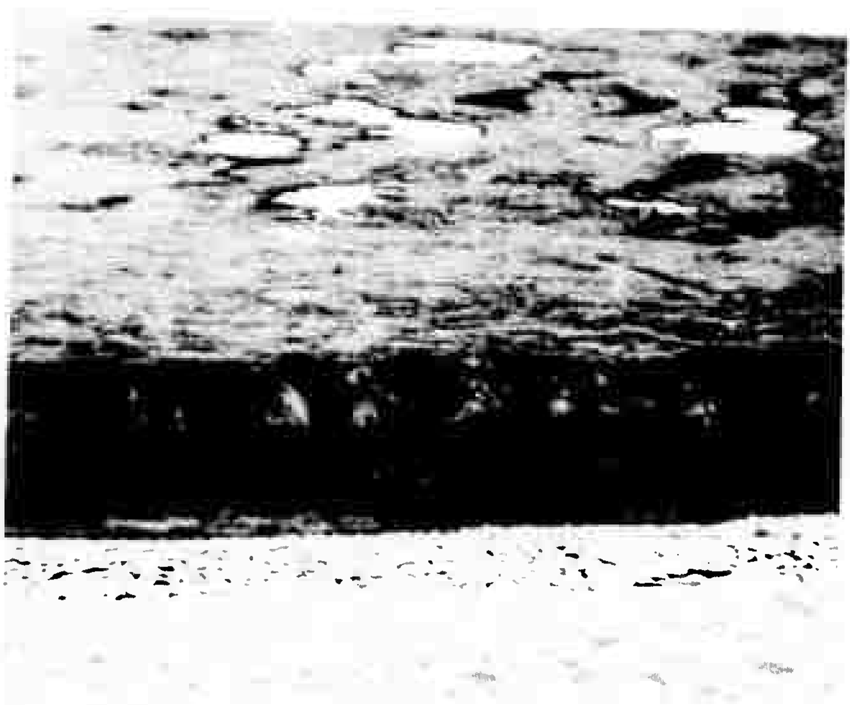

Figure 55. High-relief coast of sea cliffs about 12 m high located near Skull Cliff between Point Barrow and Wainwright.

