Geogr. Fis. Dinam. Quat.
13 (1990), 139-163, 26 figg., 2 tabb., 1 tav. f.t.

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LATE CENOZOIC GLACIAL HISTORY OF THE TERRA NOVA BAY REGION, NORTHERN VICTORIA LAND, ANTARCTICA

Abstract: OROMBELLI G., BARONI C. & DENTON G.H., *Late Cenozoic glacial history of the Terra Nova Bay region, northern Victoria Land, Antarctica*, (IT ISSN 0391-9838, 1990)

Glacial geological and geomorphological research in the Terra Nova Bay region was undertaken to decipher late Cenozoic ice-sheet behavior in northern Victoria Land. The work is part of a continuing program to understand and anticipate the response of the Antarctic Ice Sheet to climatic change.

The Transantarctic Mountains inland of Terra Nova Bay exhibit four major landscapes. 1) The first type consists of deep troughs propagated inland by headward cutting. The lower portions of these troughs form ice-covered fjords, where present-day grounding lines extend inland beneath outlet glaciers. 2) Well-developed alpine glacial topography (with cirques, ridges, horns, and spurs) characterizes the region. Alpine topography has propagated from the deep troughs into the intervening mountain blocks. This morphology can locally be very old and reflects a different-from-present climatic regime. Furthermore, the formation of the alpine topograpy and of the glacial troughs did not require an East Antarctic Ice Sheet. 3) Relict summit mesas occur in the high central mountain ranges between troughs. Thin ice caps cover the central mesa topography and commonly spill over the mesa edges to feed cirque or tributary glaciers within the alpine topography. 4) The fourth type of morphology features undulating coastal piedmonts that are tilted seaward. The process of inland erosion by outlet glacier troughs and adjacent alpine topography has left isolated nearly intact remnants of the original topography. Near the coast, these remnants include the coastal piedmonts; farther inland they include the summit mesas.

Trimlines superimposed on the alpine and outlet-trough topography mark the maximum possible expansion of the northern Victoria Land ice cover since erosion of the alpine topography. This expansion was minor in the upper reaches of outlet glaciers and in mountain accumulation areas while it represented great thickening in the coastal area. There is no definitive evidence that the East Antarctic Ice Sheet overrode northern Victoria Land nunataks or mountains.

Several glacial drifts have been differentiated. Terra Nova drift (late Wisconsin) is well-exposed and preserved along coastal ice-free areas, where it was cut beginning 7 000-8 000 yr B.P. by beaches now up to 30 m above present sea level. The Terra Nova drift limit can be traced far inland along the main glaciers. During late Wisconsin time, the glacier thickening was greatest in coastal regions, where a grounded piedmont glacier filled Terra Nova Bay. The Terra Nova piedmont glacier was probably part of a marine-based ice sheet in the inner Ross Embayment.

High-elevation striations in the Eisenhower Range seem to have been carved during Terra Nova glaciation. If so, local mesa ice caps and mountain glaciers expanded to feed the Terra Nova piedmont glacier during late Wisconsin time, unlike the situation farther south where alpine glacier termini in the Dry Valleys were less extensive than now during late Wisconsin time.

KEY WORDS: Glacier, Ice Sheet, Victoria Land, Antarctica.

Riassunto: OROMBELLI G., BARONI C. & DENTON G.H., *Storia glaciale del territorio di Baia Terra Nova, Terra Vittoria settentrionale, Antartide*. (IT ISSN 0391-9838, 1990).

Nel territorio di Baia Terra Nova sono state condotte ricerche di geologia glaciale e geomorfologia al fine di investigare la storia della calotta antartica. Il lavoro è parte di un programma di ricerca più ampio che si propone di capire e prevedere il comportamento della calotta antartica in risposta a cambiamenti climatici.

Nella Terra Vittoria settentrionale le Montagne Transantartiche sono caratterizzate da quattro morfologie principali. 1) La prima è costituita da ampie ed estese valli glaciali che si sono propagate verso l'interno per erosione regressiva. Le porzioni inferiori di queste valli costituiscono dei fiordi, occupati da lingue di ghiaccio galleggianti che si estendono verso l'interno per un lungo tratto. 2) Una ben sviluppata morfologia di tipo alpino caratterizza la zona dei rilievi interposti tra le valli principali, dai fianchi delle quali si è propagata. Localmente, questa morfologia è molto antica e testimonia un regime climatico differente da quello attuale. Inoltre, l'evoluzione della morfologia alpina non è da porsi necessariamente in relazione alla presenza della Calotta Estantartica. 3) Rilievi tabulari residuali (*mesas*) si trovano tra le principali valli glaciali e, soprattutto, nelle zone più interne delle Montagne Transantartiche. Sottili calotte glaciali coprono le *mesas* e, generalmente, ne oltrepassano l'orlo per alimentare circhi minori o ghiacciai tributari delle valli principali. 4) Anche i rilievi costieri con sommità arrotondate possono essere considerati di tipo residuale. Si tratta di superfici relitte, di erosione glaciale, dislocate e inclinate verso mare. Il processo di erosione regressiva indotto dall'evoluzione delle principali valli glaciali e dalla morfologia alpina ha isolato lembi pressoché

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The field research was supported jointly by Programma Nazionale di Ricerche in Antartide (Italy) and the Division of Polar Programs of the National Science Foundation (United States). New Zealand Helicopters Ltd. provided helicopter support under contract to Programma Nazionale di Ricerche in Antartide. Data analysis by G. OROMBELLI *and* C. BARONI *was financially supported by ENEA through a joint research program on Antarctic Earth Sciences with the University of Siena. Data analysis by* G.H. DENTON *was funded by the global change program of NOAA as part of a study to determine the response of the East Antarctic Ice Sheet to global warming.* $\delta^{18}O$ *values of buried ice from ice-cored drift were kindly supplied by* A. LONGINELLI *(University of Trieste).* T.B. KELLOGG *and* J.F. SPLETTSTOESSER *provided helpful comments on the manuscript.*

intatti della topografia originaria. Nella zona costiera, questi relitti sono costituiti dai rilievi pedemontani mentre, più internamente, comprendono le *mesas*.

I limiti erosionali di glaciazione incisi nella topografia alpina e sui fianchi delle valli dei ghiacciai di sbocco, delimitano la massima possibile estensione della copertura glaciale nella Terra Vittoria settentrionale dopo l'evoluzione della morfologia alpina. L'espansione glaciale fu minore presso le testate delle valli e nelle aree più rilevate, mentre nella zona costiera raggiunse i massimi valori di spessore. Non sono state individuate evidenze che testimonino un ispessimento della Calotta Estantartica tale da coprire i nunatak e le cime della Terra Vittoria settentrionale.

Sono stati differenziati depositi glaciali di varia età. Quello più diffuso e meglio conservato è rappresentato dal «complesso glaciale Terra Nova», attribuibile all'ultima glaciazione (late Wisconsin). Affiora principalmente nella zona costiera dove, fino a circa 30 m s.l.m., è tagliato da spiagge emerse oloceniche evolute a partire da 7 000-8 000 anni B.P. Il limite del «complesso glaciale Terra Nova» può essere seguito molto all'interno lungo le valli principali. Durante l'ultima espansione glaciale, l'ispessimento dei ghiacciai fu massimo nella zona costiera, dove si sviluppò un ghiacciaio pedemontano probabilmente collegato a una calotta glaciale poggiante sul fondo del Mare di Ross.

Strie glaciali individuate sugli alti rilievi della Eisenhower Range sembrano essere state incise durante l'ultima espansione glaciale. In tal caso, le calotte locali delle mesa ed i ghiacciai montani si sarebbero espansi ed avrebbero alimentato il ghiacciaio pedemontano di Terra Nova, contrariamente a quanto avvenuto più a S, dove i ghiacciai alpini delle Valli Secche erano meno estesi di ora durante il medesimo periodo.

TERMINI CHIAVE: Ghiacciaio, Calotta glaciale, Terra Vittoria, Antartide.

INTRODUCTION

The Terra Nova Bay region in northern Victoria Land lies along the western margin of the Ross Sea (fig. 1). Terra Nova Bay itself extends from the Drygalski Ice Tongue in the south to Cape Washington in the north (fig. 2). On the inland flank of Terra Nova Bay, the Transantarctic Mountains trend nearly north-south and culminate in Mt. Nansen (2 737 m), Mt. Hewson (3 720 m), and Mt. Melbourne (2 732 m). Long outlet glaciers pass through the mountains to Terra Nova Bay. Campbell Glacier is fed from mountain accumulation basins in the Transantarctic Mountains; it heads near the Mesa Range and terminates as the floating Campbell Glacier Tongue. The Reeves and Priestley Glaciers drain local mountain ice and interior East Antarctic ice from near Talos Dome. Both of these glaciers flow into the Nansen Ice Sheet, which floats on western Terra Nova Bay and is pinned by the Northern Foothills, Vegetation Island, and Inexpressible Island. Farther south, the huge David Glacier drains interior East Antarctic ice from near Dome C and also from the divide inland of Talos Dome; it terminates in the huge floating Drygalski Ice Tongue. Today marine waters of Terra Nova Bay, which reach depths of 800-1 000 m, extend far inland beneath floating ice into the glacier troughs.

Strong katabatic winds characterize both Reeves and Priestley Glacier troughs, but not the Campbell Glacier trough. One result is extensive blue-ice areas on Priestley and Reeves Glaciers. Another result is that extensive ice-free areas occur alongside these glaciers, as well as in low-lying areas near the glacier mouths, such as Tarn Flat, the Northern Foothills, and Inexpressible Island.

Our purpose was to decipher late Cenozoic ice-sheet behaviour in northern Victoria Land as part of a continuing program to understand and anticipate the response of the Antarctic Ice Sheet to climatic change. To achieve this goal we reconstructed past longitudinal profiles of outlet glaciers that extended into Terra Nova Bay. We also extended our Terra Nova map area northward so that it overlapped with upper Rennick Glacier, which flows into the Pacific Ocean and which was mapped earlier (DENTON & *alii*, 1986); taken together these two map areas cover a large fraction of northern Victoria Land and hence the combined results afford a regional scheme for glacier behaviour. Finally, we attempted to define a chronology for our reconstructed glacier profiles.

We undertook field work for this project in January and February of both 1989 and 1990. Our project built on reconnaissance and detailed studies already carried out on late Quaternary drift sheets in the Terra Nova Bay region (DENTON & *alii*, 1975; STUIVER & *alii*, 1981; OROMBELLI, 1986; BARONI, 1989; BARONI & OROMBELLI, 1989 a, b and 1991). The field work was jointly supported by Programma Nazionale di Ricerche in Antartide (Italy) and by the Division of Polar Programs (United States). Our headquarters was the Italian base at Terra Nova Bay. With helicopter support from this base and using remote fuel caches, we examined numerous ground localities from sea level to near the crest of the Transantarctic Mountains. Our glacial geologic studies were necessarily reconnaissance. Coverage was very good in the Northern Foothills, on Inexpressible Island, and in the Tarn Flat area; coverage was good alongside Reeves Glacier and on the summit mesa surfaces of the Eisenhower Range; coverage was fair alongside Priestley, Campbell, and David Glaciers and in the high mountains beside Campbell and David Glaciers.

We mapped conspicuous erosional glacial trimlines by ground examination and by slow helicopter traverses between ground localities. Within the trimlines, we plotted striations and mapped drift and moraines on the ground. We then traced moraines and the upper limits of perched erratics between ground localities, again by slow helicopter traverses. Elevations were determined from available topographic maps and from altimeter measurements corrected for low polar atmospheric pressure by crosschecking with known elevations. We estimate that the resulting elevations are generally accurate to within ±50 m.

MORPHOLOGICAL LANDSCAPES

The Transantarctic Mountains inland of Terra Nova Bay exhibit four major landscapes. The first type consists of deep troughs occupied by Campbell, Priestley, and Reeves Glaciers (fig. 3). These troughs head in theater-like bowls cut into bedrock beneath local or inland ice; David's Cauldron is a particularly prominent such feature. The lower portions of these troughs form ice-covered fjords, where present-day grounding lines extend inland beneath outlet glaciers.

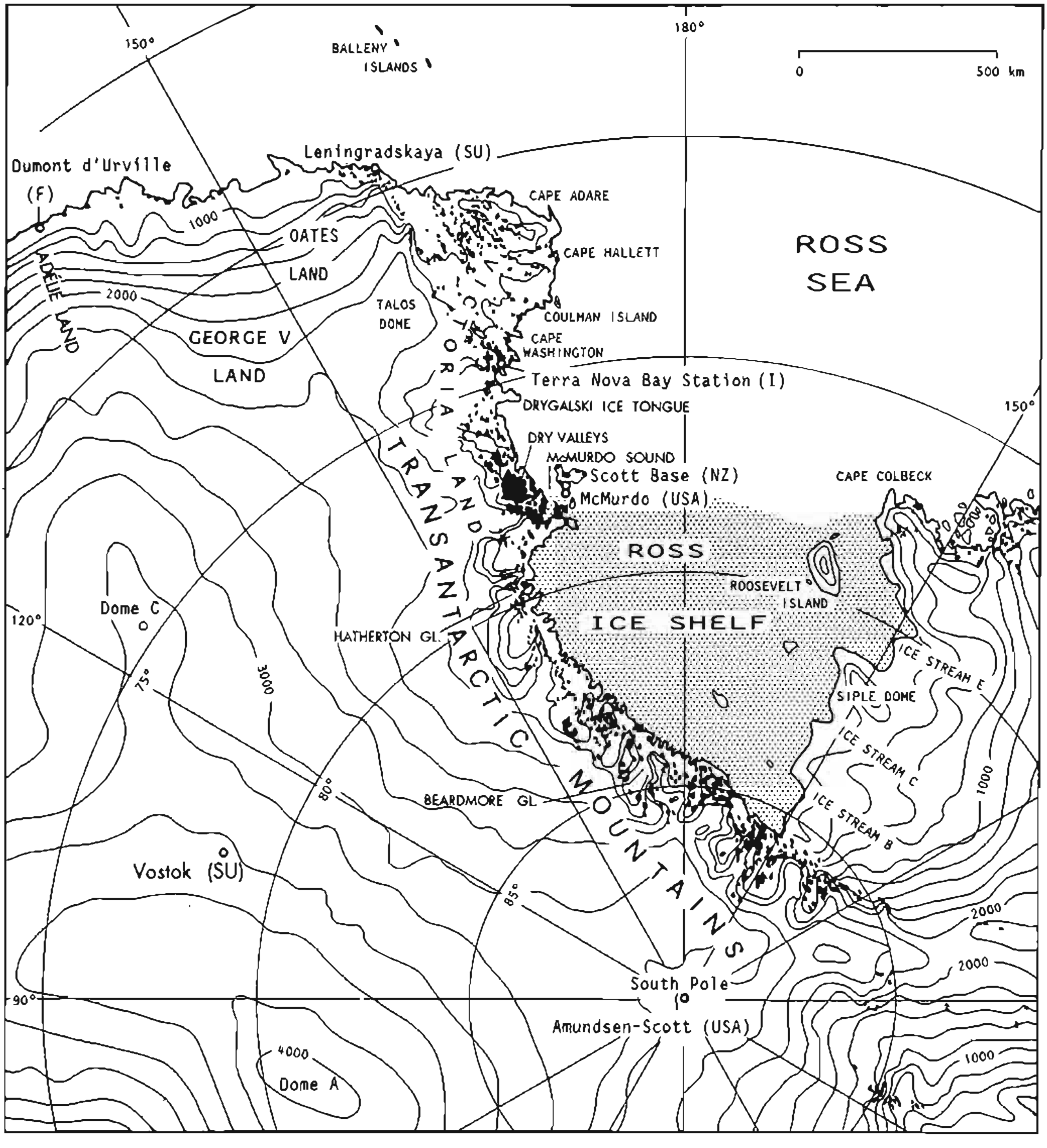


Fig. 1 - Index map of the Ross Sea area, Antarctica. Ice surface elevations are from Drewry (1983).

