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US Army Corps
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Cold Regions Research &
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Airfields on Antarctic glacier ice

Cover: Blue ice areas near the Scott Glacier. There is a possible landing field at 86°35'S, 148°25'W (5600 ft—or 1700 m—a.s.l.), but approaches are obstructed by mountains on three sides.

CRREL Report 89-21

December 1989

Airfields on Antarctic glacier ice

Malcolm Mellor and Charles Swithinbank

Prepared for
DIVISION OF POLAR PROGRAMS
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The physical characteristics of blue-ice ablation areas in Antarctica are described and some representative ablation rates are given. The possibilities for using blue-ice areas as airfields are outlined and exploratory surveys are mentioned. Site details are given for icefields at Mount Howe, Mill Glacier, Patriot Hills, Rosser Ridge, Mount Lechner, S1 near Casey station, and on the Ross Ice Shelf near McMurdo station. The surface roughness of blue ice is discussed, microrelief surveys are presented for Mount Howe and Patriot Hills, and spectral analyses are used to develop relations between bump height and wavelength. U.S. military specifications for the roughness limits of various types of runways are summarized and graphical comparisons are made with the roughness analyses for Mount Howe and Patriot Hills. Special machines for smoothing ice runways are discussed and design specifications are developed. Some notes on ground facilities and ground transport are included. Appendices give discussions of weather patterns in the Transantarctic Mountains and methodology for making spectral analyses of surface roughness.

It is concluded that glacier-ice airfields for conventional transport aircraft can be developed at low cost in Antarctica. Recommendations for further work are offered.

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PREFACE

This is an interim report on current studies directed towards the development of hard-surface airfields on Antarctic glacier ice. It provides a record of information that has been gathered so far and gives guidelines for future efforts. The work was carried out by Dr. Malcolm Mellor, Experimental Engineering Division, USA CRREL, and by Dr. Charles Swithinbank, CRREL consultant, under a continuing program of Antarctic Engineering Services for the Division of Polar Programs, National Science Foundation (DPP 87-001).

The authors are grateful to R. La Count and his colleagues in the Polar Operations Section of DPP/NSF for supporting the work and providing the chartered Twin Otter aircraft. They are also grateful for support in the field from CRREL colleagues, from employees of the logistics contractor, ITT Antarctic Services Inc., from personnel of the U.S. Navy (NSFA and VXE-6), and particularly from the pilots and mechanics of Kenn Borek Air Ltd. Valuable help was provided by the U.S. Geological Survey (air photographs and maps) and by the Technical Communication Branch at CRREL (typesetting, illustrating, editing, and so forth).

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MALCOLM MELLOR AND CHARLES SWITHINBANK

INTRODUCTION

The idea of using blue-ice ablation areas as Antarctic airfields is believed to have originated during the period when Admiral George Dufek commanded Operation Deepfreeze (1955–60). An airfield on the snow-free glacier ice of the Ross Ice Shelf (Outer Williams Field) was operated during the period 1966–67 to 1970–71. A firm proposal for use of inland blue-ice areas was apparently made about 1972 by Col. Joseph Fletcher, a retired Air Force pilot who was at that time serving as director of the Office of Polar Programs in the U.S. National Science Foundation. The idea was to fly large conventional aircraft (C-141, C-5), from South America or from New Zealand, either direct to the interior of Antarctica or else via Seymour Island or via McMurdo. A study of the logistic and economic consequences was prepared (Day et al. 1973). In 1973–74, CRREL was assigned the task of investigating the technical feasibility of using blue-ice areas for runways, focusing on the Pensacola Mountains as a terminus location for flights from South America (Kovacs and Abele 1977).

Austin Kovacs and Gunars Abele located a number of promising sites, surveying two of them, at Rosser Ridge and Mount Lechner (Fig. 1). These sites were never used. In 1986 the concept was picked up by a private group that had been flying mountaineers to the Ellsworth Mountains in small ski–wheel aircraft. Charles Swithinbank and Giles Kershaw, who had been interested in blue-ice areas for a decade, were contracted by Adventure Network International to locate and reconnoiter potential blue-ice airfields in the Ellsworth Mountains. Wheel landings were made in a Twin Otter at two sites, and one of them was subsequently surveyed (Swithinbank 1987). This site, located near the Patriot Hills at 80°19'S, 81°20'W, began operation as an airfield for conventional aircraft in November 1987, when a DC-4 commanded by Captain Jim Smith landed there after a flight from Punta Arenas, Chile.

In 1987, CRREL was asked by NSF to study the feasibility of building all-season wheel runways from compacted snow on the Ross Ice Shelf near McMurdo and at the South Pole. For the type of wheeled aircraft that were being considered (C-141, KC-10), the study indicated that development of snow runways would be too risky, and the use of blue-ice ablation areas was offered as an alternative (Mellor 1988a). Mount Howe and its neighbor D'Angelo Bluff were identified as the primary target areas for a search; these are the mountains that are nearest to the Pole, and the USGS 1:250,000 topographic map showed snow-free moraines at Mount Howe, thus suggesting the presence of bare ice.

Charles Swithinbank was contracted to make a selective search of the SCAR* air photo library in August 1988. The goal was to identify blue-ice areas that might be used as airfields to support South Pole operations. The search was to cover a region between latitudes 84°and 88°S, and between longitudes 160°E and 120°W. From an examination of some 7000 photos, 37 potential runway sites were found in the designated search areas (Swithinbank 1988a). Plans were made for air reconnaissance of all these sites, and for ground survey of the most promising sites.

Air reconnaissance of the sites began in December 1988, operating from South Pole station with a ski–wheel Twin Otter chartered by the U.S. Antarctic Program. The first wheel landing at Mount Howe was made on 10 December by Twin Otter C-GKBG of Kenn Borek Air (Calgary). For this and other reconnaissance flights, operations were directed by Charles Swithinbank and the aircraft was flown by Brydon Knibbs and Brian McKinley.

*Scientific Committee on Antarctic Research

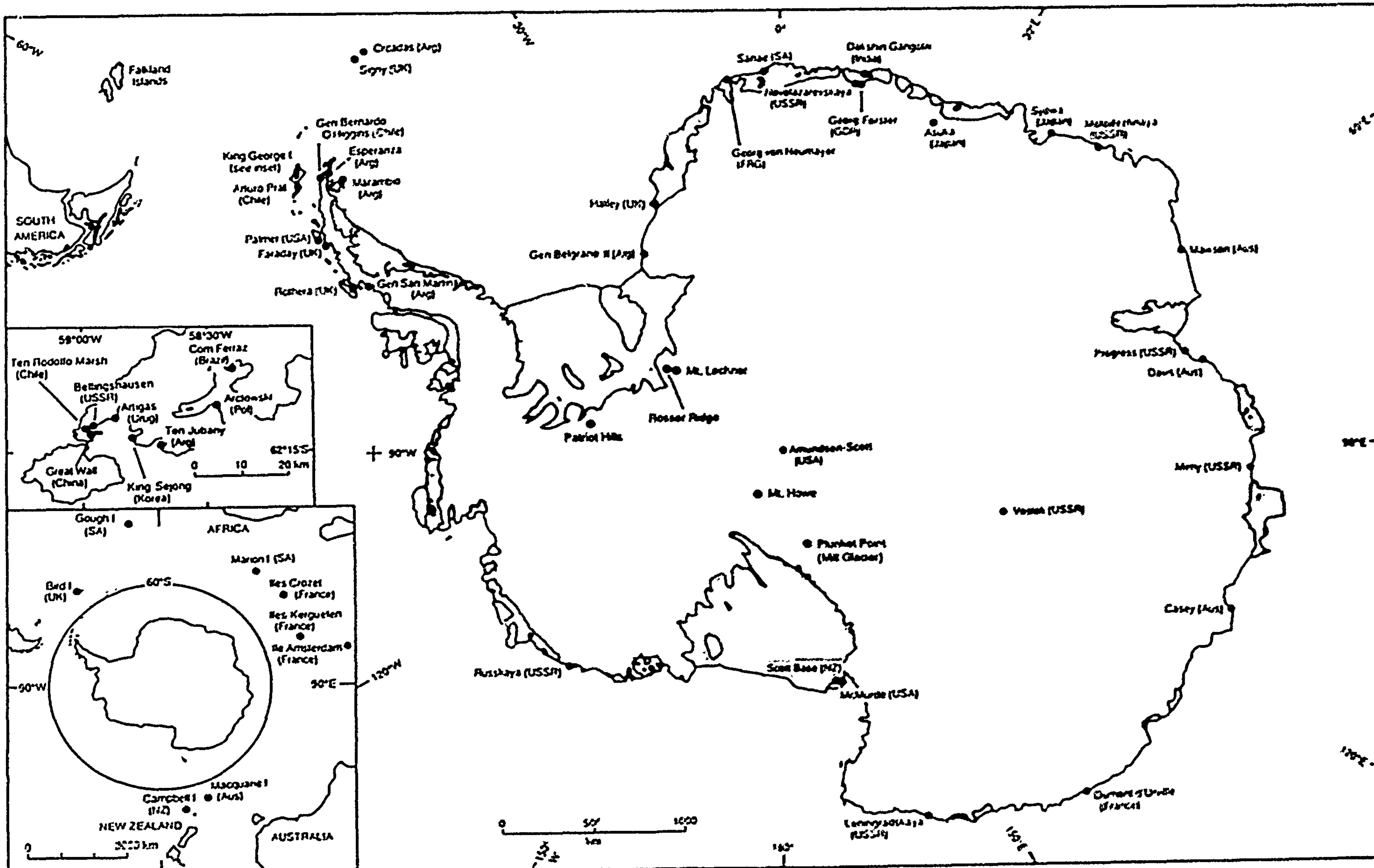

Figure 1. Locations of places discussed in this report. In the peninsula, gravel runways exist at the Chilean Marsh base (King George Island) and at the Argentine Marambio base (Seymour Island). A short gravel runway is under construction at the U.K. Rothera base. In east Antarctica, a paved rock-fill runway is under construction at the French Dumont d'Urville station, and a blue-ice runway is being developed at the Australian Casey station. The U.S. McMurdo station operates a sea ice runway from the beginning of October to mid-December. Compacted snow runways for certain types of wheeled aircraft operate for limited periods at two Soviet Coastal stations, Molodezhnaya and Novolazarevskaya. There is also a compacted snow runway at Vostok. (Base map adapted from one published in Polar Record, 1988.)