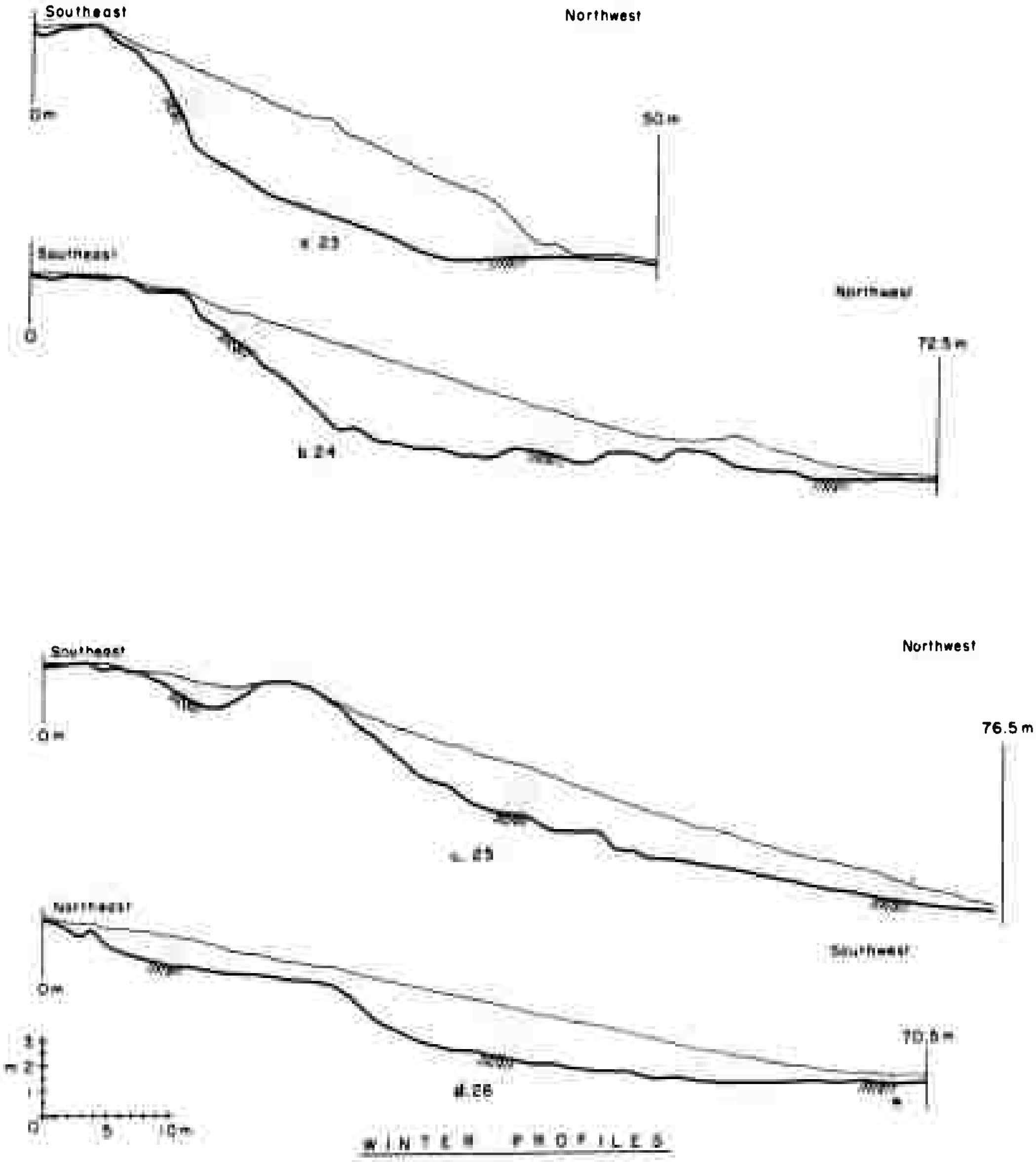

Figure 56. High-relief coastal profiles southwest of Barrow.