Second, well-developed alpine glacial topography characterizes the flanks of the troughs and intervening mountains. Numerous cirques, ridges, horns, and spurs mark the alpine topography; alpine glaciers drain into the major outlet glaciers. There are sharp morphologic changes where the mesa edges have been scalloped by the fringing alpine topography. The alpine morphology extends unbroken from the mesa edges (fig. 4) down to the present-day outlet and tributary glaciers. The alpine glacial topography is nearly filled with glacial ice, except for ice-free areas beside Reeves and Priestley Glaciers that are characterized by strong katabatic winds. Third, the high central

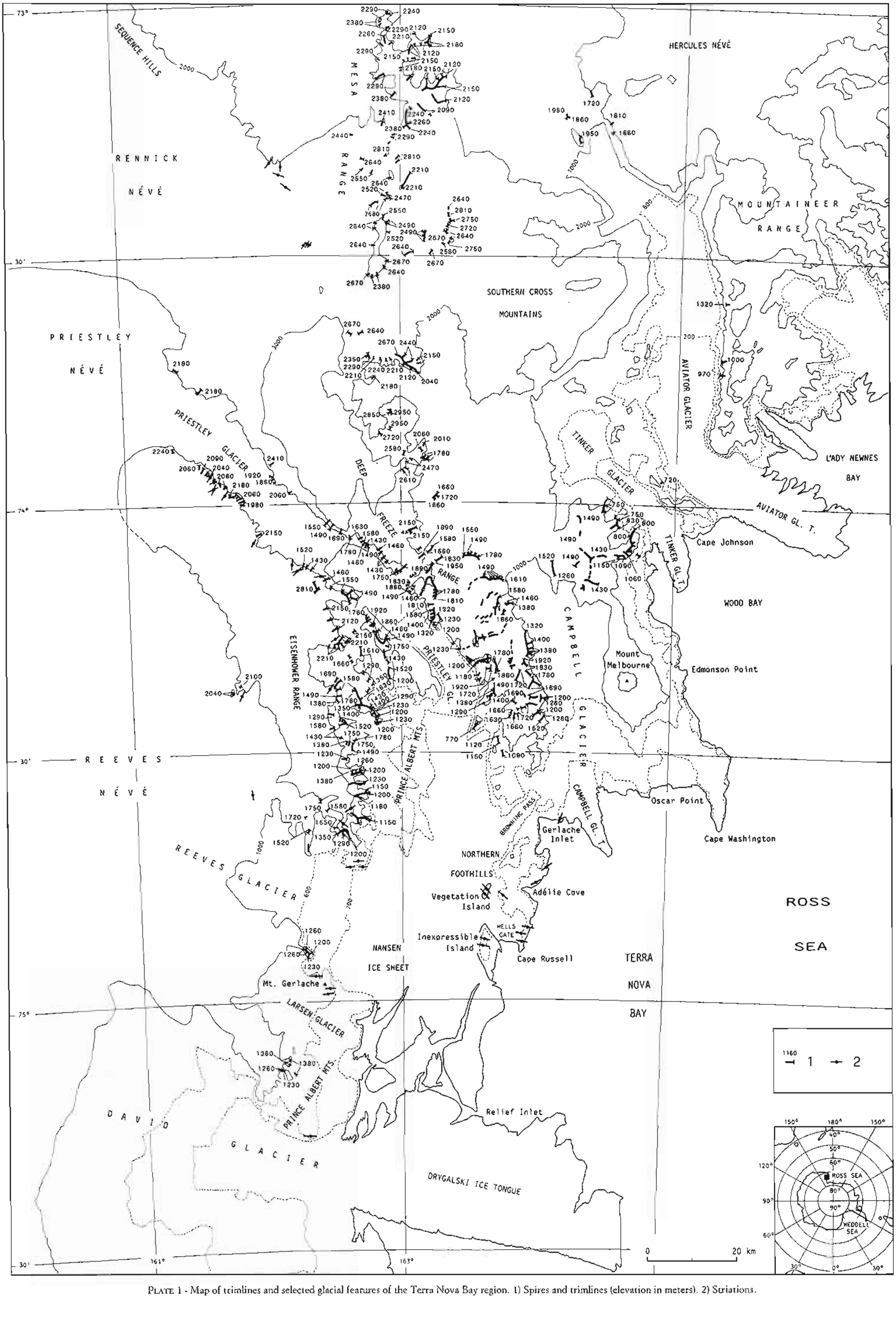


PLATE 1 - Map of trimlines and selected glacial features of the Terra Nova Bay region. 1) Spires and trimlines (elevation in meters). 2) Striations.

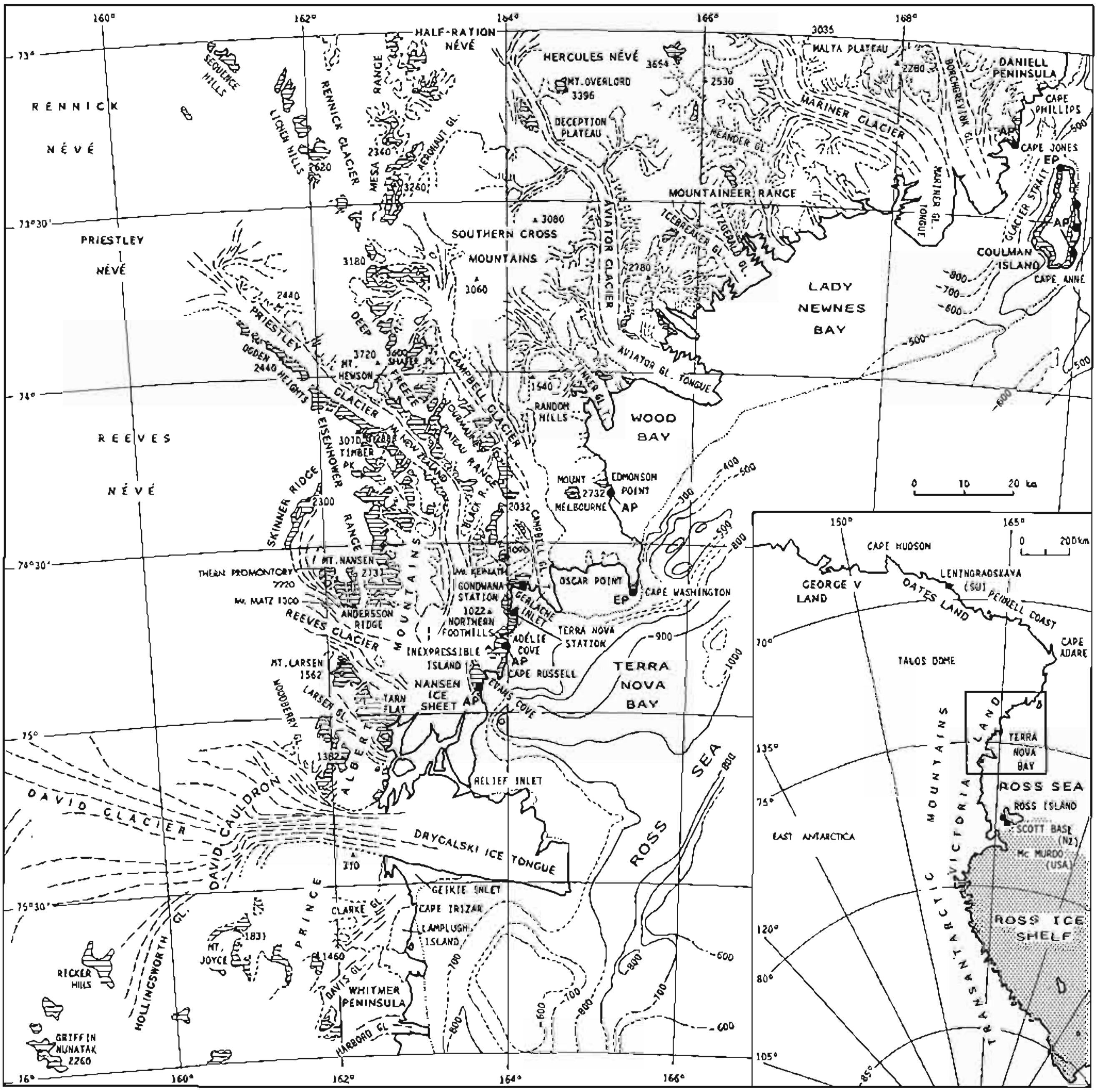


FIG. 2 - Index map of the Terra Nova Bay region. Adapted from U.S. Geological Survey 1:250,000 topographic maps. AP: Adélie penguin rookery. EP: Emperor penguin rookery.

mountain ranges between troughs commonly have summit mesas (fig. 4) of Ferrar Supergroup dolerite or of the granite surface of the exhumed Kukri Peneplain. Thin ice caps cover all but a few fringes of the central mesa topography. These caps commonly spill over the mesa edges to feed cirque or tributary glaciers within the alpine topography, which in turn drain into the main outlets.

The fourth type of morphology features undulating coastal piedmonts that are tilted seaward. Examples are the Northern Foothills, Inexpressible Island, and Tarn Flat. Inexpressible Island and Northern Foothills show alpine cirques in their steep inland flank and deep theater-shaped depressions cut partly below sea level in their eastern flank. Where they meet the undulating piedmonts, these troughs feature a sharp morphologic change from steep trough walls to the piedmont surfaces.

We draw several inferences from the geometric relationships of the differing landscapes in the Terra Nova Bay region. First, the glacier troughs have propagated inland by headward cutting. This process has left theater-shaped cauldrons at trough heads. Second, the alpine topography has propagated from these deep troughs into intervening mountain blocks. Third, this process of inland erosion by outlet glacier troughs and adjacent alpine topography has left isolated nearly intact remnants of the original topography. Near the coast, these remnants include the coastal piedmonts; farther inland they include the summit mesas. The coastal piedmont surfaces now have large ice-free areas, which in the Northern Foothills are interrupted by numerous snowbank glaciers. Presumably, the reason for these ice-free coastal piedmonts is the establishment of the present katabatic wind system in the deep outlet glacial troughs cut through the Transantarctic Mountains. Fourth, the fact that it is possible to associate all the landscape morphologies solely with mountain glaciation indicates that the presence of the East Antarctic Ice Sheet, which today spills over into the David and Priestley Glacier drainages, is not a necessary ingredient to erode the deep outlet troughs. Finally, there are indications that some alpine topography may be old and reflect a different-from-present climatic regime. Obviously, much glacial erosion can be taking place beneath the modern ice cover. But extensive tracts of alpine topography north of Reeves Glacier are now kept ice-free by the modern katabatic wind system, as are smaller tracts near Black Ridge beside Priestley Glacier and large tracts of coastal piedmonts. The modern

FIG. 3 - Priestley Glacier trough. This aerial view is to the northwest. The highest mountain in the center is Shafer Pk. (3 600 m). Priestley Glacier is about 8 km wide.

FIG. 4 - Summit mesa of the Eisenhower Range. The mesa surface (2 400-2 700 m elevation) is scalloped by the cirque headwalls of the fringing alpine topography. Aerial view is to the northwest from near the eastern edge of the range.

FIG. 5 - Spires developed in granite on alpine ridge on the eastern flank of the Eisenhower Range.

