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Formation and Age of Raised Marine Beaches, Northern Scott Coast, Antarctica

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FORMATION AND AGE OF RAISED MARINE BEACHES, NORTHERN SCOTT COAST, ANTARCTICA

By

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The stability of the West Antarctic Ice Sheet (WAIS) is a key problem because of its potential effect on global sea level and climate. Some geologic evidence suggests that the ice sheet has collapsed in the past, which, if correct, implies that future disintegration is possible. Isolation of the mechanism(s) that have affected WAIS behavior since the last glacial maximum (LGM) may yield information about factors that control it today. Previous studies have indicated that recession of the WAIS from the LGM position occurred in the middle to late Holocene. However, the data come from points too far south to assess accurately the timing and cause of the early phase of deglaciation.

Reconstruction of ice retreat in the Ross Sea Embayment since the LGM relies heavily on the development of relative sea-level curves from raised beaches. In turn, the accuracy of these curves depends on the manner in which the beaches form and in which organic material is incorporated. The present study has two main objectives. The first is to determine the processes that formed beaches now uplifted along the northern Scott

Coast. The second is to obtain radiocarbon samples, which will determine the ages of the raised beaches, and aid in relative sea-level interpretations.

My results suggest that storm waves formed most beaches in the study areas. Moreover, nearly every wave-formed beach ridge is a single-storm deposit. These conclusions, at least for the southern part of the field area, support the idea that Holocene sea-ice extent was less than it is today. This is in agreement with glacial geologic and faunal proxies that suggest that temperatures were generally warmer and sea ice was less extensive during the mid-to-late Holocene.

The radiocarbon data from this study have led to the first identification of pre-Holocene beach deposits along the coast of the Ross Sea. Every sample recovered from Cape Ross predates the last glacial maximum, and additional old samples come from Spike Cape and Inexpressible Island. There are two hypotheses to explain the pre-Holocene material. One is that Holocene beach sediments overlie a core of preserved older deposits. The other is that the entire set of beaches predates the last glacial maximum and that Holocene deposits are absent. It is not possible to distinguish conclusively between these two hypotheses at this time. However, these new data show that undated beaches along the Antarctic coast can no longer be assumed to be Holocene in age. Moreover, the presence of older beach deposits complicates the process of reconstructing Holocene relative sea-level curves and reaffirms the need for detailed dating and stratigraphic analysis of beach ridges.

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INTRODUCTION

West Antarctic Ice Sheet Stability

The stability/instability of the marine-based West Antarctic Ice Sheet (WAIS) remains a key problem in Quaternary geology and climate studies (Weertman, 1976). Grounded as much as 2500 meters below sea level, the WAIS is believed to be susceptible to processes that cause rapid disintegration (Hughes, 1973; Weertman, 1974; Mercer, 1978; MacAyeal, 1992). Limited evidence suggests that the WAIS may have collapsed completely in the past (Scherer et al., 1998), and therefore may collapse in the future. However, the nature, cause, and even existence of such an event remain uncertain. Weertman (1976) suggested several reasons for the vulnerability of marine ice sheets. These include susceptibility to climate change, internal ice dynamics (surging/streaming), and sea-level/temperature forcing. Climate warming was dismissed as a possible trigger for disintegration because there is net accumulation on the ice sheet under today's interglacial conditions. Moreover, ice cores do not indicate a period of significant ice-sheet melting. Weertman (1976) concluded that rising sea level is the most likely cause of ice-sheet collapse.

One way to determine the possible cause of past collapse and hence the likelihood of future disintegration is to examine geologic indicators that serve as proxies for past ice-sheet behavior. The grounding line of the WAIS was at or close to the edge of the continental shelf at the last glacial maximum (LGM) (Stuiver et al., 1981; Shipp et al., 1999; Denton and Hughes, 2000). Stuiver et al. (1981) suggested that retreat from the LGM terminal position began around 17,000 yr BP. This corresponds to an increase in sea level shown by the Barbados curve (Fairbanks, 1989), making rising sea level a prime suspect as the driving mechanism for ice retreat.

However, new evidence from the Dry Valleys (Figure 1) suggests that grounded ice was still near its maximum position at the beginning of the Holocene. Lacustrine algae in moraines at the seaward end of Taylor Valley give ages as young as 10,800 ^{14}C yr BP, indicating the presence of thick Ross Sea ice at the time (Hall and Denton, 2000a). Deltas associated with Glacial Lake Washburn—the lake dammed in Taylor Valley by grounded Ross Sea ice—are as young as 8340 ^{14}C yr BP (Hall and Denton, 2000b). Moreover, a relative sea-level (RSL) curve constructed from raised-beach deposits along the southern Scott Coast suggests deglaciation of that area about 6500 ^{14}C yr BP (Hall and Denton, 1999) (Figure 2). Conway et al. (1999) depicted the grounding line passing south of Roosevelt Island sometime after 3200 cal yr BP (Figure 3). Taken together, these recent studies show that most grounding-line retreat in the Ross Embayment occurred in middle-to-late Holocene time when the rate of sea-level rise had diminished substantially (Fairbanks, 1989). This implies that deglacial sea-level rise did not directly drive ice recession.

One limitation of the new evidence for Holocene retreat is that it is restricted to areas located from McMurdo Sound south to the present-day grounding line on the Siple Coast. The northernmost data come from Cape Roberts, 400 km from the LGM grounding-line position. Thus, the timing and cause of the initiation of ice-sheet retreat remains unknown.

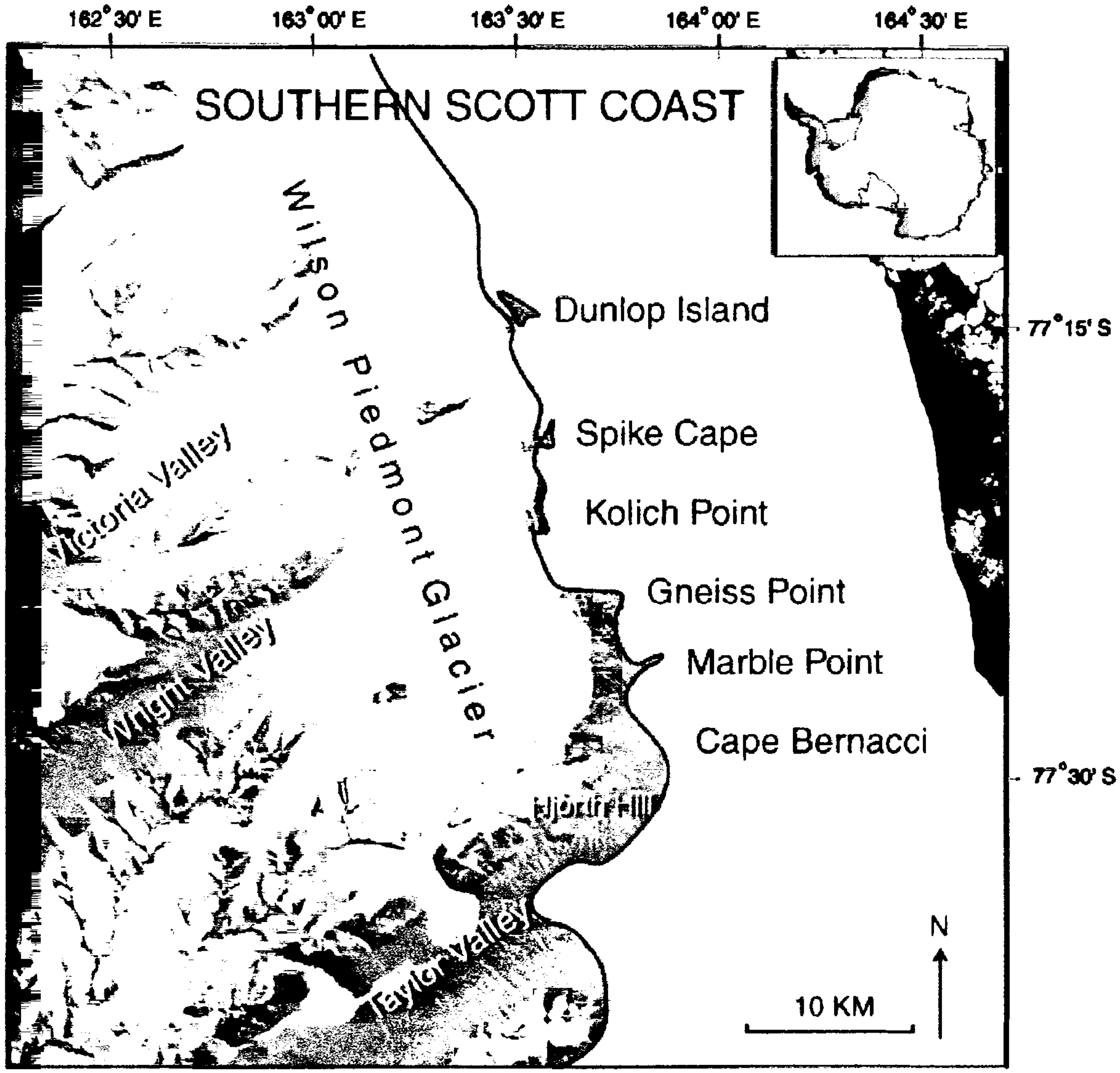

Figure 1. Location map of the southern Scott Coast. Cape Roberts is approximately 10 km north of the top of the image. The coastline, highlighted for clarity, is locked in sea ice (white). Open water appears black, whereas ice-free land is gray.

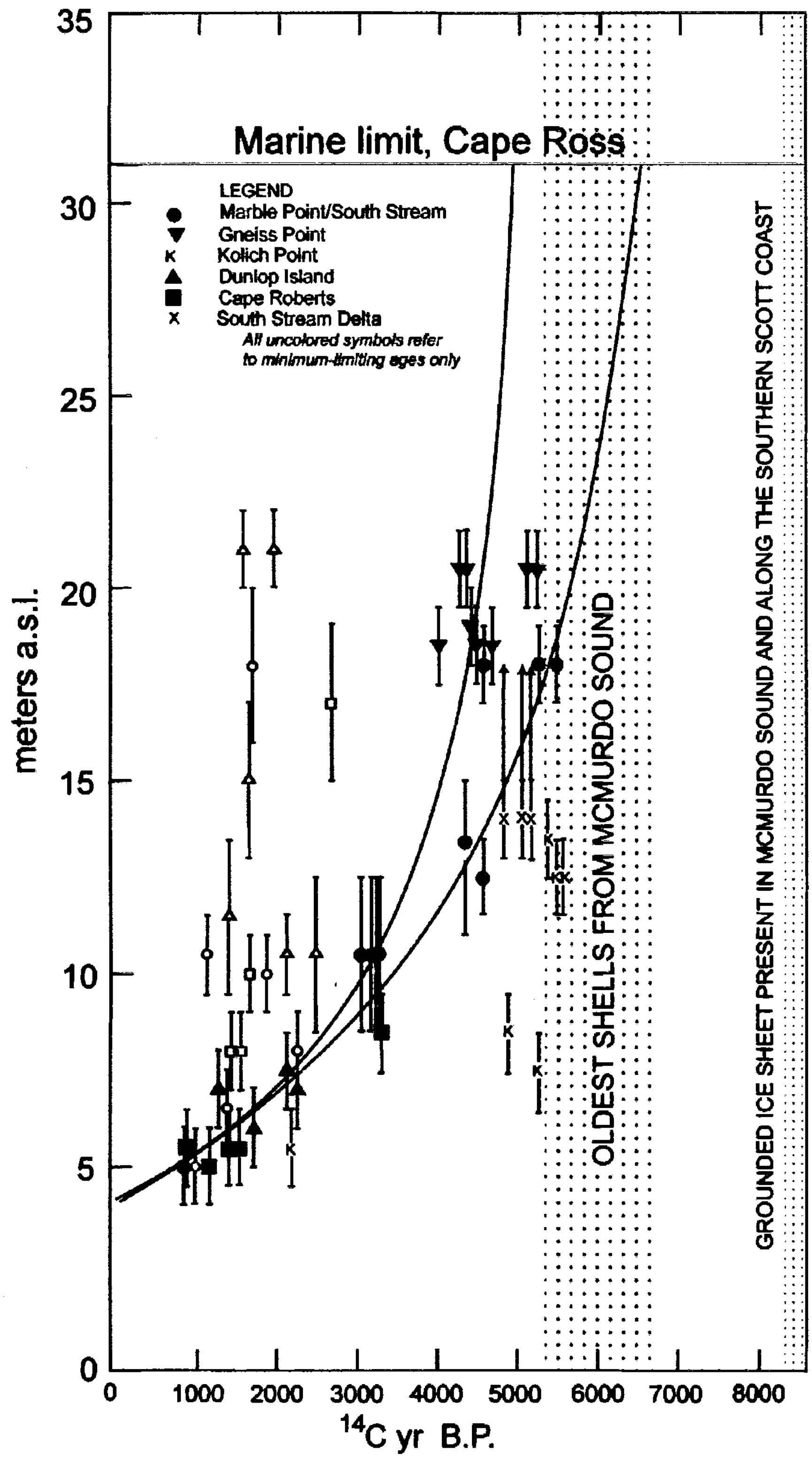

Figure 2. Relative sea-level curve from the southern Scott Coast. Open symbols indicate minimum/maximum ages (from Hall and Denton, 1999).

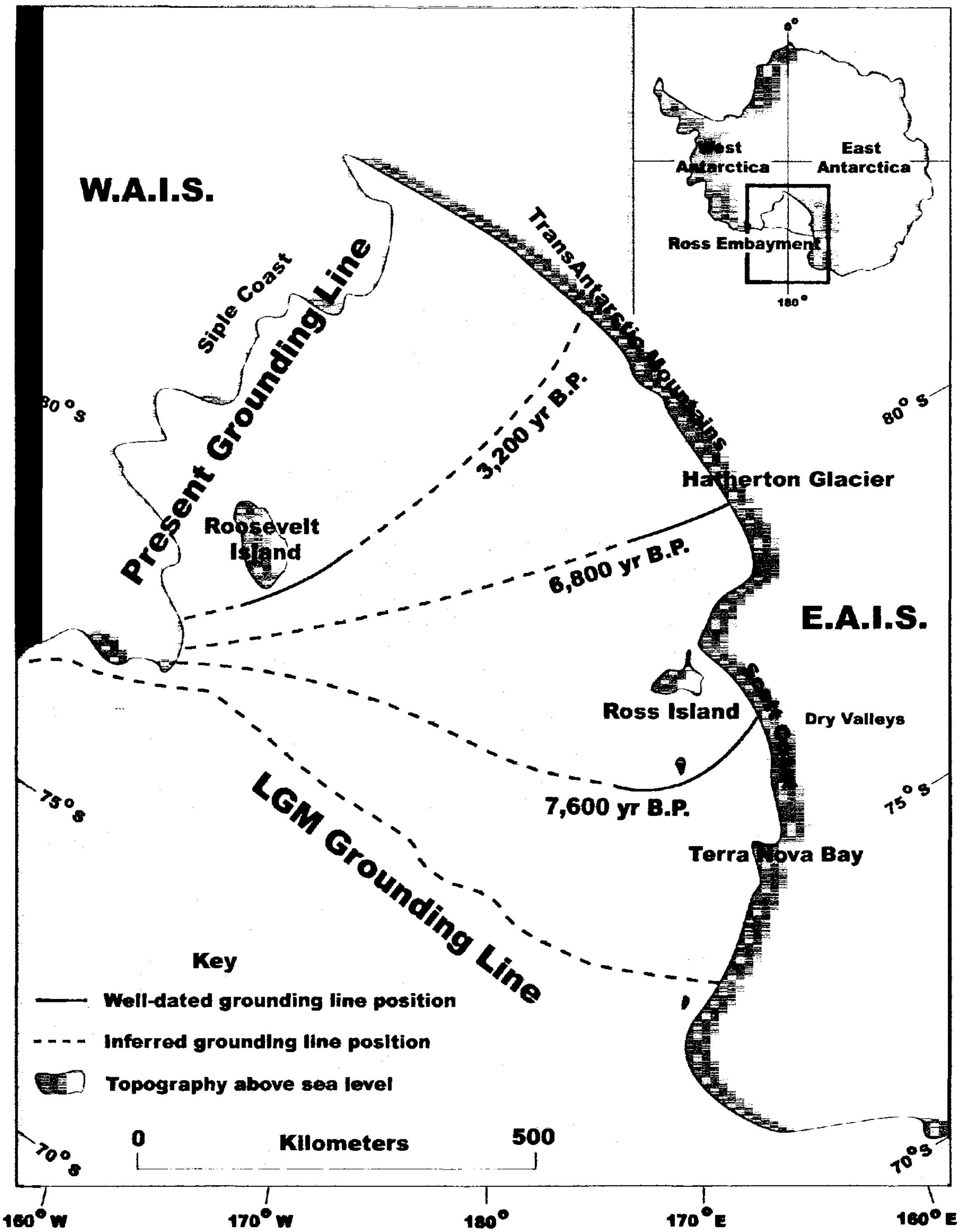

Figure 3. Map of the Ross Embayment. This map includes dated grounding line positions (in calendar years), from Conway et al. (1999).

Origin of Raised Beaches

A chronology of WAIS retreat in the northern Ross Sea Embayment depends heavily on the construction of RSL curves from raised beaches. However, the origin of these beaches and their relation to former sea level is still uncertain. Previous researchers assumed that they are storm beaches, formed about four meters above contemporaneous sea level (Hall and Denton, 1999). However, the present-day Scott Coast is nearly always locked in fast ice, and wave energy is highly attenuated before reaching the shoreline. How do beaches form in this polar environment? Were they created by storm waves or by another process, such as ice push (Nichols, 1961a)? Ice push would seem likely, given the current sea-ice conditions and the large size ($\leq$ 1 m diameter) of some clasts. Conversely, if these beaches were formed by storm waves, it may be possible to infer that there was less sea ice at times during the Holocene. A third possibility is that the beaches formed near sea level by fair-weather marine processes.

RSL reconstruction is dependent upon the deposit's initial elevation above sea level. It is imperative, therefore, to determine the process by which the beaches form. If a ridge is interpreted incorrectly as forming under normal marine conditions, it is possible that the inferred elevation of sea level is in error by as much as six meters (Nichols, 1953). This would introduce serious errors in a RSL curve, and therefore to the chronology of ice retreat in the area.

The incorporation of organic material is dependent on the process of beach formation. In turn, this is important for development of RSL curves, which rely on radiocarbon dates of shells, bone, and seal skin. Preservation potential is low in storm (high-energy) features, but is likely to have been higher in ice-push (low-energy) deposits. Therefore, there may be less chance for re-working of organic material in high-energy environments, as opposed to low-energy environments. Depending on how much time elapsed between the initial incorporation and the reworking, a date of the organic material might not represent the age of the beach itself. This would preclude the production of an accurate RSL curve.

Goals/Objectives of This Research

The main goal of this study is to determine the processes by which beaches form along the northern Scott Coast. A subsidiary goal is to provide data to be used in constructing a new RSL curve for the northern Scott Coast and for further constraint of the southern Scott Coast curve. These data bear directly on the retreat history of the WAIS.

To accomplish these goals, I have the following objectives:

1. Create detailed maps of beach deposits at primary field locations
2. Characterize the areal extent, morphology, and sedimentology/stratigraphy of beach deposits
3. Find and date organic material within the beaches
4. Assess the potential elevation correction necessary for samples used in constructing RSL curves

I chose two primary field areas for this study. The first is Cape Ross, 115 km northwest of McMurdo Station (Figure 4). The second major site is Inexpressible Island (adjacent to Terra Nova Bay), 250 km north of Cape Ross (Figure 5). Other sites examined at a reconnaissance level are the peninsula adjacent to Depot Island, Spike Cape, Dunlop Island, Gregory Island, Gneiss Point, Marble Point, and Adelie Cove (Figures 4,5). I chose the primary field areas for several reasons. First, previous researchers reported the existence of flights of beaches at these locations (Claridge and Campbell, 1966; Baroni and Orombelli, 1991, 1994a,b). Second, the process(es) of beach formation are likely to be different at the two locations. Cape Ross is nearly always locked in fast ice, and thus might be expected to show the effects of ice push. In contrast, Inexpressible Island is adjacent to Terra Nova Bay, a large polynya kept open by East Antarctic katabatic winds and the Drygalski Ice Tongue. Therefore, one would expect beaches at Inexpressible Island to be formed by open-water marine processes. Moreover, Cape Ross has the highest beaches (34 m elevation) in the Ross Sea region, and could provide key data for the southern Scott Coast RSL curve (Hall and Denton, 1999). This is important because all other beaches along the southern Scott Coast are $\leq$ 21 m elevation, and the upper part of the RSL curve is thus unconstrained. Inexpressible Island has a suite of raised beaches suitable for constructing a new RSL curve for the northern Scott Coast. This new curve will add to the deglacial history of the WAIS in the Ross Embayment by affording a chronology for ice retreat significantly closer to the LGM grounding line than that of previous studies.

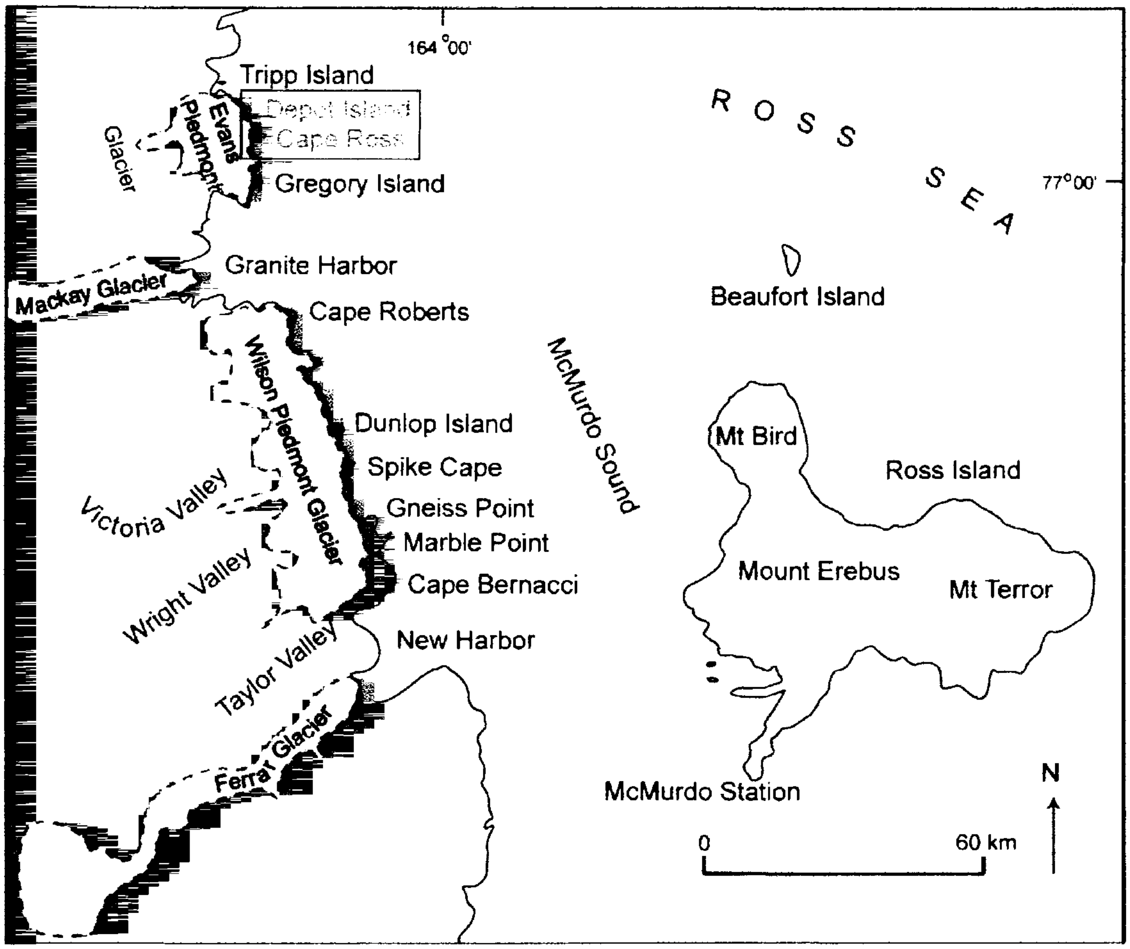

Figure 4. Map of McMurdo Sound. Primary and reconnaissance-level field areas are labeled, as well as field locations from Hall and Denton (1999, 2000a) used in constructing the southern Scott Coast RSL curve (Figure 2).

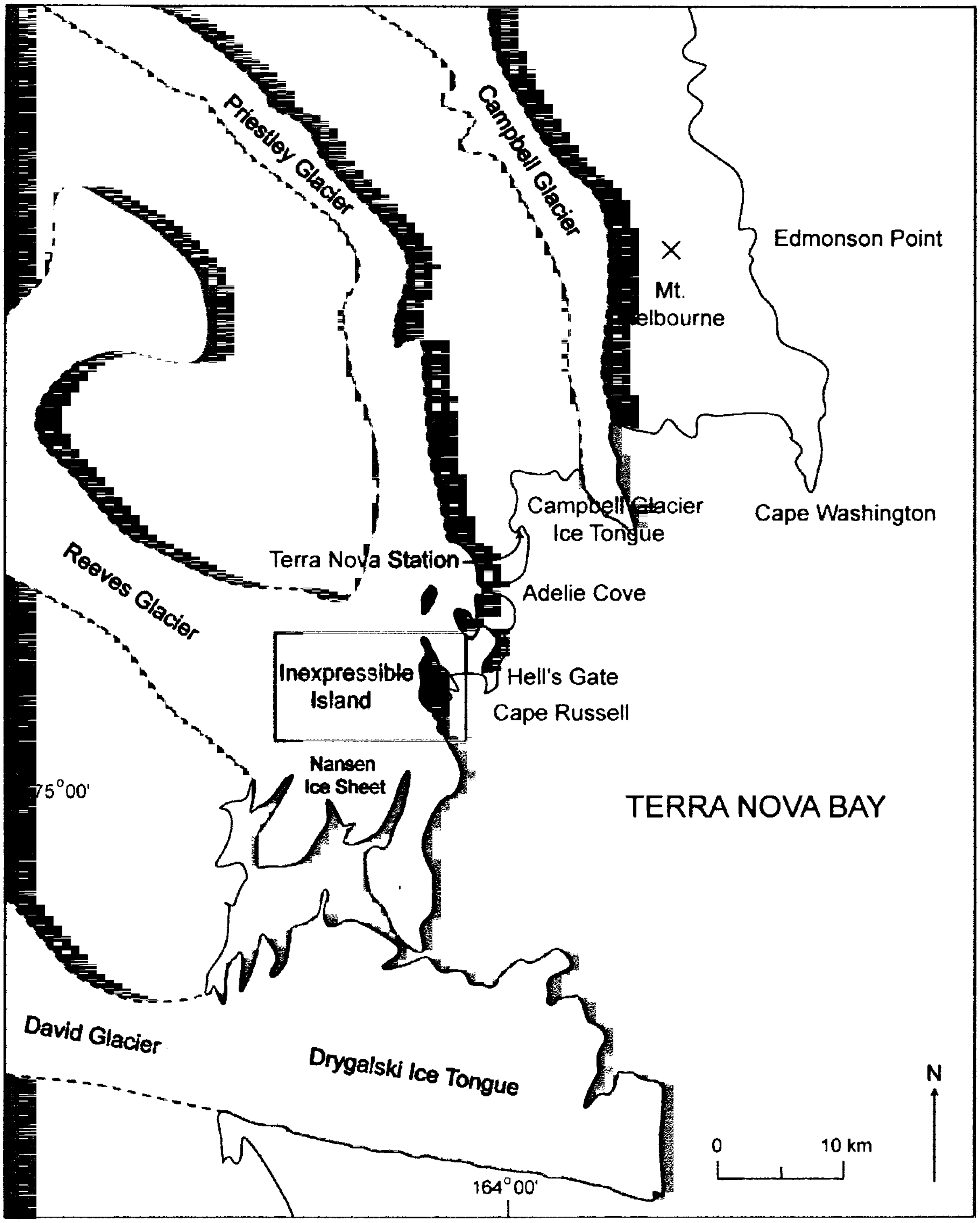

Figure 5. Map of the Terra Nova Bay area. Inexpressible Island, a primary field area, is labeled in red.