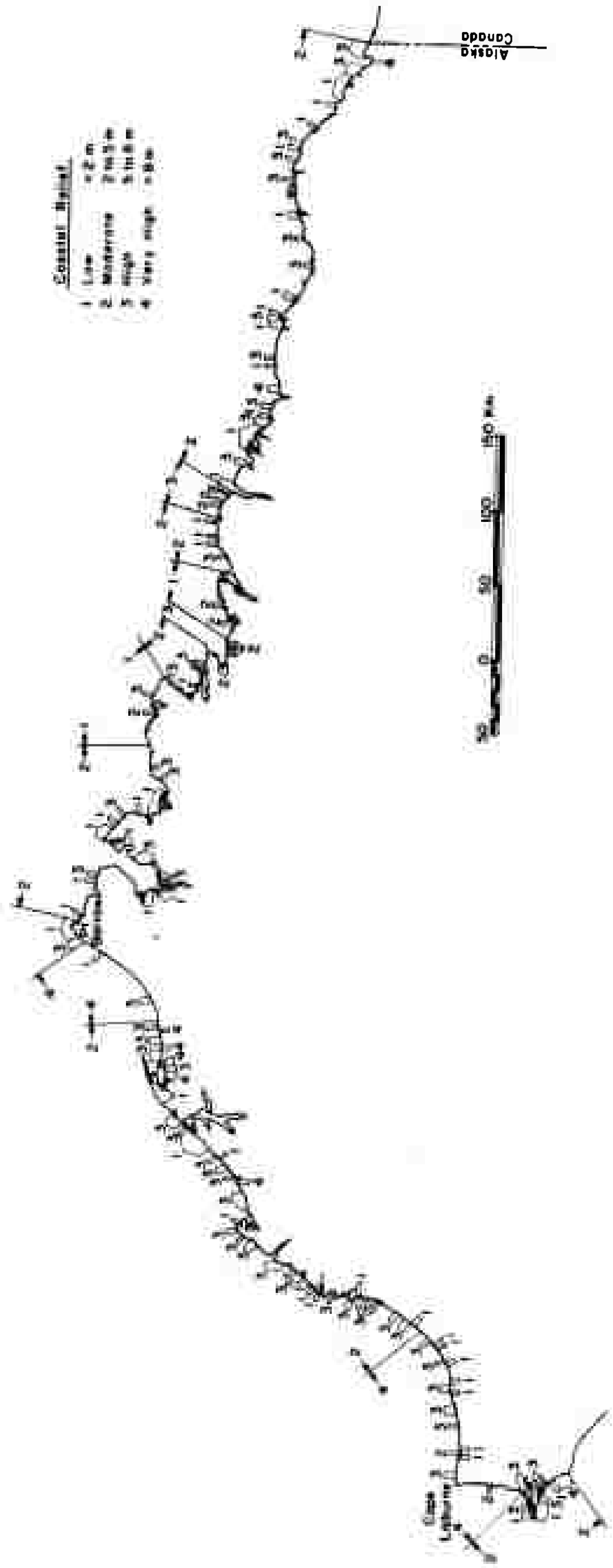

Figure 57. Distribution of coastal relief classes along the northern Alaskan coast.

Table VI. Distribution of coastal relief by geographic region; northern Alaska from Cape Thompson to U.S.-Canadian border.*

	Geographic regions						
	Southern Foothills	*Northern Foothills*	*Coastal Plain Foothill silt surface*	*Coastal Plain west of Pt. Barrow*	*Coastal Plain east of Pt. Barrow*	*Coastal Plain White Hills*	*Entire coast*
Length of coast, km	192.3	82.3	171.7	365.1	1053.7	290.0	2155.7
% of total coast	8.9	3.8	8.0	16.9	48.9	13.5	100.0
Coastal relief, m							
0-1		1.5 km 1.8%	1.8 km 1.0%	25.0 km 6.9%	58.4 km 5.5%	24.7 km 8.5%	111.4 km 5.2%
1-2	41.8 km 21.7%	11.1 13.4	16.9 9.8	59.8 16.4	292.3 27.7	34.9 12.0	456.8 21.2
2-3	52.3 27.2		56.1 32.7	41.8 11.4	331.6 31.5	109.2 37.5	590.9 27.4
3-4			17.6 10.2	56.6 15.5	148.2 14.1	32.7 11.2	255.0 11.8
4-5				13.5 3.7	47.0 4.5	32.5 11.2	93.0 4.3
5-8	25.7 13.4	12.8 15.6	72.8 42.4	77.4 21.2	111.2 10.5	40.8 14.0	340.6 15.8
>8	71.0 36.9	56.6 68.8	2.3 1.3	84.5 23.2	8.0 .8	3.3 1.1	225.6 10.5
open water (window)	1.5 .7	.3 .4	4.2 2.5	6.5 1.8	57.0 5.4	12.8 4.4	82.4 3.8
Total ≤5 m	95.6 km 49.6%	12.9 km 15.6%	96.6 km 56.2%	203.2 km 55.7%	934.5 km 88.7%	246.8 km 84.8%	1589.5 km 73.7%
Mean coastal relief, m	5.8†	8.5	4.3	5.2	2.8	3.2	3.9

*Compiled from U.S. Geological Survey topographic maps of scale 1:63,360.
†Mean relief of Southern Foothills is lower than Northern Foothills due to the cuspate foreland at Point Hope.