Sites at Mount Howe (87°20'S, 149°50'W) and Mill Glacier (85°06'S, 167°15'E) were selected as the prime prospects, and both were surveyed. The surveys were followed up by engineering inspections after Malcolm Mellor returned to Pole in January 1989 with Twin Otter C-FSJB, piloted by Bob Allen and George Cox. Altogether, eight wheel landings were made at Mount Howe, and five were made near Plunket Point on the Mill Glacier (Swithinbank 1989).

Use of blue-ice airfields in Antarctica seems likely to increase. In November 1988, Dick Smith and Giles Kershaw flew from Hobart, Tasmania, and landed on wheels at a blue-ice strip near Casey Station. At the time of writing, the Royal Australian Air Force (RAAF) is planning flights in standard wheeled C-130 (Hercules) aircraft between Hobart and Casey during the 1989–90 austral summer.

In this report we draw together currently available information for a number of blue-ice sites that have the potential to provide good runways for conventional wheeled aircraft. The report is not aimed at a single group of specialists, but rather at a range of people with varied interests in the question. It is intended for planners and logistics specialists who are concerned with the development of antarctic aviation, for engineers who may have to prepare runways and facilities, for pilots who may use glacier-ice runways, and for scientists who may find either intrinsic interest or logistic appeal in blue-ice areas.

BLUE-ICE AREAS

Over most of its area, the Antarctic ice sheet experiences net accumulation. In other words, the accumulation of snow each year (by direct precipitation, condensation and wind deposition) exceeds the annual ablation (by evaporation and wind erosion). This snow, which is mostly cold and dry, has a high reflectance (or albedo) for visible radiation and there is little spectral selection. Thus the snowfields appear bright and white in natural daylight.

Scattered over the continent are relatively small areas of net ablation, where the annual snow accumulation and some of the inflowing ice are removed by evaporation and wind erosion, and sometimes by melting and runoff. The ice surface in these ablation areas is normally ice that was formed further upstream by dry snow compaction in areas of net accumulation. This ice typically has a porosity of 6% or less, with many air bubbles that have diameters of order 1 mm. The ice absorbs and scatters solar radiation; its albedo is lower than that of clear snow, making the surface look relatively dark, and its spectral reflectance is such that incident white light reflects with a blue tinge. Hence these places are known as blue-ice areas.

Most of the blue-ice ablation areas of Antarctica owe their existence largely to the mechanical effects of local winds, not to any anomalous "warmth" in the regional climate (other than slight warming from adiabatic heating of katabatic winds). In fact, ablation areas are often in close proximity to, and at the same altitude as, areas of net snow accumulation (Fig. 2). There is a negative mass balance because the wind removes more snow than it deposits. With the ice surface revealed, the relatively low albedo favors the absorption of solar radiation, tending to enhance the evaporation rate and, in some areas, to cause either surface melting or the formation of subsurface melt cavities.

In coastal areas, the controlling wind is likely to be either a strong and persistent katabatic flow that is reinforced by steep slopes, as in the area around Mawson, or else a prevailing wind that is funneled by terrain features, as in the area downstream of the White Island – Black Island gap near McMurdo. Valley glaciers obviously favor both these effects (Fig. 3). Further into the interior, where the ice is very thick and the surface elevation is high, blue-ice areas are almost always close to mountains that project through the ice sheet and disturb the flow of surface winds, which are katabatic for much of the time. The mountains typically stand hundreds of metres (or more) above the surrounding ice, so that they completely penetrate the turbulent boundary layer for surface winds, and are much higher than the top of the turbulent diffusion layer which transports most of the windblown snow. Thus they tend to block the horizontal flow of blowing snow, inducing most of the deposition on the upwind side of the obstacle and forming a turbulent wake of snow-free air on the downstream side. The wind on the lee side of such an obstacle is typically gusty, sometimes giving fierce gusts that are followed by lulls as intermittent vortex-shedding occurs. The wind strips away any snow that might fall during calm weather, and it erodes the surface of ice that flows in from upstream areas, probably almost entirely by evaporation.

When ice flows very slowly into one of the leeside wind zones, a very thick layer of ice can be removed progressively from the surface by ablation, revealing old ice that was formerly at great depth and bringing to the surface any solids that were

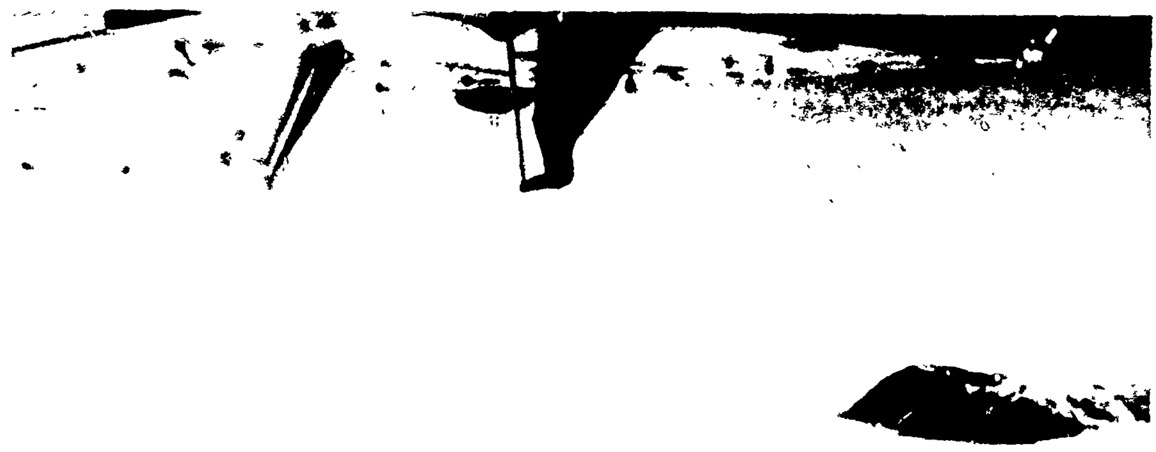

Figure 2. An area of snow-free blue ice downwind of a rock mass. (Photo by Malcolm Mellor, January 1989.)

embedded in the ice. If the surface of the upstream accumulation area has been struck occasionally by meteorites in earlier centuries or millennia, the meteorites become buried and thus embedded in the flowing ice mass. When that ice moves into an ablation area, it gives up the meteorites by a sort of distillation process—the ice evaporates, leaving meteorites behind on the surface.

Blue-ice areas as airfield sites

Unlike the cold, dry snow that covers most of Antarctica, blue ice has sufficient bearing capacity to support heavy wheel loads without rutting, even at the highest imaginable inflation pressures for aircraft tires. There is virtually no limit to the total load that can be supported. While the difference between a blue-ice ablation area and coastal sea ice ought to be evident, frequent misunderstanding by those unfamiliar with polar regions obliges us to state the obvious. Blue ice is solid glacier ice, typically hundreds of metres thick and resting on solid rock (on an ice shelf it may be afloat). By contrast, typical sea ice is a thin (< 3 m) viscoelastic plate floating freely on a liquid foundation. Another common misunderstanding concerns the texture of the blue-ice surface; some people visualize the ice as being like a skating rink, and they are apprehensive about an aircraft's ability to steer and brake when on it. In reality, the typical cuspate surface of cold, windblown ice provides excellent friction for tires, to the extent that rubber can be burned off the tire if the wheel locks at high speed. By contrast, snow-free sea ice has a slick surface when temperatures approach the melting point (saline surface, radiation absorption).

If a blue-ice area is smooth and level over a sufficient distance, and if the approaches are unobstructed by high terrain, then that area is highly suitable for use as an airfield, even for aircraft that have only conventional wheel landing gear.

As was mentioned earlier, blue-ice ablation areas are few and far-between in Antarctica. Of the relatively few that do exist, most are unsuitable for use as airfields because they are not smooth, level and unobstructed. Blue-ice areas typically lie in close proximity to mountains that project through

Figure 3. Blue ice on a valley glacier (Ramsey Glacier).

the ice sheet. The underlying relief is rugged, and thus the ice surface may not be flat. It tends to be disturbed by rolling hills and shallow valleys which have horizontal spacings of order 1–10 km. Crevasses are common in such regions. When a smooth ice surface is found, it may have an overall slope that is too steep for an airfield site, say > 2% (steep surface slope is a consequence of relatively small ice thickness—see eq 2 later). If the area is smooth and level, at least one side is likely to be obstructed by a mountain or a ridge. At low altitudes and relatively high latitudes, blue-ice ablation areas may be pitted with melt ponds and incised by summer melt streams.

In spite of all these problems, there are a number of blue-ice areas that have the potential to provide airfields for conventional transport aircraft. The best of them are so good that they can probably accept any type of transport aircraft with virtually no preparation of the surface. The trick is to find these rarities in locations that are useful for supporting research and general transport operations. Careful site selection is the key to successful airfield development.

The first deliberate search for blue-ice landing fields was made in 1974 (Kovacs and Abele 1977), when two runways were surveyed in the Pensacola Mountains. These two sites, at Rosser Ridge (82°

46'S, 53°40'W) and Mount Lechner (83°15'S, 51° 14'W), are about 420 nautical miles from the South Pole; they are within comfortable range of King George Island (Marsh base). The next major search took place in 1986 (Swithinbank 1988a); two promising sites were examined, at Wilson Nunataks (80°01'S, 80°36'W) and Patriot Hills (80°19'S, 81° 20'W). The site at Patriot Hills was surveyed and subsequently developed as an airfield for commercial operations, which began in 1987 (Swithinbank 1988b). In 1988 a strip was prepared on coastal blue ice 6 km east of Casey station and a wheel landing was made there by a Twin Otter after a flight from Hobart on 6 November.

U.S. interest in blue-ice airfields was revived in 1988, when a search for blue-ice areas to serve the South Pole was proposed, with special emphasis on the area of Mount Howe and D'Angelo Bluff (Mellor 1988a). Following a search of the air-photo archives for the Transantarctic Mountains, air reconnaissance began in December 1988. Potential airfields were surveyed at Mount Howe (87°20'S, 149°50'W) and near Plunket Point on the Mill Glacier (85°06'S, 167°15' E). In a separate initiative, a blue-ice runway site on the Ross Ice Shelf near McMurdo station (77°59'S, 166°32' E) was studied during the 1988–89 summer.