RESULTS

Methods

Aerial photographs provided the basis for hand-drawn field maps, which were created to identify and document large-scale geomorphic features. The maps primarily display beach-ridge and sample-pit locations, but also include relevant geomorphic features, such as channels and wave-washed bedrock outcrops.

I used an auto-level and staff to create one-meter-resolution profiles both across and along beach crests. Global positioning satellite (GPS) data supplemented the surveys at Cape Ross. I picked transects to include anomalies in steepness, as well as 'normal' or average values for beach slopes.

To establish general trends in rounding and shape of clasts in the beaches, I used two different grain-counting methods, the choice between the two depending on time constraints. One was detailed and included the measurement of three clast axes (in cm), roundness on a scale of 0.0-1.0 (Powers, 1953), and the estimated percentage of sand. The second method consisted of the measurement of the long axis and of roundness only. I also made a limited number of boulder counts, following a method commonly used on moraines. The number of boulders within a meter of each side of a 50 m tape (100 m^2 total area) was tallied for different sections along beaches. Each of these methods only quantified the surface grains (one clast deep).

I hand-dug excavations to examine any stratigraphic changes within the beach ridges. I characterized the stratigraphy and the surficial and internal arrangement of clasts and matrix material. I collected organic material found in excavations and placed them in plastic storage bags. At base camp, the samples were sifted and stored in plastic vials. The vials were then hand-carried back to the United States, where they were photographed and sent to the University of Arizona for accelerator mass spectrometry (AMS) dating.

Cape Ross

Cape Ross is a small (1 km^2) peninsula just north of Granite Harbor (Figures 6 and 7). The dominant bedrock is Larsen granodiorite with a gneissic texture, cut by a few frost-shattered mafic dikes (Smith, 2001). Although the peninsula is a relatively flat plateau, the topography rises sharply to the west where Cape Ross meets the mainland and the Evans Piedmont Glacier. The plateau, which is covered by beach deposits, is bordered on three sides by steep slopes and cliffs of wave-washed bedrock. In some places, chasms developed by erosion of dikes cut through the cliffs. Till covers most of the adjacent mainland and is modified by creep on slopes (Figure 8).

Land-fast ice commonly bounds the coastline in the vicinity of Cape Ross, with exceptions being rare. The sea-ice edge is as much as 10 km from the coast during summer months, whereas the entire Ross Sea is locked in sea ice during winter. Satellite images and sea-ice records suggest that this has been the climatic situation for the last century (Butler, 2001). These ice conditions cause wave energy to be attenuated almost completely and pressure ridges to form at the present shoreline. During rare times when the sea ice does break up, it commonly stays in place and thus still attenuates wave energy.

Figure 6. Photograph of Cape Ross, with view to the northwest. Cracks in the sea ice are seen to the north of the cape. The low, flat-topped island to the north is Depot Island. Distance from left to right across the photograph is about 1.5 km (January, 2001).

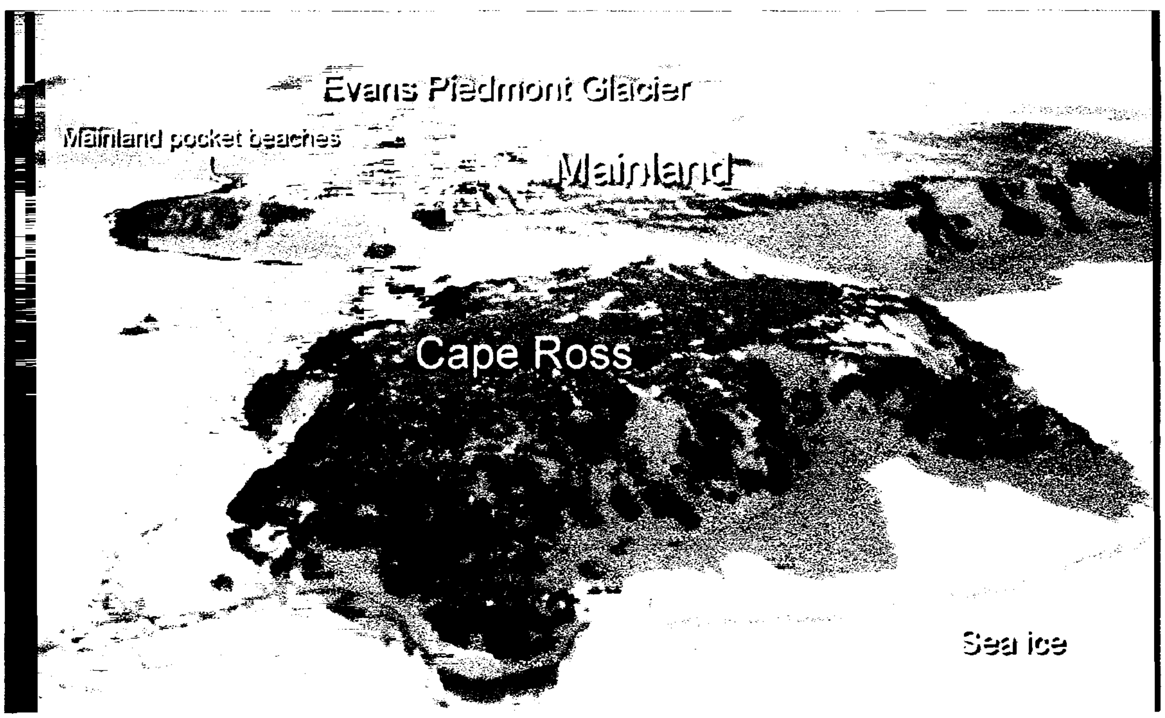

Figure 7. Photograph of Cape Ross, mainland, and the Evans Piedmont glacier. View is to the west, and distance across photograph is about one kilometer. (Photograph by Brenda Hall, January 2002)

Beach Extent and Morphology

Raised beaches are exposed from 23 to 34 m elevation on Cape Ross (Figure 9). Snow cover prevented identification of any beaches below 23 m. Beaches are developed best on the saddle between the mainland and the peninsula plateau. There are four well-defined ridges on the north side. Several smaller, less-developed beaches occur between the more prominent ridges. Three moderately to poorly developed ridges exist on the south side of the saddle. These north- and south-facing (east-west trending) pocket beaches are arcuate and sub-parallel to the present coastline. They have one-to-two meters of relief and are ≤ 100 m long.

Both the northern and southern pocket beaches extend upward to an elevated tombolo. The tombolo connects the mainland to the cape, which was once an island.

A series of beach terraces extends upward from either end of and perpendicular to the tombolo. Three poorly developed terraces rise towards the mainland on the western end of the tombolo. Four terraces continue east from the tombolo up to the main plateau on the cape (Figure 10). These latter terraces are well-developed, having flat treads and steep faces with angles of 20°-25°. The crests are spaced evenly about eight meters apart. The relief between each terrace is similar (~1.5 m). The vertices of the terraces all point west towards the tombolo (Figure 11). The largest and highest beach above the tombolo nearly forms a circle around the plateau, ranges from 0.5 to 2 m in relief, and is 600 m long.

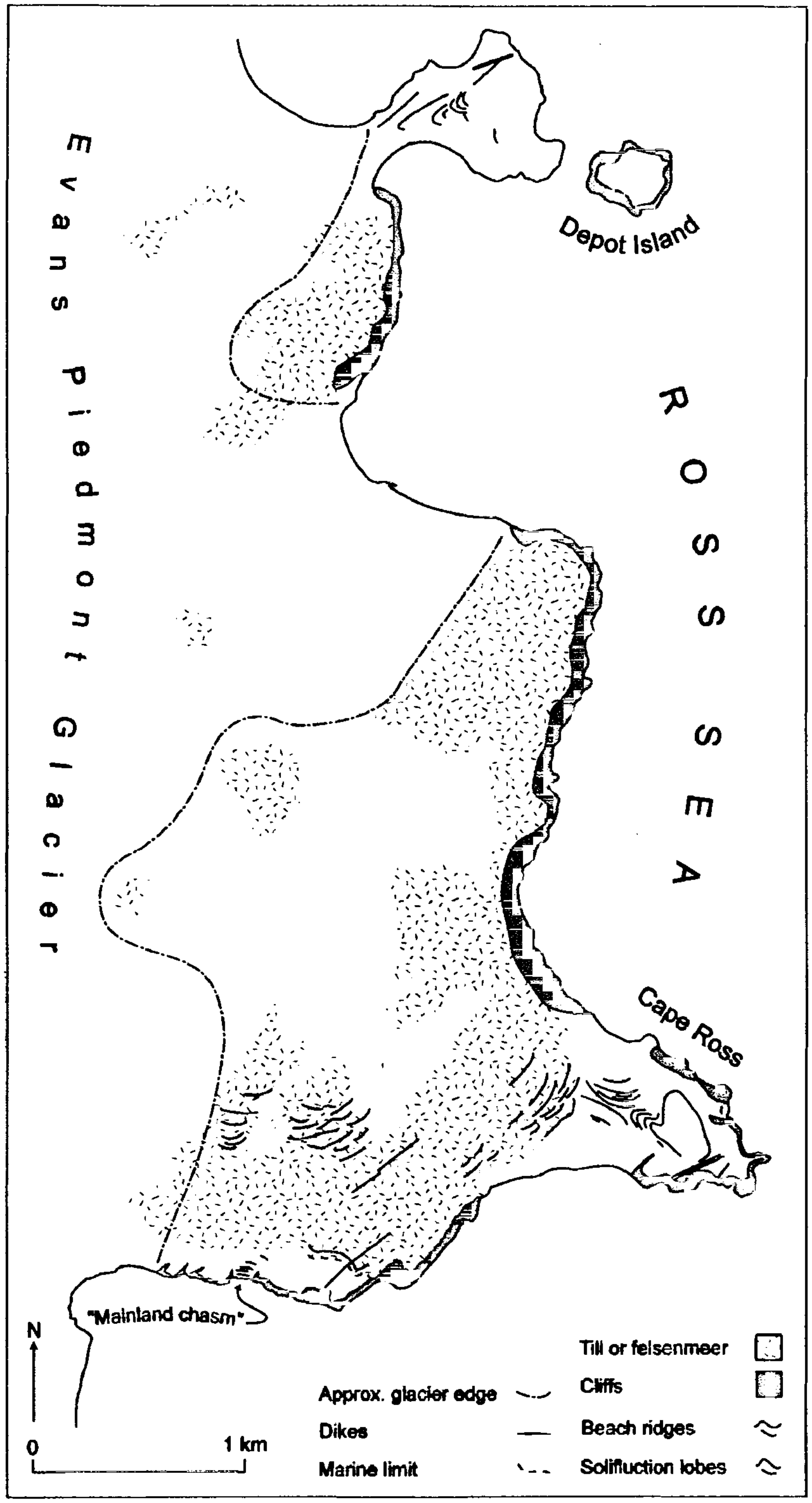

Figure 8. Surficial geologic map of Cape Ross, mainland, and Depot Island. For details of Cape Ross, refer to Figure 9. For Depot Island, see Figure 44.

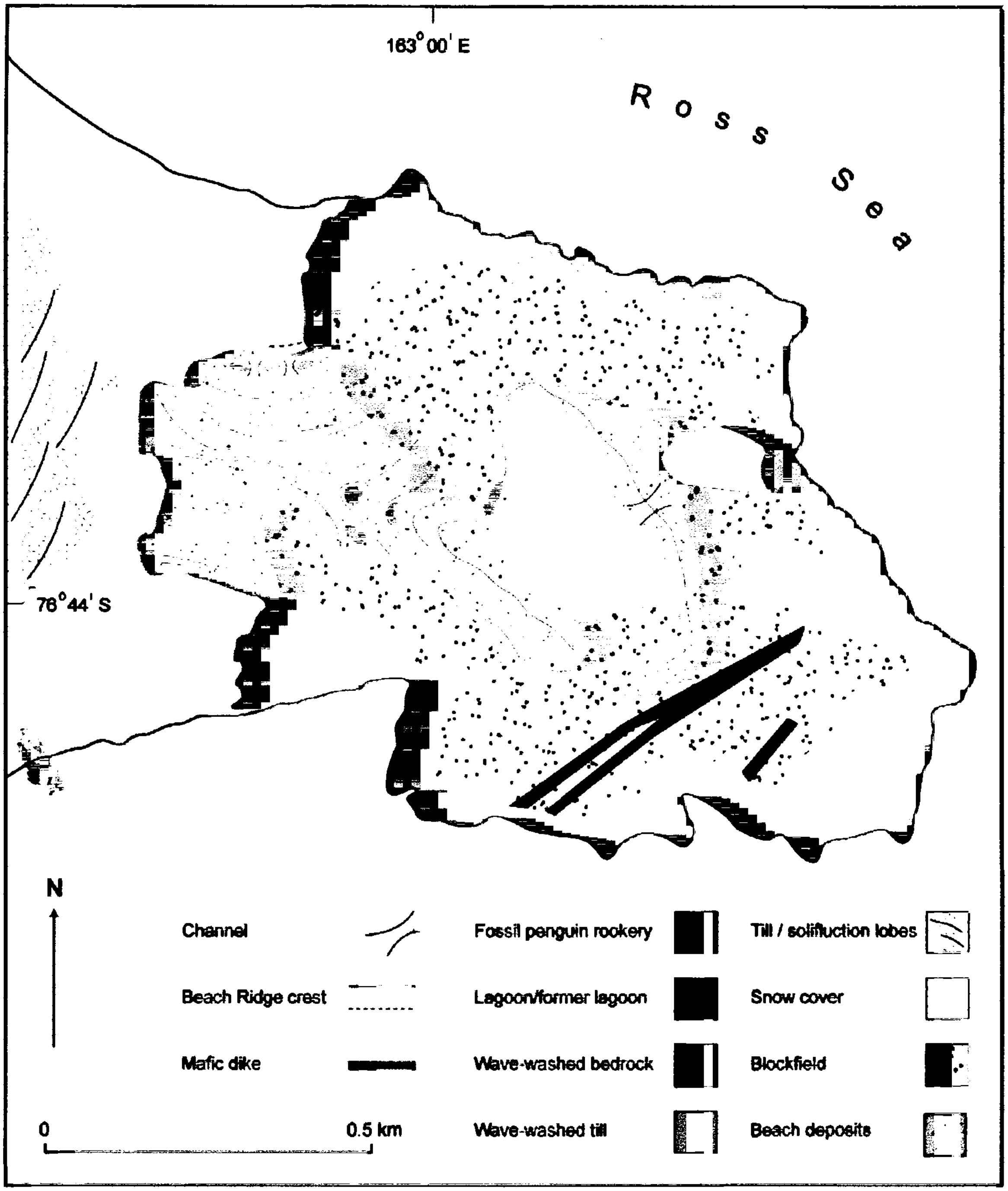

Figure 9. Surficial geologic map of Cape Ross [based on air photo interpretation and ground reconnaissance].

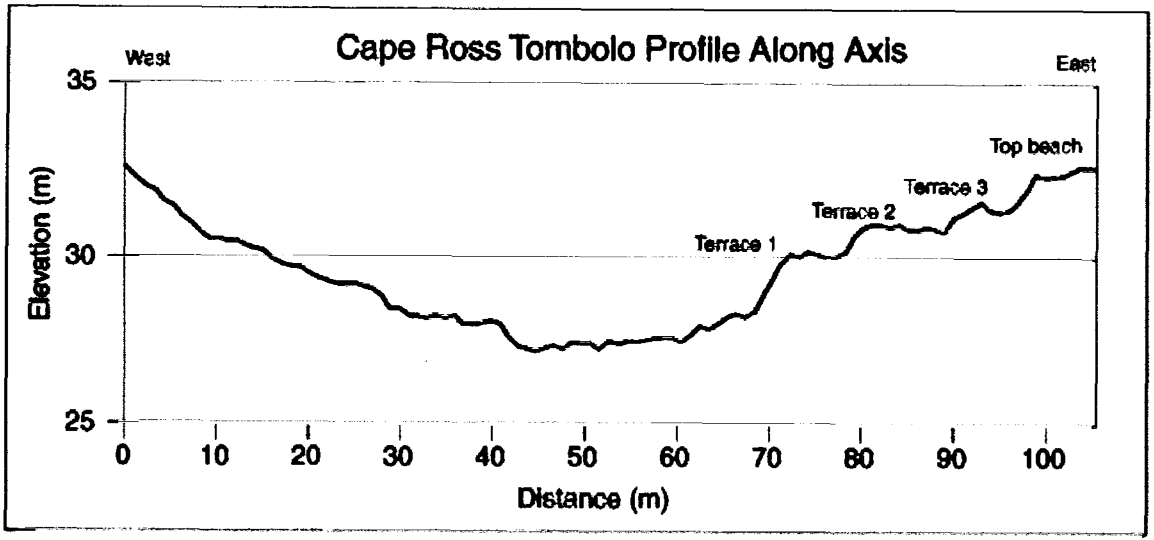

Figure 10. GPS transect along the axis of the Cape Ross elevated tombolo. This transect shows well-developed terraces on the east end and poorly developed terraces on the west end. Elevation is above mean sea level.

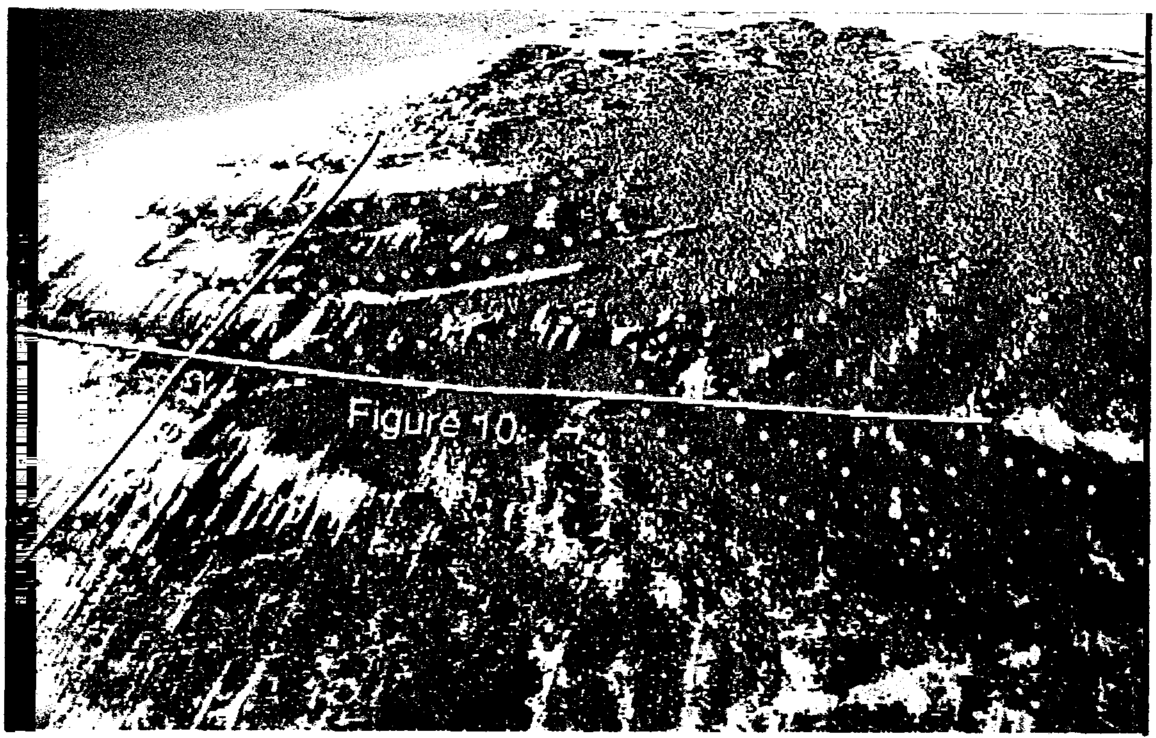

Figure 11. Photograph of beach ridges at Cape Ross. North is towards the top of the page. Beach ridges are outlined with yellow dots. Locations of transects (Figures 10 and 12) located with yellow lines. Distance across photograph is 0.3 km (January, 2001).

Pocket beaches are developed best on the north side of Cape Ross. Swales separate three major ridges, all of which exceed two meters of relief and one hundred meters in length (Figure 12). In addition, there are at least two smaller ridges among these three, including a low rounded one (≤ 1 m of relief). This latter ridge seems to be superimposed on the face of one of the major beaches. Another small ridge (30 cm high) is adjacent to the steep backside of the uppermost northern pocket beach.

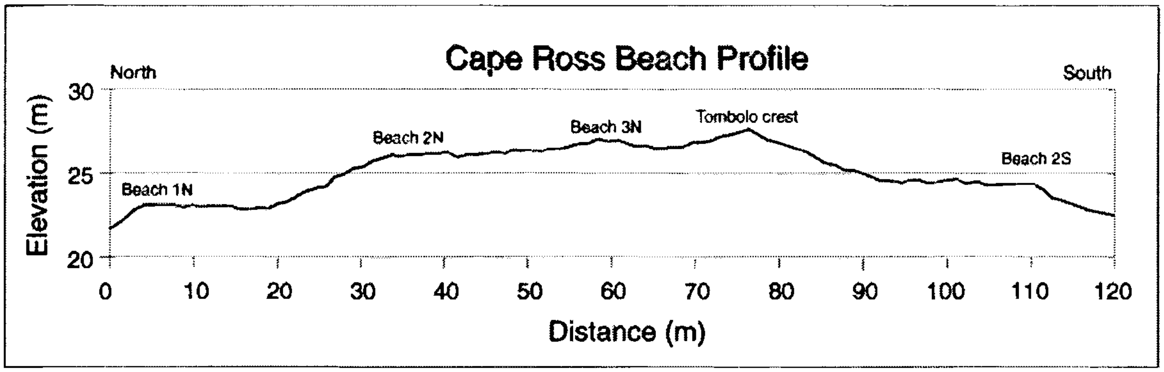

Figure 12. GPS transect across Cape Ross from north to south. Elevation is given above mean sea level.

The uppermost pocket beach (140 m long, 1 m relief) on this northern side (Beach 3N) is well defined. The most notable feature is the steep back slope, with angles ranging from 28° to 30° (Figure 13). The ridge is asymmetric, with the crest located towards the back of the beach. The crest is five meters wide, and the face is gently sloping (10°-12°).

In some cases, the swales between the pocket beaches display low-relief boulder pavements with interstitial areas filled with mud; in other cases, they are devoid of boulder or cobble-sized material. These muddy swales, probably former lagoonal areas, occur behind ridges that have significant back-slope relief. Beach ridges with a terrace-like morphology do not have swales. Channels extending from these former lagoons cut several beaches. Two channels cut the lowest beach on the northern side (Figure 14).

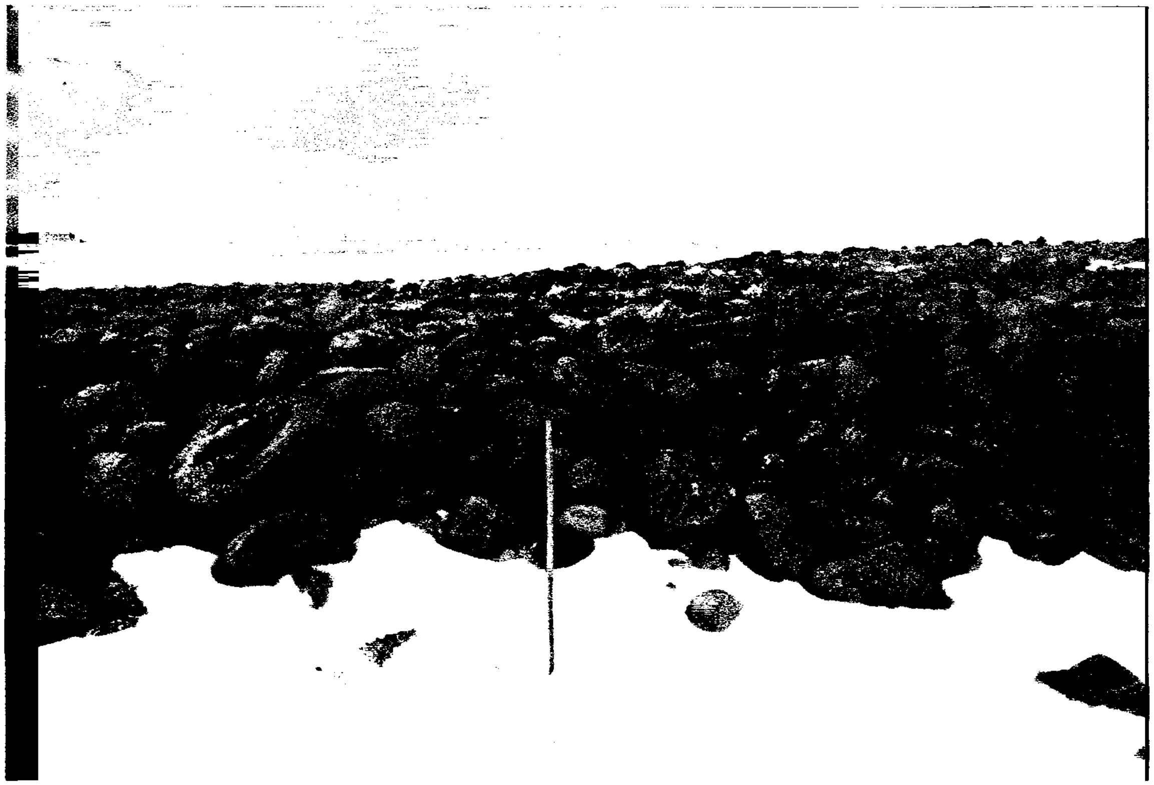

Figure 13. Photograph of the distal slope of the highest pocket beach (3N). View is to the north, and bamboo pole is one meter tall. The boulders and cobbles here are lying near the angle of repose. The snow is lying in a swale behind the beach. (Photograph by Brenda Hall, January, 2001)

A combination of low-angle sunlight, drifting snow, and small beach size makes exposures of south-facing pocket beaches rare. The largest of these beaches has a terrace-like morphology. Beach-face angles are 8°-10°, whereas the back or lagoon side is nearly level. Two smaller ridges (50 cm relief) adjacent to the large beach occur parallel to each other (one meter apart), but are only ten meters long.