Windows

As noted previously, the primary obstacle to surface transportation such as SEV's moving between inland areas and the ocean across this coast is the sections of scarp or sea cliff that are sheer and nearly continuous. Except where the coastal relief is low, the only avenues of inland movement are through windows or breaks in the coastal scarp. These can be genetically classified into four primary types:

1. Gullies - narrow V-shaped valleys, at least 30 m wide and generally extending less than about 1 km inland; carry only minor water flow; primarily erosional features developed along the margins of polygons such as in Figures 40 and 44.

2. Streams - narrow flowing bodies of water in valleys, at least 30 m wide and extending several kilometers inland; streams carry significant water flows but the mouths of the valleys are at or above sea level, preventing flooding of the valleys by the ocean (see Fig. 41, right side).

3. Embayed rivers - drowned stream valleys or wide river channels which provide wide windows that may extend tens of kilometers inland (such as deltas in Fig. 42 and 43); valleys that have been drowned by the ocean to form wide estuaries are usually fronted by low-relief barrier spits (see Fig. 44 and 48).

4. Lakes - thaw lakes (Carson and Hussey 1962) which have been intersected by the ocean and drowned; generally wide and shallow but only extend short distances inland (see Fig. 45).

Data on window type, encounter frequency, mean width, and mean inland extension are summarized by geographic region in Table VII. Note how closely the characteristics of the windows are related to the relief features of the different geographic regions. To the west there are few windows per kilometer and gullies predominate. Further east along the coastal plain windows are much more frequent and waterway-type windows such as streams, embayed rivers and lakes predominate. Data on window spacing are summarized by geographic region in Table VIII. About 83% of all windows are 1.5 km or less apart.

Seasonal variations in coastal relief

The winter profiles from the Point Barrow area illustrate how dramatically the surficial geometry of the coast is altered by the seasonal cover of windblown snow. In the winter the ocean surface is frozen fast along the coast and the actual shoreline is difficult to locate except for the difference in elevation between the tundra surface and the sea ice. Where a pronounced sea cliff or scarp is present, a compact wedge of windblown snow frequently accumulates to form a gently sloping ramp from the tundra edge down onto the frozen sea surface (Fig. 58). The adjacent beach is usually smoothly covered by the toe of the ramp but irregularities may form around grounded blocks of sea ice and ridges of sediment (see foreground of Figure 65). Rarely are the surficial sediments of the beaches visible through the snow cover. In some areas the wind deposits the snow in a steep cornice which only partially ramps the sea cliff (Fig. 59).

Data from the winter profiles which represent varying heights and orientations of coastal scarps suggest that the shape of the ramp or the potential for holding snow is controlled by the following factors:

1. height of sea cliff
2. steepness or slope of cliff face
3. configuration or roughness of slope surface
4. orientation of sea cliff with respect to prevailing winds and snow source.

Profiles 15 and 16 (Fig. 52) have no scarp where snow can accumulate and the winds have tended to scour the snow cover, making it uneven. At profile 17 on Elson Lagoon where the coast has

Table VII. Windows along the coast of northern Alaska from Cape Thompson to the U.S.-Canadian border.*

	Geographic regions						
	Southern Foothills	*Northern Foothills*	*Coastal Plain Foothill silt surface*	*Coastal Plain west of Pt. Barrow*	*Coastal Plain east of Pt. Barrow*	*Coastal Plain White Hills*	*Entire coast*
Length of coast, km	192.3	82.3	171.7	365.1	1053.7	290.9	2155.7
% of total coast	8.9	3.8	8.0	16.9	48.9	13.5	100.0
Total windows	48	29	71	125	392	144	809
No/km	.25	.35	.41	.34	.37	.50	.38
Mean width, m	390	483	133	392	149	131	207
Mean inland distance, m	1870	1534	2608	2295	5598	3269	4091
Gullies	21	19	42	37	11	1	131
No/km	.11	.23	.24	.10	.01	.00	.06
Mean width, m	35	99	32	39	35	32	41
Mean inland distance, m	480	798	348	444	355	325	440
Streams	6	5	10	19	71	51	162
No/km	.03	.06	.06	.05	.07	.18	.08
Mean width, m	67	70	37	56	44	38	45
Mean inland distance, m	1869	1040	2162	1258	620	427	789
Embayed rivers	8	2	15	39	241	82	387
No/km	.04	.02	.09	.11	.23	.28	.18
Mean width, m	308	480	720	385	147	140	168
Mean inland distance, m	7423	8461	38,131	5422	8330	5417	7610
Lakes	13	3	4	30	69	10	129
No/km	.07	.04	.02	.08	.07	.03	.06
Mean width	1226	2584	1480	1178	282	544	681
Mean inland distance, m	700	434	650	1171	3017	439	1491