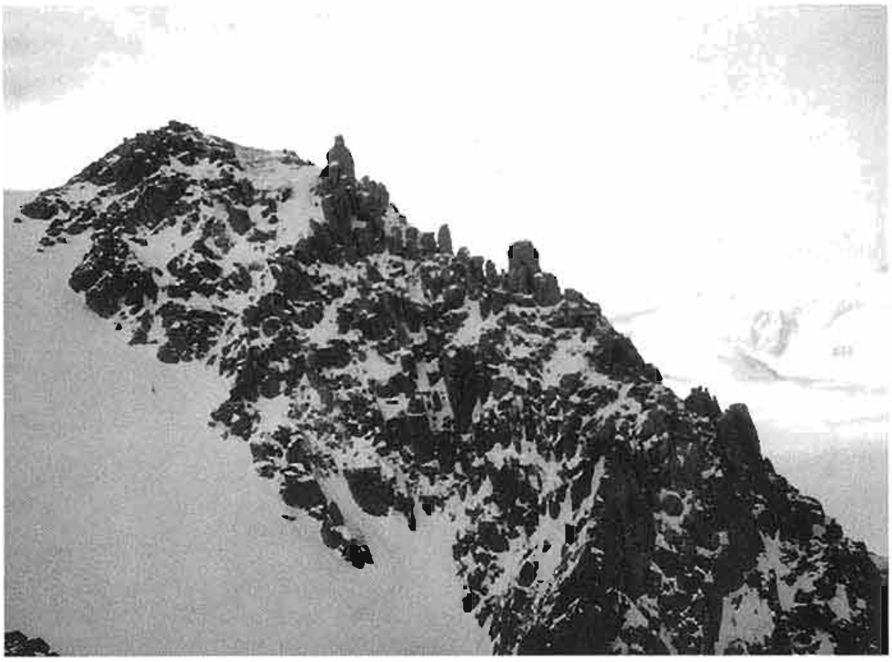


FIG. 6 - Spires developed in metasedimentary bedrock near Mt. New Zealand beside Priestley Glacier.

wind system has also superimposed an east-west asymmetry on the ice-free terrain within alpine topography cut into the fringes of the Eisenhower Range.

TRIMLINES

Well-defined erosional trimlines are etched into alpine ridges and spurs on the walls of Campbell, Priestley, and Reeves Glaciers. Plate 1 shows the distribution of serrated ridges and the elevations of trimlines within the Terra Nova Bay ice-drainage system. It is evident that many ridges and spurs, for example on the trough walls beside Priestley Glacier, show both an upper and a lower trimline. The upper and lower trimlines on these ridges and spurs persist without breaks across varying bedrock lithologies and structures. Exposed alpine ridges and spurs above the lower trimline and below the upper trimline are serrated and lack striations and erratics; similar ridges and spurs lack serrations below the lower trimline and above the upper trimline. Closely spaced spires up to 10 m high cause the serrated appearance of ridges and spurs beyond the trimlines (figs. 5 and 6). The bedrock that composes

TABLE 1 - Selected ^{14}C dates from Terra Nova Bay (Victoria Land, Antarctica)

Lab. n	^{14}C date (yr B.P.)	Location	Elevation (m a.s.l.)	Description	References
Shells from recent moraines on ice shelves					
GX-14079	2430 ± 135	Hells Gate West	4/6	Mixture of shells	BARONI (1990)
GX-14084	2495 ± 160	DO.	10/11	Mixture of shells	DO.
GX-14624	2665 ± 150	Hells Gate E	20/21	Cirripeds	DO.
GX-14097	2780 ± 145	Hells Gate E	9/10	DO.	DO.
GX-14091	2155 ± 140	Cape Confusion	4/5	Serpulids	DO.
GX-14075	2265 ± 140	Backstairs Passage	4/6	*Limopsis marionensis*	DO.
QL-174	7020 ± 60	Nansen Ice Sheet		*Adamussium colbecki*	STUIVER & *alii* (1981)
Shells collected at the surface of raised beaches					
GX-13626	2395 ± 60	Evans Cove, C. Russell	3.5	Mixture of shells	BARONI & OROMBELLI (1989b, 1991)
GX-14101	2710 ± 135	DO.	8	Cirripeds	BARONI & OROMBELLI (1991)
GX-14073	3010 ± 150	DO.	6	DO.	DO.
GX-14065	3235 ± 155	DO.	8	Mixture of shells	DO.
GX-13628	3335 ± 90	DO.	8	DO.	BARONI & OROMBELLI (1989b, 1991)
GX-14071	3545 ± 150	DO	6.5	Cirripeds	BARONI & OROMBELLI (1991)
GX-14068	4360 ± 175	DO.	14.5	Mixture of shells	DO.
GX-14077	4370 ± 170	DO.	22	Cirripeds	DO.
GX-14619	4485 ± 300	DO.	18.5	DO.	DO.
GX-14067	4885 ± 155	DO.	10.5	Mixture of shells	DO.
Pelecypod shells found *in situ* in marine sediments					
GX-14825	6620 ± 190	Evans Cove, C. Russell	10.5	*Adamussium colbecki*	DO.
GX-14627	6645 ± 95	DO.	10.5	*Laternula elliptica*	DO.
GX-14824	6765 ± 355	DO.	9.5	*Adamussium colbecki*	DO.
GX-13627	6815 ± 90	DO.	9	DO.	BARONI & OROMBELLI (1989b, 1991)
GX-14628	6890 ± 100	DO.	12.5	*Laternula elliptica*	BARONI & OROMBELLI (1991)
GX-14066	6915 ± 230	DO.	10.5	*A. colbecki & L. elliptica*	DO.
GX-14823	6935 ± 100	DO.	9	*Laternula elliptica*	DO.
GX-14070	7480 ± 260	DO.	12.5	*A. colbecki & L. elliptica*	DO.
GX-14069	7505 ± 230	DO.	14.5	DO.	DO.
Penguin guano and remains from ornithogenic soils on Holocene raised beaches					
GX-13613	3010 ± 220	Inexpressible Island	20.7	Penguin guano	BARONI & OROMBELLI (1989b, 1991)
GX-13616	3340 ± 85	DO.	6.2	DO.	DO.
GX-13617	3675 ± 90	DO.	14	DO.	DO.
GX-12757	4190 ± 80	DO.	14	Penguin remains	OROMBELLI (1988); BARONI & OROMBELLI (1989b, 1991)
NZ-6906a	4490 ± 280	Adélie Cove	4	Penguin bones	WHITEHOUSE & *alii* (1989)
GX-12755	4495 ± 135	Northern Foothills	25	Penguin bones	OROMBELLI (1988); BARONI (1989); BARONI & OROMBELLI (1989b, 1991)
GX-15494	4585 ± 105	Terra Nova Station	18	Penguin guano	This paper
GX-13620	4615 ± 85	Gondwana Station	15	DO.	BARONI & OROMBELLI (1989b, 1991)
GX-15495	4915 ± 115	Terra Nova Station	17	DO.	This paper
GX-12758	4930 ± 85	Inexpressible Island	26	DO.	OROMBELLI (1988); BARONI & OROMBELLI (1989b, 1991)
GX-13609	5315 ± 100	DO.	20.7	Penguin remains	BARONI & OROMBELLI (1989b, 1991)
GX-13608	5360 ± 90	Inexpressible Island	20.7	DO.	DO.
GX-13640	5440 ± 85	DO.	19.7	DO.	DO.
GX-13611	5530 ± 100	DO.	19.7	Penguin guano	DO.
GX-12760	5770 ± 60	Terra Nova Station	18	DO.	BARONI & OROMBELLI (1989b, 1991); BARONI (1989)
GX-13614	5945 ± 340	Inexpressible Island	20.7	DO.	BARONI & OROMBELLI (1989b, 1991)
GX-13612	6235 ± 110	DO.	19.7	DO.	DO.
GX-13615	6335 ± 110	DO.	20.7	DO.	DO.
Penguin guano and remains from ornithogenic soils on Terra Nova drift (above the marine limit)					
GX-12754	4290 ± 50	Northern Foothills	40	Penguin remains	OROMBELLI (1988); BARONI (1989); BARONI & OROMBELLI (1989b)
GX-13619	4495 ± 95	DO.	50	Penguin guano	DO.
GX-12756	5385 ± 85	Inexpressible Island	60	Penguin remains	OROMBELLI (1988); BARONI & OROMBELLI (1989b)
GX-13606	5575 ± 185	DO.	40	Penguin guano	BARONI & OROMBELLI (1989b)
GX-13618	6225 ± 105	DO.	50	DO.	DO.
GX-13621	6855 ± 195	N Adélie Cove	52	DO.	BARONI (1989); BARONI & OROMBELLI (1989b, 1991)
GX-13622	6860 ± 110	DO.	39	DO.	BARONI (1989); BARONI & OROMBELLI (1989b)
GX-14098	7065 ± 250	DO.	39	DO.	BARONI (1989); BARONI & OROMBELLI (1991)
Shells from the matrix of the Terra Nova drift					
GX-15496	25,300 ± 1650	Tethys Bay	250	Pelecypods	This paper
GX-13605	> 33.000	Boulder Clay Gl.	115	Serpulids & Pelecypods	BARONI & OROMBELLI (1989b)
GX-15497	> 33.000	Tethys Bay	250	Cirriped frags.	This paper
TO-1980	25,620 ± 230	DO.	250	Pelecypod frag.	DO.
TO-1978	31,930 ± 370	DO.	250	Cirriped frag.	DO.
TO-1977	32,100 ± 340	DO.	250	Pelecypod frag.	DO.
TO-1979	37,470 ± 460	DO.	250	Pelecypod frags.	DO.

the serrations commonly is deeply weathered and exhibits cavernous weathering. We have not found erratics, drift, or striated bedrock surfaces on serrated ridges. However, drift sheets and erratics occur in places on the ridges that lack serrations. Striated bedrock also occurs on competent high-elevation granite bodies that make up non-serrated ridges near present-day glaciers, but is generally absent elsewhere. Commonly, non-serrated bedrock ridges distant from present glaciers are deeply weathered and exhibits cavernous hollows.

The lower trimline alongide Priestley Glacier exhibits smoothly decreasing elevations along the length of the trough. A similar situation occurs for the lower trimline in the Campbell and Reeves Glacier troughs. In sharp contrast to the consistency of the lower trimline, the upper trimline shows a high degree of irregularity. It is present only below mesa ice caps or extensive mountain accumulation basins. In such situations the trimline elevations are very irregular and appear related to the elevation and size of these higher adjacent glaciers. Further, the upper trim-

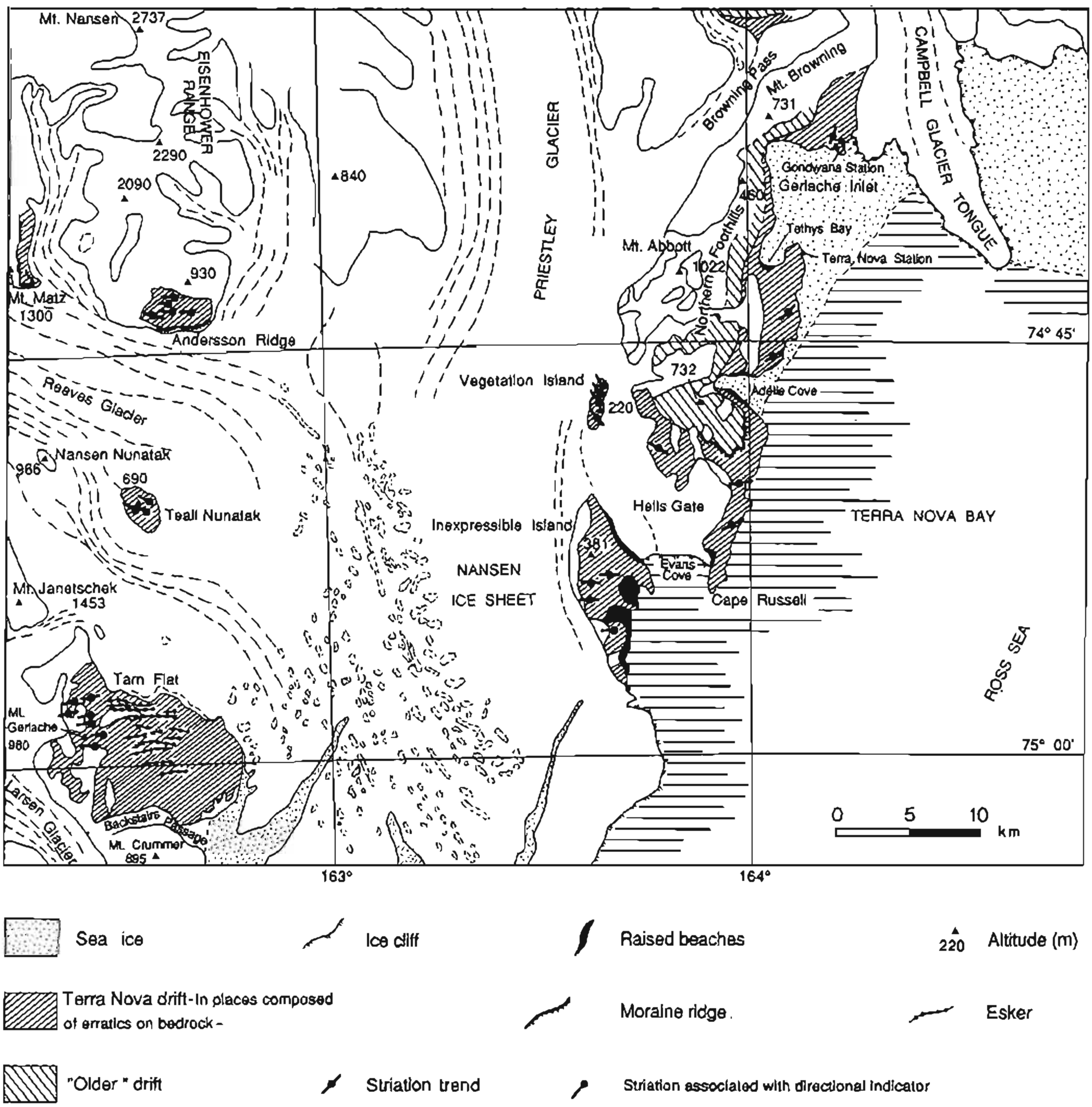


FIG. 7 - Sketch map of the general distribution of Terra Nova drift.

line is absent in steep alpine areas where there are no higher glaciers. In such situations the serrated ridges extend to summit areas.

Serrated ridges also occur on peaks that project as nunataks through thin mesa ice caps or mountain accumulation basins. Just as alongside outlet glaciers, these serrated ridges have a distinct lower trimline, below which ridges are smoothed and lack serrations. Such trimlines are generally close to current ice surfaces. For example, in the Tourmaline Plateau of the Deep Freeze Range, highly weathered granite bedrock serrations extend to within a few meters of the present ice surface. In the Eisenhower Range, the trimline on Timber Peak nunatak is also close to the present mesa ice surface.