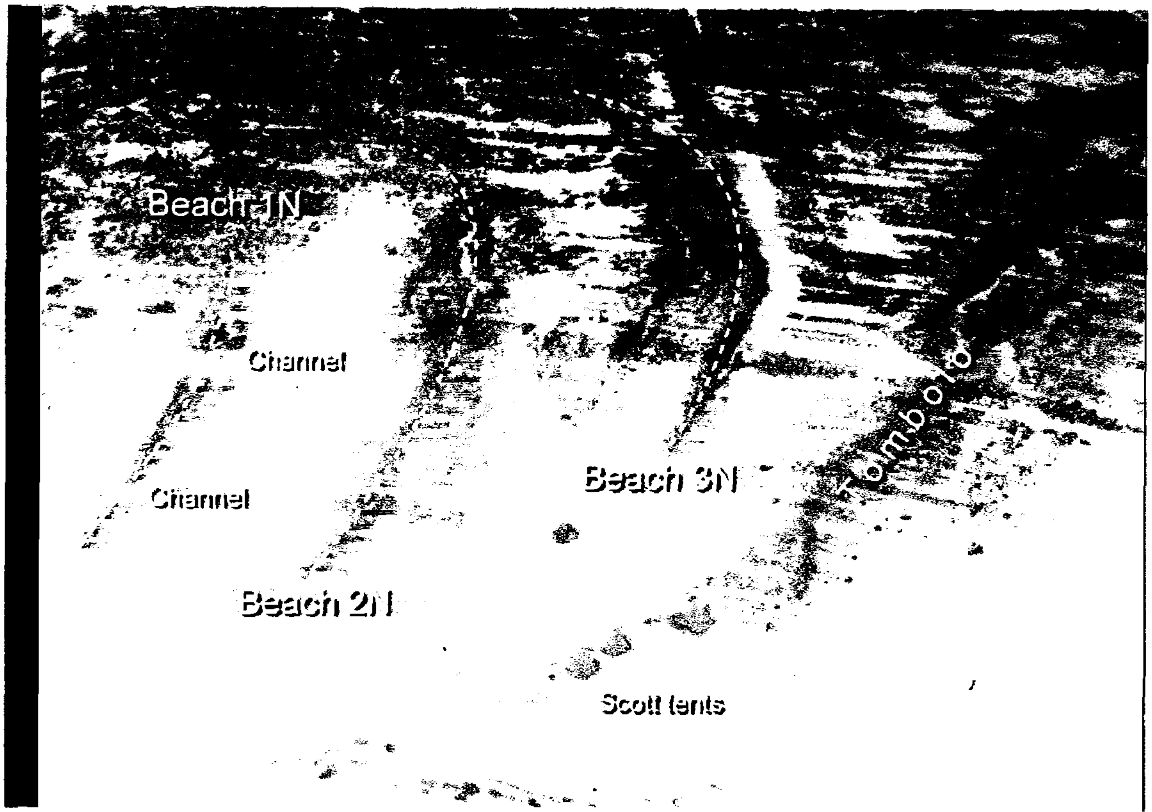

Figure 14. Aerial view of the northern pocket beaches. Scott tents in foreground for scale (2.5 m high), January, 2001. The tents are situated on the westernmost extent of the tombolo ridge (view is to the east). Two channels cut the lowest beach (Beach 1N).

On the plateau, a prominent beach ridge composed of gravel and boulders makes a ring around the eastern half of the peninsula and encloses a small pond. This ridge forms the uppermost terrace of the tombolo, and continues northeast through a blockfield, where it is barely discernible. The ridge steadily gains elevation and has its greatest relief (3 m) at the northeast corner of the cape at the head of a large chasm. Here, the beach face and crest are well-developed. The beach face has an average angle of 17°, whereas the back slope averages 28°. The beach continues southeast as a low, rounded ridge, in places indistinguishable from adjacent wave-washed till. The southern extension of this ridge fades into a blockfield and bedrock area. A fan-shaped, hummocky deposit lies landward of and below the highest section of beach at the northeast corner, and cuts through the ridge. This channel is 20 m wide and as much as 2.5 m deep (channel shown in Figure 9). The deposit fans out slightly as it extends into the low area behind the beach.

In addition to the beaches on Cape Ross, there is also an isolated occurrence of marine deposits on the adjacent mainland. The marine limit is visible at approximately 31 m elevation on south-facing parts of the mainland where the terrain is sufficiently flat (i.e., not cliffed). Thin wave-washed drift on top of rounded bedrock is typical of the area below the marine limit. A scarp caused by solifluction separates this marine unit from upland till and felsenmeer.

A large chasm on a south-facing slope of the mainland contains a flight of at least five raised beaches extending from approximately four meters above sea level to the marine limit (31 m). Two different types of beach ridges occur in this chasm. The lowest has approximately 0.5 m of relief and extends irregularly along the shoreline. The crest is sharp, and the material is very poorly sorted. Boulders seem perched on the surface, and generally are less rounded than those on higher beaches. Higher-elevation ridges are more terrace-like, and are composed almost entirely of clast-supported, well-sorted, rounded cobbles and some boulders. Some of these beaches overlie shattered and heavily weathered bedrock. The weathering intensity of beach clasts progressively increases upwards with elevation.

Sedimentology and Stratigraphy

Beaches at Cape Ross generally are composed of clast-supported boulders and cobbles with interstitial gravel and coarse sand (Figure 15). Small lenses (10 cm long) of sand and gravel also occur in some pits. I did not find distinct stratification within any of the beaches. However, a break from weathered sand and cobbles above to clean sand and cobbles below occurs in several holes (001, 009, 011, 020) (Figure 16). For example, in pit 020, the break between the two units extends the length of the pit (2 m) at a depth of 50 cm. This contact dips 1-2° to the south, similar to the beach slope. The sand in the lower unit is white and non-coherent. It is also well sorted and looks washed. This is in contrast to the sandy matrix above, which is coherent and results in stable walls. This upper unit also has weathering products like clumped grains and a silt component.

In some cases the size of surface-clasts varies along the crest of a beach. For example, observations show that clasts on the upper two pocket beaches on the north side become progressively smaller from west to east (Figures 17 and 18). This is quantified by a boulder count. On a beach at 26.4 m elevation, a count of boulders in 100 m^2 resulted in 564 boulders towards the center of the beach, and 463 boulders on the eastern portion. The higher beach (27.6 m elevation) shows the trend more clearly: 961 boulders in the center, and only 187 boulders at the eastern end. In addition, grain counts on the crest of the 27.6 m beach also show this eastward fining. The average grain sizes in two random square-meter plots on the center of the ridge are 16.51 and 13.7 cm, whereas the average size in a random square-meter plot on the eastern end is 10.6 cm. Snow concealed the western extensions of the beaches, so lateral fining in that direction could not be quantified. Grain size variations also occurred perpendicular to the crests. Large boulders seem to comprise the steep backs of several beaches, whereas the beach faces are finer-grained boulders (Appendix).

Figure 15. Excavation on the highest elevation beach at Cape Ross. Pick is 70 cm in length. Unstratified beach deposit contains well-rounded cobbles and boulders, with interstitial sand. No stratigraphy is evident. The finer material towards the surface is composed of weathered remains of surface clasts and wind-blown sand (January, 2002).

Figure 16. Weathering contact in a pit on Cape Ross. Contact in the photograph is indicated by the color change. It occurs at approximately 50 cm depth, and the largest clasts in photograph are 10 cm in diameter.

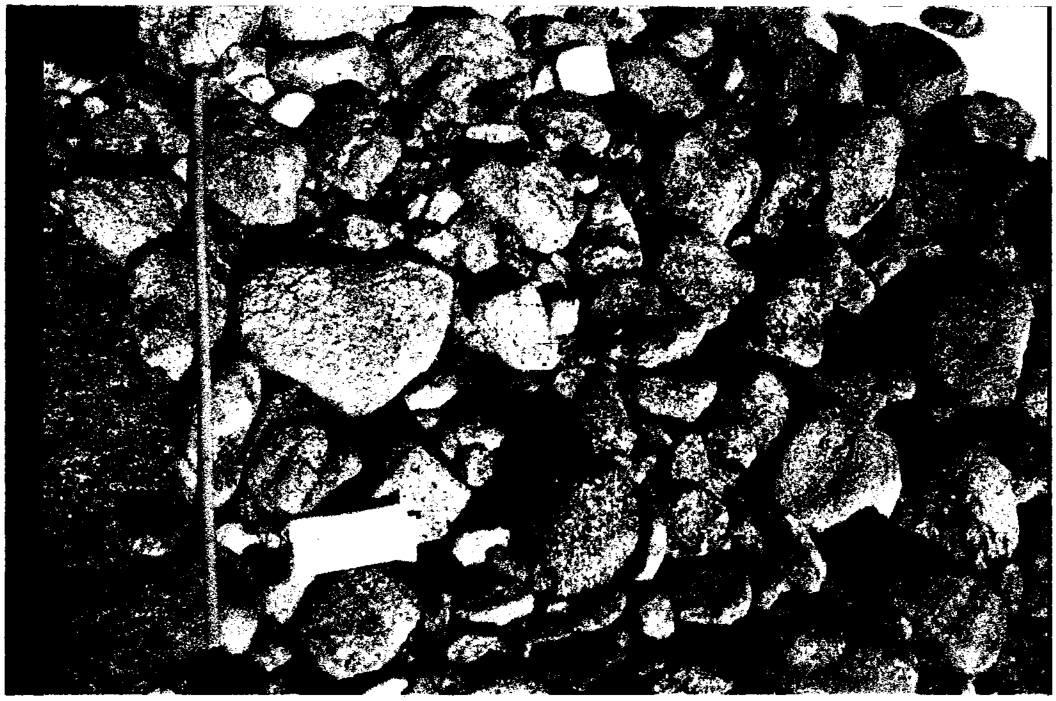

Figure 17. Photograph of beach clasts on the easternmost extension of ridge 3N. Bamboo rod is one meter in length (January, 2001).

Figure 18. Photograph of beach clasts on the middle of ridge 3N. Bamboo rod is one meter in length (January 2001).

Radiocarbon Samples

I recovered 31 organic samples at Cape Ross, including shells, seal skin, and penguin remains (Figure 19). The dated samples are from elevations ranging between 27 m to just over 32 m a.s.l. Radiocarbon ages vary from 30,150 ± 430 to 44,900 ± 3,100 ^{14}C yr B.P. (Table 1). The shells recovered all are limpets (Nacellidae), including Calyptraeidae and Crepidula (Hendy, personal communication, 2001) (Figure 20). All shell and bone material came from depths ≥ 50 cm, below the break between the weathered horizon and the lower clean sand.

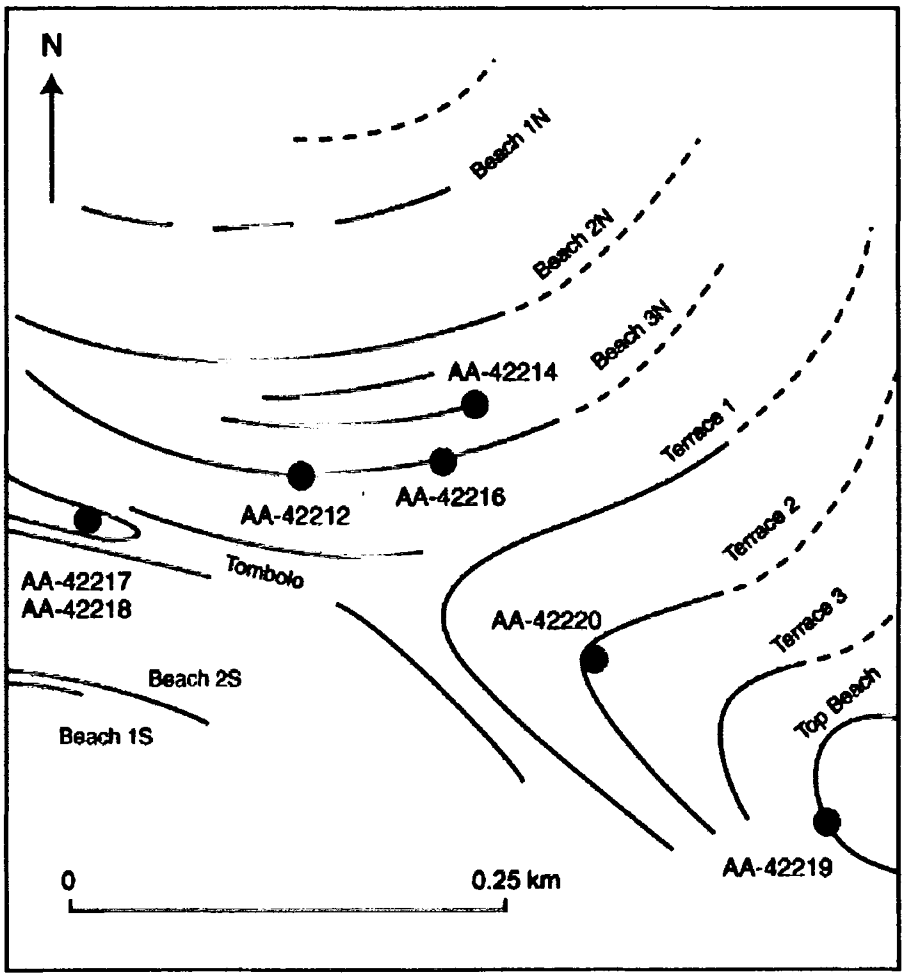

Figure 19. Cape Ross sample location and beach numbering map. Red lines are beach ridge crests, Black dots indicate pit locations, and numbers correspond to radiocarbon laboratory sample numbers.

Table 1. Radiocarbon dates of samples recovered from Cape Ross. Dates have been adjusted for $\delta\ ^{13}C$ variations, but are otherwise uncorrected. Note that for bone samples, collagen was dated. (* Dates from Baroni and Orombelli, 1994a—locations not shown on Figure 19).

Laboratory number #	^{14}C yr BP (uncorrected)	$\delta\ ^{13}C$	Elevation (m)	Description
AA - 42212	43,400 ± 1,600	1.4	27.7	Whole *Nacellidae* shell @ 50 cm
AA - 42214	30,150 ± 430	-20.1	26.9	Adelie penguin bone (collagen) @ 50 cm
AA - 42216	44,900 ± 3,100	1.2	27.4	Whole *Nacellidae* shell @ 65 cm
AA - 42217	40,400 ± 1,300	1.3	28.1	*Nacellidae* fragments @ 75 - 78 cm
AA - 42218	37,570 ± 940	-23.6	28.1	Adelie penguin vertebra (collagen) @ 75 cm
AA - 42219	35,660 ± 870	1.2	32.2	*Nacellidae* fragments @ 70 - 90 cm
AA - 42220	44,700 ± 2,100	1.1	30.9	*Nacellidae* fragments @ 80 cm
GX - 16911	4315 ± 90 *	n/a	n/a	Penguin guano @ surface
GX - 16912	4465 ± 90 *	n/a	n/a	Penguin guano @ surface
GX - 16913	4570 ± 90 *	n/a	n/a	Penguin guano @ surface
GX - 16914	4220 ± 160 *	n/a	n/a	Penguin guano @ surface
GX - 16918	4310 ± 155 *	n/a	n/a	Penguin guano @ surface
GX - 16919	4735 ± 165 *	n/a	n/a	Penguin guano @ surface
GX - 16920	4255 ± 155 *	n/a	n/a	Penguin guano @ surface
GX - 16921	4555 ± 90 *	n/a	n/a	Penguin guano @ surface
GX - 16922	4780 ± 160 *	n/a	n/a	Penguin guano @ surface

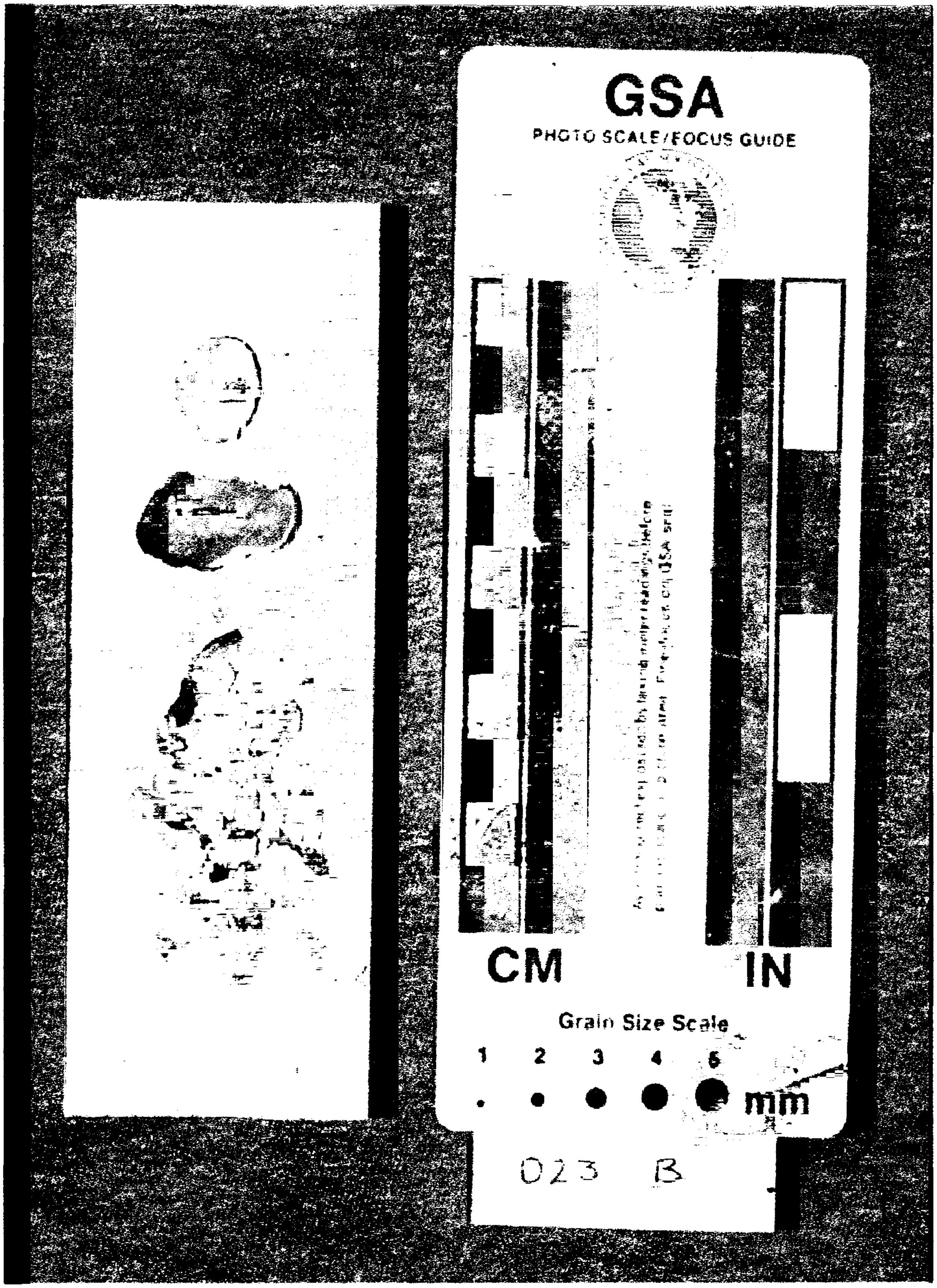

Figure 20. Photograph of Nacellidae samples. These were recovered from within the highest-elevation boulder beach at Cape Ross (January, 2001).

Inexpressible Island

Inexpressible Island is bordered on the west and south by the Nansen Ice Sheet, on the north by Hell's Gate Ice Shelf, and on the east by Terra Nova Bay (Figure 21). The island lies directly in the path of a major outlet of East Antarctic katabatic winds, which keep Terra Nova Bay open as a polynya. Several rock types crop out on the island, predominantly syenite and granodiorite.

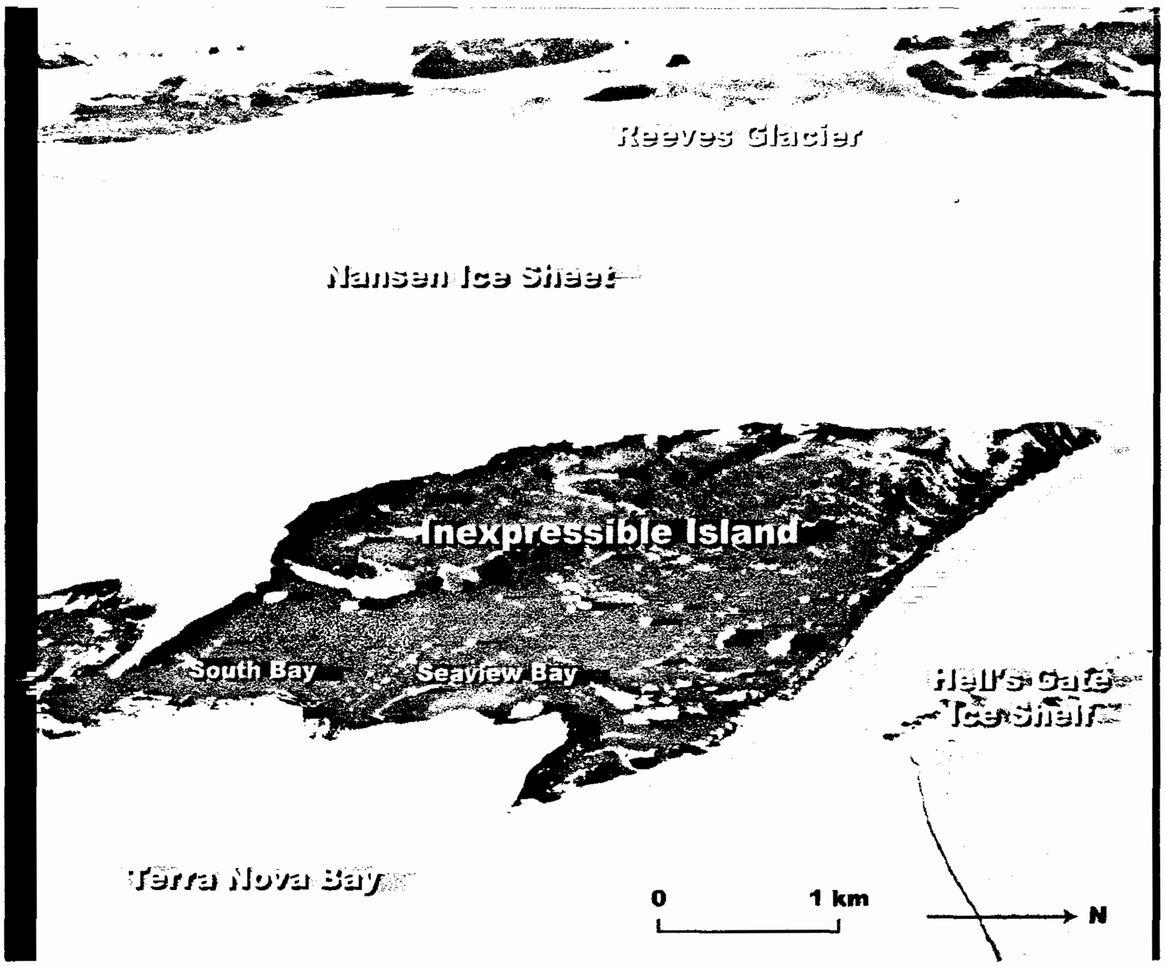

Figure 21. Aerial photograph of Inexpressible Island, with view to the west. The two major bays, South and Seaview, are shown here. Two smaller bays lie out of the picture to the left. Beaches also occur along the coast facing Hell's Gate Ice Shelf.

Inexpressible Island contains four major bays on the east coast. Beach ridges occur in all of the bays, decreasing in number and size to the south (Figure 22). Seaview, the northernmost bay, contains a large Adélie penguin rookery. During the winter of 1912, the bay was also home to a party of Scott's men led by Campbell. I chose the next cove to the south, hereafter called 'South Bay,' as the primary study site. South Bay contains a flight of beach ridges, and research could be done there without violating the Antarctic Treaty, since there were appreciably fewer penguins than in Seaview Bay. The next bay to the south contains a series of beaches that are different in character from any to the north. Ridges in this cove are small, yet sharp, and the area between the beaches is almost devoid of surficial deposits. The southernmost embayment had significant snow and ice cover in both 2001 and 2002, which precluded detailed mapping. I performed reconnaissance mapping in these two southern bays, but no detailed analysis of beach morphology or sedimentology.

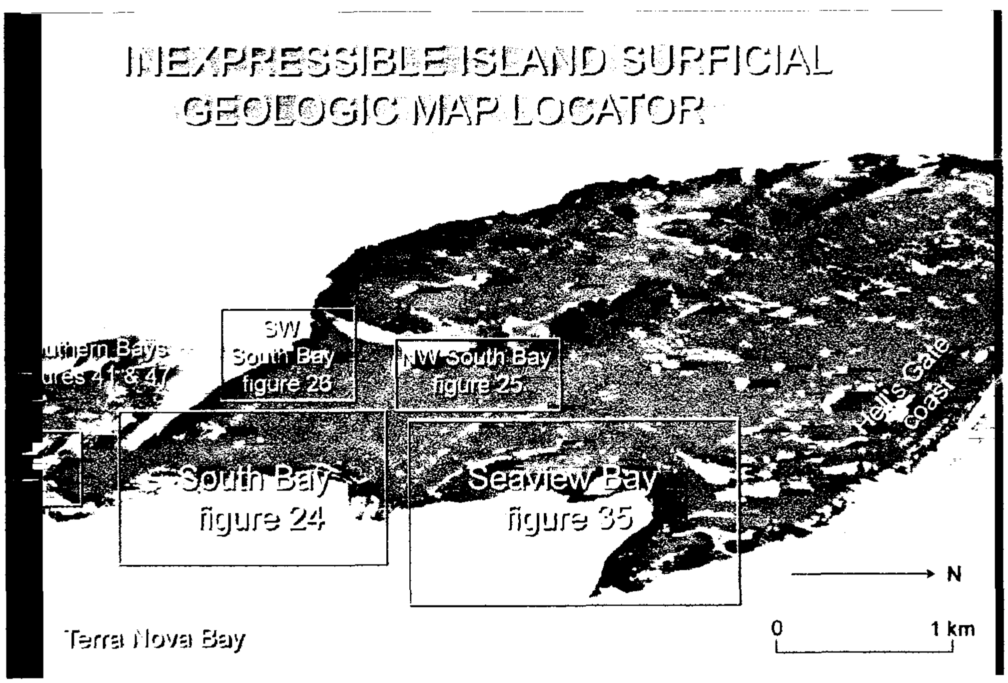

Figure 22. Inexpressible Island surficial geologic map locator. Note that the southernmost bay cannot be seen in this photo.

South Bay

As defined here, South Bay includes the present-day cove, as well as areas that have emerged from the sea during the Holocene. This area extends almost two kilometers inland and is, for the most part, flat with low local relief (2-3 m) and is covered by till with little marine modification (Figure 23). The marine limit on the north side of the cove occurs as a steep scarp at 30 m elevation, except in places where the slope is unstable and probably has failed. The marine limit on the south end of the bay is a scarp on the headlands and grades into a boulder beach towards the west. Till sheets and felsenmeer lie above the marine limit. Bedrock crops out on the headlands and on minor peninsulas within the bay.