*Compiled from U.S. Geological Survey topographic maps of scale 1:63,360.

Table VIII. Spacing between windows along the coast of northern Alaska from Cape Thompson to the U.S.-Canadian border.*

Distance between windows, km	Geographic regions													
	Southern Foothills		Northern Foothills		Coastal Plain Foothill silt surface		Coastal Plain west of Pt. Barrow		Coastal Plain east of Pt. Barrow		Coastal Plain White Hills		Entire coast	
	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%
0- .5	20	40.8	11	37.9	43	60.6	49	39.5	173	44.1	72	50.3	368	45.5
.6-1.0	8	16.3	10	34.5	9	12.7	35	28.2	98	25.0	38	26.6	198	24.5
1.1-1.5	8	16.3	3	10.3	6	8.5	17	13.7	52	13.3	16	11.2	102	12.6
1.6-2.0	4	8.2	2	6.9	3	4.2	9	7.3	28	7.1	11	7.7	57	7.1
2.1-2.5	1	2.0	1	3.4	4	5.6	7	5.6	12	3.1	4	2.8	29	3.6
2.6-3.0	2	4.1	1	3.4	3	4.2	1	.8	10	2.6			17	2.1
3.1-4.0	4	8.2	1	3.4	1	1.4	2	1.6	10	2.6			18	2.2
4.1-5.0					1	1.4	1	.8	3	.8	2	1.4	7	.9
5.1-6.0	1	2.0			1	1.4	1	.8					3	.4
>6.1	1	2.0					2	1.6	6	1.5			9	1.1
	49		29		71		124		392		143		808	

*Compiled from U.S. Geological Survey topographic maps of scale 1:63,360.

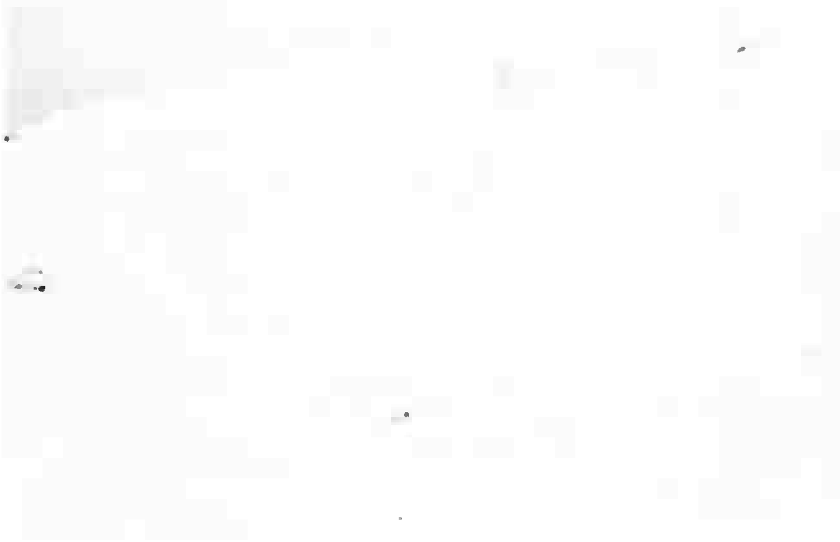

Figure 58. Ramp and small cornice along sea cliff about 9 m high near Barrow.