The formation of blue-ice areas

Not much is known quantitatively about the development and maintenance of blue-ice ablation areas.

Typical evaporation rates in the cold, dry areas seem to range up to about 7 cm/yr (3 in./yr), with 5 cm/yr (2 in./yr) as perhaps a representative value for fairly vigorous evaporation. If a rate of 5 cm/yr (2 in./yr) is maintained over a long period, a 100-m (330-ft) layer can be stripped off in 2000 years. To remove a 500-m (1600-ft) layer, it would take about 10,000 years.

Flow rates at the surface of the thick ice of the high polar plateau are probably of order 10 m/yr (33 ft/yr). If there is a restriction of the flow path across a broad front, either by a subglacial ridge or by emerging mountains, the flow velocity should tend to increase in order to maintain continuity. However, where the ice flows past a mountain or nunatak, the shearing motion produces a transverse gradient of surface velocity, with almost zero velocity at the ice/rock contact and relatively high velocities, possibly exceeding 10 m/yr (33 ft/yr), out in the free stream. The sluggish ice alongside, or downstream of, a mountain might be expected to have flow velocities of order 1 m/yr (3 ft/yr) or less. This expectation is borne out by movement surveys which show surface velocities < 1 m/yr (< 3 ft/yr) on blue ice in the Allan Hills (Annexstad 1983).

If the ice flows at 1 m/yr through a blue-ice ablation area that is 4–7 km long, its transit time is of order 4000 to 7000 years. With a net ablation rate of order 5 cm/yr, this gives enough time for 200 to 350 m of ice to be stripped off the surface.

If the wind-controlled ablation area is much bigger than a few kilometres in the flow direction, then blue ice can be formed and maintained with higher flow speeds and lower ablation rates than those mentioned above. In some ablation areas, especially those at relatively low latitudes, low altitude, or in coastal zones, the mass economy is much more vigorous than is the case in the high interior of Antarctica. For example, near Mawson the annual net ablation is about 0.5 m/yr (1.6 ft/yr), which is an order of magnitude higher than in the inland ablation areas.

In general, if ice flows through an ablation area of length L at a mean horizontal velocity U, the transit time t is L/U. If the mean net ablation rate at the surface is $\dot{A}$, the total thickness of ice H that is ablated away during transit is

$$H = \dot{A}\, L/U. \tag{1}$$

When t is of order 10^3–10^4 years, the ice flow ought to be steady, with an equilibrium relation between ice thickness h and surface slope α that represents the maximum ice shear stress τ (at the bed). The relation, which is strictly applicable only where conditions remain uniform for a flow distance that is at least an order of magnitude greater than the ice thickness, is

$$\tau = \rho_i g h \sin\alpha \tag{2}$$

where ρ_i is the mean ice density for the layer and g is the gravitational acceleration.

For the ice at Mount Howe, we can estimate the bed shear stress as about 50 kPa, and at Mill Glacier we can take a somewhat higher value, say 80 kPa. These values are taken from Sheet 5, "Driving Stresses in the Antarctic Ice Sheet," of the Scott Polar Research Institute Glaciological and Geophysical Folio. At Mount Howe, the mean surface slope along much of the main runway is $\alpha \approx 6\times10^{-3}$ rad (i.e. $\tan\alpha \approx \sin\alpha \approx 6\times10^{-3}$). If mean ice density is taken as $\rho_i \approx 0.9$ Mg/m^3, then the implied ice thickness h is about 940 m (3000 ft). At Mill Glacier, the slope of the long runway is $\alpha \approx 1.4\times10^{-2}$ rad, which implies an ice thickness of about 650 m (2000 ft).

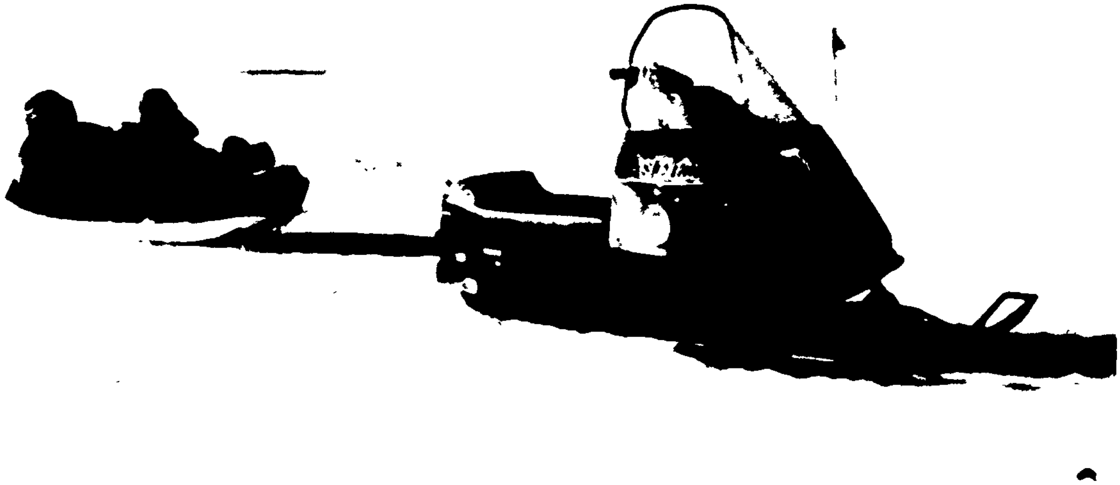

Figure 4. Typical rough texture of the ice surface near Mount Howe.

The blue-ice areas that owe their existence to strong winds typically (but not invariably) have a rough surface texture (Fig. 4 and 5). There seem to be two common patterns to the texture. One pattern is a scalloped surface formed by an array of shallow cups that are separated by ripples or sharp-edged ridges. In plan, the cups appear more or less equidimensional, with an equivalent diameter of order 15 cm, or 6 in. (Fig. 5), but there may be a lineation of the overall pattern in the wind direction. The depth of the cups is typically of order 3–5 cm (1–2 in.). The other pattern is a distinctly rippled or furrowed surface with the depressions, and the ridges that separate them, elongated in the direction

Figure 5. Scalloped ice surface at Mount Howe. The cups are about 15 cm across and the depth, from the bottom of the cup to the high points of the intervening ridges, is about 5 cm. Fresh snow is lodged on the lee slopes of the cups. (Photo by Malcolm Mellor, 23 January 1989.)

of the prevailing wind. The vertical relief can be up to 10 cm (4 in.), with 20 cm (8 in.) horizontal separation (Annexstad 1983).

The term "sun cups" has been used to describe scalloped ablation surfaces, and some glaciologists have suggested that solar radiation is a dominant factor in their formation (Annexstad 1983, p. 26). However, there is no evidence so far that radiation plays a major role. At Mount Howe, pebbles scattered over the ice by wind showed no signs of sinking into the ice in January 1989. The scalloped ice texture at this site is almost certainly formed and maintained by evaporation in a turbulent boundary layer.

Any directionality of the scalloped pattern seems related to wind, not to incidence angles for solar radiation. Near Mawson, a windy area on the coast of East Antarctica, evaporation continues through the winter at a rapid rate, equivalent to about 25 cm/yr (10 in./yr), with no significant dependence on altitude. The texture is maintained through the dark period, even though the evaporation during that period is equal to, or greater than, the vertical relief of the texture. At both Mount Howe and Patriot Hills, analysis of the small-scale relief suggests significantly different surface roughness in directions parallel and perpendicular to the wind direction. However, since the wind direction is perpendicular to the glacier flow direction, some of this effect could be due to flow bands in the ice.

Thomas (1979) discussed the scallops that are formed in solid surfaces by flowing water. Various erosion phenomena, mainly dissolution features, were explained in terms of wall turbulence, and a relation between "wavelength" ("streamwise spacing") and friction velocity was deduced. Data for the wavelength λ were plotted against ν/u_*, where ν is kinematic viscosity and u_* is the friction velocity, which is a measure of the surface shear stress. For data spanning 5 orders of magnitude, the relation took the form

$$\lambda = k\nu/u_* \qquad (3)$$

where k is a dimensionless constant. Ashton (1972) studied ripples on the underside of the ice canopy in flowing water and found a relation that was essentially the same. Ashton found inverse proportionality between λ and the free stream velocity; u_* is usually related linearly to the free stream velocity.

In the scallop-forming process described by Thomas, the size and structure of the eddies in the turbulent flow adjacent to the solid boundary (the "wall") determine the size and shape of the erosion features. The eddy structure depends on the shear stress τ at the boundary, as characterized by the friction velocity u_* ($u_* = \sqrt{\tau/\rho}$, where ρ is the fluid density). The expectation is that the size of the scallops will decrease as the flow velocity increases, but where ice is being evaporated by wind, the process is too feeble to form stable scallops in areas where wind speeds are low and, in any event, low wind speed would not form an ablation zone. However, in certain types of ice tunnels that experience gentle convection, large ablation scallops are sometimes seen.

For an Antarctic site that has high elevation and low temperature, a summer season value of the kinematic viscosity ν might be about 1.5×10^{-5} m²/s. Representative values of u_* do not seem to have been measured for blue-ice areas, but they ought to be of order $10^{-2}u_{10}$, where u_{10} is the wind speed at 10 m height (standard anemometer). For now, assume values of u_* in the range $10^{-2}u_{10}$ to $2\times10^{-2}u_{10}$. The value of k in eq 3 was taken by Thomas (1979) as $k = 10^3$, although his data suggest that a somewhat higher value, say up to $k = 2\times10^3$, could have been adopted. Rewriting eq 3 with $u_* = Cu_{10}$,

$$u_{10} = k\nu/C\lambda = 1.5\times10^{-5}k/C\lambda \qquad (4)$$

in which k/C could conceivably range from 0.5×10^5 to 2×10^5. Taking the mid-range value of $(k/C) = 10^5$, $u_{10} = 1.5/\lambda$ m/s. Substituting the value $\lambda = 0.15$ m, as it is at Mount Howe and Mill Glacier, then $u_{10} =$ 10 m/s (19 knots), which is a credible value for the mean annual wind speed at those sites. Using the lower limit value $(k/C) = 0.5\times10^5$, the value $u_{10} = 5$ m/s (9.7 knots) could still be credible as an annual mean wind speed for Mount Howe or Mill Glacier. The upper limit value $(k/C) = 2\times10^5$, obtained by doubling the Thomas value of $k = 10^3$ and combining it with a minimum value $C = 10^{-2}$, does not give a credible value for u_{10} (u_{10} = 20 m/s or 39 knots is the mean wind speed at Cape Denison, "Home of the Blizzard").