Our network of trimline measurements in the Terra Nova Bay ice drainage system overlaps with a similar network for the Rennick Glacier system (DENTON & *alii*, 1986), which drains northward into the Pacific Ocean. The lower trimlines match where the two areas overlap. For example, the upper Campbell and Rennick Glaciers meet at the southern end of the Mesa Range; here the lower trimline traced up Campbell Glacier fits the same trimline traced inland up the length hof the Rennick Glacier.

GLACIAL DRIFT AND EROSIONAL SURFACES

TERRA NOVA DRIFT

General Statement. Terra Nova drift was informally called «younger drift» by STUIVER & *alii*, (1981) and «Terra Nova I drift» by OROMBELLI (1986). It is the most prominent of two drift sheets that occur below the lower and above the upper trimlines. This drift is best displayed in coastal areas in the Northern Foothills, Inexpressible Island, and Tarn Flat. Farther inland, ice-free terrain alongside outlet glaciers is generally too steep to preserve drift, or else has been subjected to so much downslope movement that any moraines or drift have been removed. However, exceptions occur where Terra Nova drift is preserved along the northern flank of Reeves Glacier, in the Black Ridge area beside Priestley Glacier, and on the southern flank of Mt. Keinath beside Browning Pass.

Northern Foothills. Terra Nova drift mantles the eastern flank of the Northern Foothills between Cape Russell and the Campbell Glacier Tongue (fig. 7). The drift is generally a thin and discontinuous matrix-supported diamicton or else simply a scattering of clasts and erratics that rests directly on bedrock. But an important exception is that Terra Nova drift is nearly continuous for several kilometers north and south of Adélie Cove. Here it is a massive, matrix-supported diamicton with a sandy-silt matrix that ranges in color from grey-brown to olive-grey (BARONI & OROMBELLI, 1989b). Most clasts are angular, but some are bullet-shaped and show surface striations. The clast lithologies include gneiss, micaschist, granite, amphibolite, basalt and diorite; most notably, olivine-basalt erratics of the McMurdo Volcanics are also common. Here and elsewhere along the eastern flank of the Northern Foothills, Terra Nova drift up to elevations of 300 m has a muddy, light-grey matrix that is rich in shell fragments, pelecypods,

TABLE 2 - δ ^{18}O values of ice cores in Terra Nova drift

Sample n.	Description	Locality	Elevation (m a.s.l.)	δ ^{18}O (‰)
890125.01	Buried ice from ice-cored Terra Nova drift	South Adélie Cove	300	− 34.16
890125.02	DO.	DO.	DO.	− 35.40
890125.03	DO.	DO.	290	− 9.11
890125.04	DO.	DO.	DO.	− 28.21
890125.05	DO.	DO.	DO.	− 5.54
890125.06	DO.	DO.	250	− 4.06
890125.07	DO.	DO.	DO.	+ 2.03
890126.07	Buried ice from deformed ice-cored Terra Nova drift (5-15 cm depth below the ice/debris contact)	North Adélie Cove	100	− 3.24
890126.08	DO. (15-20 cm depth)	DO.	DO.	− 3.98
890126.09	DO. (30-40 cm depth)	DO.	DO.	− 19.85
890126.10	DO. (10-20 cm depth)	DO.	120	− 14.14
890126.11	DO. (30-40 cm depth)	DO.	DO.	− 26.44
890126.12	DO. (0-10 cm depth)	DO.	130	− 3.26
890126.13	DO. (10-20 cm depth)	DO.	DO.	− 12.46
890126.14	DO. (20-30 cm depth)	DO.	DO.	− 3.22
890127.02	Buried ice from ice-cored Terra Nova drift (near a Thenardite cone)	DO.	300	+ 2.02
890203.01	Buried ice from ice-cored drift	Edmonson Point	80	− 21.96
890131.01	Buried ice from debris-covered glacier	Skinner Ridge	1 600	− 33.53
890131.02	Buried ice from ice-cored drift	DO.	1 850	− 33.38
890131.03	DO.	DO.	DO.	− 29.94

FIG. 8 - Ice-cored cones of Terra Nova drift near Adélie Cove, Northern Foothills. View to the south.

serpulids, sponge spicules, echinoderms and foraminifers. Such deposits, rich in marine macrofauna and microfauna, are especially common between Tethys Bay and Adélie Cove (BARONI & OROMBELLI, 1989 a, b; CHINN & *alii*, 1989). Several conventional and AMS ^{14}C dates were obtained from fragments of marine shells collected at Tethys Bay and Adélie Cove. Fragments of pelecypods from Tethys Bay yielded a conventional ^{14}C age of 25,300 ± 1650 yr B.P. (GX-15496). Two other conventional ^{14}C dates, both greater than 33,000 yr B.P., were obtained from fragments of serpulids and barnacles (GX-13601; GX-15498). Four AMS ^{14}C dates have been obtained from single shell fragments (*Laternula elliptica* and Cirripeds) picked from among those that are less worn and have a fresh and fragile aspect. Their ages range between 25,620 ± 230 yr B.P. (TO-1980) and 37,470 ± 460 yr B.P. (TO-1979) (Table 1). Taken at face value, these dates suggest that Terra Nova drift is younger than 25,000 yr B.P. and is Late Wisconsin in age. However, this suggestion is tentative because radiocarbon dates of shell material of this age must be treated with caution.

Terra Nova drift up to 250 m elevation near Adélie Cove is commonly ice cored and hummocky, with cone-shaped hills up to 2 m high (figs. 8 and 9). The enclosed ice gives $\delta\,^{18}O$ values ranging from − 35.40 to + 2.03‰ wrt SMOW (Table 2). The more negative values are indicative of glacier ice formed in a colder environment with respect to the present one; the mean annual $\delta\,^{18}O$ value of snow at Terra Nova Bay ranges between -20 and -24‰ (MORGAN, 1982). The positive values are indicative of sea ice. Both types of ice are present in the Terra Nova ice-cored drift, where highly different values of $\delta\,^{18}O$ were obtained from samples collected in a vertical sequence of a few decimeters in the same ice-cored debris cone.

Terra Nova drift is only moderately weathered (STUIVER & *alii*, 1981; BARONI & OROMBELLI, 1989a, b). The erratics lack cavernous weathering except close to the present coast; they are commonly angular and show light-brown to reddish-brown staining. Soil development is very weak with faint oxidation a few centimeters deep in some places. Perched clasts and erratics, some delicately balanced, are common on the drift surface.

FIG. 9 - Ice-cored Terra Nova drift near Adélie Cove, Northern Foothills.

The upper boundary of Terra Nova drift in the Northern Foothills is indistinct, marked in only a few places by a moraine ridge less than one meter high. Elsewhere the upper boundary is irregular and shows transition of little-weathered Terra Nova drift to moderately weathered older drift. Part of the problem in mapping this irregular upper drift limit comes from the distribution of wind-fed snowbank glaciers in all the hollows of the terrain. Some of these glaciers have deposited or reworked Terra Nova drift. The upper indistinct boundary of Terra Nova drift ranges from 290 m to 380 m elevation on the eastern flank of the Northern Foothills.

Very few striated bedrock surfaces occur in the Northern Foothills below the upper limit of Terra Nova drift. Presumably this is because here the predominant granitic bedrock is coarse-grained and weathers rapidly enough to remove any surface polish and striations that may have been present. The best-preserved striated surfaces were found

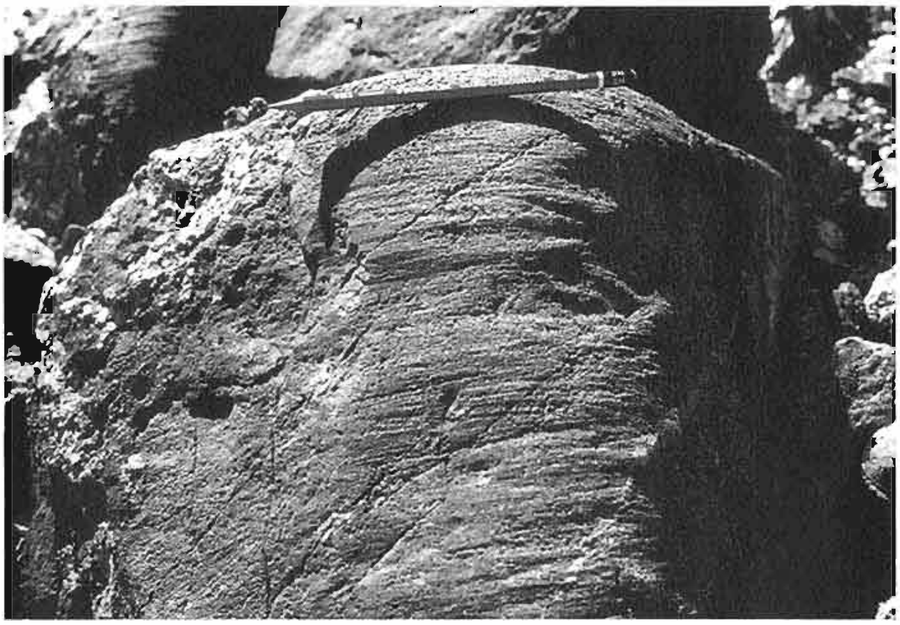
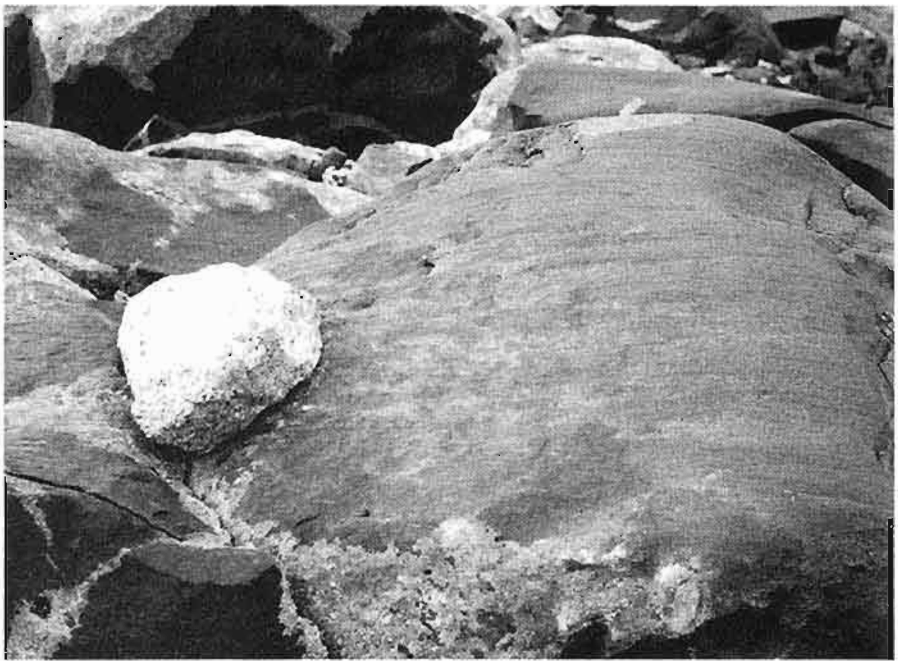


FIG. 10 - Striated mafic bedrock in the Northern Foothills near Campbell Glacier Tongue.

FIG. 11 - Terra Nova drift cone, Inexpressible Island.

FIG. 12 - Striated mafic bedrock with surface granite erratic, Vegetation Island.



on fine-grained metamorphic rocks alongside Campbell Glacier Tongue (fig. 10). Striated surfaces elsewhere are preserved merely as small patches on fine-grained dike rocks (Cape Russell, Adélie Cove).

Inexpressible Island. Terra Nova drift is nearly continuous across the eastern lowlands of Inexpressible Island. Most surface erratics are angular, with only a few showing facets and striations. Some erratics are perched. Constructional morphology, such as moraine ridges, is absent except for a few conical hummocks that may be ice cored (fig. 11). Terra Nova drift can be traced without a weathering break or intervening moraine ridge from near sea level to the top of Inexpressible Island (390 m) along the relatively gentle eastern island slope. However, the drift cover becomes increasingly less extensive with elevation, until near the island top only erratics rest on cavernously weathered bedrock.

Striated bedrock surfaces are very rare on Inexpressible Island, presumably because of the easily weathered, coarse-grained bedrock. Only a few scattered striations were observed on competent, fine-grained dike rocks.

Vegetation Island. Vegetation Island, situated between the Northern Foothills and Inexpressible Island and rising to an elevation of 220 m, exhibits numerous striated upturned edges of competent fine-grained mafic bedrock (fig. 12). Although Vegetation Island does not exhibit Terra Nova drift patches, it does have angular erratics on its striated bedrock surface.

Tarn Flat and Mt. Gerlache. Terra Nova drift covers much of Tarn Flat and the contiguous ice-free area up to, but not including, the summit of Mt. Gerlache (940 m). Terra Nova drift consists of scattered angular erratics and small patches of diamicton in much of this area. One important exception, however, is in inner Tarn Flat in a low ice-free area below Mt. Gerlache. Here, an extensive cover of Terra

FIG. 13 - Esker on Tarn Flat. Aerial view to the west. Such features are more than a hundred meters wide and several hundred meters to a few kilometers long.

Nova drift, with typical angular and perched erratics, is characterized by a swarm of eskers (fig. 13) (SKINNER & RICKER, 1968; DENTON & *alii*, 1975; STUIVER & *alii*, 1981; OROMBELLI, 1986). These eskers show an undulating pattern, are up to 30 m high, are anastomosing, show a rounded top, and consist of well-sorted and subrounded boulders, cobbles, gravel, and sand.

We could not find striations on Tarn Flat bedrock. However, striated and polished granite bedrock was widespread in adjacent higher terrain near Mt. Gerlache. Typical examples are given in figure 14 and also in figure 7-23 in STUIVER & *alii* (1981). The granite bedrock still retains extensive pits and cavernous hollows. The striated surfaces appear to postdate most of these weathering features, because striations occur even in shallow cavernous hollows. Moreover, the striated bedrock surfaces display patches of Terra Nova drift, some infilling cavernous hollows. These features strongly suggest that the striated surfaces postdate the extensive weathering and pitting of the granite surface and were produced by Terra Nova glaciation that merely retouched the preexisting bedrock with polish and striations. However, it is quite possible that minor weathering has occurred subsequent to Terra Nova glaciation, because in places small caverns sharply cut striated surfaces. Moreover, exfoliation is removing some striated patches.