Figure 59. Steep cornice along sea cliff about 10 m high located about 1 km southwest of Barrow.

higher relief and a north-south orientation, a low, gently-sloping ramp has been built (note the dramatic change from summer to winter shown in Figures 60 and 61). Profiles 18 and 19 are located along small estuaries a short distance inland from the coast. Smooth ramps have formed over the low cliffs and the entire estuary valley has been filled with snow (note summer and winter views of the same location, Figures 62 and 63). With increasing relief (see profiles 20-22, Figure 54), larger and more steeply-sloping ramps develop.

Along high relief sea cliffs (5 m or greater) very large ramps were observed (see profiles 23-26; Fig. 56). The steep summer profiles of slumped material (see profiles 23 and 24; Fig. 56a, b and 64) were completely covered by a large, gently sloping ramp of windblown snow (Fig. 65). The snow surface is generally smooth except near the toe of the ramp where grounded ice blocks may cause local irregularities (Fig. 65). Summer profiles which are less steep (such as profiles 25 and 26; Fig. 56c, d) have thinner snow cover but are still smoothly ramped. From these profiles it appears that ramps which form on the lee side of scarps tend to have smoother surfaces due to the "dumping" effect of the snow, whereas those to windward have rougher surfaces because of wind abrasion.

For several kilometers southwest of Barrow Village along sea cliffs about 9 m high no ramps were observed. Instead, steep cornices developed (Fig. 59), apparently due to the orientation of the coastline with respect to prevailing winds. That is, the winds here tend to blow over the cliffs and along the coast, reworking the previously deposited snow and forming the cornice. Summer and winter views of this area are very similar (Fig. 66, 67) with the snow forming only a thin layer over the sloping sea cliff and beach.

Data from these profiles are summarized in Table IX. Low relief profiles (mean relief 1.4 m) have a southeasterly exposure, thin snow cover (mean about 0.54 m), and summer and winter slope angles of 13.3° and 2.3° respectively. Moderate relief profiles (mean relief 3.1 m) have a northeast exposure toward the prevalent wind direction and have a thicker mean snow cover (1.04 m). Summer slopes are steep (39.7°) and narrow (3.8 m) whereas winter slopes are very gentle (5.2°). High relief profiles (mean 6.7 m) have a northwesterly exposure, thick snow cover (mean 1.52 m) and wider slopes (29.0 m). Summer slopes are about 15.4° and winter about 8.2°. Highest slope values for all profiles (excluding short, steep scarps) was 23.4° for summer and 12.5° for winter.

Operation of Surface Effect Vehicles

In summary, the primary obstacle to the operation of SEV's moving across the coastal zone between inland areas and the Arctic Ocean in northern Alaska is the long stretches of nearly continuous sea cliffs. The mean coastal relief for this coast is about 4 m (based on snow-free conditions); however, about 566 km or 26% of the coast has sea cliffs which are more than 5 m high (Table VI). The relief conditions along the coast which are summarized in Figure 57 show that highest scarps occur to the west along the foothills. The profiles from the Barrow area are typical of the coast and demonstrate that during late winter and early summer inclined ramps of windblown snow which frequently form can greatly subdue the coastal relief. These ramps can make all but the highest relief features considerably easier to cross for even small SEV's with limited slope-climbing capability.

In areas with high relief the windows or breaks in the coastal scarp along streams, rivers and lakes provide ready avenues for inland access by SEV's along much of the coast. The distribution of windows which is summarized in Tables VII and VIII shows that as relief increases the frequency of windows decreases. About 83% of the windows are spaced at 1.5 km or less. It should also be noted that local accumulations of driftwood along portions of the eastern coast (especially near large rivers) form tangled masses which may be a threat to skirts of SEV's.

Figure 60. Summer view of profile 17 along Elson Lagoon. Note slumped tundra and absence of a beach.