Ablation rates at blue-ice areas

The natural ablation rate at a blue-ice airfield site is of interest for a variety of reasons. If the ablation rate is high, seasonally and annually, operating problems can be expected as a result of differential ablation, continual loss of prepared surfaces, "pothole" formation, meltwater, and suchlike. If the ablation rate is very low, surface conditions will be very stable and, with care, operating problems should be slight.

An example of strong ablation is provided by

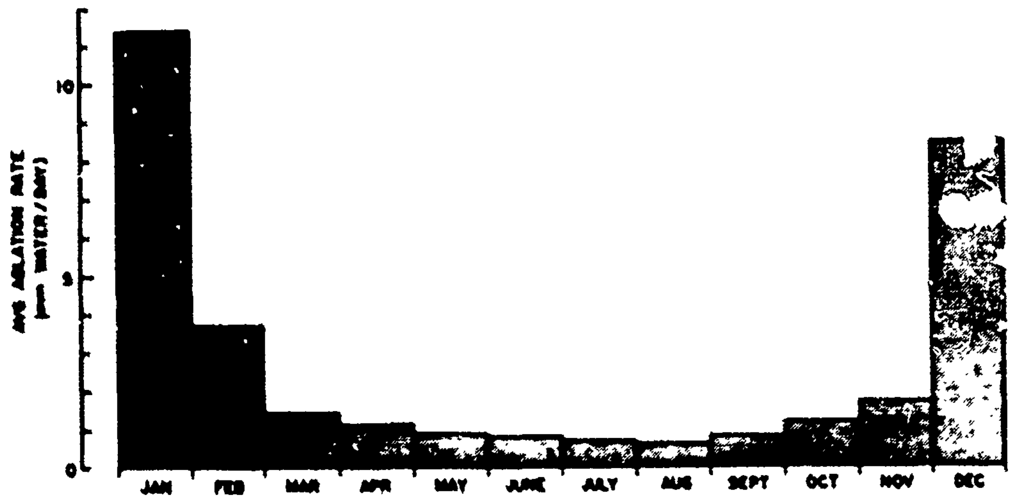

Figure 6. Monthly mean ablation rates for a blue-ice area that is subject to strong ablation (60 m a.s.l., near Mawson, 67°36'S, 62°52'E) (from Mellor 1961).

the blue ice behind Mawson station in East Antarctica (67°36'S, 62°52'E). At low elevation (60 m, or 200 ft, a.s.l.), the average daily ablation rate for January is about 11 mm of water, or about 13 mm of the bubbly ice (Fig. 6). Over the course of a year, the surface loses about 0.54 m of water, or 0.625 m of the bubbly ice. The ablation rate decreases with increase of surface elevation; at a height of 365 m (1200 ft) the annual ablation is only 40% of that at 60 m (200 ft) elevation (Mellor 1958, 1967). In this area, strong and persistent local winds (over 10 m/s mean annual) create the conditions for ablation by keeping the surface snow-free at all seasons, and by providing vigorous vapor transport away from evaporating and melting surfaces. Relatively low latitude and a regional slope to the north, together with the relatively low albedo of bare ice, favor the absorption of solar radiation. Air temperature is relatively mild (mean annual up to −11°C).

Another coastal area that has very high ablation rates is the western side of the ice shelf in McMurdo Sound. This place is 10° further south than Mawson and the mean annual temperature is about 9° lower, but summer melting is extreme. The ice is kept free of snow by valley winds from the south and it has a low albedo because large quantities of rock dust are transported from the nearby snow-free mountains. The area is heavily incised by melt streams and wind-elongated melt pools. Ablation measurements are not available, but the appearance of the surface and the abundance of summer meltwater leave little doubt that rates are high.

Coastal patches of blue ice do not necessarily have high ablation rates. At the S-1 site near Casey, the long-term ablation rate is close to zero. Around the former Wilkes station, annual balance rates have ranged from +6 cm of water to −3 cm of water (Cameron 1964).

Typical inland ablation areas, especially those at fairly high altitude, have low ablation rates. At the Allan Hills, some 230 km (120 nautical miles) northwest of McMurdo station (76°45'S, 159°0'E), the range is from zero up to about 7 cm/yr (3 in./yr), with a representative rate of about 4 cm/yr, or 1.6 in./yr (Annexstad 1983, Annexstad and Nishio 1979, 1980, Annexstad and Schultz 1982, Nishio and Annexstad 1979, 1980, Nishio et al. 1982, Cassidy and Annexstad 1981, Whillans 1982). The site elevation is about 2000 m (6600 ft) and the main icefield has an area of about 100 km^2 (40 square miles).

Another ablation area that has received much study is located near the Queen Fabiola Mountains at about 72°S, 36°E. Here again the ablation rates range up to about 7 cm/yr (3 in./yr), with a representative rate of about 5 cm/yr (2 in./yr) (Nagata 1978, Yoshida and Mae 1978, Naruse 1979). The altitude of this area ranges from about 1800 to 2300 m (5900–7500 ft).

The long-term ablation rate has been determined for an icefield near the Borg Massif, where C. Swithinbank set some stakes in 1951. These stakes were remeasured 34 years later and showed an average ablation rate of 2.9 cm of ice per year, or 2.6 cm of water per year (Brunk and Staiger 1986).

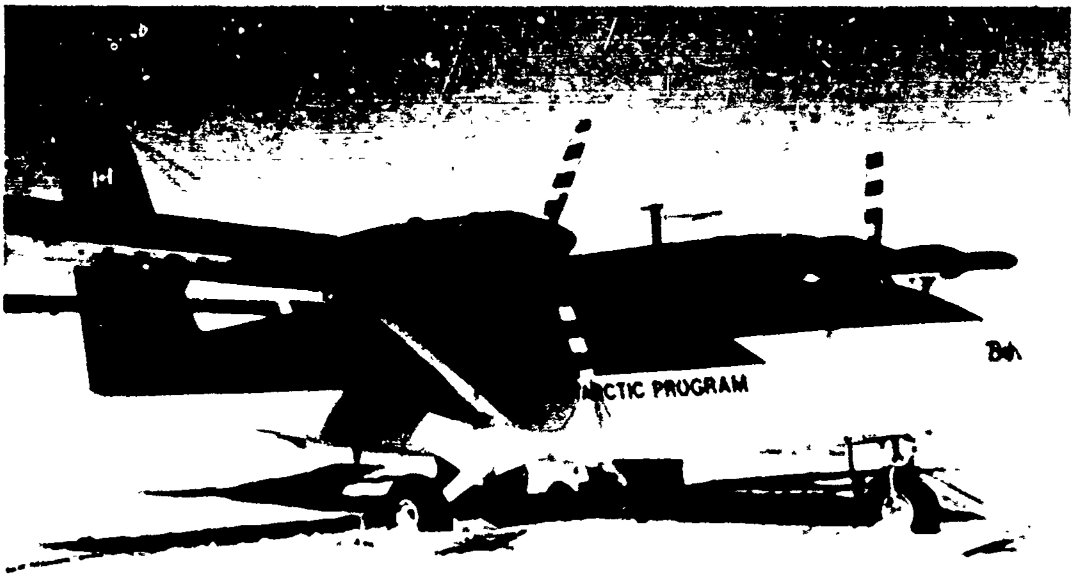

Figure 7. Ski-wheel Twin Otter at the South Pole. This was one of the two aircraft used for the Blue Ice surveys in 1988-89. (Photo by Malcolm Mellor, January 1989.)

Figure 8. Internal fuel tanks fitted inside the cabin of the Twin Otter for long-range operations. The two cylindrical cabin tanks can each hold 250 (US) gallons of jet fuel, giving an extra 5 hours at 140 knots on top of the normal operating range of 600 nm. They may only be filled to the brim under a Ferry Permit, but are part-filled in the Antarctic to extend the operating range with light cargo loads. (Photo by Malcolm Mellor, January 1989.)

Exploratory surveys at blue-ice areas

For the 1974 surveys in the Pensacola Mountains, a ground party was landed by a ski-wheel LC-130 on a snow-covered area at 82°53'S, 53°12'W. The party then traveled to Rosser Ridge and Mount Lechner by oversnow vehicles. At each site a runway line was established and level profiles were measured. Level readings were taken at 30-m intervals along the length of the runway, and every few hundred metres a set of readings was taken at 1-m spacing over a 30-m section in order to define the microrelief. Cross-sections were measured at the ends of the runway and at the mid-section to establish the transverse gradients. The old survey data for Mount Lechner cannot be traced, but most of the data for Rosser Ridge have been recovered and placed in a computer file.

For the 1986 surveys at Wilson Nunataks and Patriot Hills, flights were made in a ski-wheel Twin Otter from a base camp at Vinson Massif (78° 28'S, 86°12'W), using fuel that was airdropped from a C-130 by Fuerza Aérea de Chile. A two-man party was left at Patriot Hills to make leveling surveys along two potential runways. Microrelief surveys were made by taking readings at 2-m intervals along three sections, each 80 to 250 m long.

For the 1988–89 surveys at Mount Howe and Mill Glacier, flights were made from the South Pole in a ski-wheel Twin Otter (Fig. 7, 8). A fuel cache was laid by LC-130 at 85°12'S, 171°54' E. Ground parties established camps at both sites and made level surveys. At Mount Howe, longitudinal profiles were measured along: a) a 6.9-km runway, b) a 2.6-km cross-line, c) a 2.3-km cross-line, d) an 0.8-km cross-line. Microrelief surveys were made in two orthogonal directions by taking levels at 2.58-m horizontal intervals. These two sections were 470 and 180 m long respectively. At Mill Glacier a longitudinal runway profile was measured over a distance of 7.3 km and cross-sections were measured for two cross-lines, one 2.8 km long and one 0.66 km long.