Teall and Hansen Nunataks. These two nunataks occur in a blue-ice area of the lower Reeves Glacier. Teall Nuna-

FIG. 14 - Striated surface of weathered granite near Mt. Gerlache.

FIG. 15 - Lateral moraine at Andersson Ridge.

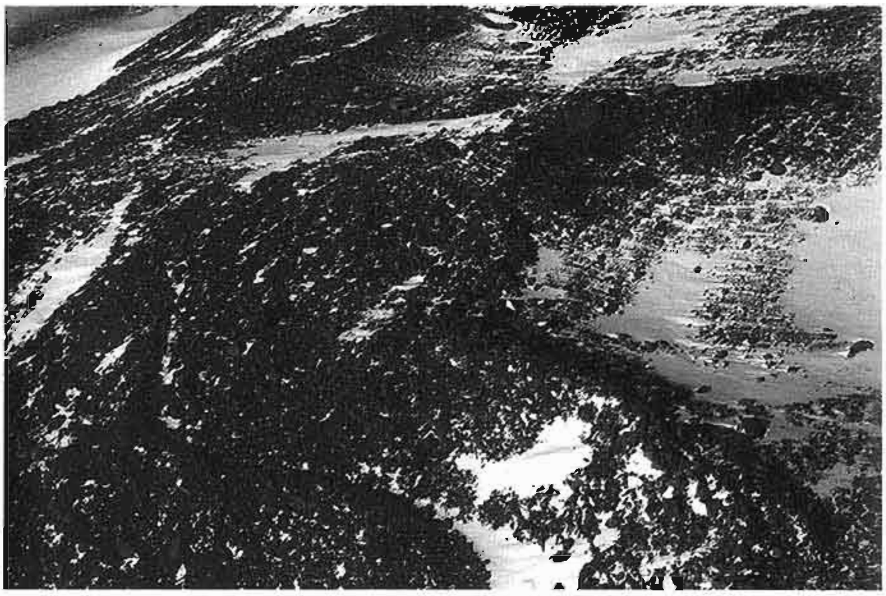


FIG. 16 - Two recessional lateral moraines below Mt. Matz within the Terra Nova drift limit; the moraine ridges are 1-2 m high and composed of coarse angular boulders.

tak, composed of granite and mafic rocks, exhibits well-preserved striated surfaces with Terra Nova erratics and drift patches from the present ice surface to the summit at 490 m elevation. Hansen Nunatak, also composed of granite, has sides too steep to preserve drift or to be examined for striations. But the summit area at 966 m elevation shows highly weathered bedrock without surface drift or striations.

North Side of Reeves Glacier. Extensive ice-free areas in competent granite bedrock occur alongside the northern edge of Reeves Glacier. Here the Anderton and two unnamed glaciers flow as tributaries into Reeves Glacier. Elsewhere, troughs, ridges, and horns representing former alpine glaciation are now ice-free, presumably because of the extraordinary katabatic winds that drain down Reeves Glacier. This situation affords a unique opportunity to trace Terra Nova drift inland beside an outlet glacier.

Terra Nova drift occurs in most ice-free areas alongside northern Reeves Glacier. Morphologically distinct moraine ridges occur in a few localities. For example, the upper limit of Terra Nova drift is marked by moraine ridges 1-2 m high composed of angular, stacked boulders and cobbles near Mt. Matz and also on the bedrock ridge 3 km northwest of Mt. Matz. Large lateral moraines with steep faces towards Reeves Glacier occur well within the Terra Nova drift limit both on Andersson Ridge (fig. 15) and on the ridge below Mt. Matz (fig. 16). Elsewhere, Terra

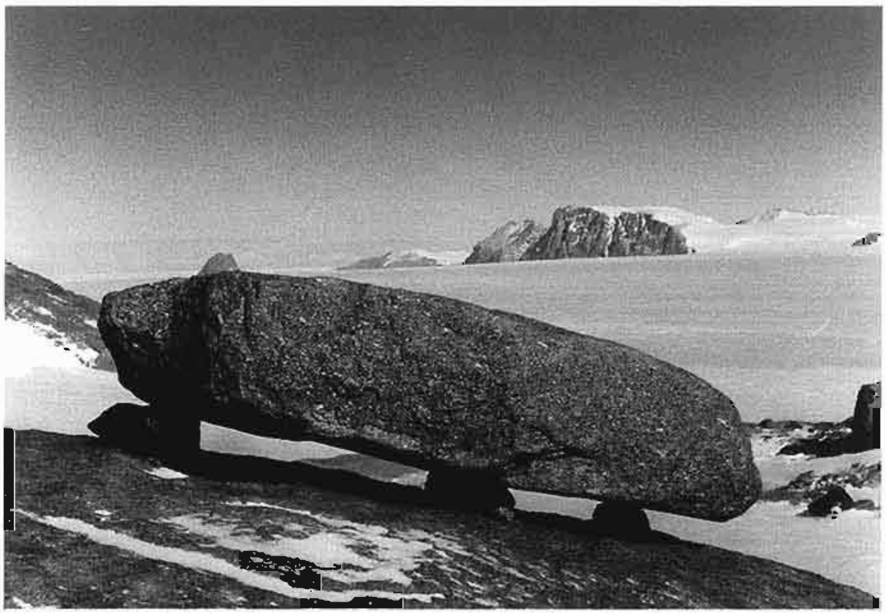


FIG. 17 - Perched boulder on striated granite bedrock surface within the Terra Nova drift limit in the southern Eisenhower Range beside the northern edge of Reeves Glacier. View is toward the southeast. The boulder is 1.5 m long.

Nova drift consists of erratics or small drift patches resting directly on granite bedrock. The drift shows angular clasts with some surface staining but no cavernous weathering. Angular perched erratics are common (fig. 17). The granite bedrock surface preserves excellent bossed-and-striated surfaces near the present-day glacier. In the wide granite bedrock expanse below Thern Promontory, well-preserved striations and bossing extend from the present Reeves Glacier surface to the upper limit of Terra Nova drift. At this limit the angular and perched erratics end together with the striated granite bedrock, to be succeeded at higher elevations by weathered drift resting on weathered granite bedrock that lacks preserved surface striations. The low-lying granite bedrock north of the lateral moraine on Andersson Ridge also shows well-preserved Terra Nova drift patches and erratics. The granite bedrock here is bossed with striations in numerous localities. These striations occur even in shallow cavernous hollows and, as in the similar situation near Mt. Gerlache, almost surely postdate most of the weathering that produced the surviving pits and hollows in the granite bedrock. On the adjacent northern hillslope north of Andersson Ridge, Terra Nova drift and erratics, but not striated bedrock, extend to 950 m elevation.

Skinner Ridge. Skinner Ridge, composed of Ferrar and Beacon supergroup rocks, is situated in the western Eisenhower Range on the western side of the mesa ice cap. A tributary glacier from the Eisenhower Range mesa ice cap flows southward past the eastern flank of Skinner Ridge and then curves southeastward to join Reeves Glacier. Mt. Mackintosh (2 300 m) and the high peak 2 km to the southwest both show serrated ridges with a lower trimline. Terra Nova drift, featuring angular clasts, perched erratics, and ice cores, mantles ice-free areas near Mt. Mackintosh and beside the tributary glacier, where it rests on striated dolerite and sandstone bedrock. This drift extends close to the lower trimline. We could not determine if Terra Nova ice overran Mt. Fenton (2 480 m) or the long ridge south of the serrated peaks. In both places the dolerite bedrock was shattered and not suitable for preserving glacial features.

Black Ridge and Mt. Keinath. Black Ridge is a large snow-free area exposed to katabatic winds between Priestley and Corner Glaciers. The bedrock is composed of magmatic and metasedimentary rocks. Terra Nova drift is present throughout this area and at its upper boundary, at about 950 m elevation, is a well — pronounced moraine ridge. The moraine is 1-2 m high and rests directly on the more weathered and stained sediments of the older drift.

On the southern slope of Mt. Keinath (1 090 m), at the confluence of Boomerang and Browning Pass Glaciers, a widespread cover of Terra Nova drift occurs up to an elevation of 580 m, where it is in sharp contact with the older drift. The uppermost part of the Terra Nova drift forms a terrace with hummocky ice-cored topography. Less evident terraces occur at lower elevations at about 500 m, 350 m and 200 m, where large olivine basalt erratics are scattered on the surface.

Eisenhower Range. The Eisenhower Range features two extensive summit mesas. The lower-elevation mesa basically represents the top of the exhumed Kukri Peneplain cut in granite. Along the eastern edge of the Eisenhower Range, this granite mesa ranges from 2 290 m to 2 400 m elevation. The surface of the mesa dips to the west. Isolated pieces of this granite mesa occur as the Ogden Heights, reaching 2 470 m elevation, in the northernmost Eisenhower Range. A higher but less extensive mesa, topped by Mt. Nansen (2 737 m), is constructed of Ferrar Supergroup rocks. An ice cap covers most of these mesa surfaces. Presumably because of the regional tilt of the mesa surfaces, this ice cap generally flows westward and southwestward into the upper Reeves Glacier. Little ice now flows eastward over the mesa edge and down the steep eastern Eisenhower Range flank into the alpine glacial topography, except in the O'Kane Canyon and Foolsmate Glacier areas. The result is that small ice-free granite and dolerite outcrops occur along the eastern rims of the Eisenhower Range mesas. The outcrops of competent granite on the lower mesa are commonly striated, whereas the less competent Ferrar Supergroup outcrops on the upper mesa show no striations.

We now discuss the results from the eastern edge of the Eisenhower Range granite mesa, starting in the south. The southern tip of this mesa at 2 200 m elevation is a narrow remnant between headward-cutting cirques of the fringing alpine topography. About half of this remnant surface is covered by thin snow and ice slabs. On the ice-free half, many granite outcrops show bossed and striated surfaces, commonly with crescentic gouges and occasionally with polish. These bossed surfaces have no cavernous weathering, in sharp contrast with the adjacent steep eastern Eisenhower Range face which has advanced weathering with deep hollows. The bossed granite surfaces are nearly free of debris except for a few surface clasts of local granite. No erratics were found. Taken together, the striation trends and the crescentic gouges indicate southwestward flow across the entire mesa, even up to its sharp and scalloped eastern edge. We are currently unable to distinguish between two explanations for this flow direction. The first explanation is that the striations are ancient and represent ice flow across the mesa from an accumulation surface to the northeast now removed by headward erosion of the fringing alpine glacial topography. But such a situation is at odds with the differential cavernous weathering of the granite plateau surface and eastern mesa flank. The second explanation is that the striations are young and represent growth of the mesa ice cap. However, in this case the expanded ice cap would have had curious unidirectional flow, rather than radiating flow from a central dome.

In the Mt. Baxter (2 430 m) area, granite bedrock is deeply weathered. Numerous striated surfaces occur on a patina crust that covers this weathered granite. The striated surfaces and adjacent non-striated surfaces exhibit only a few erratics of locally derived Ferrar Supergroup rocks.

At Eskimo Point (2 700 m) bossed granite bedrock reveals numerous patches of striations that are best preserved

FIG. 18 - Striated and polished granite surface with erratics on rim of Eisenhower Range mesa near Timber Peak at 2 600 m elevation on the edge of the Priestley Glacier trough.

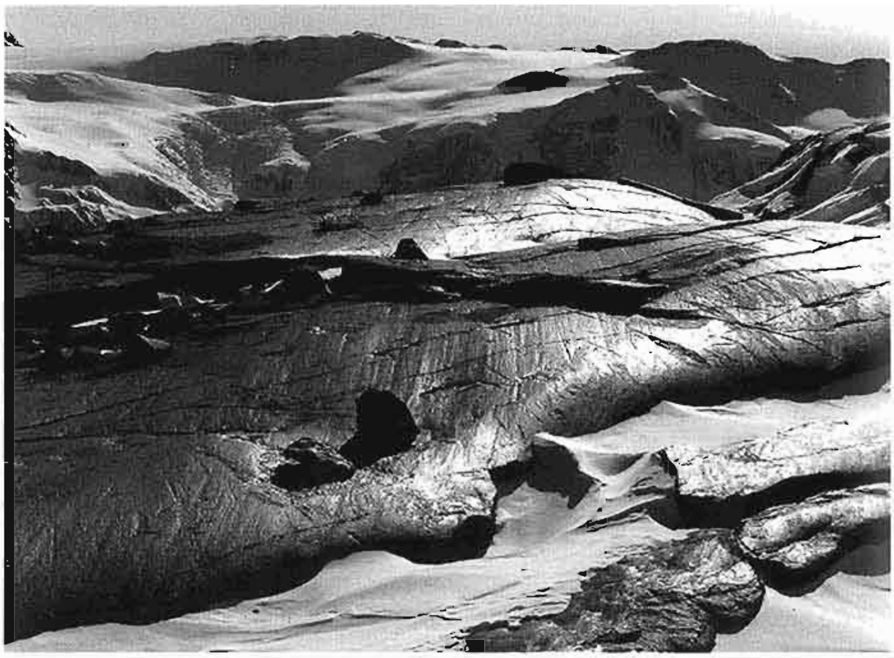


FIG. 19 - Granite rim at edge of Ogden Heights mesa at 2 500 m elevation above the Priestley Glacier trough. The granite bedrock outcrops, which lie near the edge of the mesa ice cap, are polished and striated.

near local snowbanks that appear to have receded recently. The glaciated granite surfaces are virtually debris-free, and no erratics were observed.