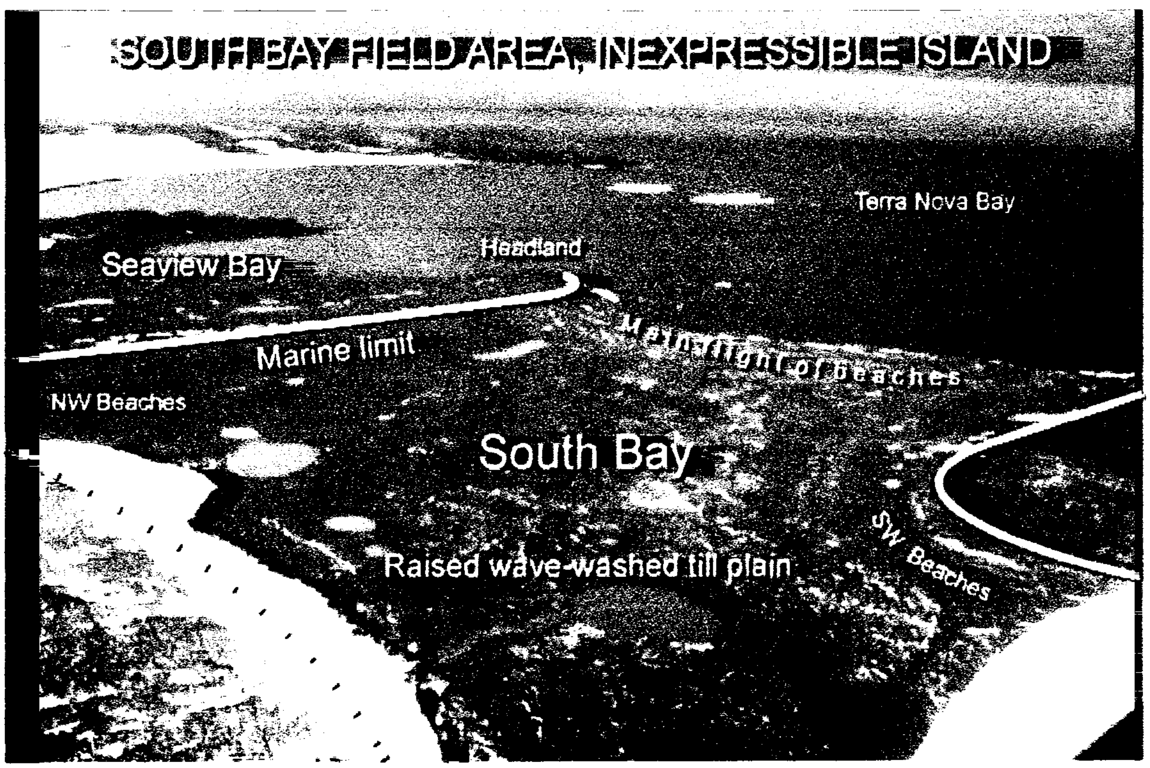

Figure 23. South Bay field area, with view to the northeast. South Bay includes areas that were covered by seawater at the Holocene highstand. The marine limit, shown as a heavy yellow line, marks a scarp produced at this highstand. Note that the continuation of the marine limit in Seaview Bay is not shown (January, 2002).

Beach Extent and Morphology

More than 14 major shore-parallel beach ridges occur within half a kilometer of the current coastline (Figure 24). The surficial character of the deposits—including lithology, pocket beach geometry, and relief—changes from north to south. Only two beach ridges extend without interruption from the northern headland to the southern headland, whereas others are either localized pocket beach sets or parts of spit complexes. Raised spits in South Bay originate at either headland, extend parallel to the present coastline (towards each other), and are composed of several raised ridges. Most of the beaches forming the northern spit are higher in elevation than those forming the southern spit. There are also raised marine deposits and beaches well inland of the primary beach set, in both the northwest and southwest corners of the South Bay field area (Figures 25 and 26—see Figure 22 for location).

The marine limit is a well-defined scarp at 30 m elevation. It occurs as a nearly straight line extending from the northern bedrock headland inland across a till sheet, and curving southward at the base of the island foothills. The scarp is steep and not significantly denuded by mass-wasting processes. Where it extends across the headlands, the marine limit marks the boundary between wave-washed bedrock (below), and deteriorating bedrock and thin drift (above). The marine limit is indiscernible along the base of the western hills, but is visible near a lobe of the Nansen Ice Sheet that covers part of the island (Figure 21). East of this ice lobe, the marine limit curves northward around a hill and extends eastward, towards the southern headland of South Bay (Figure 24). Along most of this exposure, a well-defined ridge of boulders and cobbles (1 m in relief) marks the marine limit, except where it crosses bedrock. Till that does not show obvious marine modification occurs above this uppermost beach. However, ten meters above what seems to be the marine limit, a small (1 m relief) scarp encircles a high area. Aerial photographs also show a faint color change at ~ 40 m elevation in this area, but during reconnaissance I did not find any morphological or sedimentological evidence for a shoreline. Marine evidence also exists higher than the clear 30-m marine limit in the southwest region of the bay. Highly weathered beach cobbles lie on a faint ridge at 45 m elevation in this area.

The main flight of beaches, which occurs parallel and relatively close to the present shoreline, can be divided into north and south groups (Figure 27). To the north, three beaches occur at low elevation and extend southward to terminate at a high area of exposed bedrock near the center of the cove. These beaches (2 m relief, 20 m wide) (Figure 28) contain the largest, roundest, and least-weathered boulders in the area. The next five beaches inland rise in elevation, but decrease in size progressively. Beaches 4 (Figure 29) and 5 are continuous from the north to the south ends of the embayment; beach 6 terminates near the middle of the bay; beaches 7 and 8 are barely distinguishable.

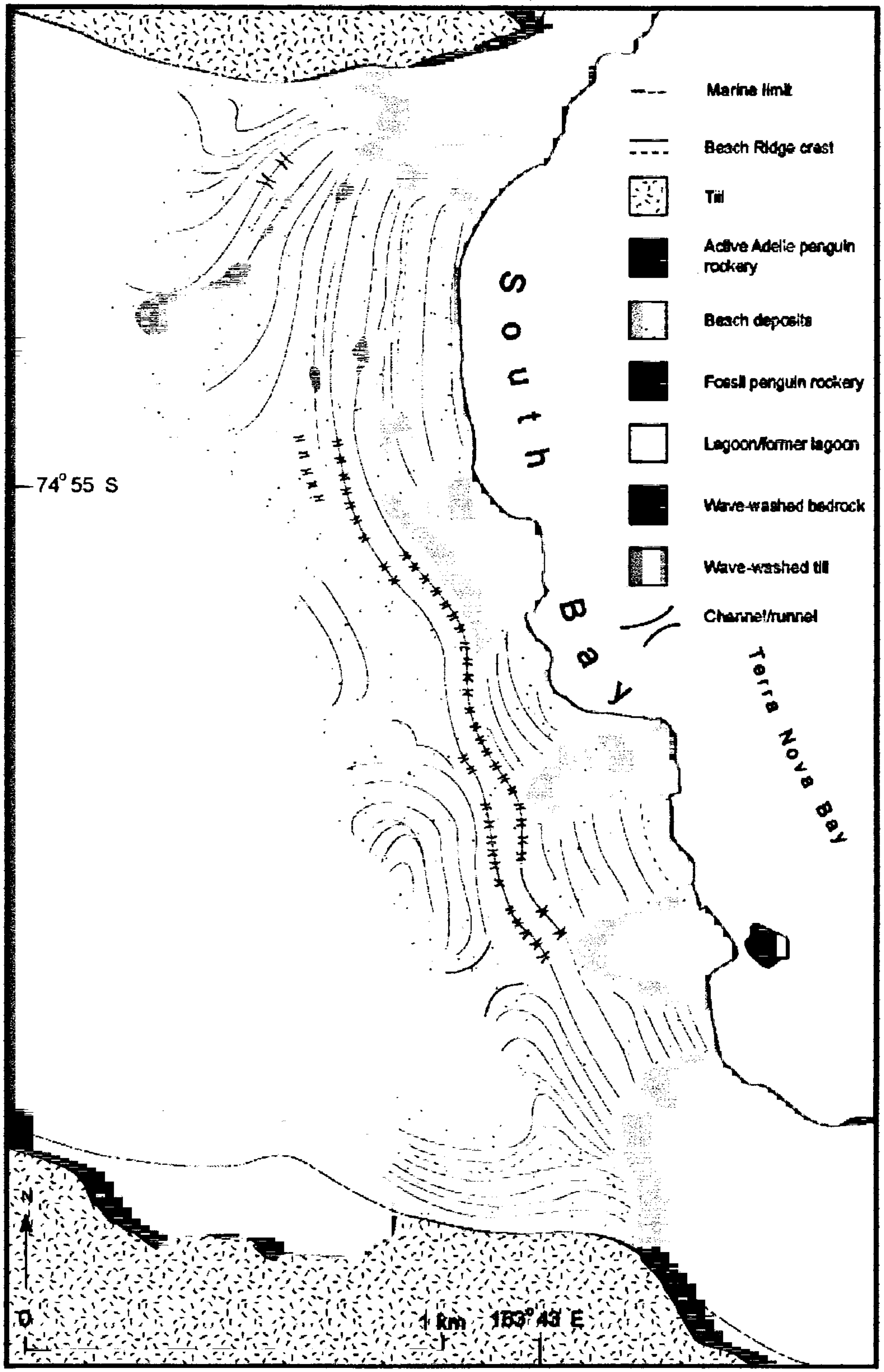

Figure 24. Surficial geologic map of South Bay [based on air photo interpretation and ground reconnaissance]. See Figure 20 for location.

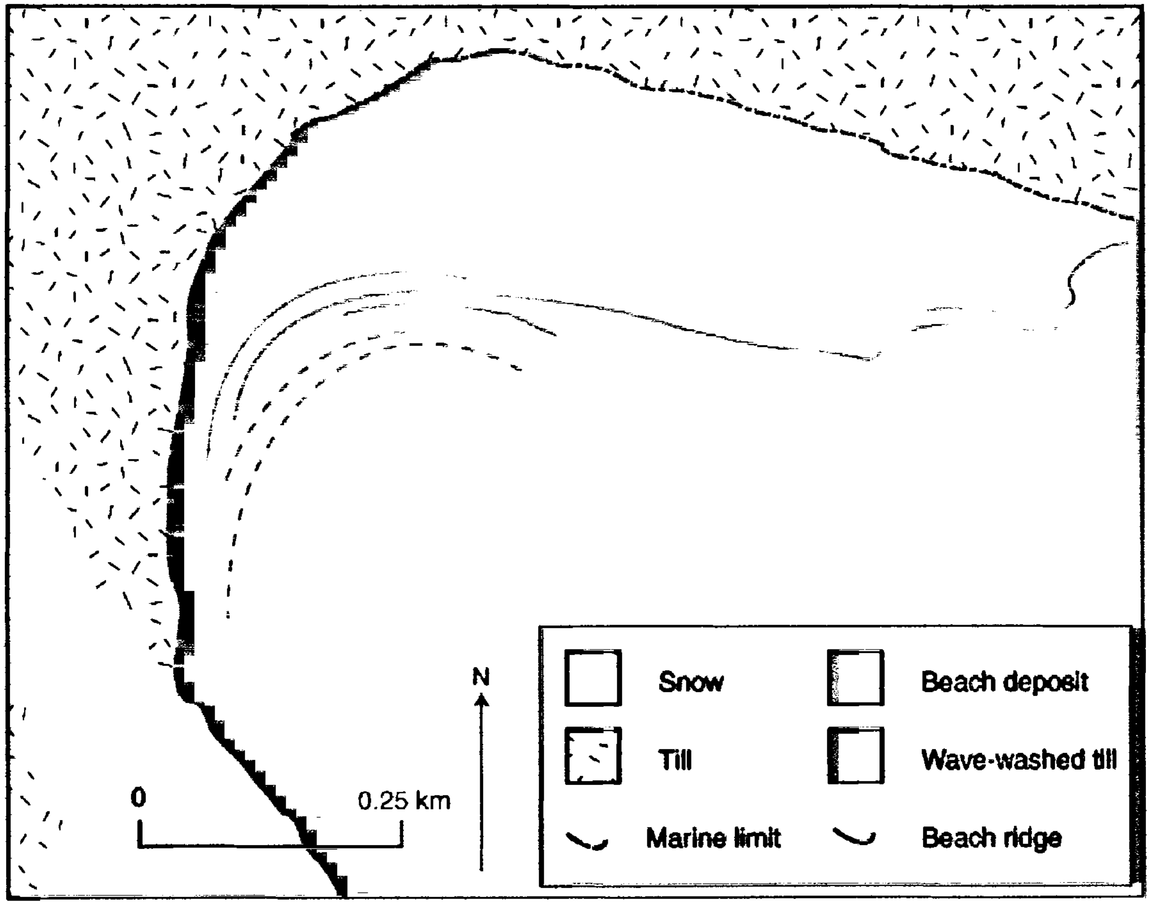

Figure 25. Surficial geologic map of beaches in northwestern South Bay [based on air photo interpretation and ground reconnaissance]. See Figure 22 for location.

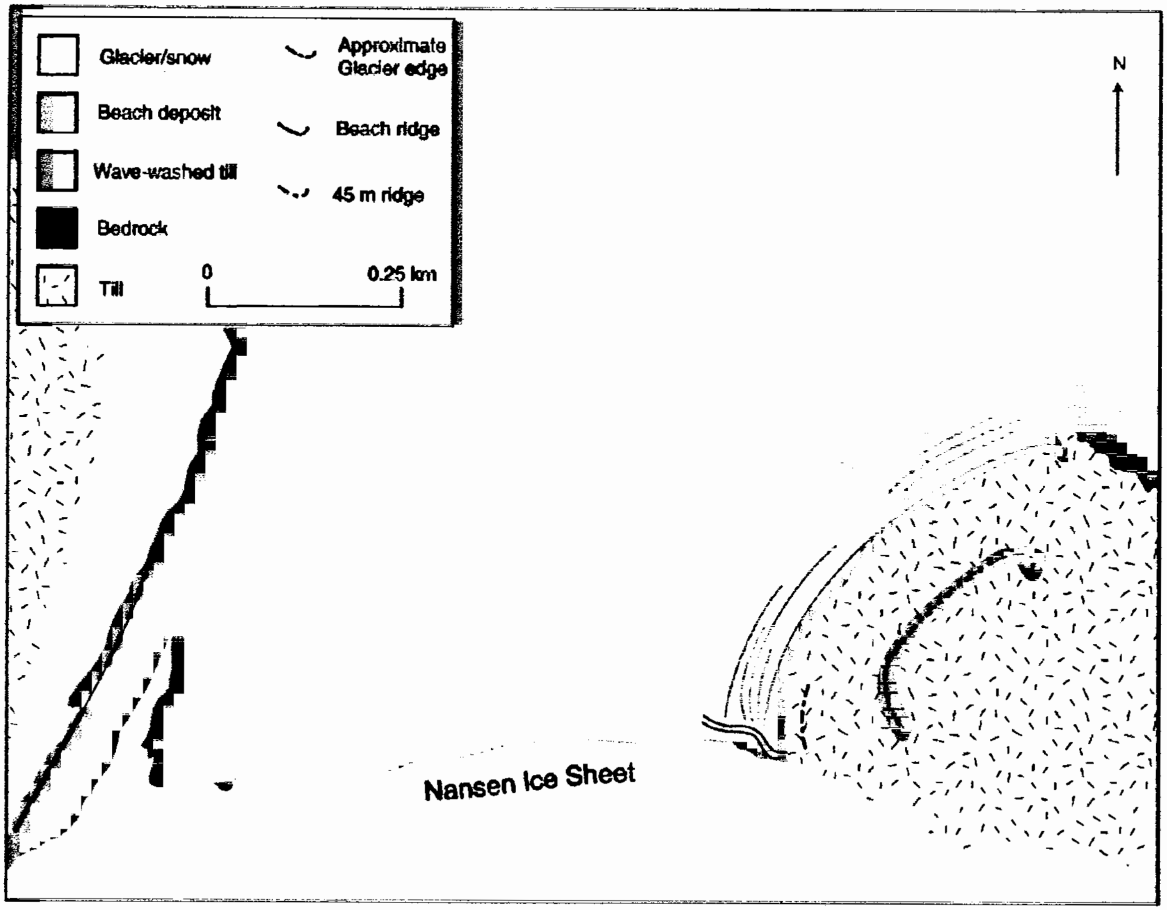

Figure 26. Surficial geologic map of beaches in southwestern South Bay [based on air photo interpretation and ground reconnaissance]. See Figure 22 for location.

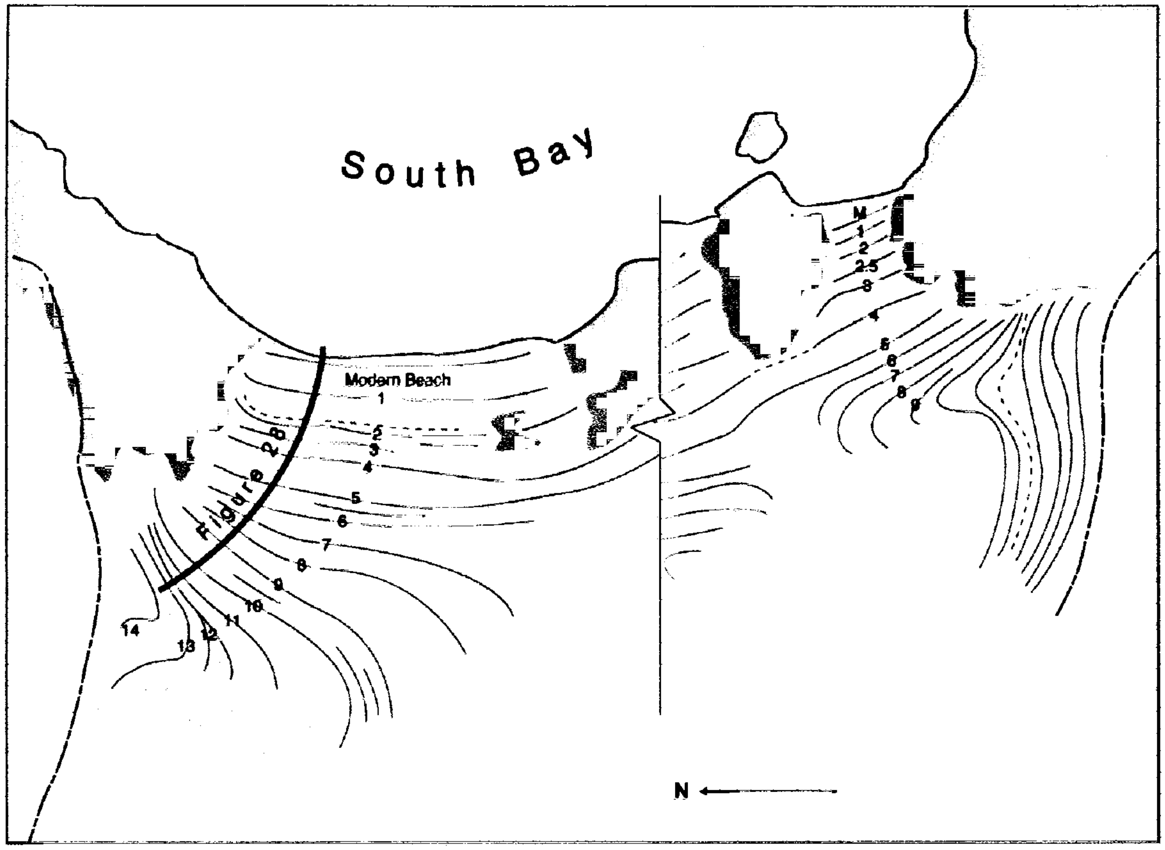

Figure 27. Map of South Bay, showing beach numbering scheme. Note that scale and map symbols are the same as in the surficial geologic map of South Bay (see Figure 24). Heavy black line indicates the location of the profile shown in Figure 28. Original map has been cut to show the northern and southern ends of the bay.

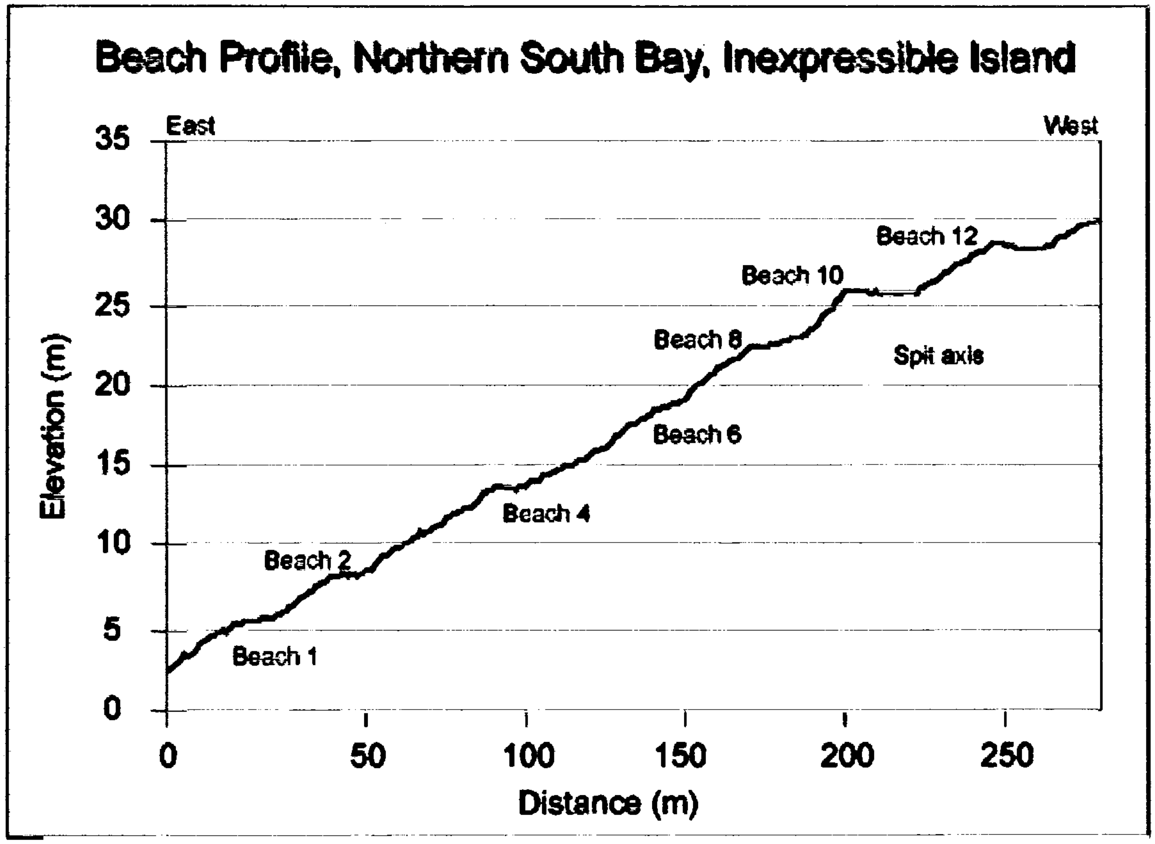

Figure 28. Transect perpendicular to ridge crests on the northern end of South Bay.

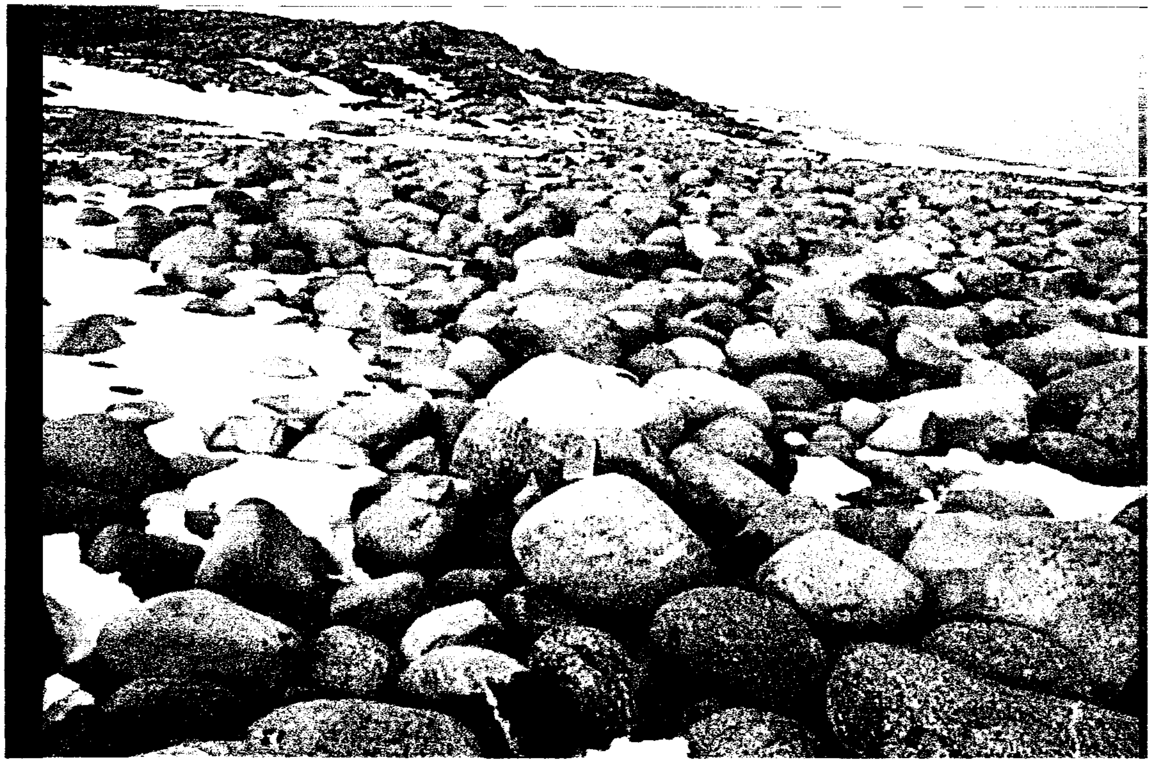

Figure 29. Photograph of beach 4, South Bay, with view to the north. Field book for scale. Ridge is 20 m wide and 1 m high. A wave-washed bedrock headland is seen in the background (January, 2001).

Beaches 9 through 14 extend southward from the steep bluff, which forms the marine limit on the headland, to make up the northern spit. Each consecutively higher beach ridge composing the spit is progressively shorter in length. The largest ridge, beach 10, has a relief of three meters, and the beach-face slope attains angles of 15°. The back side is steep in some places and has slopes ranging from 10° to 36°. As beach 10 curves inland to form the spit, it decreases in elevation and becomes markedly finer-grained. Two channels, with floors two meters below the crest of the beach, cut through this ridge. The ridges above beach 10 are shorter in length, but have the same geometry. All beaches forming the spit intersect the marine limit, here cut into glacial drift. Some ridges bifurcate, and some have small swales behind them.

In the middle of the bay, ridges decrease in relief (as compared to the north and south), and are difficult to recognize in some locations. Beaches 4 and 5 are the only two ridges that are continuous along the length of the bay. Runnel-like features characterize both of these beaches (Figure 30). The runnels are linear and perpendicular to the ridge axis. They consist of depressed boulders in rows that are spaced regularly by rows of boulders that are not as well set in.

There is also an elevated spit at the southern end of the bay, although it is lower in elevation than the northern one. The character of the beach boulders and morphology in the south is significantly different from that to the north. At low elevation, steep beaches that are high in relief occur in pockets between outcrops of disintegrated syenite (Figure 31). Unlike the northern beaches, whose sediment is derived from till, syenite bedrock is the primary southern source of beach sediment.

Above the pocket beaches, the ridges are continuous across the bay (beaches 4 and 5). The southern spit occurs above these two beaches and consists of five small (~1 m relief), nearly concentric ridges. A low, broad (5 m) channel cuts through these small ridges and opens into a fan-like deposit on the back of the spit. The back side of the spit is very steep (25^{o}-28^{o}) and has as much as four meters of relief. A former lagoon below the channel holds an ephemeral pond. At least five ridges (each < 1.5 m in relief) extend upwards from the crest of the southern spit (20 m) to the marine limit scarp (31 m) (Figure 32). These are east-west trending beaches that are parallel to the marine limit.

I also mapped beach deposits in both the northwest and southwest corners of South Bay (Figures 25 and 26). Beaches in the northwest form either small, pebble and cobble terraces or steep boulder terraces. Beach faces composed of gravel are inclined 5^{o}-8^{o}, whereas boulder and cobble beach faces slope 10^{o}-15^{o}. In the southwest corner, a large ridge occurs near the marine limit and is the uppermost in a set of five beaches. There is a shallow swale behind this ridge. A broad (25 m wide), flat, fine-grained beach exists at the bottom of this set, and is cut by a channel on its southern edge. This beach is inclined 1°-2° to the west, and is crossed by numerous frost cracks.