Mount Howe

Mount Howe is in the Transantarctic Mountains with its highest peak at about 87°22'S, 149°30'W. It is a north-south mountain ridge, about 9 km (6 miles) long, that projects from the ice cap near the head of the Scott Glacier (Fig. 9). A few small nunataks just emerge from the ice surface in an area extending about 5 km (3 miles) to the south of the main ridge, the highest having an elevation of about 2710 m (8900 ft). The two highest peaks on the main ridge have elevations of about 2930 m and 2790 m (9600 and 9200 ft). On the west side of the ridge is a broad area of bouldery moraine, up to about 2.5 km (1.5 miles) wide and some 8 km (5 miles) in length (Fig. 10–23). If the small nunataks are ignored, Mount Howe is the world's most southerly mountain.

The snowfields to the east of the ridge are at an altitude of approximately 2600 m (8500 ft). The snow and ice to the west of the ridge lies at somewhat lower elevation, approximately 2400 m (7900 ft) above sea level. To the south of Mount Howe the surface of the ice sheet has a humpy relief produced by the underlying mountains. In this area there appears to be considerable variation of the snow accumulation rate, with the windswept high points receiving little net accumulation or, in some cases, perhaps experiencing net ablation. Large areas of crevasses exist to the north and east of Mount Howe, but crevasses to the south appear to be localized in quite small areas (≤ 2 km across).

Limited aerial reconnaissance along the 150° meridian between Mount Howe and the South Pole indicates that the noticeable surface relief and the associated crevasse areas end at about 87°50'S, i.e. about 25 nautical miles south of the most southerly of the exposed nunataks, or 30 nautical miles south of the main mountain ridge.

At 88°S the surface relief becomes almost imperceptible and the snow surface is typical for the high inland plateau, with sastrugi formed by the surface winds. Between 88°36'S and 88°47'S there is a zone where the sastrugi appear to be small and without a strongly preferred orientation, suggesting that the local winds in this area are usually light. This area is probably higher than the South Pole. Further south, for the last 73 nautical miles down to the South Pole, surface conditions appear to be similar to those which prevail in the area around Pole station, with mild sastrugi produced by winds that are generally light.

In the present context, the most significant feature of the Mount Howe area is a snow-free ice field that lies immediately to the west of the ridge and the moraines. This area of blue ice is about 9 km (30,000 ft) long in the direction NNE–SSW. The ice closest to the moraine is free from crevasses and snowdrifts and, overall, is remarkably smooth and flat (Fig. 12 and 18–22). As distance from the moraine increases, patches of drifted snow become more frequent and small crevasses are encountered eventually. The prevailing winds blow down from the mountain ridge with the characteristic gustiness and vortex-shedding of such situations, but under ordinary conditions this is probably not unduly hazardous. The wind direction in summer appears to be 120° true.

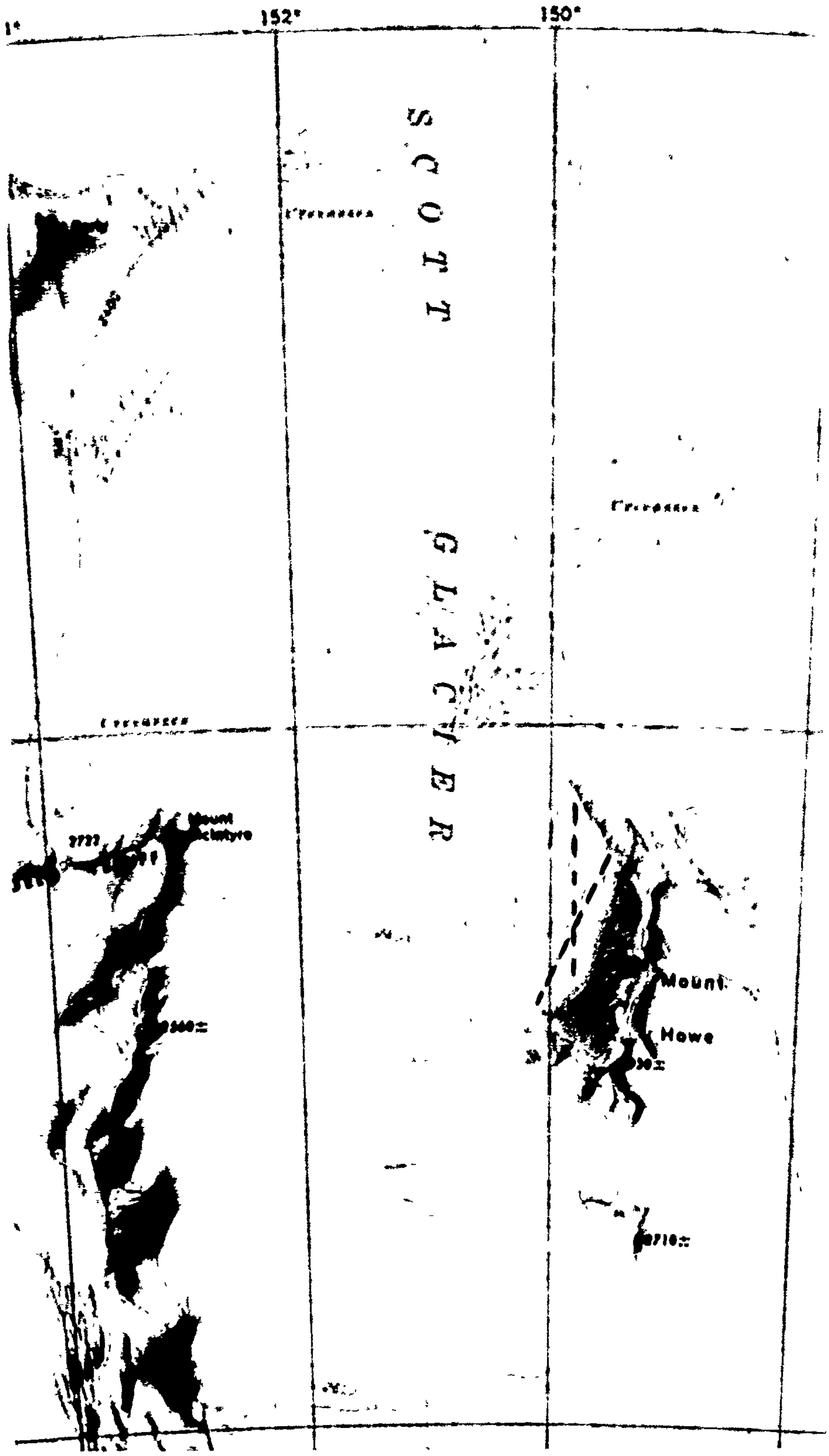

Figure 9. Location map for Mount Howe. Approximate alignments are shown for the runway oriented 27°/207° true, and for the north–south runway. (From the USGS map "D'Angelo Bluff," SV 1-10/15°, 1:250,000.)

Figure 10. Mount Howe seen from the north (South Pole is straight ahead over the horizon). The rock exposure on the right is D'Angelo Bluff. The ice is flowing downhill towards the camera. (U.S. Navy photo for USGS, TMA 894 F31 268, 9 December 1961.)

Figure 11. The Mount Howe ridge, the moraines, and the blue-ice airfield site. (U.S. Navy photo for USGS, TMA 891 F33 106, 9 December 1961.)

Figure 12. A vertical view of part of the Mount Howe icefield (about two-thirds of the way from the northern end of the moraine as seen in Fig. 11). Flow bands, some containing a low concentration of dust, can be seen. Note the patches of sastrugi (snow), which cover much of the surface at the bottom of the picture. (U.S. Navy photo for USGS, TMA 1202 F32 008, 31 October 1963.)

Figure 12. A vertical view of part of the Mount Howe icefield (about two-thirds of the way from the northern end of the moraine as seen in Fig. 11). Flow bands, some containing a low concentration of dust, can be seen. Note the patches of sastrugi (snow), which cover much of the surface at the bottom of the picture. (U.S. Navy photo for USGS, TMA 1202 F32 008, 31 October 1963.)

Figure 13. A view of the ice sheet looking south from the southern tip of the Mount Howe ridge. The rolling relief of the icecap surface continues in a southerly direction for about 40 nautical miles (≈75 km). (U.S. Navy photo for USGS, TMA 1202 F31 009, 31 October 1963.)

Figure 14. The Mount Howe icefield, as seen when looking north from the southern end of the ridge. The ice flows away from the camera into the Scott Glacier. Note the long-wave undulations in the icefield. (U.S. Navy photo for USGS. TMA 1203 F31 045, 1 October 1963.)

Figure 15. The Mount Howe ridge, the moraines and the icefield, looking north. Note the step in the ice surface at the northern end of the airfield site. (U.S. Navy photo for USGS, TMA 1203 F31 046, 31 October 1963.)

Figure 16. Northern end of the Mount Howe icefield, looking north into the Scott Glacier. This is likely to be the approach end of the long runway. (U.S. Navy photo for USGS, TMA 1202 F33 008, 1 October 1963.)

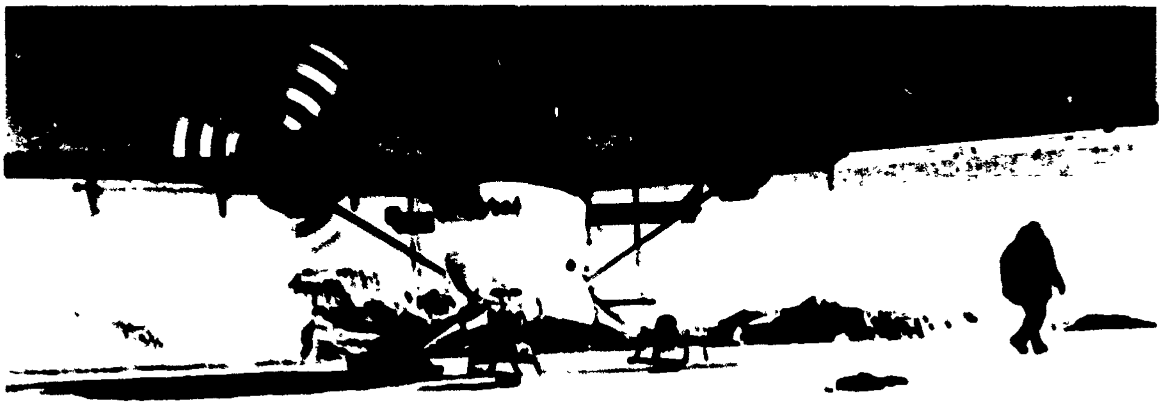

Figure 17. First wheel landing at Mount Howe. Note the scale of the surface roughness in relation to the wheels of the Twin Otter. The camera is facing due south. (Photo by Charles Swithinbank, 10 December 1988.)