The entire granite rim at about 2 600 m overlooking the Priestley Glacier trough near Timber Peak exhibits excellent bossed and polished striated surfaces (fig. 18). The striation trend and common friction marks together show ice flow to the northeast. This flow direction is confirmed by the extensive cover of fresh, angular Ferrar Supergroup erratics that are scattered over the glaciated surface and were derived from the Timber Peak area a short distance to the southwest. The Ferrar Supergroup erratics, along with locally derived granite clasts, are angular and unweathered except for surface staining. Delicately perched cobbles and boulders are common. These striated surfaces are immediately adjacent to the ramp edge of the mesa ice cap, which here features a double set of ice-cored moraines. A critical observation concerns outcrops of Ferrar Supergroup bedrock that occur at the same elevation alongside the freshly striated granite outcrops. The glacial geologic situation is precisely the same on these two side-by-side bedrock types. Although it is also littered with fresh, angular clasts, some delicately perched, and is also beside a pair of fresh ice-cored moraines, the Ferrar Supergroup bedrock lacks polish and striations.

The Odgen Heights form an isolated and elongated flat-topped mesa of granite beside the upper Priestley Glacier trough. This mesa is scalloped on all sides by theater-depressions of the alpine topography. In several places, opposing cirques cause constrictions of the mesa. Again most of the plateau surface of Ogden Heights is covered by thin ice caps. These caps spill southwestward down the mesa edge to feed Foolsmate Glacier and Reeves Névé. However, just as elsewhere in the Eisenhower Range, the mesa ice cap does not spill northeastward down the steep wall of Priestley Glacier trough. Alongside the mesa ice caps of Ogden Heights are ice-free rims of granite bedrock (fig. 19). These granite outcrops commonly exhibit bossed and striated bedrock surfaces, some of which project out from under the edge of the ice cap cover (fig. 20). Crescentic gouges are common on these glaciated surfaces. The glaciated surfaces show only very rare surface clasts. No erratics were found. The striation trends and orientation of crescentic gouges show a variety of ice-flow directions.

Holocene moraines

Holocene moraines are widespread near margins of outlet glaciers, ice shelves, and small local glaciers (Orombelli, 1986; Baroni and Orombelli, 1989b, Chinn & *alii*, 1989).

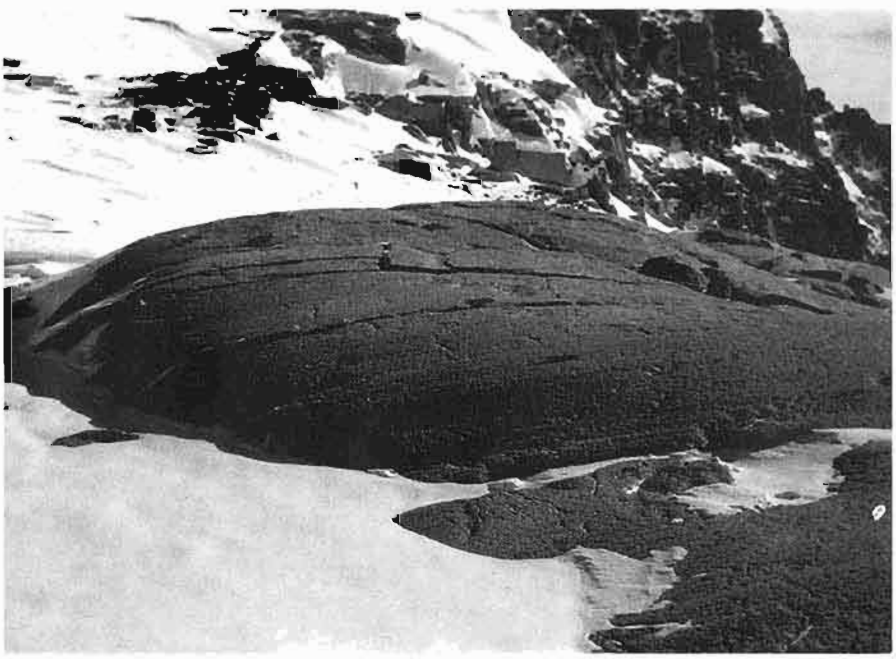


Fig. 20 - Polished and striated granite bedrock on rim of Ogden Heights mesa at 2 500 m elevation above the Priestley Glacier trough.

Fig. 21 - Strongly rubified relict soil with large salt flakes developed on metamorphic rocks at Mt. Browning.

FIG. 22 - East coast of Inexpressible Island. Headlands of bedrock are washed to 30 m. The coves exhibit raised beaches to an elevation of about 30 m cut into Terra Nova drift.

They generally consist of several subparallel ice-cored ridges or aligned hummocks. Among each group of moraines it is possible to differentiate a sequence on the basis of the depth of ice core, color of staining, stability of the surface, and development of lichen cover and patterned ground. In many localities, there exists a sharp contrast in color of staining between Holocene ice-cored moraines and oxidized Terra Nova drift.

Small local glaciers, for example in the Northern Foothills, generally show two fringing ice-cored moraines that can be separated on the basis of relative weathering criteria. Larger glaciers show more complex suites of Holocene moraines, but again they can commonly be subdivided into two sets on the basis of relative weathering criteria. Particularly prominent Holocene moraines occur on northern Tarn Flat beside the Nansen Ice Sheet, near Andersson Ridge, north of Mt. New Zealand, south of Black Ridge, on the southeastern side of Corner Glacier, and at the confluence between Boomerang Glacier and Browning Pass.

At Edmonson Point, a local glacier flowing off the flanks of Mt. Melbourne deposited a complex sequence of Holocene moraines on both its sides. The terminal part of these moraines is made up of pebble beach stones and silty-sandy marine deposits testifying to at least two different Holocene advances. At the southern margin of the glacier several articulated and unbroken shells of *Adamussium colbecki* and *Laternula elliptica* have been collected from the more internal moraine. The age of the shells ranges from 1840 ± 95 yr B.P. (GX- 13603) to 2290 ± 140 yr B.P. (R- 1885). Taking into account the large marine reservoir correction which must be applied to these dates, the results show a glacier advance within the last seven centuries.

OLDER DRIFT(S) AND WEATHERED BEDROCK

Patches of older drift(s) occur above the limit of Terra Nova drift in the Northern Foothills and also on the north side of Reeves Glacier below Thern Promontory. This drift is composed of massive, matrix-supported diamict with sandy-silty matrix ranging in color from dark greyish brown to olive-grey. Clasts at the surface are deeply weathered and oxidized with yellowish red or red staining. Many of them show cavernous weathering. The older drift lacks perched erratics and constructional morphology.

Highly weathered bedrock occurs in numerous localities below the lower trimline. For example, the summit areas of Mt. Keinath (1 090 m) and Mt. Abbott (1 022 m) near the coast show deep weathering and pitting of granite bedrock. Likewise Mt. Matz (1 300 m) and the granite mesa below Thern Promontory and above Terra Nova drift show deep pitting and caverns. Deep bedrock weathering also extends locally below the Terra Nova drift limit. We have already given the examples near Mt. Gerlache and Andersson Ridge, where Terra Nova striations and erratics postdate deep caverns in the granite bedrock. Another example is in the Northern Foothills where in places deeply weathered metamorphic rocks underlie Terra Nova drift.

Near Mt. Browning (Northern Foothills) strongly rubefied paleosols developed on bedrock were observed buried beneath a thin layer of Terra Nova drift or preserved as relict soils at higher elevation up to about 700 m (fig. 21). We compare them with soils of weathering stage 5 or 6, which CAMPBELL & CLARIDGE (1987) considered as pre-Quaternary in age.

HOLOCENE RAISED BEACHES

The shoreline of Terra Nova Bay consists of ice cliffs for about two thirds of its length (GREGORY & *alii*, 1984). These ice cliffs fringe the Campbell Glacier Tongue, the Hells Gate Ice Shelf, the Nansen Ice Sheet, and the huge Drygalski Ice Tongue.

Elsewhere the shoreline consists of rock cliffs, rock headlands, and indented coves. The rock headlands have been washed free of glacial drift to about 30 m elevation.

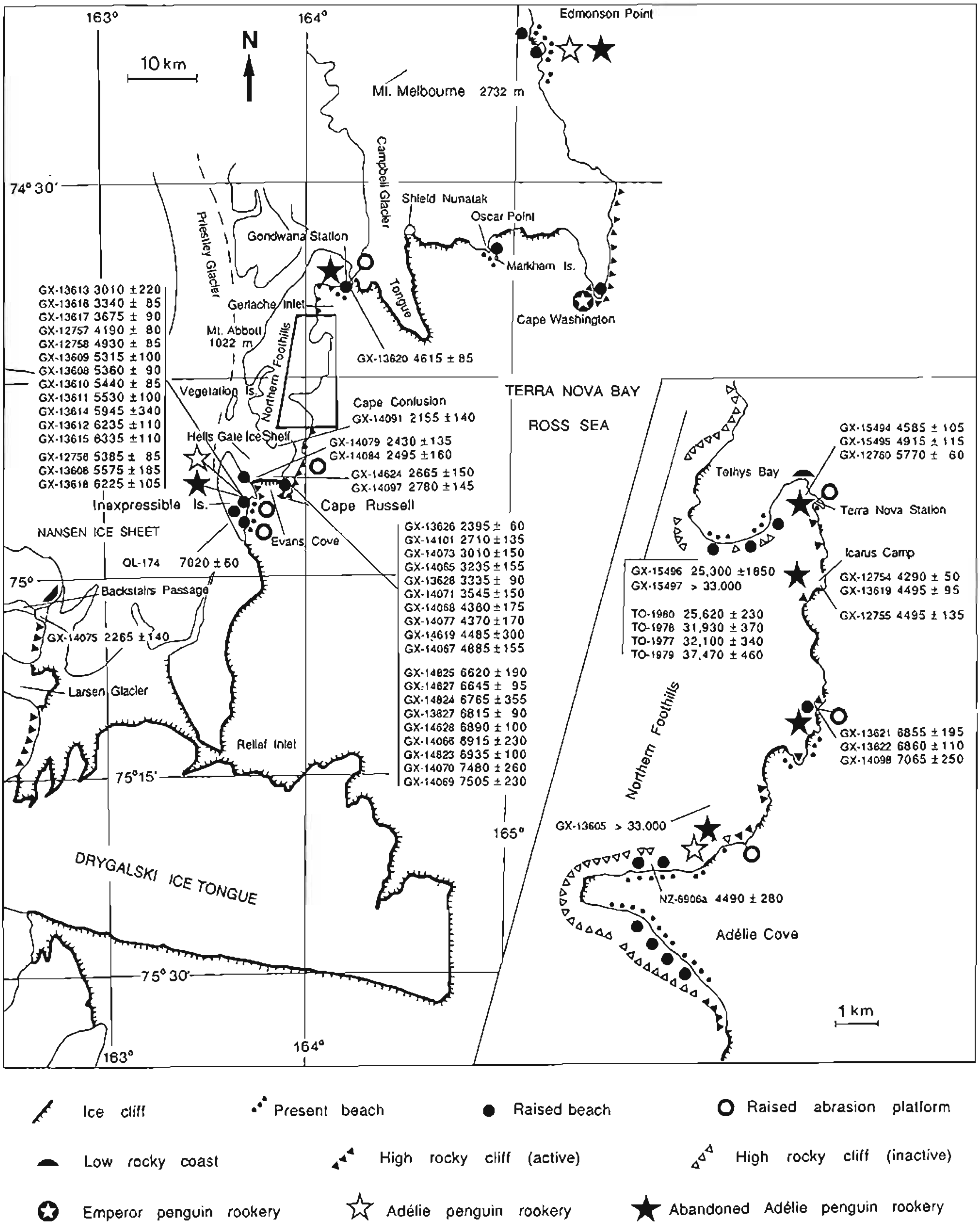


Fig. 23 - Radiocarbon sample localities of marine materials, most associated with raised beaches along the coastline of Terra Nova Bay.

The coves exhibit raised beaches near Campbell Glacier Tongue, at Tethys Bay near the Italian Terra Nova Bay Station, in Adélie Cove, in Evans Cove beside Hells Gate Ice Shelf, and on the east coast of Inexpressible Island (fig. 22). The beaches rise to a maximum elevation of about 30 m at several of these localities.

All these raised beaches are cut into Terra Nova drift or rest directly on bedrock. They consist of berms of gravel and pebbles up to well-rounded blocks. Fine marine sediments are present at Evans Cove on Cape Russell peninsula. Numerous radiocarbon dates of penguin remains obtained from abandoned nesting sites give minimum ages for these beaches. Other radiocarbon dates of reworked marine fauna (pelecypods, serpulids, corals, cirripeds and bryozoans) also afford minimum ages for the beaches. At Evans Cove in the Northern Foothills, *Laternula elliptica* and *Adamussium colbecki* occur in place in marine muds, thus affording maximum ages for the overlying beaches.

Figure 23 shows the location of important radiocarbon samples from OROMBELLI, (1988), BARONI & OROMBELLI (1989b, 1991), STUIVER & *alii* (1981), WHITEHOUSE & *alli* (1989) and this paper. Figure 24 displays these samples on an age-elevation diagram from BARONI & OROMBELLI (1991). Two relative sea-level curves show the maximum limits of postglacial uplift allowed by existing radiocarbon dates. Projections of these relative sea-level curves show that the uppermost beaches at 30 m elevation formed abour 7 200-8 000 yr B.P. The oldest conventional radiocarbon date pertaining directly to the raised marine deposits is 7 505 ± 230 yr B.P. (GX-14069) on *in situ* pelecypods in Evans Cove. This age is consistent with others showing early Holocene marine conditions in Terra Nova Bay. These include ages of 7 065 ± 250 yr B.P. (GX-14098) for penguin guano at 39 m elevation beside Adélie Cove (BARONI & OROMBELLI, 1991) and 7 020 ± 60 (QL-174) for *Adamussium colbecki* shells from recent moraine at the edge of the Nansen Ice Sheet (STUIVER & *alii*, 1981); both dates are uncorrected for marine reservoir effects.