Figure 30. Runnel-like features on beach 5, South Bay, with view towards the east. Field book for scale (January, 2001).

Figure 31. Photograph of heavily weathered syenite outcrop in southern South Bay. View is towards the north. Distance across outcrop from left to right is about five meters (January, 2001).

Figure 32. Aerial photograph of the southern half of South Bay. View is to the south. Distance from left to right across the photograph is about 0.5 km. (Photograph by Brenda Hall, February, 2002)

Sedimentology and Stratigraphy

Most beaches in South Bay lack significant stratification. Beaches parallel to the present-day coastline are clast-supported boulder and cobble deposits with gravel and sand matrix. Southern beaches have a higher fine-grained component than those to the north, although they are also clast-supported. In a few pits, I encountered lenses of coarse sand or faint pebble layers; however, these were rare. In contrast, pits within the northwest gravel beaches reveal stratification in the form of pebble layers 5 to 10 cm thick. Each layer dips in the same fashion as the beach face (5°-8°). The broad pebble-sized beach deposit in the southwest also has stratification. The surface of this beach is a deflation pavement, with only gravel-sized clasts remaining. However, an excavation revealed faintly bedded sand with gravel clasts. These layers dip parallel to the beach face (1^{o}-2^{o} to the west).

Low-elevation beaches along the present-day coast have a larger mean grain size than those at high elevation (Appendix). These low beaches are primarily bi-modal, clast-supported boulder deposits with interstitial sand. Average clast diameters from meter-square plots on the four lowest northern beaches range from 23.5 to 27.1 cm. Most other beaches have average clast diameters that range from 12.3 to 19.4 cm. These numbers, although not significant in a statistical sense (because of limited number of plots), bear out field observations. An excavation in beach 2 revealed that the surficial material is clast-supported with little to no interstitial sand, whereas below the surface the deposit is bimodal with only boulders and sand. Pebbles and cobbles are rare to absent. The southern beaches show trends similar to the northern ones (Figure 33). The average clast diameters range from 21.3 to 31.7 cm for the lowest four beaches, and 10.2 to 26.5 cm for the next five highest beaches.

Distinct sedimentological trends exist on the large-scale geomorphological features. The northern spit fines both distally and landward. It is comprised of a well-mixed marine diamict with no stratification. In comparison, the southern spit also fines landward, but does not fine laterally. Surfaces of the fine-grained sections of the spits are deflation pavements.

The fine-grained fan that extends landward of the southern spit displays stratification. An excavation revealed surface-parallel bedding, although due to permafrost, the pit was only 30 cm deep. Mud occupies the former lagoon behind the spit.

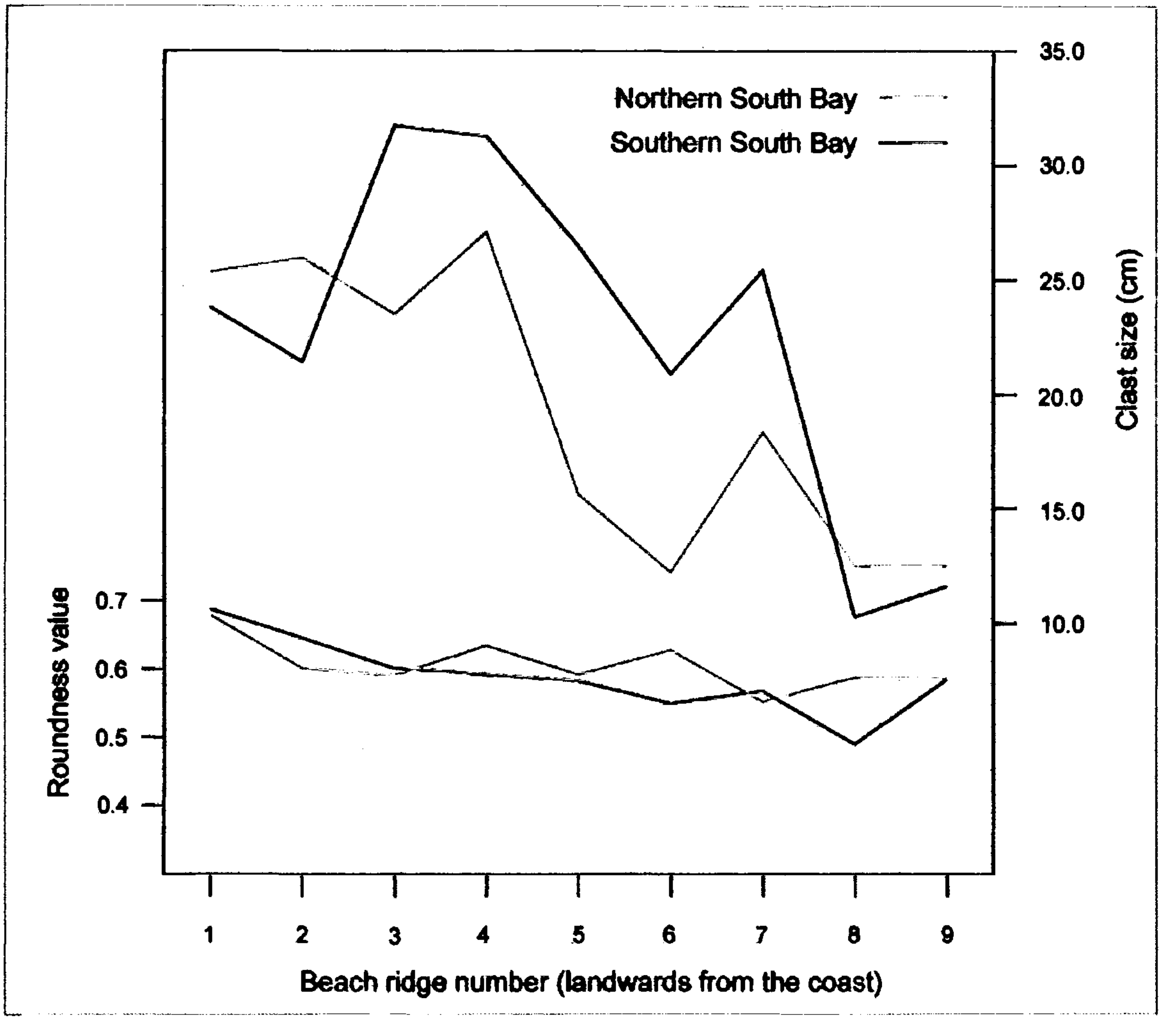

Figure 33. Comparison of clast size and roundness values for beaches in South Bay. Beaches range from 6 to 22 m elevation. See Appendix for source data.

Northern beaches are composed predominantly of boulders ofHell's Gate Granite, whereas syenite of the Granite Harbor Island Intrusives is the main rock type in southern beaches. This seyenite weathers much more quickly than the Hell's Gate Granite. Clasts on the northern beaches are considerably less weathered than those to the south, although at high elevations they are pitted, and in some cases, lightly stained. To the south, finer-grained syenite is stained tan/orange, whereas coarse syenites are weathered and nearly grussified. The syenite bedrock outcrops are more weathered than the boulders on the beaches.

Seaview Bay

Seaview Bay is similar to South Bay in that it encompasses a large inland area that was once covered by seawater. Beaches in this area are steeper, have higher relief, and have a larger average grain size than anywhere else on the island. Along the south side of the bay, a scarp at 30 m elevation clearly separates the marine deposits from the upland till sheets. In the middle of the bay, a high beach marks the marine limit. This beach continues north where it merges into a blockfield. The marine limit is visible in some places at the northern end of the bay, but it is modified by solifluction in other locations. There are as many as 25 beach ridges, although none extends the full length of the bay.

Ridges are largest and most continuous in the southern part of the bay (Figure 34) where they bifurcate and truncate one another. All beaches are at least sub-parallel with the present-day coast (Figure 35). The ridges fade towards the north where the uplifted bay reaches further inland. At the northern extent of the bay, beaches redevelop, but do not attain the same size. Most of the beaches have distinct crests (Figure 36) and are separated by swales, which most likely represent former lagoons. One beach has over two meters of relief, and its corresponding swale is 15 m wide.

Upper-elevation beaches in the middle of the bay are arcuate and parallel with the marine limit. Several of these fine northwards and end in spits. The uppermost beach in the center of the bay is made up of pebbles and cobbles and is modified strongly by ice processes, including frost cracks and ice melt-out pits (0.3 m depth, 3 m diameter) (Figure 37). The lowest beach and another small ridge in the center of the cove are arcuate, but curve in a direction opposite to that of other ridges (Figure 35). The lowest beach holds a modern lagoon, whereas the higher ridge retains a large ephemeral pond.

A south-facing slope on the northern headland contains a flight of over 20 small ridges (0.5 to 1 m relief). The upper-elevation beaches of this series form a spit that progrades southwest (Figure 38). This spit acts as a barrier to a muddy lagoonal area farther inland. The lowest elevation beaches on the northern headland are low, wide, and sandy, whereas the upper beaches have very large boulders (>70 cm diameter).

Figure 34. Aerial view (looking south) of southern Seaview Bay. The marine limit at the very southern end of the area is enhanced by a snow patch. The marine limit towards the lower right of the photo is the highest beach, which merges with till. A large, active Adélie penguin rookery occurs along the coast. The largest clasts in this picture are boulders at least six meters in diameter. The ponds in the left of the photograph are modern and recent lagoons (January, 2002).

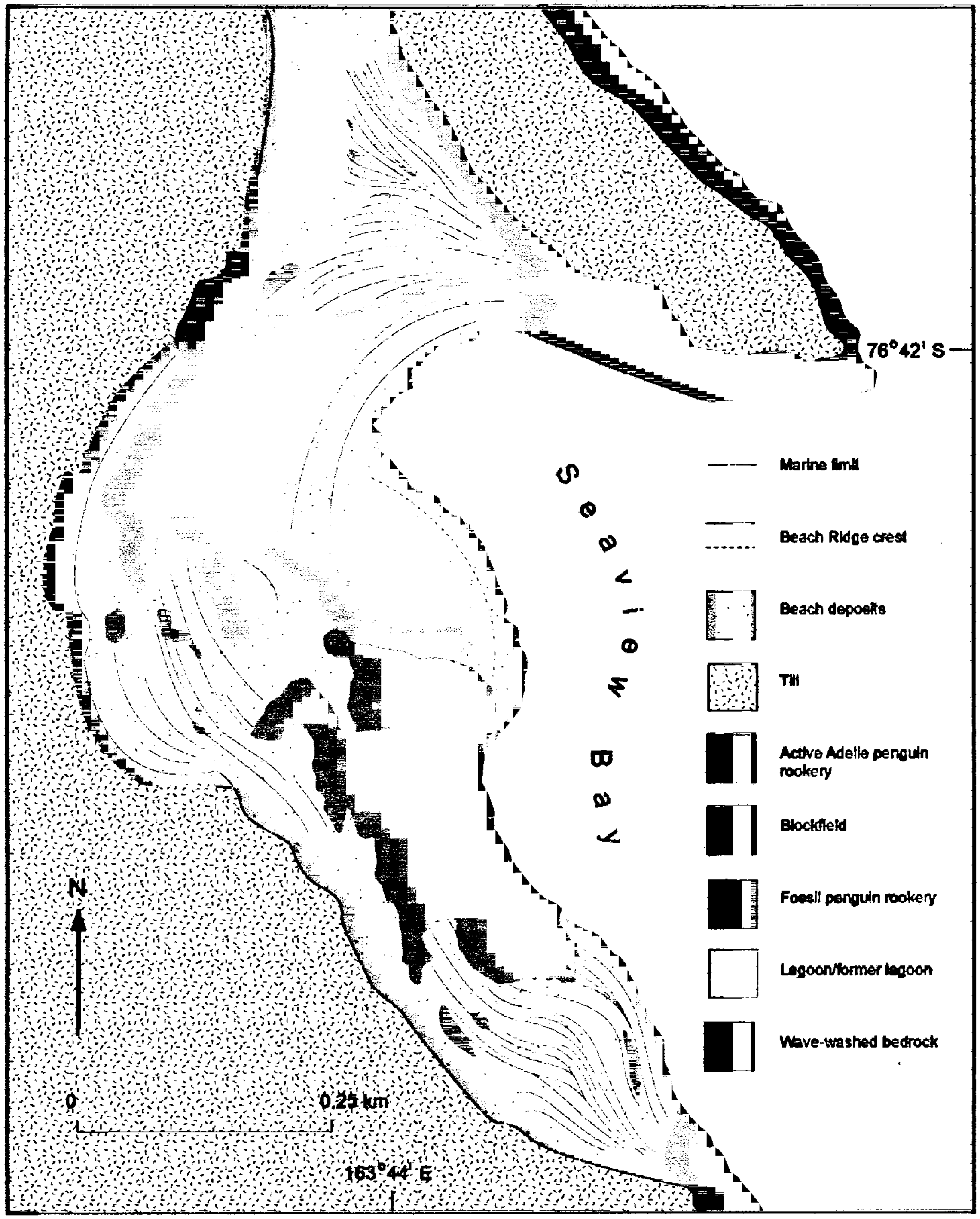

Figure 35. Surficial geologic map of Seaview Bay [based on air photo interpretation and ground reconnaissance]. See Figure 22 for location.

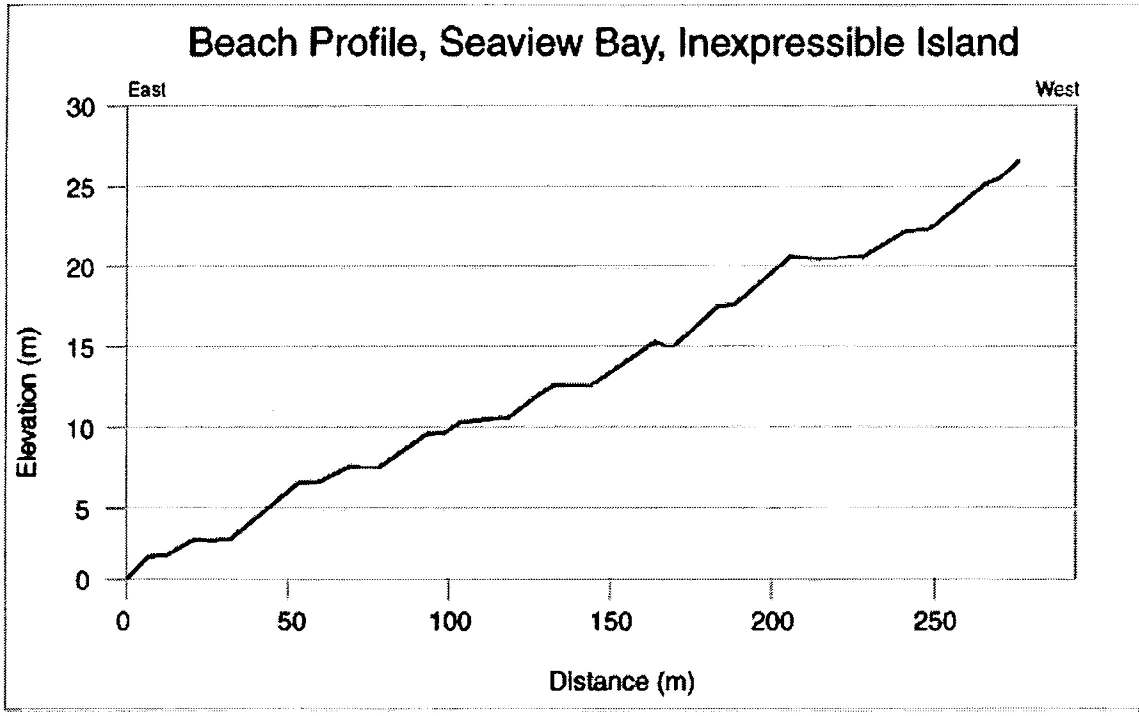

Figure 36. Profile perpendicular to raised beach crests in Seaview Bay. Redrawn from Baroni and Orombelli (1991).

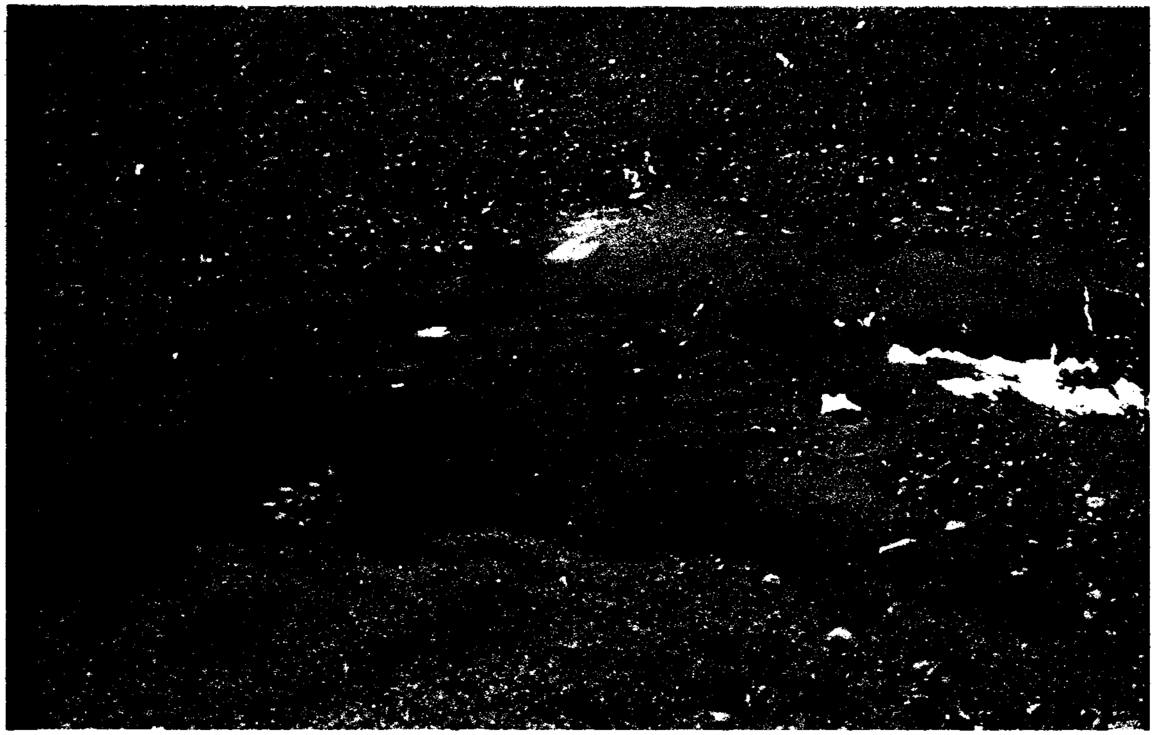

Figure 37. Aerial photograph of the highest elevation beach in Seaview Bay. View is to the west. Note the frost cracks and ice melt-out pits. The crest of the beach at this location is the marine limit, and the sediment to the west of the beach is till. Distance across photograph is 120 m (January, 2002).

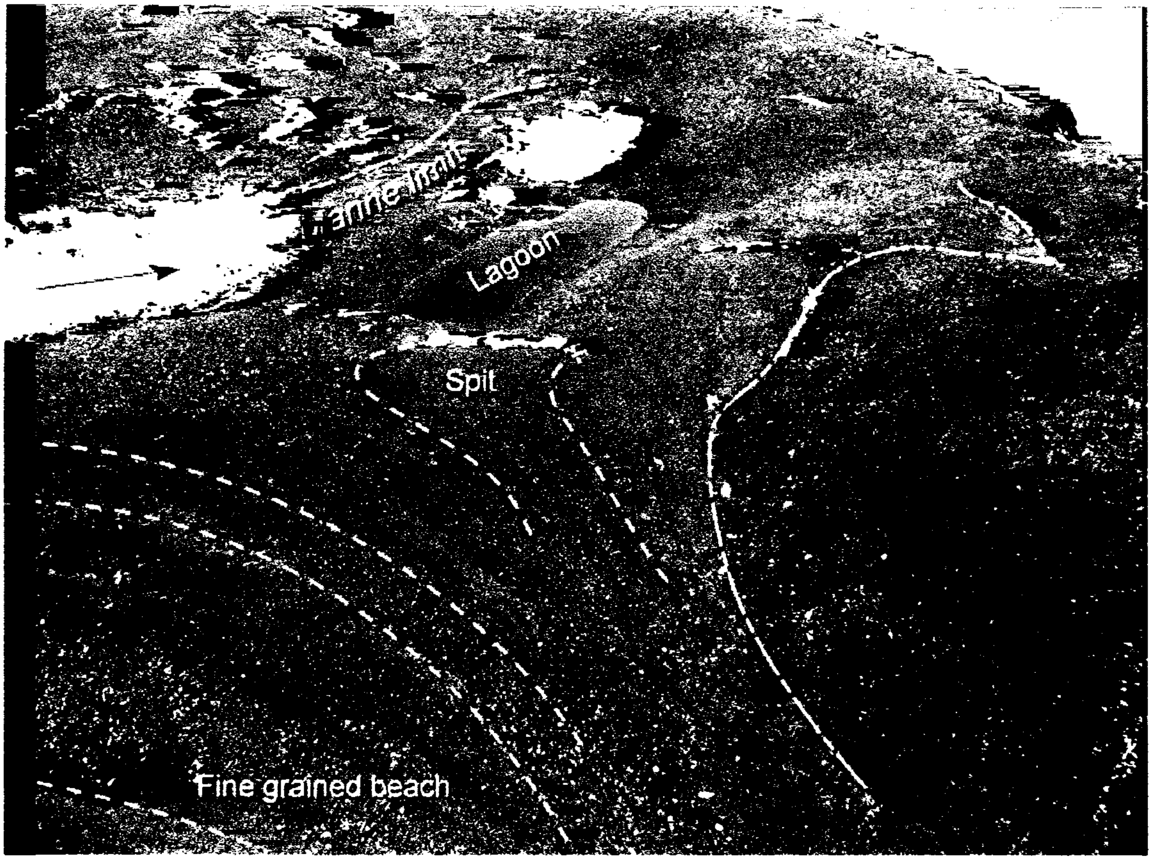

Figure 38. Photograph of spit and pocket beach complex in northern Seaview Bay. View is to the northwest. Dashed lines indicate beach crests. Note that not all beaches are marked to sustain the clarity of the original photograph (refer to the northernmost region of Figure 35). The marine limit fades into till towards the top of the photograph. The pond occupying the former lagoon is approximately 70 m wide (Photograph by Brenda Hall, February, 2002).

Smaller Bays

The cove south of South Bay displays beach ridges that are different from those anywhere else on the island. Several parallel ridges are straight with little curvature. Others, such as the highest beach, are arcuate and shore-parallel. Several beaches are discontinuous ($\leq$100 m long), and most do not extend the entire length of the cove. Where ridges are absent, there is little-to-no surficial material. Between beach ridges, cobbles and boulders are rare and rest on bedrock.

The largest and highest beach has two meters of relief and forms the marine limit (30 m elevation) in the center of the bay. Towards the northern headland, the beach fades out and the marine limit is marked by a sharp contact between wave-washed, grussified granite and the upland till plain. The marine limit rises slightly towards the headland. On the southern headland, four small ($\leq$ 0.5 m relief) ridges form an elevated tombolo complex. This tombolo connects the mainland to a peninsula of wave-washed bedrock. This small peninsula has several minor chasms, but none contains beach material.

Beaches are composed of boulder- and cobble-sized material, have steep crests, and are generally about a meter or less high. The clasts are rounded and most are pitted and stained. In some cases, a beach 'ridge' is composed only of a barricade one boulder high and one-to-two boulders wide (Figure 39). These boulder lines are at most 30 m long, are straight, and directly overlie heavily weathered bedrock. A similar beach exists in southwestern South Bay (Figure 40).

The southernmost bay on Inexpressible Island is covered with ice and snow, but displays some small, discontinuous beach ridges (Figure 41). These ridges are more similar to those in the next bay to the north, than to those in South or Seaview Bays. However, they seem to be composed of a wide range of grain-sizes, and clasts are rounded. Lengths and true heights of ridges are unknown due to snow cover.

Figure 39. Boulder 'beach' in the bay south of South Bay. Note absence of beach material on either side of the ridge. One meter-tall shovel for scale (January, 2002).

Figure 40. Boulder 'beach' in southwestern South Bay. One meter-tall shovel for scale. Photograph by Brenda Hall, January, 2002.

Hell's Gate

Raised-beach ridges occur parallel to the present coastline for almost three kilometers on the northern end of Inexpressible Island (Figure 42). This coastline is now adjacent to Hell's Gate Ice Shelf and hence lacks open water. There is no modern storm beach. Beaches range from three to thirty meters in elevation. Ridges are generally steep, reflecting underlying bedrock topography. Beaches are high (~2 m relief) and are made up primarily of cobbles and boulders, which range from poorly to well-rounded. The sediments fine towards the northwest.

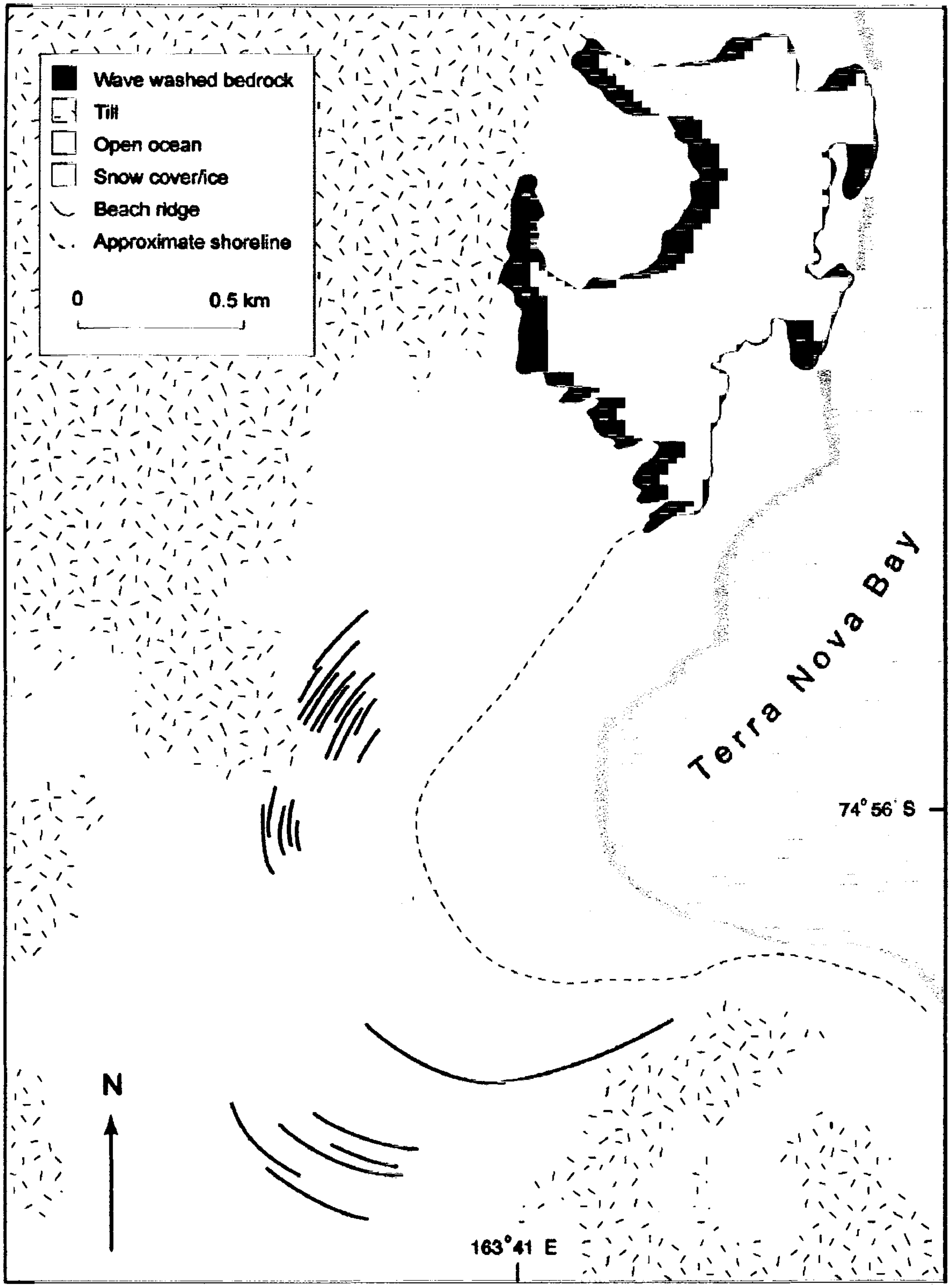

Figure 41. Surficial geologic map of the southernmost bay on Inexpressible Island [based on air photo interpretation and ground reconnaissance].