The useful extent of the ice field can be seen from Figure 11. Approximate distances can be scaled from Figure 9. Figure 25 gives a sketch map of the airfield site, with form lines at 2-m vertical intervals. The survey lines along which 1988 levels were taken are plotted on Figures 24 and 25. Bamboo marker stakes were set in drill holes at the locations shown in Figure 24. Each stake is identified by a number and its exposed length (ice surface to top of stake) was measured on 28 December 1988, so that ablation measurements can be made later. Measurements of stake heights are given in Appendix A.

The large-scale surface characteristics of the site can be seen in the air photographs of Figures 10–16. Flow bands in the ice show quite clearly; in the color air-mapping photographs, some of these bands have a brown tinge, presumably due to low concentrations of dust particles. On the surface there is no evidence of preferential ablation on the flow bands and there are no noticeable changes in surface elevation associated with the flow bands (the roughness analysis throws doubt on this perception). The ice that is closest to the moraine appears to be unblemished by crevasses, snow patches, boulders, melt pits or melt streams. Further out from the moraine, scattered patches of windblown snow appear on the surface. Further out still, an orderly pattern of closely spaced snowdrifts develops.

The air photographs also give an idea of where fixed facilities might be located. The moraine field, seen clearly in Figures 11–16, is a possible site for buildings, fuel storage, and suchlike, and it is a source of building material. One possible procedure would be to construct thick base slabs of boulders, cobbles and gravel. Another possibility is to build on piles that are drilled into the ice. The small bluff at the southern end of the moraine field might be a site for permanent buildings on rock, possibly including a research station and observatory. Some facilities and pieces of equipment could be mounted on sleds and parked on the ice.

Details of the surface characteristics are seen in the ground photographs (Fig. 17–23). Figure 18 illustrates the flatness of the ice field and shows some of the scattered snow patches that act as temporary ablation shields (thus creating ice bumps). The dark bluff under the starboard wing of the Twin Otter in Figure 18 is the place mentioned above as a possible site for buildings. Figure 19 shows the small-scale roughness of the ice surface, which is covered in cup-shaped depressions and is also furrowed in the wind direction. This photo also shows the moraine terrace and the ridge behind. The tents are about 3.3 km (11,000 ft) from the

Figure 18. Southern end of the Mount Howe icefield. Note the scattered patches of thin snow cover and the rising terrain to the south. (Photo by Douglas Chichester, December 1988.)

Figure 19. Survey camp on the Mount Howe icefield. Note the small-scale furrows which run from upper left to lower right (i.e. parallel to the prevailing wind). The black spots in the left foreground are wind-blown pebbles. (Photo by Douglas Chichester, December 1988.)

Figure 20. The Mount Howe icefield, looking towards the northern end of the ridge. (Photo by Douglas Chichester, December 1988.)

Figure 21. The Mount Howe icefield, looking north towards the Scott Glacier. The black spots in the right foreground are small pieces of rock blown onto the ice from the moraine. (Photo by Douglas Chichester, December 1988.)

Figure 22. The Mount Howe icefield, looking from the moraine towards D'Angelo Bluff. (Photo by Douglas Chichester, December 1988.)

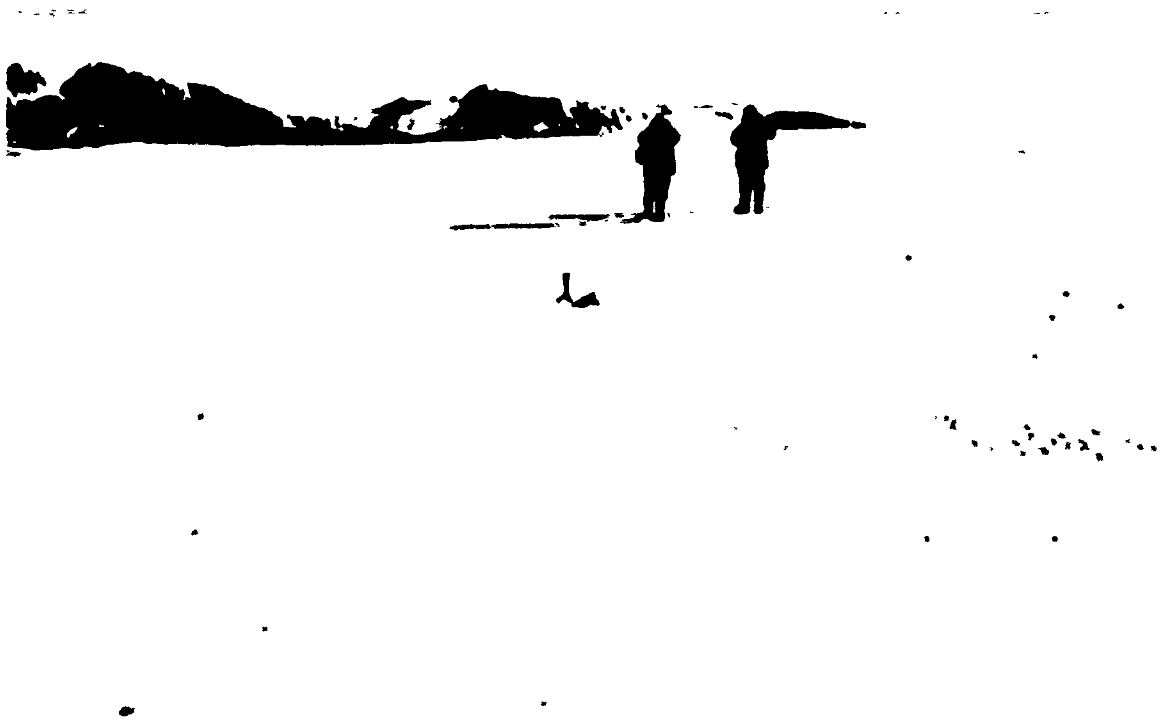

Figure 23. Mount Howe icefield, looking SSW. The long runway with orientation 207°/27° true is directed at the dark bluff just to the right of the figures. An alternative north-south runway would have a climbout passing over the low saddle that is seen about one-third of the distance from the left margin of the picture. (Photo by Charles Swithinbank, December 1988.)

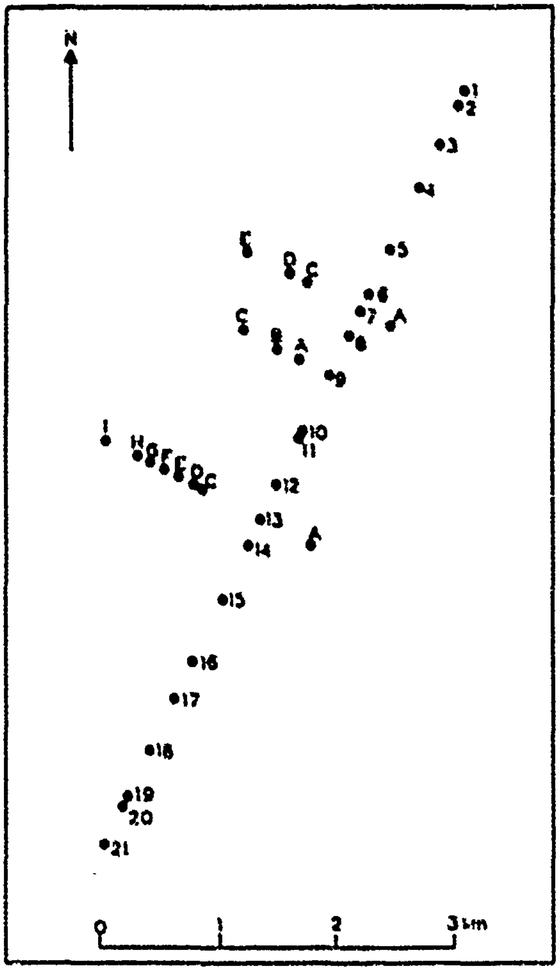

Figure 24. Location of bamboo markers set up to guide Howe icefield leveling survey. Each marker is numbered in pencil and topped with a green flag.

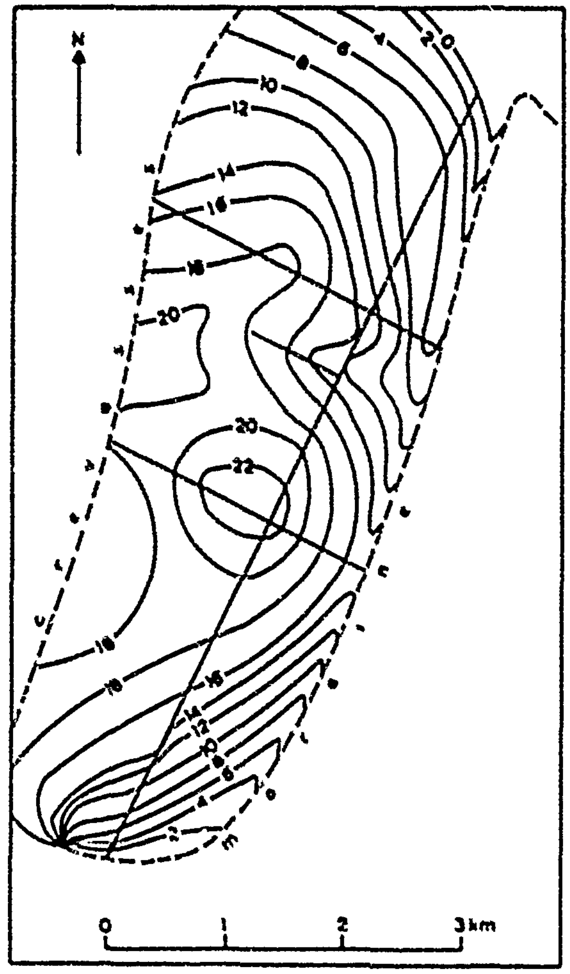

Figure 25. Sketch map of Howe icefield covering the same area as Figure 24. Form lines at 2-m (6.6-ft) intervals are conjectural except where surveyed along the four straight lines. Elevations refer to an arbitrary datum at the threshold end of the runway oriented 207° true (Fig. 26).

ridge. Figure 20 shows the continuation of the moraine terrace to the north, and the snow-covered northern end of the ridge. The small-scale pockmarks in the ice surface can be seen; a close-up of this pitting is shown in Figure 5. The small-scale roughness is highlighted in the contre-jour picture of Figure 21, which gives a view looking north, past the northern tip of the moraine and onto the mountains that flank the Scott Glacier. Figure 22 shows the size gradation of the moraine material, with a view across the ice field towards D'Angelo Bluff. The rocky moraine material is believed to be just a thin layer (about cobblestone thickness) lying on the glacier ice.