DISCUSSION

Figures 25 and 26 show former longitudinal profiles of Reeves and Campbell Glaciers derived from the lower trimline and from the Terra Nova drift limit. It is evident from figure 25 that Reeves Glacier was thicker along its entire length when it stood at the Terra Nova drift limit, with the greatest thickening in its lower reaches. Figure 26 shows that lower reaches of Campbell Glacier also thick-

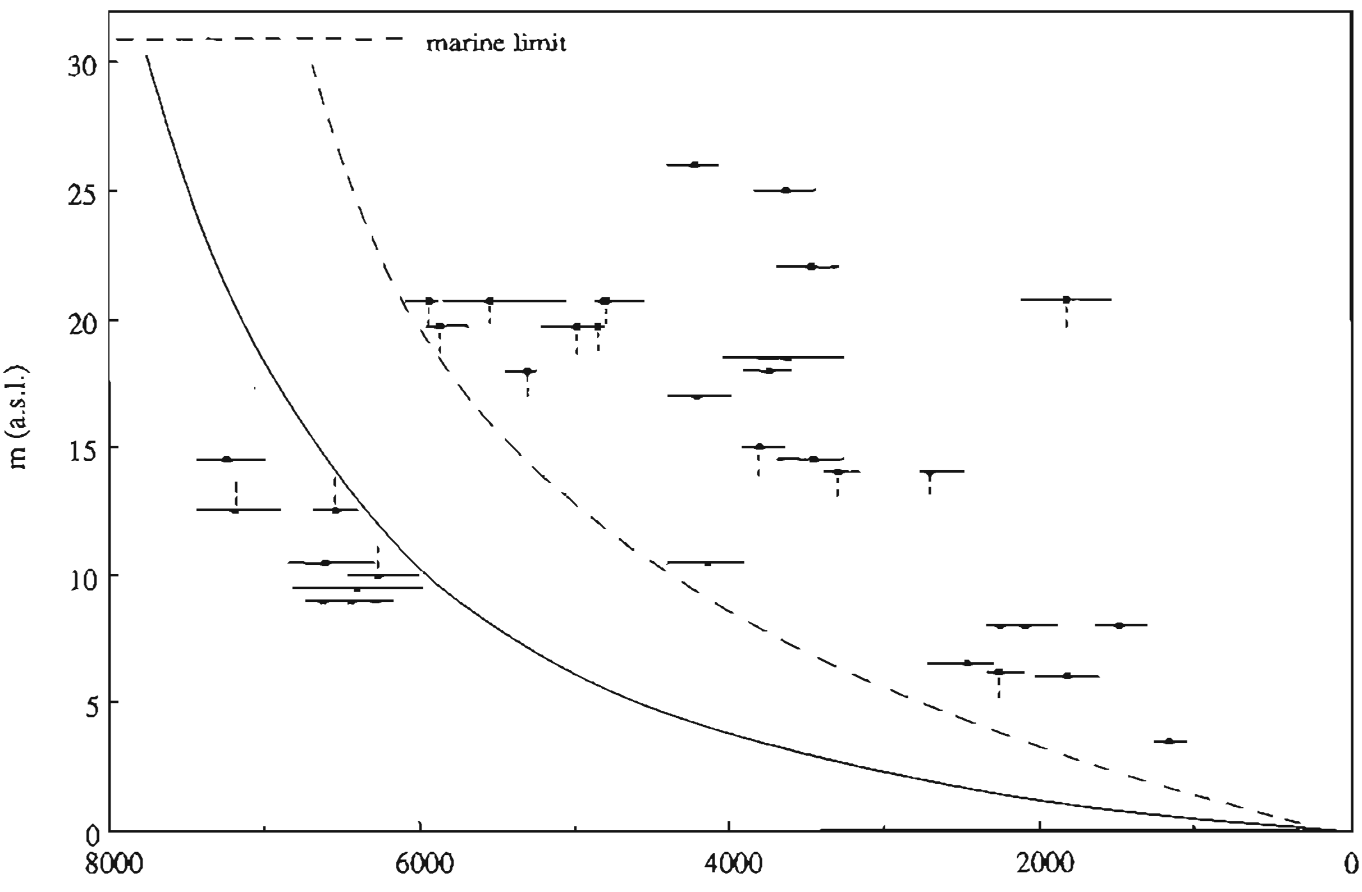


FIG. 24 - Calibrated ^{14}C ages plotted against elevation of the sampling sites shown in fig. 23, along with the interpolated relative sea-level curves redrown from Baroni and Orombelli (1991).

ened greatly when it stood at the Terra Nova drift limit in the Northern Foothills beside Campbell Glacier Tongue; unfortunately the Terra Nova drift limit cannot be traced inland along the length of Campbell Glacier because of extensive mass-wasting on adjacent slopes. However, we infer from the distribution of olivine basalt (presumably from Mt. Melbourne volcanics beside and under Campbell Glacier) that Terra Nova drift along much of the eastern flank of the Northern Foothills was deposited by outflow of a thickened Campbell Glacier that was squeezed up against the Northern Foothills, where it merged with ice flowing seaward across Vegetation Island from Priestley Glacier and its tributaries. This ice-flow direction inferred from our new data is different from that indicated by STUIVER & *alii* (1981).

From the elevation of Terra Nova drift above present-day sea level in the Northern Foothills and on Inexpressible Island, we conclude, as did STUIVER & *alii* (1981), that Terra Nova ice must have been grounded on the floor of Terra Nova Bay. Such grounded ice is also consistent with the premise that expanded Campbell Glacier ice was pushed against the Northern Foothills.

In most respects Terra Nova drift closely resembles Ross Sea drift in the McMurdo Sound area (STUIVER & *alii*, 1981). Both drifts occur in a similar geographic setting beside a sound or bay; both include shells in marine muds; both show little weathering and have internal ice cores with a marine component; both are cut by Holocene raised beaches of approximately the same age; both represent the youngest glaciation of similar coastal areas; and both involve grounding in embayments in the western Ross Sea. For these reasons we correlate Terra Nova with Ross Sea drift. If the old radiocarbon dates on shells are valid, Terra Nova drift postdates 25,620 ± 230 ^{14}C yr B.P. (TO-1980) which is the youngest age obtained from shell fragments contained in the muddy till matrix. Terra Nova drift is older than 7505 ± 230 ^{14}C yr B.P. (GX-14069), which is the oldest age obtained from *in situ* shells in raised marine sediments.

Again if the old radiocarbon dates are reliable, from 37,470 ± 460 yr B.P. (TO-1979) to 25,620 ± 230 yr B.P. (TO-1980) marine organisms were living in the water of Terra Nova Bay probably beneath or in front of the Campbell Glacier Tongue, when the glacier extent was comparable to the present one and no ice was grounded in Terra Nova Bay.

In the McMurdo Sound area the age of the outer edge of Ross Sea drift in Taylor Valley is placed between 23,800 ± 200 yr B.P. (QL-1708) and 12,980 ± 90 yr B.P. (QL-1570) on the basis of radiocarbon dates of blue-green algae in perched deltas of Glacial Lake Washburn, which was dammed in the valley by a lobe of the Ross Sea ice sheet grounded in McMurdo Sound (STUIVER & *alii*, 1981; DENTON & *alii*, 1989a). This age is consistent with radiocarbon dates of 16,100 ± 250 yr B.P. (QL-1803) to 13,040 ± 190 yr B.P. (QL-1569) on blue-green algae in glacial-lacustrine Ross Sea drift in eastern Taylor Valley (DENTON & *alii*, 1989a; PRENTICE, 1990). The ages of proximal Ross Sea drift near the present coastline range between 11,370 ± 120 yr B.P. (QL-1914) and 8 340 ± 120 yr B.P. (QL-993), again from radiocarbon dates of blue-green algae in glacial-lacustrine sediments and perched deltas near the mouths of Taylor and Ferrar Valleys (STUIVER & *alii*, 1981; DENTON & *alii*, 1989a). Holocene raised marine deposits in Explorers Cove at the mouth of Taylor Valley extend back to 6 670 ± 200 yr B.P. (QL-191); shells in a raised marine delta set in raised beaches at the mouth of South Stream 15 km north of Taylor Valley date to 6 430 ± 70 yr B.P. (QL-72) (STUIVER & *alii*, 1981); Holocene shells in the McMurdo Ice Shelf repository are as old as 7 750 ± 90 yr B.P. (QL-1443) (KELLOGG & *alii*, 1990); all these radiocarbon dates on shells are uncorrected for marine reservoir effect. Penguin guano younger than Ross Sea drift on Cape Bird on the northern tip of Ross Island (uncorrected for marine reservoir effects) dates to 7 070 ± 180 yr B.P. (NZ-5590, SPEIR & COWLING, 1984) and 8 080 ± 160 yr B.P. (NZ-5990, HEINE & SPEIR, 1989).

DENTON & *alii* (1989a) correlated Ross Sea drift not only with Terra Nova («younger») drift but also with Britannia II drift beside Hatherton and Darwin Glaciers (BOCKHEIM & *alii*, 1989); with Beardmore drift beside Beardmore Glacier (DENTON & *alii*, 1989b); and with Reedy III drift beside Reedy Glacier (MERCER, 1968). Together, these drifts were interpreted to represent a grounded ice sheet at least in the inner reaches of the Ross Embayment. In this scenario, the Terra Nova piedmont glacier that filled Terra Nova Bay and reached a surface elevation of 380 m against the Northern Foothills was part of a marine-based ice sheet in the inner Ross Embayment during late Wisconsin time. Outlet glaciers from the East Antarctic Ice Sheet (e.g. Beardmore, Hatherton, Darwin, Reeves) and from the northern Victoria Land mountains (Priestley, Campbell) thickened considerably along their lower reaches to flow into this grounded ice sheet. In contrast, along the western coast of McMurdo Sound where outlet glaciers did not reach the sea, glacial lobes from the grounded ice sheet in McMurdo Sound flowed westward into the mouths of ice-free valleys.

From the radiocarbon dates in Taylor Valley, maximum grounding was achieved between 23,800 and 13,040 yr B.P. (DENTON & *alii*, 1989a). Grounding-line recession from the inner Ross Embayment in early Holocene time apparently was nearly simultaneous at Terra Nova Bay (minimum age of 7 505 ± 230 yr B.P.; GX 14069); McMurdo Sound (minimum age of 7 750 ± 90 yr B.P.; QL-1443) (KELLOGG & *alii*, 1990); and at Hatherton Glacier (minimum age of 6 630 ± 150 yr B.P.; QL-134). The first two ages for grounding-line recession are of marine shells and are uncorrected for the marine reservoir effect.

Figures 25 and 26 show elevations of the lower trimline along the lengths of Reeves and Campbell Glaciers. At the head of Campbell Glacier in the southern Mesa Range, the lower trimline matches that previously mapped in the Pacific Ocean ice drainage of the Outback Nunataks and Rennick Glacier (DENTON & *alii*, 1986). In the Rennick Glacier area the favored interpretation of the trimline is that it represents the approximate upper surface of a former expanded glacier system that included the Rennick Glacier itself, tributaries to the Rennick Glacier, and the peripheral Talos Dome of the East Antarctic Ice Sheet beside the Outback Nunataks (DENTON & *alii*, 1986). Because of its consistent pattern, the trimline was assumed to have been cut during a single expansion, taken to be the greatest recognized in northern Victoria Land. In the absence of isotopic dating, DENTON & *alii* (1986) suggested two age models for the trimline. By one model it was cut during late Wisconsin time. This model was based on poor soil development in drift below the trimline, along with excellent preservation of striated bedrock in a number of localities. By the second model, the trimline predates late Quaternary time and represents an enormous expansion of the East Antarctic Ice Sheet and northern Victoria Land mountain glaciers, equivalent to postulated overriding of the Transantarctic Mountains farther south in the Dry Valleys region (DENTON & *alii*, 1984).

Our new data from the Terra Nova ice-drainage system show that the interpretation of the lower trimline is more complex than previously inferred. First, it is probable that this trimline in the Terra Nova drainage system was cut by expanded glaciers because of its smooth profile downglacier across structural features and varying bedrock lithology and because of its relationship to glacial drift and striations. But it is also probable that the lower trimline is not simply of one age, but rather represents a number of expansions that reached varying parts of the trimline at different times. Further it is possible that the outer, older portion of the lower trimline is high above present-day glaciers because of tectonic tilting. A metachronous origin of the trimline, with the outer portion being older than the inner one, is compatible with the interpretation of such trimlines in temperate mountain belts. Figures 25 and 26 show that in coastal regions the trimline lies far above the Terra Nova drift limit and hence predates late Wisconsin in age. But in the high accumulation areas of Transantarctic Mountains, the Terra Nova drift limit is close to or at the trimline. Further, the internal mountain accumulation areas high in the Eisenhower and the Deep Freeze Ranges are now close to or at the trimline. These observations suggest that the trimline is old near the coast and, in contrast, is late Wisconsin and even Holocene in age in the interior, high-elevation accumulation areas. Two important conclusions arise from trimline elevations, if we assume that tectonic tilting is not a major factor. The first is that during extensive coastal thickening the interior accumulation areas changed little more than they did during Terra Nova glaciation. Second, during the maximum expansion to the trimline, ice must have been extensively grounded in Terra Nova Bay and at least the western Ross Sea. This is particularly evident by comparison of the trimline and Terra Nova drift longitudinal profiles.