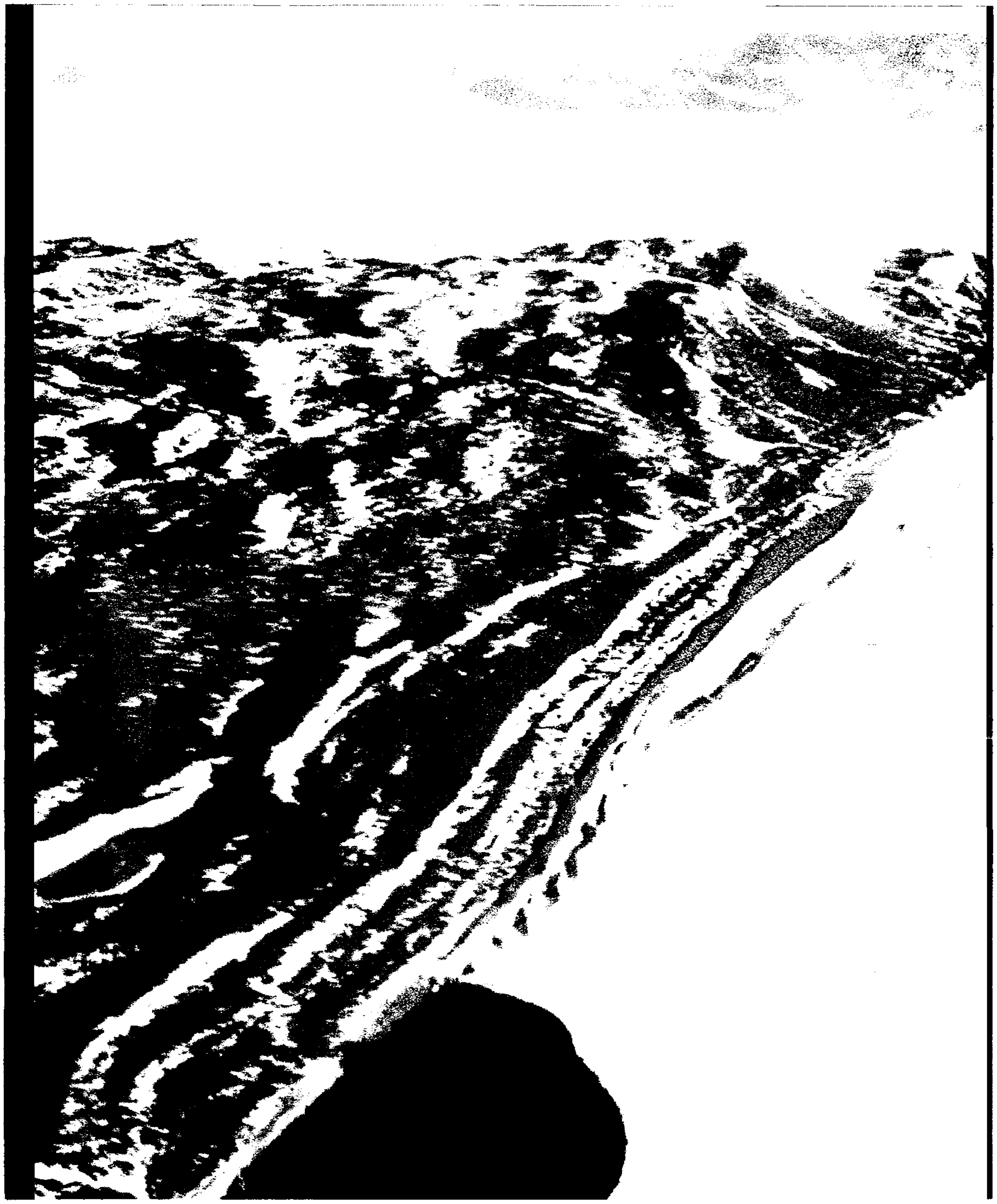

Figure 42. Aerial photograph of the coastline adjacent to Hell's Gate. View is to the west. Beaches extend for approximately three kilometers.

Radiocarbon Samples

Seventeen new radiocarbon dates come from organic remains recovered at Inexpressible Island (Table 2). Datable material consisted mainly of elephant seal skin and hair from carcasses (Figure 43) or found under large boulders (30-100 cm) set into the beach crests. As elephant seals are known to disturb beach surfaces, I conservatively interpret these dates as minimum for the beach deposits. One deeper sample (45 cm depth) from Seaview Bay, AA-42242 (6740 $\pm$ 59), is believed to date the beach.

A single whole shell from 30 cm depth on beach 10 (25 m elevation) dates to 46,000 $\pm$ 2600 ^{14}C yr B.P. This shell was weathered and possibly was reworked. Two shells, from the 3 m and 8 m beaches at Hell's Gate, found under boulders resting on the surface afford minimum ages for the deposit. The top beach at Hell's Gate also produced several samples of *Nacella*, which are not yet dated (Table 2).

Samples from the Antarctic coast need to be corrected for a marine reservoir effect because of upwelling of old water. The best estimate of the marine reservoir effect is 1,300 years based on dates of pre-bomb samples of known age (Berkman and Forman, 1996). This value, however, may be variable through time or by species. The radiocarbon ages presented in this thesis are not corrected for the marine reservoir effect.

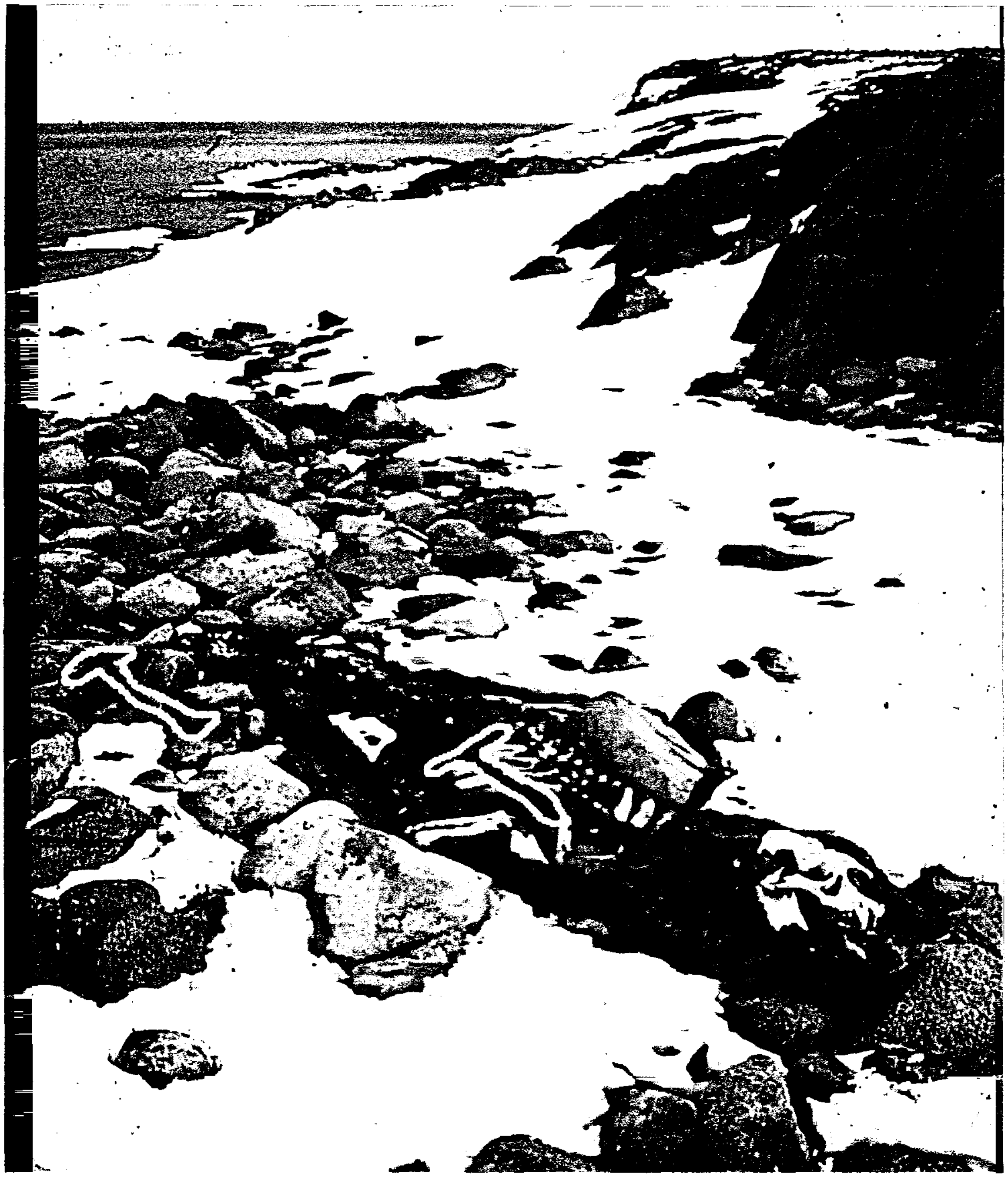

Figure 43. Elephant seal carcass found on a pocket beach in South Bay. Beach elevation is eight meters above sea level. Mummified carcass is approximately four meters in length (pick and shovel outlined for scale).

Table 2. Radiocarbon dates of samples recovered from Inexpressible Island. Dates have been adjusted for $\delta^{13}C$ variations, but are otherwise uncorrected.

Laboratory number #	^{14}C yr BP (uncorrected)	$\delta^{13}C$	Elevation (m)	Location	Description and significance
AA - 42223	3190 ± 48	- 21.4	15 ± 1	South Bay	Seal skin, minimum age
AA - 42224	3459 ± 46	- 20.3	17 ± 1		Seal skin, minimum age
AA - 42225	2089 ± 43	- 21.4	19 ± 1		Seal skin, minimum age
AA - 42226	3120 ± 48	- 22.3	24 ± 1		Seal skin, minimum age
AA - 42231	4874 ± 83	- 22.7	27 ± 1		Seal skin, minimum age
AA - 42232	2520 ± 71	- 28.9	4 ± 1		Seal skin, minimum age
AA - 42233	2354 ± 51	- 24.1	8 ± 1		Seal skin, minimum age
AA - 42234	2269 ± 37	- 24.2	11 ± 1		Seal skin, minimum age
AA - 42235	2847 ± 43	- 22.2	14 ± 1		Seal skin, minimum age
AA - 42236	2174 ± 50	- 23.8	14 ± 1		Seal skin, minimum age
AA - 42237	2083 ± 51	- 21.7	15 ± 1		Seal skin, minimum age
AA - 42238	5722 ± 56	- 22.2	~24 ± 1		Seal skin, minimum age
AA - 42221	46,000 ± 2600	1.1	25 ± 1		Whole *Nacellidae*, dates beach
AA - 42241	5139 ± 68	- 21.4	30 ± 1	Seaview Bay	Seal skin, minimum age
AA - 42242	6740 ± 59	- 22.4	24 ± 1		Seal skin, dates beach
AA - 42227	1503 ± 52	1.2	3 ± 1	Hell's Gate	Shell fragments, probably *Laternula*, minimum age
AA - 42228	1957 ±46	3.3	8 ± 1		Shell fragments, probably *Laternula*, minimum age

Depot Island

The peninsula to the west of Depot Island is a high bedrock headland tied to the mainland by beach deposits and bedrock outcrops (Figure 44). Beach terraces prograde westward from the marine limit (34 m elevation) on the headland (Figure 45). The lowest few beaches form a tombolo that extends to the mainland. The terraces are as much as three meters high with faces inclined as much as 28°. Surface clasts range from 6 to 57 cm in diameter (average of 20 cm), and have a roundness of 0.3 to 0.8 (average of 0.5). Boulders on upper-elevation beaches are intensely weathered; they are pitted and stained orange. Creep has modified some beaches, as indicated by rotated boulders on the front slope of several ridges. Felsenmeer and cavernously weathered rocks occur above the marine limit.

An excavation in a 25 m-elevation beach shows clast-supported boulders (in some cases > 100 cm diameter) overlying a matrix-supported unit. The contact occurs at approximately 70 cm depth. This lower unit fines upward and consists of gravel and large boulders. The upper unit is stained, and the top 30 cm is modified by frost action (Hall, personal communication, 2002). In another excavation at 20 m elevation the beach consists of gray medium-to-coarse sand with boulders. This unit displays orange staining and weathering to 70 cm depth.

Some small pocket beaches occur in chasms on the eastern coast of the peninsula. These deposits are finer grained than the terrace beaches on the western side. Ancient penguin rookeries are developed on several of the crests, as well as on top of the peninsula.

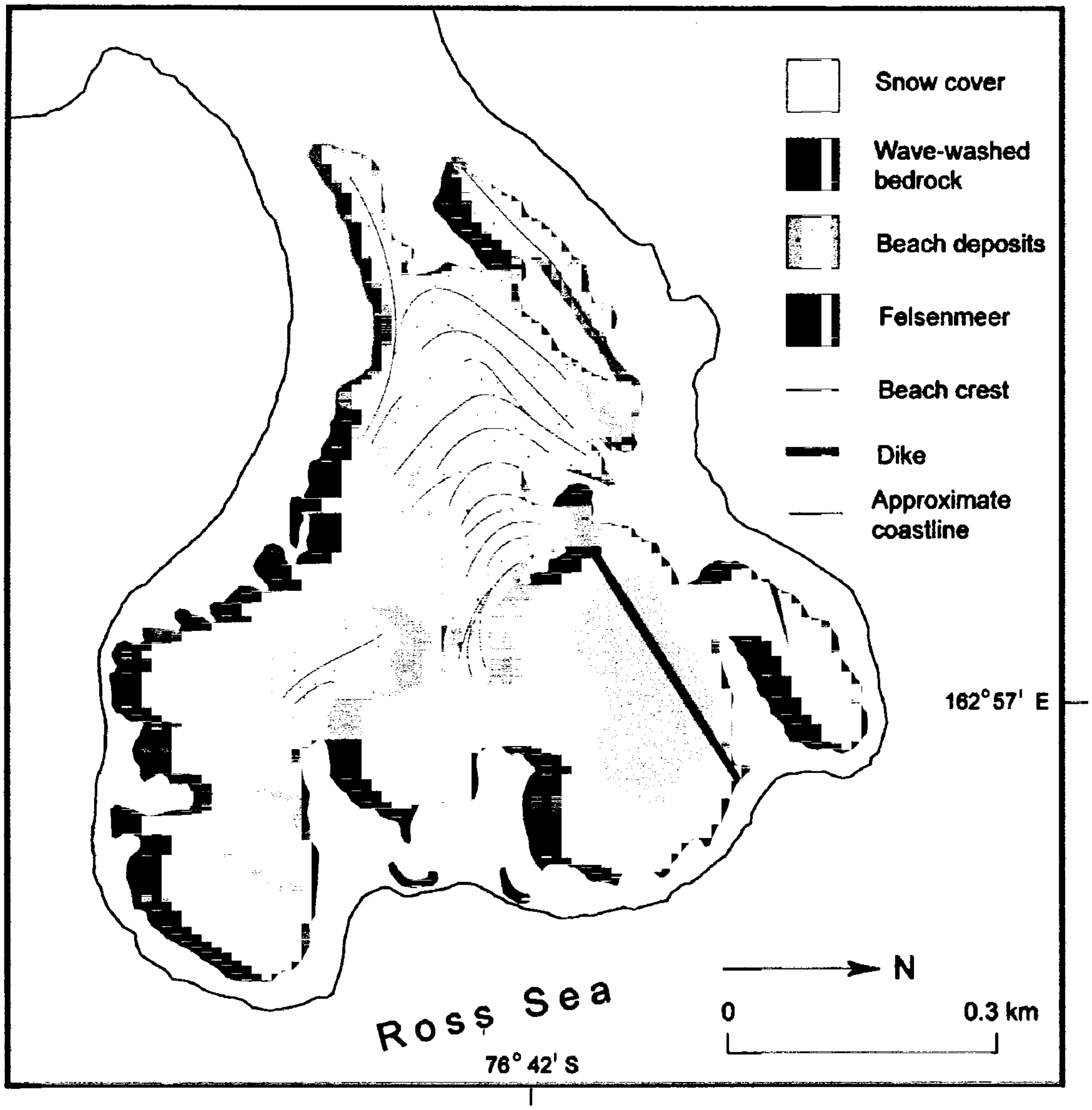

Figure 44. Surficial geologic map of the peninsula near Depot Island [based on air photo interpretation and ground reconnaissance].

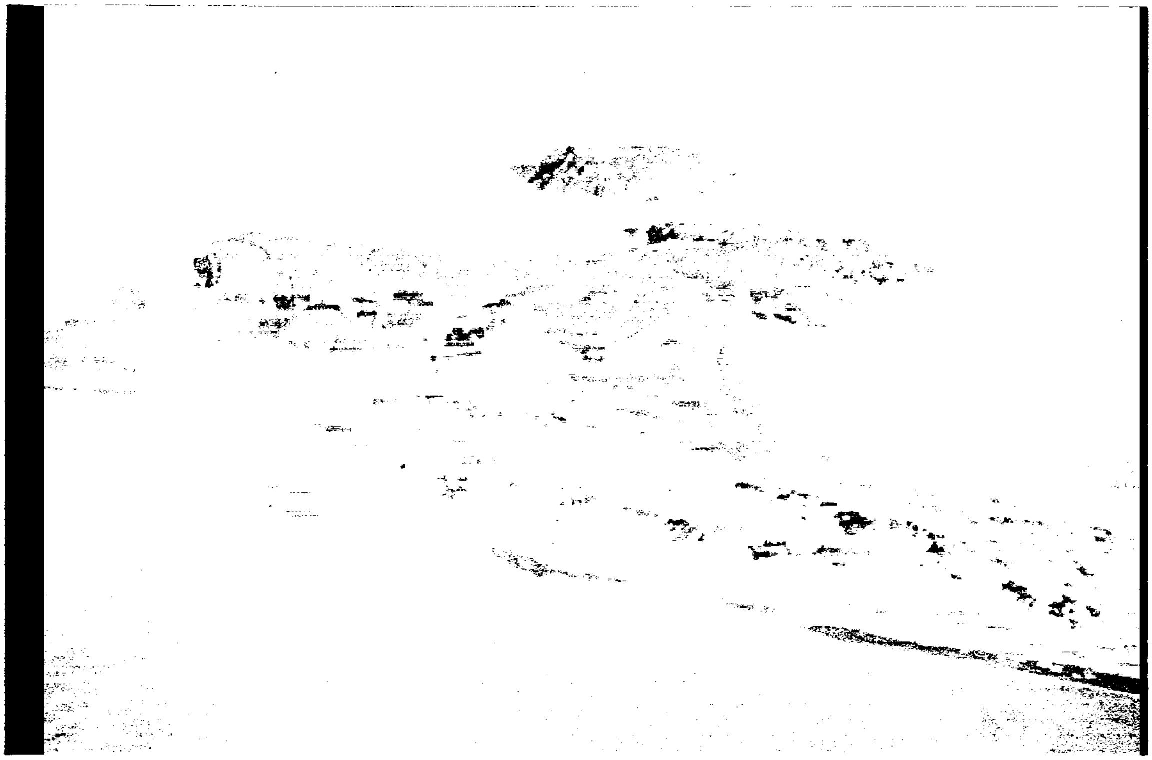

Figure 45. View east towards Depot Island (background) and adjacent peninsula. Beach deposits prograde west from the headland on the peninsula towards the mainland. Scale is approximately one kilometer from left to right across the photograph (January, 2001).

DISCUSSION

Beach Formation

The formation of polar beaches has been investigated primarily in the Arctic (Taylor and McCann, 1983; Forbes and Taylor, 1994; Forbes et al., 1995). Similar studies come from North American cold-climate coastlines, such as the Great Lakes and St. Lawrence Estuary (Dionne and Laverdiere, 1972; Marsh et al., 1973). In contrast, Antarctic coastal processes have received little scientific investigation. There are only a few studies on beach development and morphology in the Antarctic (Nichols, 1953, 1961a, b, 1968; Butler, 1999, 2001), and these have concentrated in the McMurdo Sound region.

Ice and waves are the two primary means by which beaches are created and modified in polar regions. Taylor and McCann (1983) categorized ice processes as direct and indirect. Direct processes include ice rafting, push, scour, and melt. Buckling of ice pressure ridges causes erosion and sediment transport (Hume and Schalk, 1964), as does movement of free-floating sea ice. Ice-push ridges near Barrow, Alaska are several meters high and hundreds of meters long (Hume and Shalk, 1964), whereas those on Somerset Island (Canada) are typically only a meter high (Taylor, 1978). Some ice-cored ridges can be as much as seven meters high and have melt pits or a hummocky nature (Hume and Shalk, 1964; Owens and McCann, 1970; Taylor, 1978). Ice-push ridges on sandy lakeshores are generally hummocky and asymmetrical in cross section (landward slope steeper). They may also display features such as ice-contact cusps and shore-ice kettles (Dionne and Laverdiere, 1972).

Sea ice indirectly affects beach formation by dampening wave energy. The reduction of wave energy in pack ice is exponential, with an attenuation coefficient that increases as periods decrease (Squire and Moore, 1980). Thus, sea-ice cover influences the amount of energy (especially every-day wave energy) reaching the coast, thereby decreasing the overall capacity for sediment transport. In general, longshore transport rates on polar coasts are lower than those on temperate coasts (Taylor and McCann, 1983). Sea ice and land-fast ice inhibit movement of shoreline sediments, therefore limiting longshore movement to periods during large storms (McCann, 1980). Permafrost also indirectly affects beaches by limiting sediment mobility (Taylor and McCann, 1983).

Based on this previous work, one would expect ice-push beaches to be generally sharp-crested and discontinuous. This is likely due to the irregularity of the ice-pressure ridge. The ridge may be hummocky and pitted. The deposit that makes up the beach is poorly sorted and lateral fining along the ridge is usually absent. Beach cobbles are only poorly or slightly rounded, because they are not exposed to intense and prolonged wave action.

In contrast, beaches formed by wave action should be less sharp, wider and more continuous than ice-push beaches. They can contain rounded to well-rounded clasts. In some cases, the sediments fine laterally from the most exposed segments of a beach to the more protected areas. Evidence of longshore transport in the form of spits and tombolos also is present (Nichols, 1961b).

Oak (1984, page 80) cites six characteristics of wave-formed boulder beaches:

1. *Landward fining of sediments* [due to change in the competency of a wave]
2. *Abundant particle breakage*
3. *Positive skewness of the grain-size distribution*
4. *Absence of shape zoning*
5. *Absence of sphericity grading*
6. *Low foreshore slopes* [7-10^{o}]

The lack of shape zoning also could be a characteristic of ice-push beaches, however, the landward fining of sediments is an important characteristic of wave-formed beaches. Because wave energy decreases inland, larger clasts are deposited closest to the sea.

I differentiate two wave-classification regimes: fair-weather and storm. The two may be distinguishable on the basis of clast size, because storm beaches generally contain larger material than fair-weather deposits (assuming that the sediment supply is not limited). In addition, there should be stratigraphic differences between the two types of beaches. Fair-weather beaches generally develop bedding in the form of lag deposits, which are then buried. In contrast, beaches produced during single storm events likely would contain a mass of unsorted, clast-supported material, perhaps with fine sediment settling into pore spaces.

Few studies directly address the issue of beach formation in the Ross Embayment. Nichols (1961a, b, 1968) characterized beaches in the McMurdo Sound area and suggested that ice is an important factor in their formation. He listed thirteen characteristics of polar beaches, seven of them directly related to ice* (Nichols, 1961b, pg. 103):

1. *They rest on ice*
2. *They are pitted* [because of melting ice blocks]
3. *They have ridges or mounds which were formed because of ice push and/or deposition from stranded ice*
4. *They have ridges which terminate abruptly because* [glacial] *ice was* [more extensive than at] *present when they were formed*
5. *Ice rafted fragments are found on them*
6. *They are associated with striations formed by sea ice and icebergs*
7. *The beaches can be associated with ice-contact features (pro-glacial deltas) and glaciomarine deposits*

*Only 3 and 6 relate directly to *ice push*; a storm beach can be formed on top of ice.

Nichols (1961b) noted that ice-push beaches are hummocky and are associated with erosional scars.

Despite the presence of land-fast ice today, wave-formed features have been identified in the McMurdo Sound region (Nichols, 1961a, 1961b, 1968; Butler, 1999, 2001; Hall and Denton, 1999). For example, Spike Cape consists of two elevated paleo-islands connected to each other and to the mainland by tombolos. A coarse-grained spit, indicative of longshore transport, exists within two meters of sea level in an adjacent cove. Other locations along the southern Scott Coast also show evidence of wave action, such as continuous, arcuate beach ridges, wave-washed bedrock surfaces, and deposits of rounded clasts. Butler (1999) concluded that the deposits are the result of storms, but unless large storms remove almost all of the sea ice from the area, it is not possible to form a tombolo or spit under present-day conditions.

Some sites in the McMurdo Sound region also show evidence of ice-dominated processes. Citing many examples of pitted beaches and ridges formed on ice, Nichols (1961a) suggested the presence, at least at times, of a fast-ice environment similar to that of the present day. Butler (1999) indicated that modern beaches form by a combination of waves and ice, depending on the direction of exposure.

The processes of ice push and wave deposition involve different environmental conditions. Ice-push ridges require either a high density of sea ice or fast ice. On the other hand, for wave deposits to form, sea ice must break out during storms. Fair-weather beach deposits would require nearly constant open water for an extended period during the summer.

The northern Scott Coast (the subject of this study) differs from the McMurdo Sound area in that it now displays large areas of permanent land-fast ice and perennially open water. For example, Terra Nova Bay, at the northern end of the field area, is a polynya, and waves reach the coast. Cape Ross, on the other hand, is annually locked in fast ice, and little, if any, wave energy reaches the shore.

Cape Ross

Present-day fast-ice conditions at Cape Ross suggest that the dominant beach-forming process should be ice push. However, field observations unequivocally show that nearly every beach at Cape Ross is wave-formed. First, longshore processes are evident in the geometry and morphology of the beach ridges. Beaches are arcuate, continuous, parallel to the coastline, and occur between bedrock headlands. Ridges on the north- and south-facing coasts of Cape Ross are pocket beaches, a type commonly found in wave-dominated climates (Summerfield, 1991) (Table 3).

Table 3. Features associated with different beach-formation processes.