In Figures 19 and 21, small stones can be seen scattered around on the ice surface. These are apparently transported from the moraine by strong winds. The pebbles typically have a mass of about 45 g and commonly range in mass from 20 to 80 g. Maximum linear dimensions of the pebbles are typically in the range 30 to 75 mm, and many are flat and thin. The rock types are mainly fine-grained metasediments, with some basalt and perhaps gabbro. In December and January there were no noticeable signs of stones sinking into the ice under the influence of solar radiation. These widely scattered stones are not likely to affect aircraft operations, or to cause problems for ice-planing equipment.

As part of the exploratory site survey in Decem-

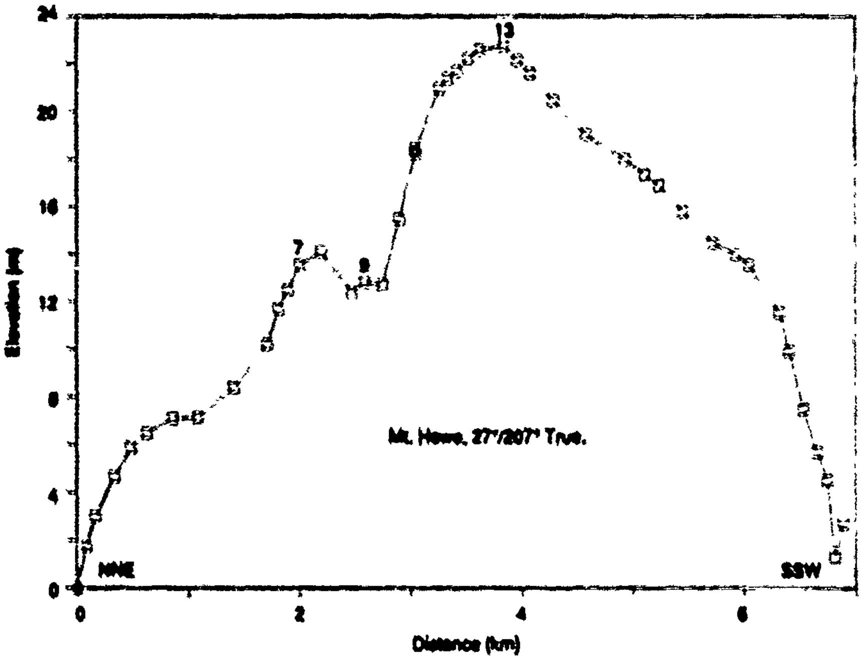

Figure 26. Profile along a line oriented 207°/27°true on the Mount Howe icefield. The arbitrary datum for the levels is at the northeast end (see Fig. 24, 25).

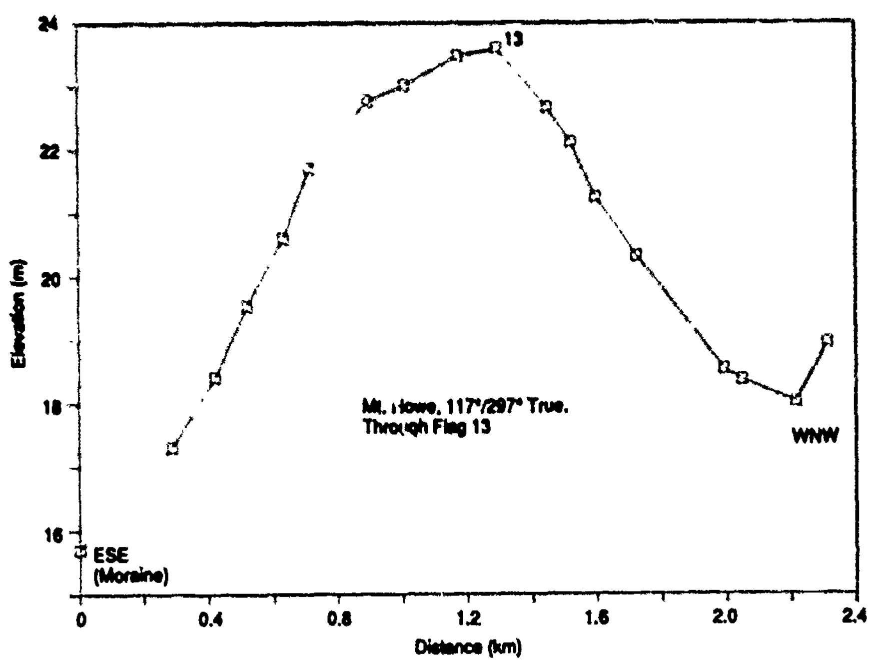

Figure 27. Profile of a cross-line at Mount Howe. This line runs through flag 13 (see Fig. 24) and has an orientation of 297°/117°true. The arbitrary datum for the levels is that for the profile of Fig. 26.

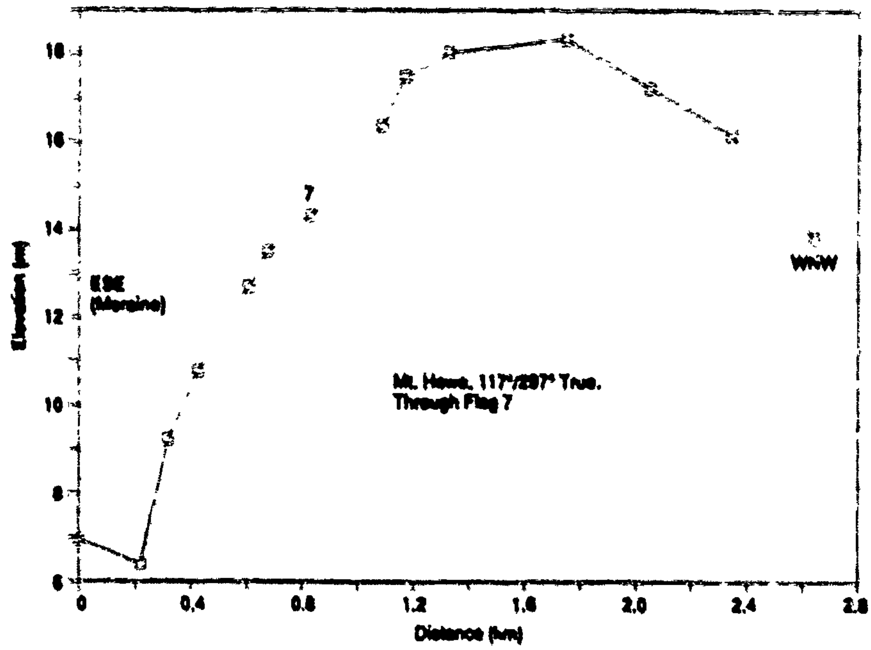

Figure 28. Profile of a cross-line at Mount Howe. This line runs through flag 7 (see Fig. 24) and has an orientation of 297°/117° true. The arbitrary datum for the levels is that for the profile of Figure 26.

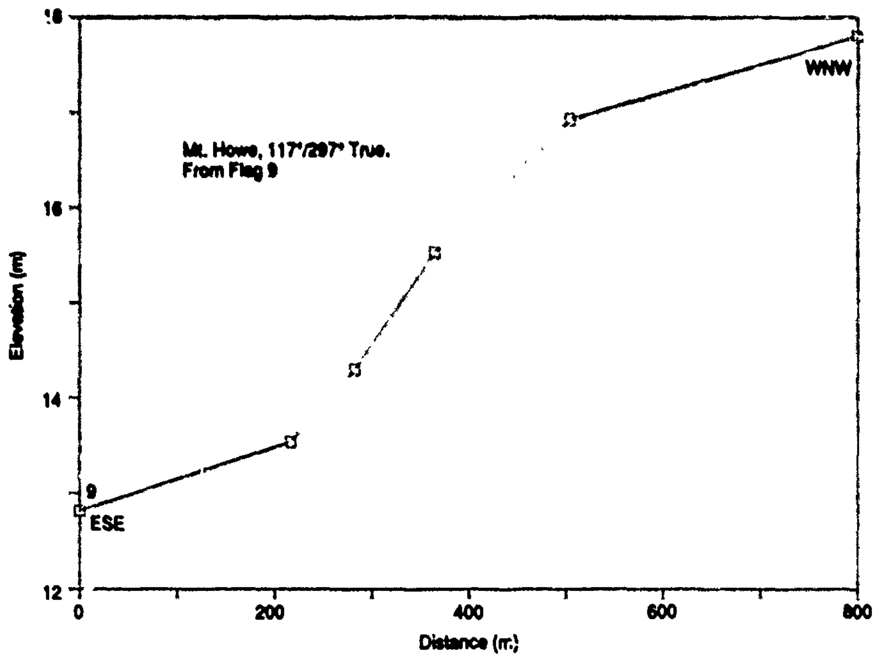

Figure 29. Profile of a short cross-line at Mount Howe. This line runs from flag 9 (see Fig. 24) in the direction 297°/117° true. The arbitrary datum for the levels is that for the profile of Figure 26.

ber 1988, a 6.9-km (22,600-ft) line was laid out as a possible centerline for a long runway. This line, with orientation 207°/27° true, is less than 2 km (< 6600 ft) from the moraine for much of its length. The approach is completely unobstructed from the north and the climbout to the south is virtually unobstructed, being limited only by a 1° climb to clear rising terrain. The profile along this line is given in Figure 26, taking levels from an arbitrary datum at the north end. Over most of the length the gradients are well under 1%, but they approach 2% where the line crosses a shallow valley. This valley is located near flag 9 in Figure 24 and at the intersection with the shortest cross-line in Figure 25. The tents in Figure 19 are located at flag 9 in the shallow valley.

After all the data from the exploratory survey had been plotted and the form lines of Figure 25 had been drawn, it seemed that it might be advantageous to locate the 207°/27° (true) runway further to the west, up to 0.8 km (2600 ft) west of the line that was surveyed. This should put it on more level terrain without materially affecting the approach and climbout, but it is possible that the small-scale roughness of the ice might be more of a problem further out from the moraine.