Figure 61. Winter view at same location as Figure 60. Note smoothing effect of snow ramp.

Figure 62. Summer view of estuary near profile 19. Note slumped tundra along shore.

Figure 63. Winter view at same location as Figure 62. Note that snow has filled in the estuary valley.

Figure 64. Summer view of eroding sea cliff about 9 m high near profile 23.

Figure 65. Winter view at profile 23. Note large ramp of windblown snow and sea ice blocks on beach in foreground.

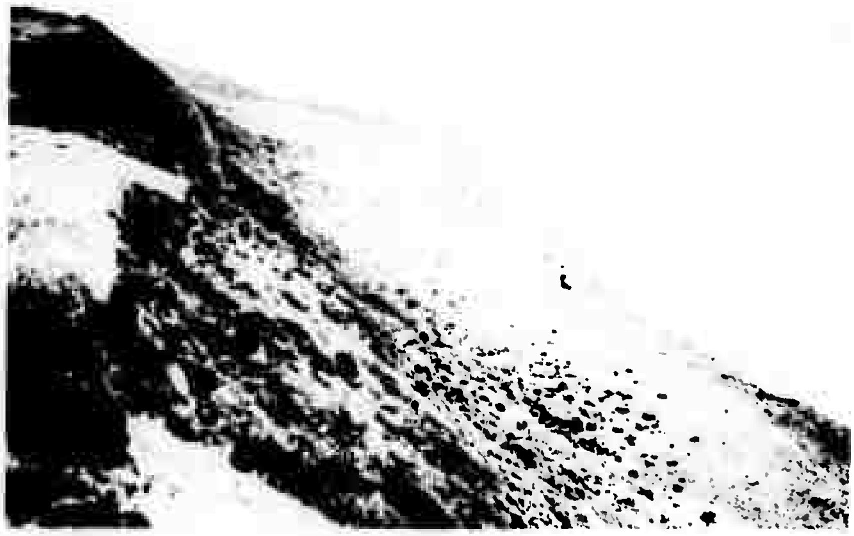

Figure 66. Summer view of sea cliff and beach at Barrow. Relief about 7 m.

Figure 67. Winter view at same location as Figure 66. Note thin snow cover and cornice in background.

Table IX. Data from coastal profiles located in the vicinity of Point Barrow.

Profile no.	Bearing of profile, °	Coastal relief, m	Width of coastal slope, m	Total slope: Summer (snow-free)	Total slope: Winter (snow-cover)	Thickness of snow cover, m: Mean	Max	Min
Low relief profiles								
15	322.3	2.0	35.0	3.3	2.8	.26	.50	.10
16	5.3	.6	1.0	31.0	1.4	.34	.55	.10
17	92.3	1.5	4.5	1.9	2.6	.74	1.30	.20
18	152.3	1.5	10.0	8.5	2.1	.64	1.10	.10
19	115.3	1.6	4.0	21.8	2.6	.70	1.25	.40
Mean	137.5	1.4	10.9	13.3	2.3	.54	.94	.18
Moderate relief profiles								
20	62.3	3.3	5.0	33.4	5.3	1.03	2.25	.50
21	25.3	3.4	2.5	53.7	6.5	1.32	2.60	.65
22	5.3	2.5	4.0	32.0	3.7	.76	1.60	.30
Mean	31.0	3.1	3.8	39.7	5.2	1.04	2.15	.48
High relief profiles								
23	304.3	9.0	29.0	17.2	12.5	1.65	3.65	.10
24	301.3	5.2	12.0	23.4	7.1	2.06	3.05	.25
25	305.3	6.7	28.0	13.5	8.5	1.34	2.10	.25
26	247.3	6.0	47.0	7.3	4.7	1.03	2.10	.20
Mean	289.6	6.7	29.0	15.4	3.2	1.52	2.73	.20
Grand mean	152.7	3.7	14.6	22.8	5.2	1.03	1.48	.26

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