	Ice Push	***Storm waves***	***Fair-weather waves***
Beach morphology	Sharp-crested, discontinuous ridge, non-arcuate	Broad or sharp-crested, continuous, arcuate, large cusps and overwash possible	Broad or sharp-crested, continuous, arcuate, cusps possible
Sedimentology	Poor to well-rounded clasts, poorly sorted	Moderately rounded clasts, poorly to well-sorted, large (boulder-sized) clasts; in some cases a bimodal distribution	Well-rounded clasts, well-sorted, generally small clasts (pebble, gravel)
Stratigraphy	None	None or multiple storm units; lenses possible; fining upwards	Lag deposits possible
Misc. Features	Scour pits, striations, melt pits/kettles	Low percentage of fine material possible, longshore drift features (spits, tombolos, etc…)	Longshore transport features (spits, tombolos, etc…)

The raised terraces and tombolo on Cape Ross are further examples of geomorphic features attributed to wave energy. Tombolos are created by convergence of wave energy on the lee side of an island that is close to the mainland (Farquhar, 1967). Once the tombolo at Cape Ross became well established and raised above sea level, pocket beaches began to form on its flanks.

Other features indicative of wave action include channels and overwash fans. There are several channels on Cape Ross, such as those cutting through the lowest beach on the north side. These probably represent breaching of the beach barrier by water from a lagoon. Another channel cuts through the highest beach and leads inland to a hummocky, fan-shaped deposit that projects into a former back-barrier lagoon. The hummocky deposit probably is beach material from the ridge that was reworked into a breach deposit. Farther south along the same beach, small lobes of landward-extending beach material most likely represent washover deposits.

The sedimentology of the beach ridges also favors a wave origin. Sediments comprising the pocket beaches fine laterally, indicating a decrease in wave energy towards the east, where the shore was more sheltered by the bedrock cliffs. Moreover, clasts on the beaches are moderately well rounded with average values ranging from 0.4-0.5 (Appendix). Sand-sized sediment below the weathering horizon is clean and sorted. Smaller grain sizes appear to be winnowed from the deposit. All of these factors suggest that waves—not ice—formed the beaches.

All bedrock surfaces below at least eight meters elevation are smoothed and rounded. Above eight meters, the bedrock is smooth, but pitted and more weathered than the bedrock below. Although sea ice can abrade bedrock surfaces, this abrasion generally results in striations. Such striations are present farther south at Spike Cape (Hall, personal communication) but are absent at Cape Ross. Moreover, at Cape Ross all parts of the bedrock are smooth, even in hollows and on lee faces. Thus, I believe that the bedrock was smoothed by sediment-laden waves instead of by sea ice.

Because of the beach geometry, morphology, and sedimentology, I conclude that the deposits at Cape Ross are all wave-formed. At the highstand, Cape Ross would have been a shoal, with only a ring of beach material and some bedrock exposed. As relative sea level dropped, longshore processes formed terraces aggrading towards the mainland as waves refracted around the shoal (Figure 44). A tombolo formed once sea level was at a position where shallow refracting waves met on either side of the island (Cape Ross). As sea level dropped farther, the pocket beaches formed below the tombolo in the saddle between the plateau and the mainland.

A contact exists at $\geq$ 50 cm depth in the beach deposits at Cape Ross. The material above the contact has the same relative percentage of each clast size as the lower unit. However, more sand and smaller grains can be found in the matrix of the upper layer—presumably due to mechanical weathering of surface clasts and infiltration of wind-blown particles—than can be found in the lower layer. The coarse sand matrix below the contact is unconsolidated, clean, well-sorted, and unstained. There are not any particles smaller than coarse sand. In contrast, the top unit is coherent and contains poorly sorted silty sand. In addition, the clasts are stained and fractured. Therefore, I conclude that the upper unit found in Cape Ross excavations is a weathering horizon. Other than this weathering horizon, beaches at Cape Ross do not display any stratigraphic units.

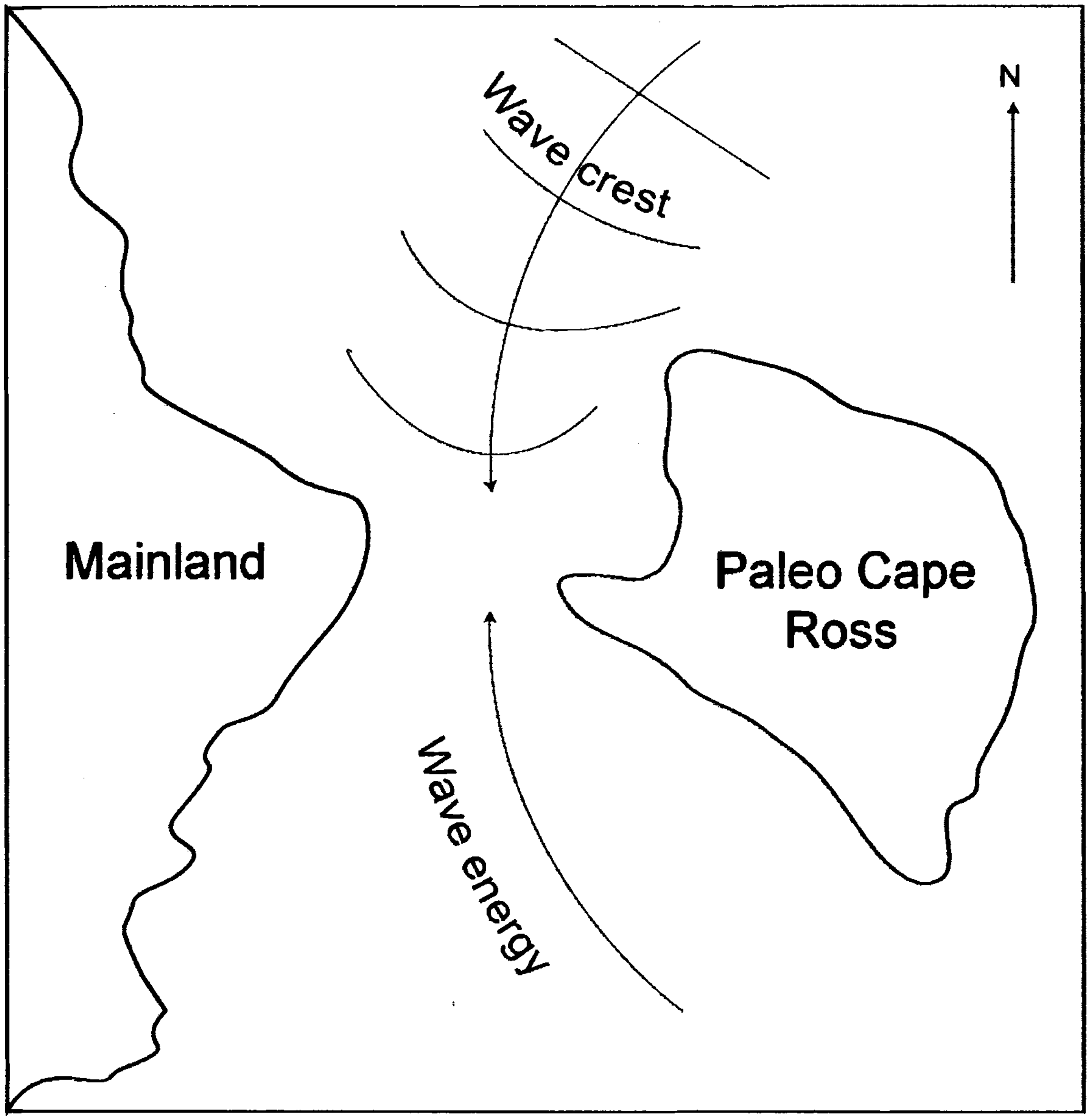

Figure 46. Diagram of Cape Ross just after the highstand in the early Holocene. Wave energy from the northeast refracts around the shoal/island and converges behind, creating a tombolo.

The lack of stratigraphy and the large mean clast size (8.4-16.5 cm average diameter; 99 cm diameter maximum size) (Appendix) indicates that fair-weather processes did not form the beaches. Rather, the beaches were created during storms. Furthermore, both the lack of stratigraphy and the morphology suggest that each beach at

Cape Ross is a single-event deposit. One would expect to find several layers within the pits if these were multiple-storm accumulations. In such a case, a typical layer would most likely be in the form of a boulder lag deposit, overlain by a fining upwards sequence. This might result from the deposition of progressively finer clasts as storm energy wanes. Multiple storms might also produce superimposed ridges. There are no such features at Cape Ross, and therefore the evidence favors single-storm deposits. The small beaches that are between, and in some cases seem to be superimposed on the larger beaches are likely to be deposits from lower-intensity storms.

A beach close to sea level in the chasm on the mainland adjacent to Cape Ross is an exception to the hypothesis that all beaches were formed by waves. This ridge is discontinuous and sharp in profile (Figure 47). Moreover, it is poorly sorted and composed of the entire range of clast sizes from fine sand to boulders. These features suggest that it was produced by ice push. Other beaches in the chasm, however, exhibit features of the wave-forming processes, including well-rounded and well-sorted clasts (one ridge is clast supported with no interstitial material to the depth of permafrost—about 30 cm), and continuous crests extending the width of the chasm.

The hypothesis that most beaches at Cape Ross were wave-formed has several implications. First, large storms must have eradicated any sea ice present along the coast before the beaches began to form. Such large storms could erase any evidence of recent ice-push features. Another possibility is that it was warmer than present when the beaches formed, and sea ice around Cape Ross was less extensive than it is today, or even non-existent.

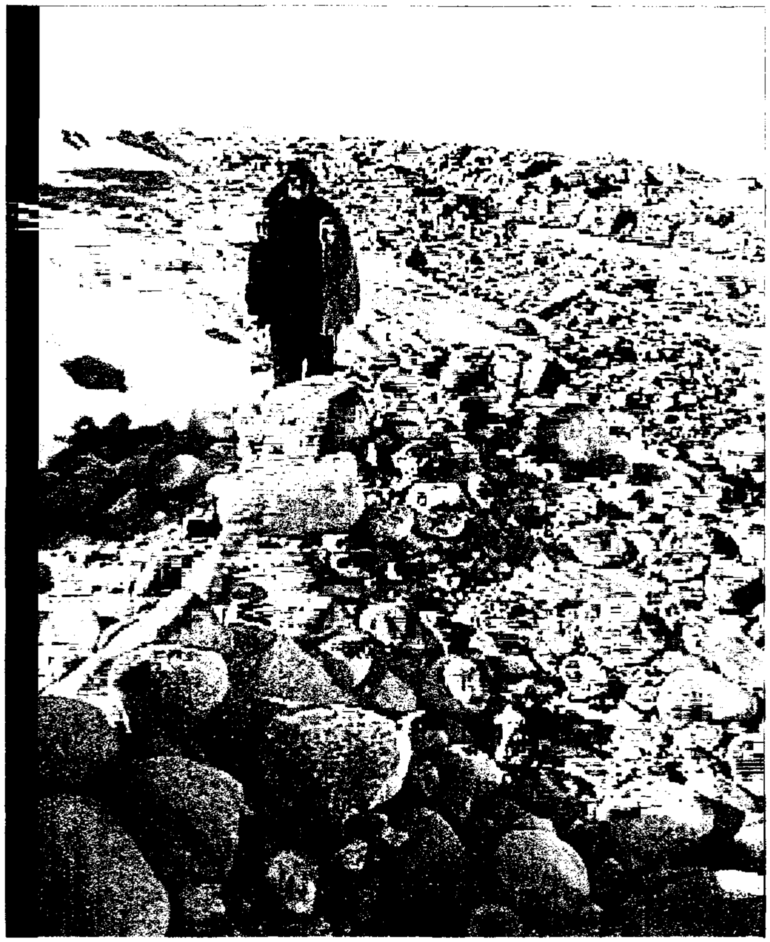

Figure 47. Ice-push beach ridge in the chasm on the mainland near Cape Ross. Person is 1.8 m tall. Ridge occurs at 6 m elevation. Note the sharp crest, poorly-sorted nature of the deposit, and discontinuous character of the ridge.

Inexpressible Island

Inexpressible Island borders Terra Nova Bay, a polynya. Thus, the Terra Nova Bay field area has an environment that is significantly different from that at Cape Ross, or even from sites just south of the Drygalski Ice Tongue. Assuming that the bay has been open continuously during the Holocene, one would expect all beaches in this area to be wave-formed. In fact, the presence of only wave-formed beaches with well-rounded clasts might suggest that the polynya *has* been open throughout the Holocene and is not a recent feature.

Both Seaview and South Bays contain beaches that were formed by waves. Geomorphological evidence for this conclusion includes large-scale spits, log-spiral beach forms, arcuate pocket beaches, and low, wide beach crests.

Sedimentological evidence, such as lateral grain-size variation (fining towards protected areas) and well-to-very well-rounded clasts, also supports a wave interpretation. The spits in South Bay both fine distally from the headlands. The northern spit consists of five aggrading ridges that drop in elevation towards the south. Sediments on these beaches fine landward. The southern spit is very similar. It is composed of several beaches, most of which have clasts that fine both to the north and landwards. The ridges on this spit also drop in elevation with increasing distance from the headland. A wide (10 m), shallow (< 0.5 m) channel cuts this spit and leads to a small overwash fan. The fact that these spits are at different elevations and oppose each other could be due to sheltering of fetch, which would change the direction of longshore transport. This sheltering could result from varying sea-ice distribution and density, fluctuations in the geometry of the Drygalski Ice Tongue, or changes in topographic geometry as relative sea level dropped.

All evidence leads to the conclusion that waves formed every beach in both Seaview Bay and South Bay. As is the case at Cape Ross, the average size of beach clasts and the fact that stratigraphy is generally absent, suggest storm deposition (or re-working). The lack of stratigraphy in most pits also implies that many of the beach ridges formed during single storms.

In contrast, the discontinuous and commonly sharp-crested nature of the ridges in the southern bays of Inexpressible Island (Figures 37, 38, 45) leads me to conclude that ice push was the dominant beach-forming process. In particular, a series of beaches in the bay south of South Bay resembles boulder barricades in Labrador described by Rosen (1979). Such barricades are rows of shore-parallel boulders that form when icebergs or sea ice entrain sediment. These clasts subsequently drop when the ice grounds again and melts on the shore. According to Rosen (1979, p. 1122), three conditions must exist for these ridges to form:

1. *A rocky coastal setting to serve as a source for boulders*
2. *Sufficient winter ice and water-level fluctuations to entrain boulders in ice rafts*
3. *A distinct break in slope in the nearshore zone.*

Because the tidal range in this area is only about a meter, it may be that ice rafts push boulders into shore-parallel lines, instead of 'dropping' them. In some places there is no distinct break in slope in the nearshore zone. However, the relatively uniform, steep foreshore slope of the beach may cause ice to ground parallel to the coast. The idea that these are boulder barricades formed by ice push is supported by the fact that even though the rest of the coast on the island is ice free during summer months, these southern bays still contain a significant ice foot. If the hypothesis that these are ice-push beach ridges is correct, then they are the first documented occurrence of boulder-barricade beaches in the Ross Embayment.

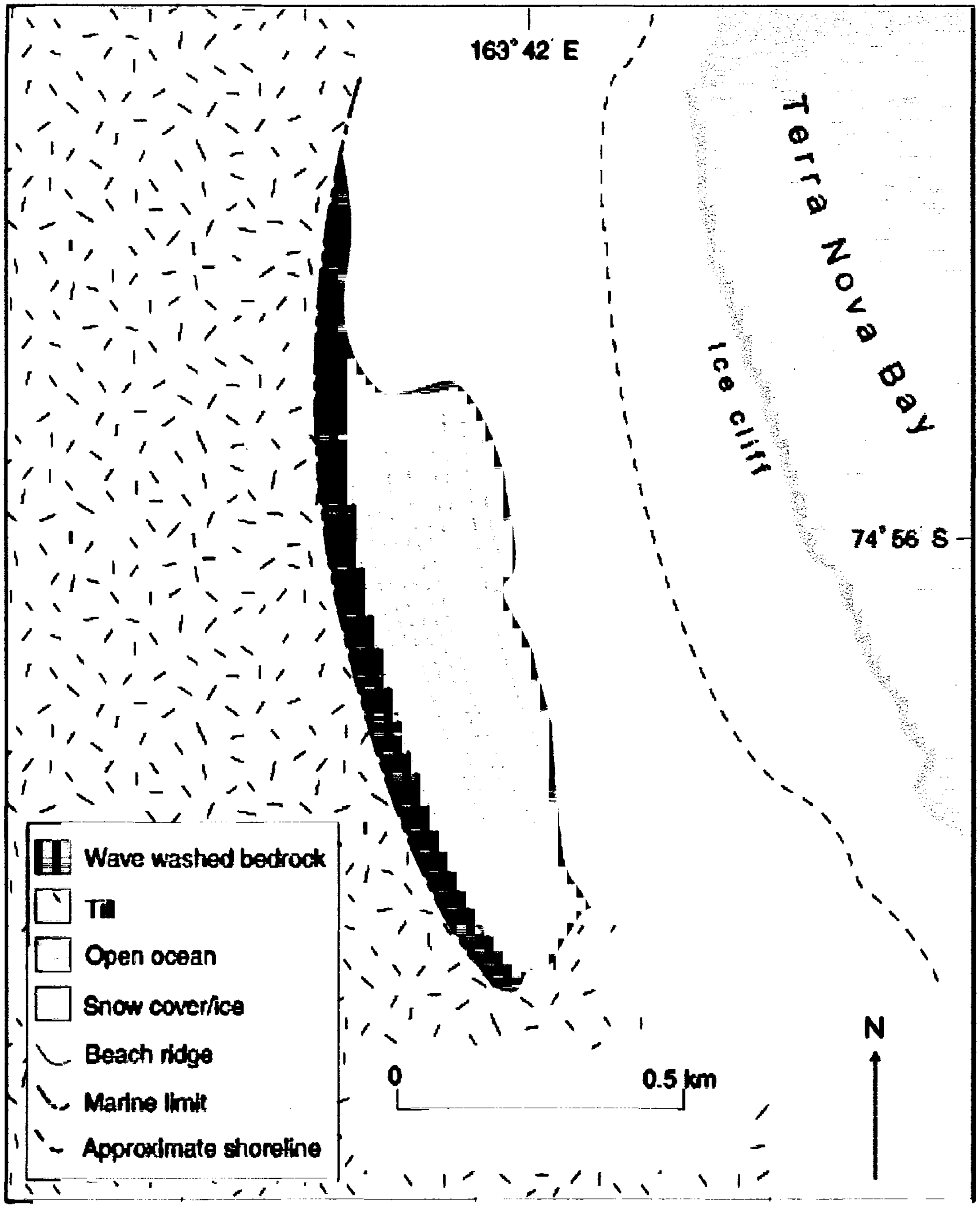

Figure 48. Surficial geologic map of the bay immediately south of South Bay, Inexpressible Island.

The hypothesis that waves formed most of the beaches at Inexpressible Island may be evidence that the Terra Nova Bay polynya has been open for most of the Holocene. This, in turn, suggests that the katabatic winds and the Drygalski Ice Tongue have persisted through this time. One hypothesis is that the open water exists because strong katabatic winds blow the sea ice out to sea. In addition, the Drygalski Ice Tongue blocks sea ice from blowing in from the south (Hall, personal communication). It is possible that the polynya is not a requisite feature for formation of these beaches because storms may be able to break ice away from the coast. However, the high degree of rounding displayed by the beach clasts favors long periods of open water, consistent with a polynya.

Although the current environments at Cape Ross and Inexpressible Island are different, raised beaches at both locations show evidence that they were formed by waves during storm events. However, the average roundness of clasts on all beaches in South Bay is significantly greater than that at Cape Ross. In addition, the average clast size of the four lowest elevation beaches at South Bay is notably larger than that of any of the beaches at Cape Ross, including those at low elevation in the mainland chasm. These data support the hypothesis of more open water (polynya) at Inexpressible Island, although it is possible that sediment supply limitations, bathymetric controls, and a larger fetch exposure also could have caused these differences.

Age of Northern Scott Coast Beaches

Cape Ross

Ages of the seven samples (Adélie penguin bone and Nacellidae shell) from Cape Ross range from 30,150 ± 430 to 44,900 ± 3,100 ^{14}C yr B.P. (Table 1). These dates are significantly older than any found previously in beaches along the coast of the Ross Sea. There are several explanations for these dates. The first is that they are erroneous, due to some sampling or laboratory problem. The second is that the dates are correct. A third possibility is that they are of infinite age, because the results are at the limit of the radiocarbon technique (Hall, personal communication). A fourth possibility is a combination of the second and third; that is, some dates may be correct, and some may be infinite.

I am confident that sampling and dating error do not affect these ages. First, each sample was taken from well within the beach (50-90 cm depth). There were no recognizable stratigraphic breaks, and there is no evidence of reworking—both bone and fragile shells (some of which were nearly complete) were found. Thus, the samples must date the deposit. Second, every sample from Cape Ross is greater than 30,000 years. This consistency lends credibility to the idea that these ages are in fact old, and not erroneous. The presence of a large weathering horizon, which was found from the surface to ~50 cm depth in nearly every excavation, gives credence to older-than-Holocene ages.

DNA analysis suggests that at least some of the dates can be taken at face value. Rates of DNA evolution in Adélie penguins recently calculated for the Ross Sea place the age of the penguin bones (30,150 ± 430 and 37,570 + 940 ^{14}C yr B.P.) at substantially less than 60,000 years, but older than Holocene (Lambert et al., 2002; Lambert, personal communication). Although this suggests that the dates of the penguin bones may be correct, it does not prove that the shells are of the same age. The dates of the shells could be infinite.

The third possibility is that all of the ages are infinite, despite the DNA evidence. This would be because the materials are at the limit of the radiocarbon dating technique. A final option is that the shells are beyond the limit of radiocarbon dating and the bones, despite occurring in close association with the shells, are 30,000-40,000 years old. This hypothesis suggests that some or all of the organic material was reworked—something that is inconsistent with the preservation of fragile shells.

Regardless of age, the species of bones and shells found within the beaches both suggest a warmer-than-present climate. Nacellidae are not found currently along the Ross Sea coast, probably because sea ice is prevalent and grounded well below the intertidal zone. They live today in the warmer climate of the Antarctic Peninsula (CCAMLR, 1995). Similarly, Adélie penguins do not live at Cape Ross today probably because the sea-ice edge is kilometers from land even during summer. Taken together, the incorporated organic material, as well as the beach geometry and sedimentology, both indicate that the beaches at Cape Ross date to a period as warm as, or probably warmer than today, when there was less sea ice. This conclusion is based solely on temperature control on sea-ice extent. It is possible that intensified katabatic winds could decrease the sea ice around Cape Ross. Globally, oxygen isotope stages 5 and 11 are times when temperatures were similar to or higher than those of today. Data from the nearby Taylor Dome ice core indicate that stage 3 also was warmer than present in the Ross Sea region

(Steig, personal communication). It is not possible at this time to determine conclusively the period to which these samples date, although the DNA evidence favors stage 3. The most important result is that the organic remains are not of Holocene age.

Based on the radiometric data, there are three possible interpretations for the ages of the beaches (Table 4). The first is that all of the beaches at Cape Ross are pre-Holocene in age, including the lowest, least-weathered ridges. A second possibility is that all of the beaches are indeed Holocene in age, but contain re-worked older material and lack Holocene organic remains. The third alternative is akin to the situation at Spike Cape, where there seems to be a mix of both pre-Holocene and Holocene beaches (Hall, personal communication). Such a combination could consist of Holocene beaches superimposed on top of older beaches. Or, there could be older beaches with only a thin veneer of Holocene sediment.

Besides the radiocarbon data, other evidence lends credence to the hypothesis that the beaches at Cape Ross are pre-Holocene in age. There are common occurrences of cavernous boulders and deep accumulations of grus at the highest elevations of Cape Ross. Although weathering rates are unknown along the Antarctic coast, in the nearby Dry Valleys this degree of weathering is known to require a long period of time (Campbell and Claridge, 1987). Most boulders on Cape Ross, if not cavernously weathered, are heavily pitted. This, too, is an indication of a high degree of weathering which might not be possible in the short, unglaciated part of the Holocene. A deep weathering horizon, generally found to 50 cm depth in excavations, also is evidence for a thick soil-forming layer that could have taken a considerable period of time to develop.

The possibility that the beaches are entirely Holocene in age and contain re-worked pre-Holocene material is undermined by the occurrence of whole shells in the deposits. Reworking during storms probably would degrade such shells. The lack of any Holocene-aged organic remains also argues against the beaches being exclusively of Holocene age. Therefore, in the next section I concentrate solely on the other two hypotheses—that the beaches are of multiple ages or that they are of pre-Holocene age.

Table 4. List of evidence for ages of beach ridges at Cape Ross. A strong positive rating means that the specified evidence (left column) strongly supports that relative age. "Old beaches" are considered pre-Holocene, "Young beaches" Holocene, and "Mix" is evidence for two beach sets—one "old" and one "young."

	Old beaches	***Young beaches***	***Mix***
Radiocarbon results	Strong +	Strong -	Strong -
Cavernous weathering/grus	Weak +	Weak -	N/A
Presence of spalled/pitted boulders	Weak +	Weak -	N/A
Weathering/soil horizon	Strong +	Weak -	Strong -
Whole Nacellidae within deposits	Strong +	Strong -	Strong -
Only one marine limit	Strong -	Strong +	Weak -
Gradational weathering (unweathered to pitted)	Strong -	Strong +	Strong -

The beaches could be a mix of Holocene and pre-Holocene material. This could result either from 1) complete reworking of the upper few tens of centimeters of old beaches by Holocene wave action, or 2) only slight retouching of older beaches by Holocene marine processes. However, there is no evidence for two distinct beach sets. This is a problem for the hypothesis that some or all of the beaches are old, because nearby evidence indicates that the Holocene marine limit at Cape Ross should be $\geq$ 21 m elevation. However, there isn't any break in weathering that could indicate a Holocene marine limit lower than 34 m elevation. Rather, gradational weathering on the beaches in the mainland chasm, which ranges from very slight on clasts at sea level to substantial with pitted and stained clasts at 34 m elevation, suggests that there is only one set of beaches. This and the fact that there is not any geomorphological evidence for superimposed beaches suggests that the Holocene marine limit at Cape Ross may be at 34 m elevation and that all of the older beach material was inundated and perhaps reworked slightly during the Holocene.

The lack of stratigraphy within the beaches argues against there being a mix of materials of different ages. One would expect to see a break between the Holocene and pre-Holocene beach sediments if the deposit had been mobilized in the last few thousand years. In addition, dated material from Cape Ross is all older than 30,000 years old. Twenty-five excavations on Cape Ross and in the chasm on the adjacent mainland did not produce a single Holocene-age sample.

If the hypothesis that there are both Holocene and pre-Holocene beaches is correct, then it implies that factors such as dense sea-ice cover hindered modification of these sediments, leaving the older set of beaches intact. However, if sea ice protected the older beaches from being re-worked, one would expect ice-push features to be evident.

Preservation of old beaches also would be also possible if there were an ice shelf abutting the coast. Hall and Denton (1999) suggested that the presence of an ice shelf caused the disparity in the marine limit on the southern Scott Coast (the marine limit drops from $\geq$ 21 m at Cape Roberts to 0 m south of Explorers Cove). If an ice shelf did protect pre-Holocene beach deposits at Cape Ross, then it is the first evidence of the existence of an ice shelf so far north.

I favor the interpretation that the beach deposits at Cape Ross mostly are pre-Holocene in age. This is supported by the radiocarbon ages, stratigraphic and geomorphologic evidence, and the fact that there is only one marine limit.