The interpretation of the mesa striations and trimlines in terms of possible ice-sheet overriding of northern Victoria Land mountains is a remaining major question, par-

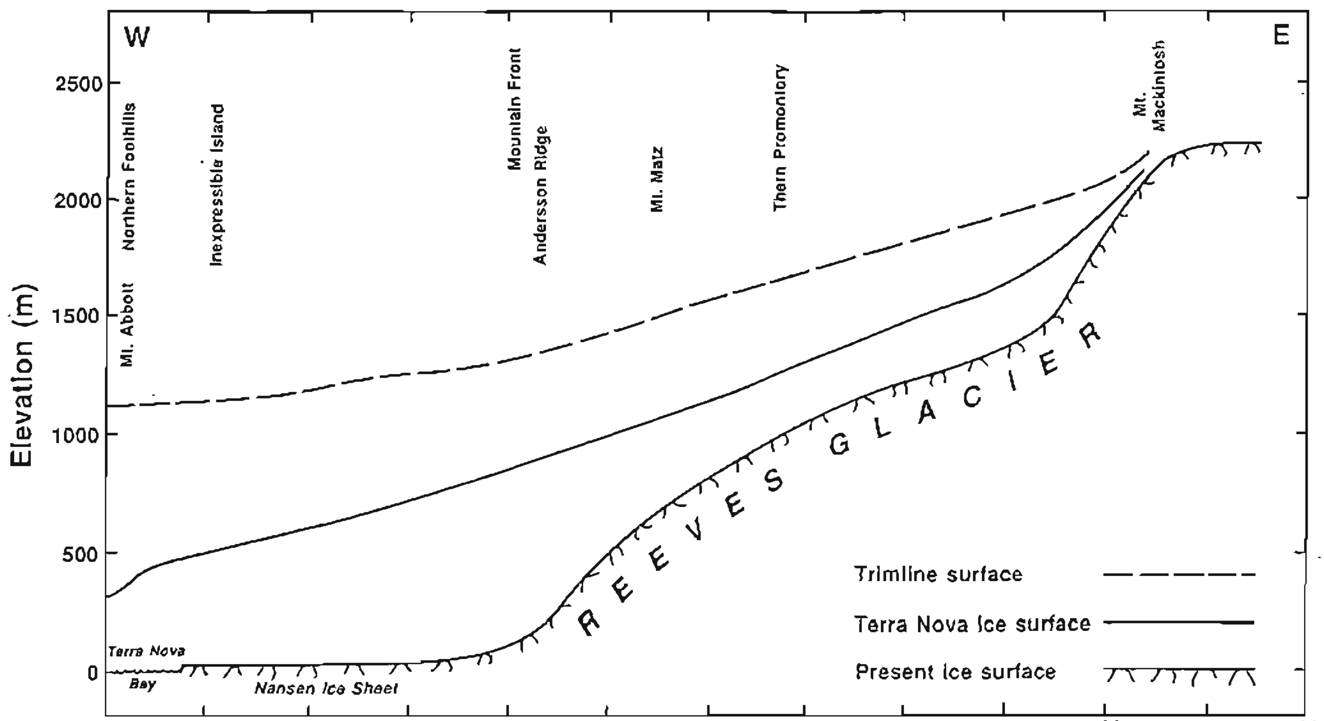


FIG. 25 - Former longitudinal profiles of Reeves Glacier derived from trimline and drift limits.

ticularly in view of the controversy about whether the Transantarctic Mountains in the Dry Valleys area have been overrun by an expanded East Antarctic Ice Sheet in late Tertiary time (DENTON & *alii*, 1984; SELBY, 1986; AUGUSTINIUS & SELBY, 1990; ACKERT, 1990; MARCHANT, 1990; SUGDEN & *alii*, 1990; MARCHANT & *alii*, 1990). DENTON & *alii* (1986) interpreted the mesa striations and serrated ridges in the Outback Nunataks not in terms of local ice cap expansion but in terms of inundation and overriding by a thickened Rennick Glacier and Talos Dome. Their major question involved the timing of this expansion. Two age models were presented, one that the expansion was late Wisconsin in age and the other that it was late Tertiary in age. HOEFLE (1989) and DELISLE & *alii* (1989) argued that striations and polished surfaces on summits of the mesas and mountains of the Outback Nunataks (particularly Miller Butte, Frontier Mountain, and Roberts Butte) represent overriding by an expanded East Antarctic Ice Sheet in late Tertiary time. The striations and friction cracks are taken to represent a wet-based ice-sheet, which they took to imply 200-800 m of ice overlying the buttes. HOEFLE (1989) further inferred that basal glacial drift must have been present to produce the striations. The fact that neither drift nor erratics are now present suggested to HOEFLE (1989) a long interval of weathering that began in late Tertiary time. Terrestrial ages of meteorites in blue ice at the base of Frontier Mountain, along with old exposure ages of adjacent bedrock, also suggest an ancient age (DELISLE & *alii*, 1989).

Is ice-sheet overriding necessary to explain the mesa features, as DENTON & *alii* (1986) and HOEFLE (1989) claimed? Or can these features be explained simply in terms of expansion of local mesa ice caps? Most of the geologic data from the Eisenhower Range can be explained by the local ice cap model; including the Timber Peak and Skinner Ridge trimlines, the striations and crescentic gouges, and the lack of erratics. Likewise, most of the features in the Outback Nunataks can be explained by expansion of local ice. For example, the striations on granite bedrock in the Lichen Hills (figs. 8 and 9 in DENTON & *alii*, 1986) near the Outback Nunataks lie just distal to ice-cored moraines of probable Holocene age; they could well simply represent relatively modest expansion of local ice. By this model the striated summit surface on Miller and Roberts Buttes represents expansion of local ice caps, apparently with undirectional flow, over these buttes. It would be this mesa ice cap that cut the trimline on Roberts Butte. By this model it is not necessary to postulate thickening of up to 900 m for the Talos Dome to inundate buttes of the Outback Nunataks (DENTON & *alii*, 1986; HOEFLE, 1989). Rather, modest thickening of upper Rennick Glacier simply could have been accompanied by expansion of ice caps over the buttes.

There are three arguments against the local ice cap model. First, it is difficult from modern glaciological principles to understand how high-elevation and relatively thin mesa ice caps could have produced striated and bossed granite surfaces with friction cracks; especially in view of

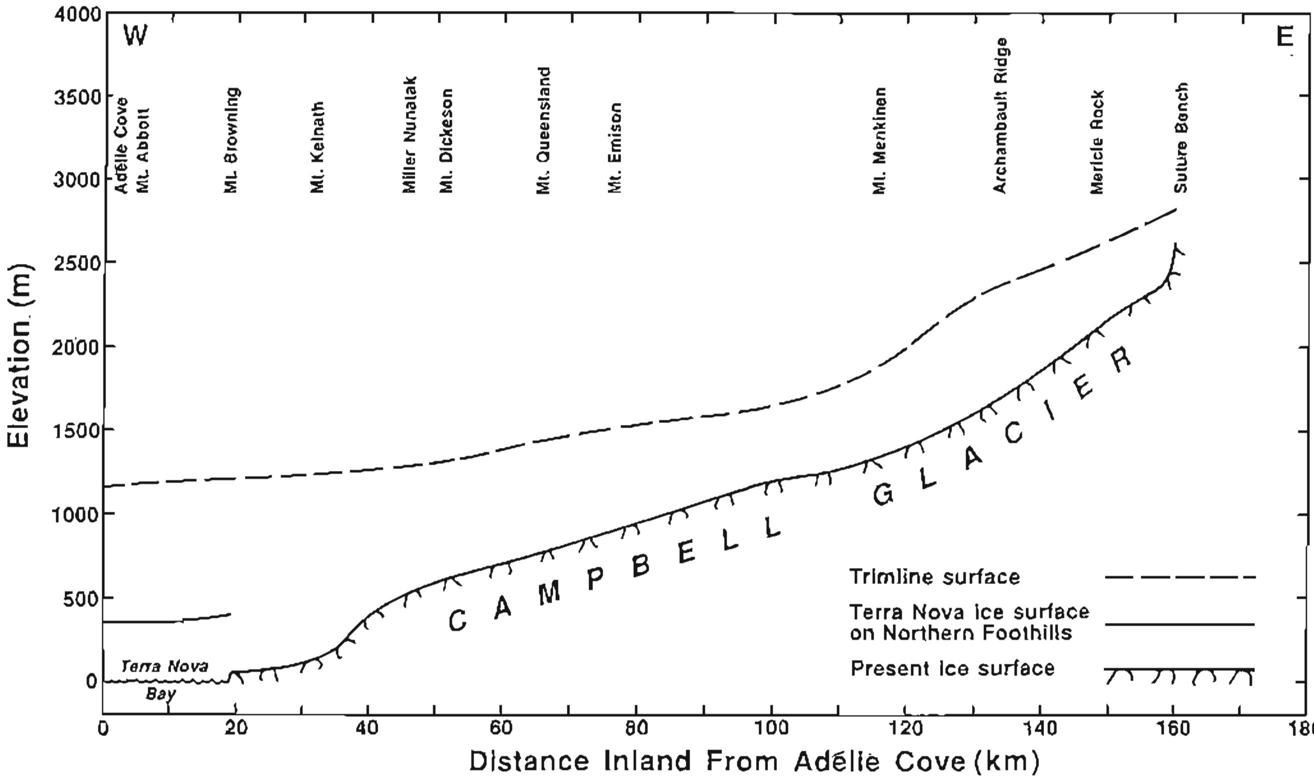


FIG. 26 - Former longitudinal profiles of Campbell Glacier derived from trimline and drift limits.

the very sparse drift cover. This is what led HOEFLE (1989) to infer that the buttes must have been covered with at least 200-800 m of ice in order to achieve the wet-based conditions assumed necessary to produce striations; such thickening would almost surely imply ice-sheet overriding. HOEFLE (1989) further inferred that there must originally have been an extensive layer of surface drift as tools to cut striations. HOEFLE (1989) attributed the current lack of drift to extensive weathering of a postulated initial drift layer and concluded that overriding was pre-Quaternary in age on the basis of this inferred drift weathering. But we note that striated surfaces beside Reeves Glacier, below the Terra Nova drift limit, show a sparse drift cover, thus throwing doubt on the necessity of an extensive basal drift to striate and polish the bedrock. Further, the Terra Nova striated surfaces beside Reeves Glacier extend right up to the limit of Terra Nova drift, thus indicating that thick ice was not necessary to form these striated surfaces.

The second argument against the ice cap model is the fact that striation trends and friction cracks in the southern Eisenhower Range and on Miller and Roberts Butte (HOEFLE, 1989) suggest a consistent flow direction accross the mesas that appears peculiar for local mesa ice caps. The third argument involves the exposure and terrestrial ages of meteorites from the Frontier Mountains. On the face of it, these dates suggest that the striated mesa surfaces are ancient, but the case cannot be considered conclusive until numerous exposure dates of striated surfaces, perched clasts, and adjacent ice-cored moraines are available.

When could local mesa ice caps have carved the high-elevation striations on the granite rims of the Eisenhower Range and the Ogden Heights? This question cannot be answered definitively in the absence of isotopic dates. As mentioned earlier, two age models were given by DENTON & *alii* (1986) and a late Tertiary age was favored by HOEFLE (1989) for similar mesa-top striated surfaces in the Outback Nunataks. Thus one possibility is that the striated surfaces are ancient. But we think that a reasonable case can be made that this expansion occurred during Terra Nova glaciation, which is late Wisconsin in age. This case rests on three observations. The first is that the preservation of the striated mesa granite surfaces is equivalent to preservation of striated granite bedrock surfaces alongside northern Reeves Glacier below the Terra Nova drift limit. Second, in both places angular and delicately perched clasts rest on the striated granite surfaces. Third, the striated granite mesa surface near Timber Peak lie just beyond a double set of fresh ice-cored moraines. The situation is very similar to that elsewhere in northern Victoria Land, particularly in the Northern Foothills, where such moraines are assigned a late Holocene age (BARONI & OROMBELLI, 1989a, b). If the high Eisenhower Range moraines are also late Holocene in age, which seems likely, then it is reasonable that the well-preserved striated surfaces that lie beyond them are late-Wisconsin or early Holocene in age.

Several implications come from assuming that the mesa striated surfaces date to Terra Nova glaciation. The first is that expanded mesa and mountain accumulation areas fed the thickened outlet glaciers that poured into Terra Nova Bay during late Wisconsin time. In such a case response to lowered sea level could not have been the only factor responsible for widespread thickening and grounding of the Terra Nova Bay ice-drainage system. Rather, expansion of high-level mountain glaciers suggests a shift to a positive mass balance during late Wisconsin time. This is in sharp contrast to the situation in the McMurdo Sound/Dry Valleys region, where expansion of Ross Sea grounded ice was accompanied by recession of termini of alpine glaciers in the Dry Valleys (DENTON & *alii*, 1989a). Under this scenario the general expansion of the ice cover in the Terra Nova Bay region would leave relatively restricted ice-free areas. In the high-elevation areas, these would include only the serrated ridges, particularly in view of the fact that mesa and mountain glaciers spilled down outlet trough walls between serrated ridges. More ice-free terrain was exposed at lower coastal regions, where trimlines lie far above current outlet glaciers. Here the higher Northern Foothills were partly ice-free, along with many weathered mountain tops and ridges below the trimline but above the Terra Nova drift limit. Thus this interpretation of the age of the mesa-striated surfaces results in a simple and unified history of the Terra Nova Bay ice-drainage system during the last glacial cycle.

CONCLUSIONS

1) Alpine topography and deep outlet glacier troughs that reached far below sea level propagated inland by headward glacial erosion of the Transantarctic Mountains, leaving remnant coastal piedmonts and high-elevation mesas. The formation of the glacial topography did not require an East Antarctic Ice Sheet.

2) The trimlines superimposed on the alpine and outlet-trough topography mark the maximum possible expansion of the northern Victoria Land ice cover since erosion of the alpine topography. This expansion was minor in the upper reaches of outlet glaciers and in mountain accumulation areas. But it represented great thickening along lower reaches of outlet glaciers, implying extensive grounding in the Ross Sea. There is no definitive evidence that the East Antarctic Ice Sheet overrode northern Victoria Land nunataks or mountains.

3) Terra Nova drift is well-exposed along coastal ice-free areas, where it was cut beginning 7 000-8 000 yr B.P. by beaches now up to 30 m above present sea level. The Terra Nova drift limit can be traced far inland along Reeves Glacier. Reeves Glacier was thicker along its entire length when is stood at the Terra Nova drift limit; however, thickening was greatest in coastal regions, where a grounded piedmont glacier filled Terra Nova Bay. From local radiocarbon dates and by correlation with Ross Sea drift, we conclude that Terra Nova drift is late Wisconsin in age. It is probable that the expanded Terra Nova glacier was part of a marine-based ice sheet in the inner Ross Embayment during late Wisconsin time.

4) A reasonable geological case can be made that high-elevation striations in the Eisenhower Range were carved during Terra Nova glaciation. If so, local mesa ice caps and mountain glaciers expanded to feed Terra Nova grounded ice during late Wisconsin time, unlike the situation farther south where alpine glacier termini in the Dry Valleys were less extensive than now during late Wisconsin time.

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