This interpretation is not without problems and has credible opposing evidence, such as the gradational weathering and the lack of a Holocene marine limit. The first of the problems is that the beaches must have been preserved beneath ice during stage 2, because the adjacent Evans Piedmont Glacier likely expanded at this time (see Figure 4, page 9). Although there is no direct proof of the glacier expanding, there are three lines of evidence that support the occurrence. First, Mackay Glacier (just south of Cape Ross) thickened several hundred meters at the LGM and merged with the Ross Sea ice sheet at present-day Granite Harbor (Denton and Hughes, 2000). The Evans Piedmont Glacier is less than 20 km from the present-day Mackay Glacier, and probably also was in contact with the Ross Sea ice sheet. The latest reconstruction shows that the Ross Sea ice sheet should have reached ~500 m elevation at Cape Ross (Denton and Hughes, 2000). Second, the nearby (30 km to the south) Wilson Piedmont Glacier, which is very similar to the Evans Piedmont Glacier in shape, topography, and probably origin, expanded at the LGM (Hall and Denton, 2000a). The two piedmont glaciers probably respond in a similar manner, suggesting advance of the Evans Piedmont Glacier at the LGM. Last, the Evans Piedmont Glacier must have had a greater extent at some time in the past, because the area above the marine limit on the mainland adjacent to Cape Ross is covered by till of local origin (although likely due to an accumulation from multiple advances).

Cold-based ice is known to have little effect on the landscape (Sugden and John, 1976). For example, beaches at Spike Cape, Kolich Point, and Cape Roberts are now emerging seemingly unscathed from beneath the Wilson Piedmont Glacier (Hall and Denton, 2002). Thick soil horizons and dated whalebone suggest that beaches on Svalbard are Pre-Holocene in age despite the fact that they were covered by ice at the LGM (Forman and Miller, 1984; Forman et al., 1987; Forman, 1989; Lønne and Mangerud, 1991). Both of these sites afford proof that beaches can be preserved under cold-based ice. I therefore conclude that it is possible that either the Evans Piedmont Glacier or the Ross Sea ice sheet could have covered Cape Ross at the LGM without destroying the beaches.

One could argue that sublimation till should be present on the beach surfaces if indeed the Evans Piedmont Glacier overran them. I have not found any evidence of till or perched erratics on the beaches at Cape Ross. However, sublimation till is also absent at Spike Cape and in places on Svalbard where beaches have been overridden (Hall, personal communication; Lehman and Forman, 1992; Mangerud et al., 1992). I suggest that since the Evans Piedmont Glacier lacks significant amounts of debris, it is possible that it could override Cape Ross without depositing till.

A second problem with a pre-Holocene age for the Cape Ross beaches is that a Holocene sea-level high stand of $\geq$ 21 m has been recorded at sites less than 35 km away. It would seem likely that a Holocene high stand of similar magnitude would have existed at Cape Ross. However, there is nothing in the geomorphology or weathering to suggest a marine limit below 34 m elevation at Cape Ross (although snow cover may have prevented this from being identified). For example, there isn't a scarp separating Holocene and pre-Holocene beaches. All of the beaches on the Cape Ross peninsula seem to show a similar degree of weathering as if they formed in a close time frame. The same is also true for the nearby peninsula at Depot Island. A set of beaches there extends from near sea level to 34 m elevation with no weathering or geomorphic break. In addition, a chasm on the Cape Ross mainland contains a set of beaches that rises from near sea level to a soliflucted marine limit at about 31 m elevation. These beaches show gradational weathering from very little modification near sea level to more severe weathering on the highest beaches. There is not a sharp contact that could indicate a Holocene marine limit. Moreover, the slight weathering on the lower beaches is not consistent with a pre-Holocene age.

Both pre-Holocene and Holocene-aged materials have been recovered from the beach ridges at Spike Cape. Field observations and data suggest that small ridges seem to rest upon larger forms (Figure 46) (Hall, personal communication). This, and the fact that Holocene organic remains occur at shallow depths and pre-Holocene remains at deeper depths in the beaches suggest that there are multiple sets of beaches at Spike Cape. However, I have not found similar geomorphic and stratigraphic evidence at Cape Ross in support of superimposed beaches of different ages.

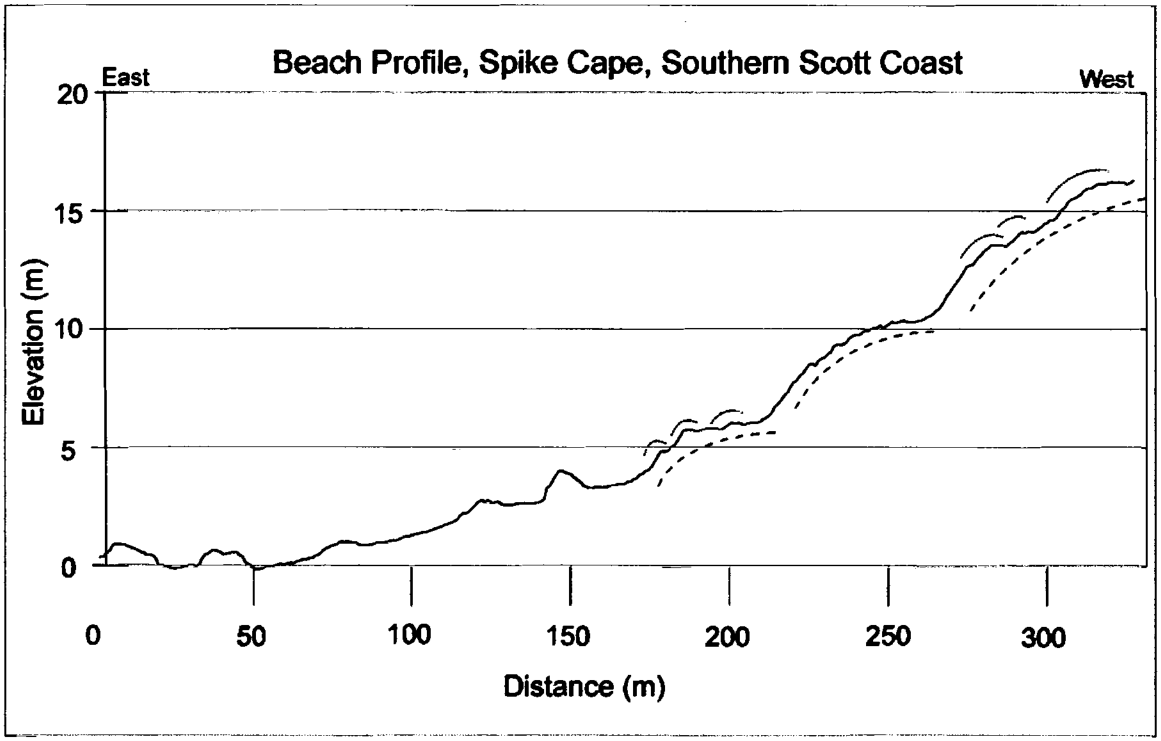

Figure 49. Profile of beaches at Spike Cape. Large beach forms are interpreted by dashed lines, and smaller, superimposed beaches are indicated by dotted lines.

The suggestion that there are not any Holocene beaches at Cape Ross is problematic, because relative sea level should have been $\geq$ 21 m higher during deglaciation than it is today. One possibility for the lack of a Holocene marine limit is that the Evans Piedmont Glacier covered Cape Ross until recently and protected the area from marine influence. However, this is unlikely if one assumes that the Evans Piedmont Glacier responds in a manner similar to that of the Wilson Piedmont Glacier. The Wilson Piedmont Glacier was less extensive than at present by the mid-Holocene (Hall and Denton, 2002). In addition, penguin remains from Cape Ross date to 3,000-4,000 yr B.P., indicating that the area was ice free during the mid-to-late Holocene (Baroni and Orombelli, 1994a).

In conclusion I prefer the idea that the beaches at Cape Ross are mostly pre-Holocene in age because I feel that the bulk of evidence (i.e., only pre-Holocene organic material, deep soil horizons) supports this hypothesis. The beaches would have to have been protected from Holocene marine influence. Perhaps the top few centimeters of sediment may have been modified.

Inexpressible Island

Chronological data from Inexpressible Island are ambiguous. Dates of seal skin and penguin remains place beach formation in Seaview and South Bays in the middle-to-late Holocene (Baroni and Orombelli, 1991; Hall, personal communication; this study). However, a single *Nacella* shell from the 25-m-elevation beach dates to 46,000 $\pm$ 2600 ^{14}C yr B.P. (uncorrected). More *Nacella* have been found in upper-elevation beaches at Hell's Gate, but have not yet been dated. Although there doesn't seem to be any evidence for superimposed ridges, the mix of dates from Inexpressible Island suggests that there might be both Holocene and pre-Holocene beach materials.

Implications of Pre-Holocene Ages

The marine limit at Cape Ross (34 m) has long been thought to be Holocene in age. If the beaches at Cape Ross antedate the Holocene, then the chronology of ice retreat based on southern Scott Coast RSL curves (Hall and Denton, 1999) may be too old. In fact, if the Holocene marine limit is not 34 m, but is instead closer to 21 m (the elevation of the highest marine deposits and ice-free land at Cape Roberts), the grounding line may have passed up to 1000 years later than the date of 6,500 ^{14}C yr B.P. originally suggested (Hall and Denton, 1999). However, dates of shells from the sea floor in McMurdo Sound do seem to agree well with an age of 6,500 yr. B.P. for deglaciation (Kellogg et al., 1990; Licht et al., 1996).

Whether or not the beaches at Cape Ross are entirely of pre-Holocene age or are a mix of ages, they do contain significant amounts of pre-Holocene sediments and organic remains. An implication of this fact is that construction of new RSL curves must take into consideration the possibility of pre-Holocene beach deposits—beaches can no longer be assumed to be of Holocene age. Consequently, future workers will need detailed stratigraphic and dating analyses to determine the ages of the beaches and to develop RSL curves.

Construction of an accurate RSL curve is dependent on a reliable estimation of the original elevation of the beach above mean sea level (MSL). This, in turn, is contingent on the specific beach-forming process and environment. Previous researchers have relied on generalized assumptions regarding beach formation when constructing RSL curves. For example, Hall and Denton (1999) assumed that the beaches were storm deposits and used a correction of four meters—the elevation of the modern storm beach—to account for storm surge.

Hall and Denton (1999) were correct about the beaches having formed during storms, but it is nearly impossible to determine at what elevation above sea level the ridges originally formed. It is certain that these beaches did not form at mean sea level and that some elevation correction is necessary. However, the storms that created the beaches probably differed in intensity. The best solution would be to analyze each beach used in the RSL reconstruction to make a correction evaluation based on inferred wave energy from grain-size and elevation differences. Butler (1999) attempted to use beach-face slope angles and trends in beach size as proxies for paleo-wave energy. He suggested that using lower-energy beaches would decrease the error associated with storm surge, although such beaches are rare north of his study area. With some careful work, it should be possible to determine at least relative storm size based on grain-size data and morphology. This analysis would have to take into account any problems that arise due to changes in geometry as land rebounds, and assume that the sediment sources for the beaches are not limited. Determining paleo-wave energy is a topic for future study.

Holocene Climate Variability

Most, if not all, of the raised beaches along the Scott Coast were formed by waves. Several modern beaches at Cape Ross, Spike Cape, and Marble Point display characteristics of an ice-push process, including discontinuous ridge segments, steep and hummocky crests, and poorly-rounded clasts. Assuming that these low-elevation beaches are ice-push ridges, it is possible that the current fast-ice environment has not been present throughout the Holocene. On the other hand, ice-push ridges may not occur at higher elevations, because they have a low preservation potential (Nichols, 1953; Hume and Schalk, 1964; Taylor and McCann, 1983). Storm waves generally reach higher than ice, and remove any ridges formed by ice processes.

Raised beaches on north-facing slopes of the Scott Coast (from Depot Island south) are generally more abundant and are larger in scale than those on south-facing slopes (Figure 47). At Cape Ross, there are three major ridges (as much as two meters

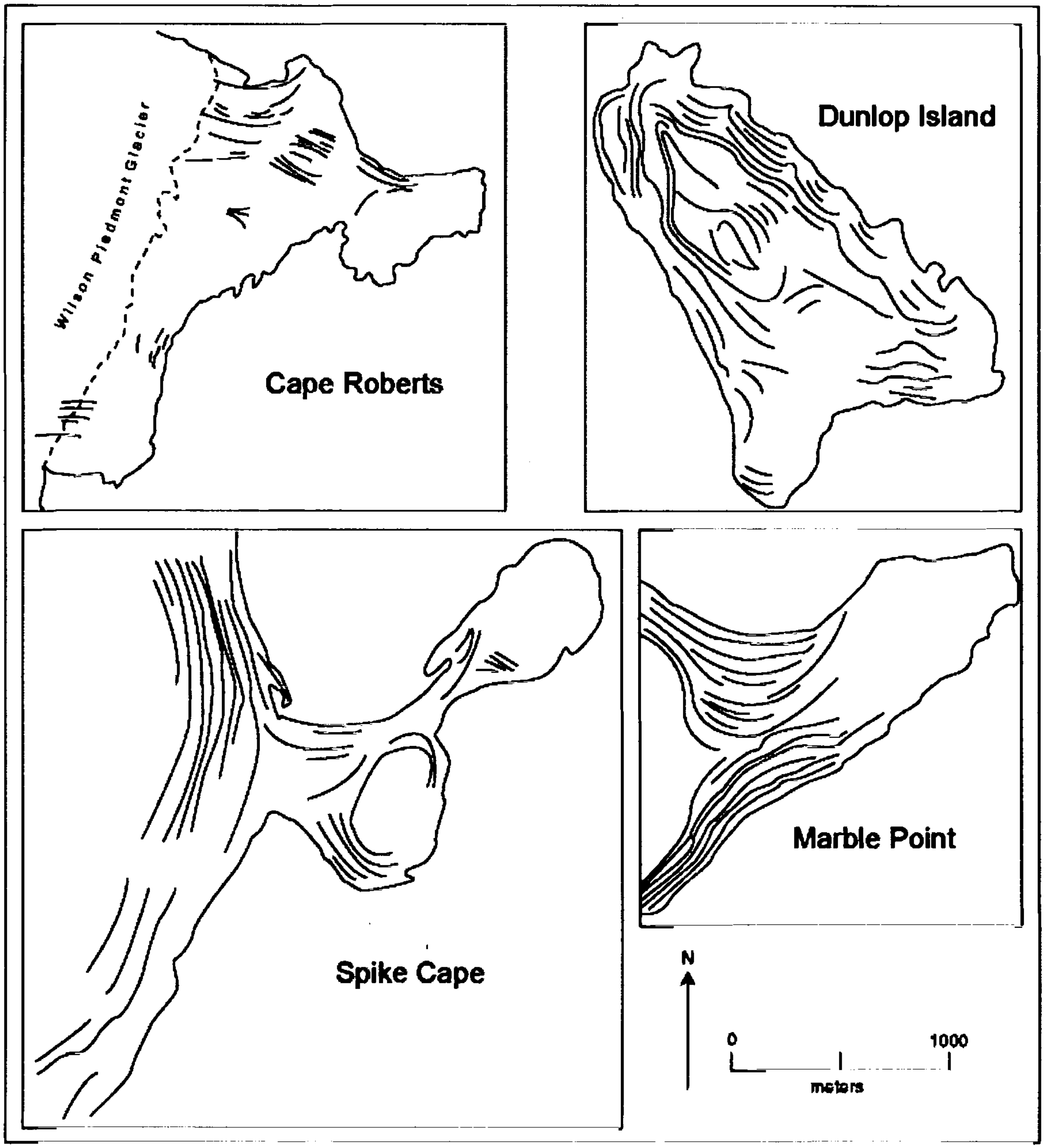

Figure 50. Maps of beach ridges at locations on the southern Scott Coast. The majority of beaches (particularly those of high-relief) at these sites occur on the north-facing shores. At Marble Point, beaches that are north-facing are larger than those that are south-facing. Figures redrawn from Hall and Denton (2000).

high) and several smaller ones on the north side of the tombolo. In contrast, only three minor ridges occur on the south side (although snow cover limited observation). These southern ridges are less than a meter high and do not continue laterally more than 30 m. In addition, the highest beach on the cape, which makes a circuit around the plateau, rises in elevation towards the northeast. Therefore, the best-developed and highest beaches on Cape Ross are on the north and northeast sides.

Other areas along the southern Scott Coast also display this asymmetry. Most well-defined beaches at Cape Roberts occur on the north coast. Pocket beaches are developed best on the north coast of Dunlop Island, and are significantly larger than those with southern exposure. At Marble Point, beaches also are better developed on the north-facing shoreline. The implication of this asymmetry is that the dominant storm-wave energy has been from the northeast. It is possible that bathymetric variations may cause this asymmetry, but this is unlikely given the number of sites at which it occurs. Both north- and south-facing coastlines have equivalent sediment sources, which rules out supply differences. Butler (1999) described beaches in southern McMurdo Sound as occurring more commonly "in sheltered south-facing locations, because they are protected from open-marine conditions..." I disagree with this conclusion because of the above data. However, Butler (1999) did suggest that the highest wave energy is from the northeast, which is in agreement with my evidence. The asymmetric distribution of the raised-beach deposits indicates that the northeast wave direction was dominant throughout the Holocene.

Sea-ice extent during the middle and late Holocene may have been considerably less than it is today. Waves from the northeast would tend to pile sea ice on the coast during storms, and there is no evidence of such. This conclusion is consistent with other available information. For example, Hodell et al. (2001) suggested that the sea-ice extent in the Antarctic increased after 5000 cal yr. B.P., and a general cooling has progressed since. Baroni and Orombelli (1994a) dated fossil rookeries along the northern Scott Coast and discovered that penguins were more common between 5,000 and 3,000 yr B.P., a period that they call the "penguin optimum." Adélie penguins lived at Cape Ross between 4,000 and 5,000 yr. B.P. (Baroni and Orombelli, 1994a), but do not live there today. Baroni (1994) advocated sea-ice extent as the most important factor in determining their rookery location. Too much sea ice hinders their access to the open ocean, and therefore they must move to areas where open water is adjacent to the shoreline. If this interpretation is correct, then sea-ice extent around Cape Ross must have been less at least during the penguin optimum.

Other evidence in support of less sea ice in mid-to-late Holocene time includes the remains of elephant seals (see figure 41, page 58) along the Scott Coast dating between 5,000 and 900 ^{14}C yr B.P. (Hall and Denton, 1999; Hall, personal communication). Elephant seals do not live in the area today and generally prefer sub-Antarctic areas with milder environment. The relative profusion of elephant seal remains on the Scott Coast might imply that periods during the Holocene were warmer than present. In addition to the presence of the seals, Hall and Denton (2002) concluded that the Wilson Piedmont Glacier, which is adjacent to the southern Scott Coast, was less extensive in the mid-Holocene than it is today. A readvance culminated less than 250 years ago. All of the above data are consistent with the hypothesis that sea-ice extent may have been less during the mid-to-late Holocene.

Data at Inexpressible Island also suggest Holocene variations in sea-ice extent. Grain-size data from South Bay show that the largest beach boulders occur on the lowest four ridges. The average size drops sharply from nearly 26 cm (average of largest axis) on these four beaches to 14 cm on the next seven higher beaches. The upper most beach boulders averaged 18 cm. Although the grain-size data may not be statistically significant, these trends were seen clearly during the course of field work. One possible reason for this change is that wave energy was more intense in the early and especially late Holocene, allowing for transportation of larger clasts. The higher wave energy, in turn, could be related to the reduced sea-ice extent in the Terra Nova Bay region. The reduction of sea ice could be due to the expansion of the polynya (allowing for greater fetch), owing to local factors such as an increase in katabatic winds. Or it could reflect a general decrease of sea ice in the Ross Sea. Another possibility is that storm intensities have increased in the late Holocene allowing for transport of the larger clasts. However, there is no independent supporting evidence for this hypothesis.

The lowest-elevation beaches in South Bay also contain the most rounded clasts. This could imply several things. First, the polynya might be more extensive now than in the past, allowing more fair-weather wave energy to reach the coast and round the clasts. Alternatively, the degree of roundness could indicate that isostatic rebound has slowed, and these clasts have been subject to prolonged wave influence, and are thus the most rounded. Other than along the southern end of South Bay where the syenite clasts weather rapidly, I do not believe that weathering has significantly altered roundness.

CONCLUSIONS

- All of the beaches at Cape Ross, save the lowest-elevation (modern) ridge, were created by storm waves. Stratigraphic and geomorphologic evidence indicates that the beaches probably formed during single storm events.

- The radiocarbon data unequivocally indicate that at least the deeper (>50 cm) beach sediments at Cape Ross are of pre-Holocene age. However, one cannot rule out the possibility that the beaches formed during the Holocene but contain a core of older material. Regardless of the age of the beaches, the remains of *Nacella* and Adélie penguins suggest that the interval in which the beaches formed was warmer than today.

- Geomorphic observations on Inexpressible Island indicate that waves formed nearly every beach in Seaview and South Bays; preliminary sedimentological results suggest that most ridges represent single-storm deposits. However, there are a few exceptions, where distinct units within the beaches may represent multiple storm events. In contrast, reconnaissance in the two southern bays established that beaches there are similar to ice-push ridges found in the Arctic.

- Beaches at Inexpressible Island contain material of both Holocene and pre-Holocene age. More work is needed to determine if beaches of both ages exist, or if the older organic remains are worked into younger sediments.

- The fact that all beaches at Inexpressible Island were formed by waves and show well-rounded clasts suggests that the Terra Nova Bay polynya may have persisted throughout the mid-to-late Holocene.

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Grain Size Data

Beach	ID #	Avg Size (cm)	Std Dev (s)	Largest (cm)	Avg Rnds †	Std Dev (r)	% small **	Elevation ‡	n
CAPE ROSS									
1N, m, crest	BS-02	12.3	14.2	99.0	0.37	1.4	10	23.3	51
2N, m, crest	BS-03	8.9	11.7	65.0	0.39	1.4	35	26.4	77
3N, m, crest	BS-04	13.7	10.1	46.0	0.47	1.7	25	27.6	27
3N, m, crest	BS-05	16.51	10.8	56.0	0.37	1.4	N	27.6	18
3N, e, crest	BS-08	10.6	5.9	30.0	0.42	1.9	N	27.6	89
3N, m, back	BS-06	13.5	7.6	38.0	0.39	1.4	20	27.6	43
3N, m, back	BS-10	8.4	4.6	28.0	0.48	1.6	20	27.6	108
3N, m, front	BS-07	14.5	9.4	37.0	0.39	1.6	30	27.6	30
Top, crest	BS-01	12.1	6.7	35.5	0.52	2.1	20	31.4	67
Top, crest	BS-09	14.4	8.3	35.0	0.38	1.6	30	31.4	37
DEPOT ISLAND									
Unknown	BC1	24.0	13.4	57	.49	1.2	15	Unknown	25
Unknown	BC2	24.1	11.8	54	.49	1.2	45	Unknown	22
Unknown	BC3	17.0	8.1	39	.48	1.2	15	Unknown	44
Unknown	BC4	18.4	7.5	37	.48	0.9	10	Unknown	34
Unknown	BC5	15.9	7.0	34	.56	1.0	45	Unknown	39
Unknown	BC6	22.3	6.8	36	.54	0.8	45	Unknown	18
SOUTH BAY NORTH									
1	N/A	25.4	12.7	92.0	.68	0.9	20.0	5.5	24
2	N/A	25.9	13.5	71.0	.60	0.8	20.0	8.2	27
3	N/A	23.5	10.3	49.0	.59	0.8	25.0	10.2	26
4	N/A	27.1	12.7	45.0	.63	1.0	35.0	11.8	18
5	N/A	15.7	12.5	51.0	.59	0.9	40.0	13.5	41
6	N/A	12.3	9.2	64.0	.62	0.8	30.0	15.1	79
7	N/A	18.3	12.5	63.5	.55	1.1	35.0	18.5	34
8	N/A	12.5	6.2	40.0	.59	1.0	35.0	21.3	94
9	N/A	12.5	5.3	33.0	.58	1.1	25.0	22.4	89
10c	N/A	14.6	7.6	46.0	.53	1.0	5.0	25.5	51

Beach	ID #	Avg Size (cm)	Std Dev (s)	Largest (cm)	Avg Rnds †	Std Dev (r)	% small **	Elevation ‡	n
10b	N/A	13.7	5.6	26.0	.53	1.1	5.0	25.5	45
11	N/A	18.8	17.0	92.0	.47	1.1	10.0	27.4	38
12	N/A	22.0	8.9	54.5	.62	0.9	20.0	28.9	33
13	N/A	19.4	8.7	50.0	.50	1.4	20.0	29.4	52
14	N/A	13.3	7.2	33.0	.55	0.9	25.0	29.8	68
SOUTH BAY SOUTH									
1	N/A	23.9	14.8	69.0	.69	1.1	10.0	6.1	29
2	N/A	21.3	12.3	55.0	.64	1.2	25.0	9.5	29
3	N/A	31.7	15.9	57.5	.60	1.0	20.0	13.4	14
4	N/A	31.3	13.4	65.0	.59	0.7	25.0	14.3	15
5	N/A	26.5	9.7	52.0	.58	0.9	25.0	15.3	23
6	N/A	20.9	6.0	32.5	.55	0.7	35.0	16.3	31
7	N/A	25.4	9.5	46.5	.61	0.7	30.0	17.9	22
8	N/A	10.2	5.5	29.0	.49	0.9	50.0	18.7	97
9	N/A	11.7	7.8	40.0	.58	0.9	50.0	19.5	58
SEAVIEW BAY									
Unknown	BC1	24.5	14.3	74	.55	0.6	10.0	Unknown	27
Unknown	BC2	21.0	18.2	75	.60	0.6	10.0	Unknown	35
Unknown	BC3	29.6	24.5	91	.63	1.0	3.0	Unknown	25
Unknown	BC4	16.7	10.1	63	.65	0.9	15.0	Unknown	56
Unknown	BC5	20.6	10.9	57	.60	0.9	10.0	Unknown	34
Unknown	BC6	13.5	7.0	36	.59	0.9	25.0	Unknown	74
Unknown	BC7	18.7	9.2	48	.60	0.8	10.0	Unknown	40
Unknown	BC8	31.0	13.7	75	.50	0.8	5.0	Unknown	21
Unknown	BC9	18.7	10.7	50	.53	0.8	10.0	Unknown	40

* - approximate. Taken from transect.
** - percentage of material in a meter-square plot that is smaller than 1 cm in diameter (largest axis)
† - Average roundness measurements based on Powers (1953)
‡ - Elevation in meters above sea level
St Dev (s) - standard deviation of size
St Dev (r) - standard deviation of roundness
n - population size

BIOGRAPHY OF THE AUTHOR

Born on a frigid New England day in December of 1976, Nathan Gardner grew up on the southeastern Connecticut coast. He attended Ledyard public schools and graduated in 1995. Following his life-long aspiration to become an architect, he matriculated to Lehigh University in Bethlehem, Pennsylvania in the fall of 1995. After discovering a hidden interest in geology, Nathan switched majors, and received superb mentoring, training, and support from the Geology Department's faculty and students.

To fulfill his strong interest and aptitude in coastal and glacial geology, he chose to pursue an advanced degree at the University of Maine after graduating from Lehigh University with a B.S. in Environmental Science and a minor in History. His Master's degree has taken him to exotic places such as Antarctica, New Zealand, and Newfoundland, although his favorite landforms are found in Connecticut and New Hampshire.

He is currently searching for a position in an environmental firm close to the hills, so he can pursue his next goal of becoming a renowned downhill mountain biker and bump skier. Nathan is a candidate for the Master of Science degree in Geological Sciences from The University of Maine in December, 2002.