Although 207°/27° true gives a very long runway with excellent approach and climbout, a runway of that orientation would have a prevailing crosswind. During the December 1988 survey the wind was consistently from 120° true, averaging 10 knots (5.1 m/s) but rising to 30 knots (15.4 m/s) on one day. The snowdrift patterns in Figures 11–16 seem to confirm 120° as the usual wind direction, even during periods of blowing snow.

The crosswind component of the long runway could be reduced by changing the orientation closer to 180°/360° true. The line might still pass through the 22-m high point of Figure 25, with the north-end threshold moved west to the limit of the crevasses and the climbout passing over the low saddle that is seen in Figures 17 and 23.

Runways that are parallel with the prevailing wind direction can be laid out, but they are relatively short and the climbout is obstructed by the Mount Howe ridge. Two major lines at right angles to the "long runway" were surveyed, together with one short line (Fig. 25). Their orientations are .297°/117° true, which is close to the accepted value of 120° for the wind direction. The two major survey lines with this orientation had lengths of 2.64 km (8700 ft) and 2.31 km (7600 ft). The short line was 800 m (2600 ft) long. The profiles for these lines are shown in Figures 27–29.

On the cross-line that runs through flag 7, the usable length is estimated as 1.97 km (6460 ft), with the runway terminating 0.67 km (2200 ft) from the edge of the moraine terrace. The maximum gradient on this "runway" is 0.8%. On the cross-line that runs through flag 13, the usable length is estimated as 1.6 km (5250 ft), with the runway terminating 0.71 km (2330 ft) from the edge of the moraine terrace. For these two runways the required climbout angle is around 5°. The approach from the west is unobstructed for both these runways, allowing glide angles as low as 1°. For STOL aircraft taking off into the wind from these runways, a left turn out before reaching the ridge should be well within safe operating limits.

Mill Glacier/Plunket Point

The Mill Glacier is a valley glacier in the Transantarctic Mountains, its main part lying between 85° and 85°30'S, and between 167° and 171°E. It flows down from the Grosvenor Mountains, past Otway Massif, and down between the Dominion Range and the Supporters Range, finally joining the Beardmore Glacier at about 85°S.

The ice of the Mill Glacier is remarkably smooth and crevasse-free over large areas. From 85°S its western side appears to offer a much better surface route to the Pole than does the Beardmore Glacier.

Where the Mill Glacier joins the Beardmore, there is an area of smooth and level blue ice just upstream of Plunket Point, at 85°06'S, 167°15' E (Fig 30). The western limit of this ice field is a large snow-free rock massif known as the Meyer Desert (Fig. 31–32). The northernmost extremity of the massif is Plunket Point. To the east, the area of smooth ice is bounded by giant rifts in the glacier surface (Fig. 41). The smooth ice that is suitable for use as an airfield is over 7 km (> 23,000 ft) long in the NNW–SSE direction, which is also the flow direction of the glacier at that location. The usable width varies from about 1 km (3300 ft) at the northern end to about 100 m (330 ft) at the extreme southern end. The long direction of this ice field appears to be almost coincident with the direction of the prevailing wind, which seems to blow from 160° true in summer. The altitude of the site is approximately 1800 m (5900 ft).

The surface relief of the ice field is indicated in Figure 33, which gives form lines at 5-m vertical intervals. Figure 33 also shows the position of the survey lines along which levels were measured. The positions of bamboo marker stakes, with their designations, are plotted in Figure 34. The exposed length of each stake was measured on 6 January

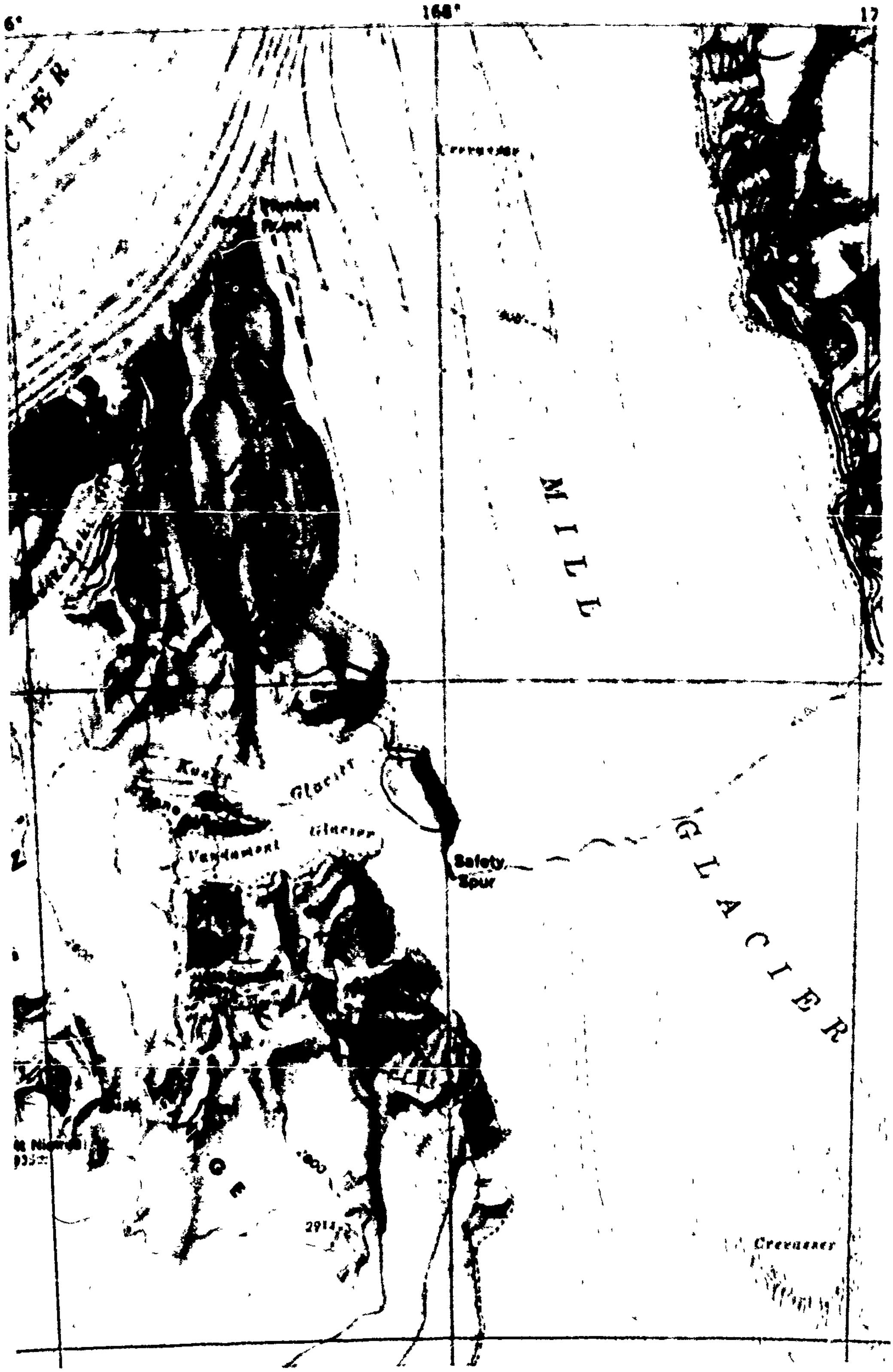

Figure 30. Location map for Plunket Point and the Mill Glacier. The approximate alignment of the long runway at Plunket Point is shown. (From the USGS map "Plunket Point," SV 51-60/8, 1:250,000.)*

Figure 31. Aerial oblique looking to the east (097° true) across the Mill Glacier to the Supporters Range. The rock mass in the foreground is the Meyer Desert, which has Plunket Point as its extremity on the left. The runway site is the strip of smooth ice lying alongside the Meyer Desert, upstream from Plunket Point. The crevassed ice at the lower left is part of the Beardmore Glacier. (U.S. Navy photo for USGS, TMA 776 F31 315, 7 November 1960.)

Figure 32. View across the Mill Glacier looking southwest, with the Beardmore Glacier on the upper right. The rock mass in the center is the Meyer Desert, with Plunket Point on the right. The runway site lies immediately below the Meyer Desert in this photograph. (U.S. Navy photo for USGS, TMA 2186 F31 030, 7 January 1969.)

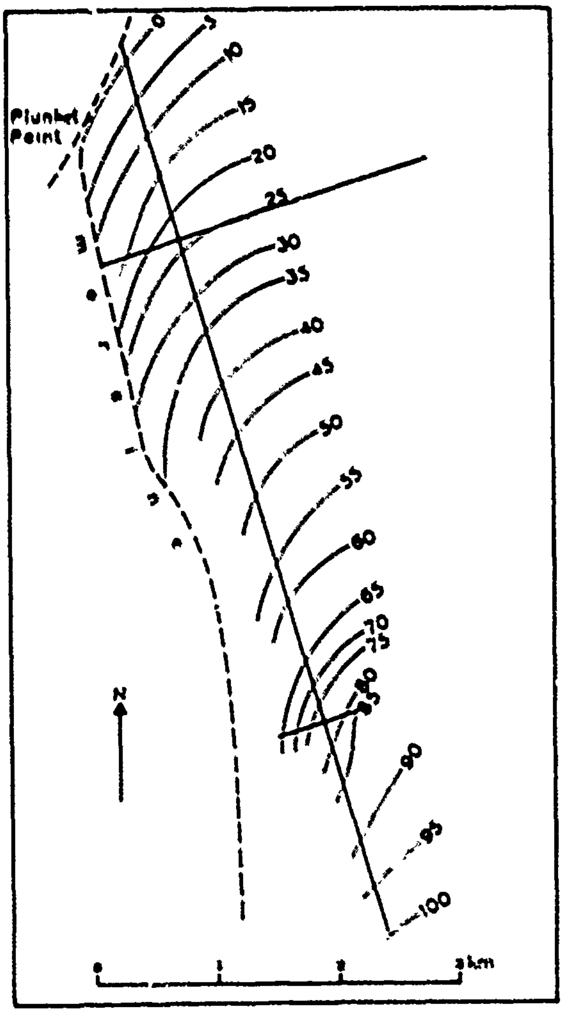

Figure 33. Sketch map of Mill icefield covering the same area as Figure 34. Form lines at 5-m (16-ft) intervals are conjectural except where surveyed along the three straight lines. Elevations refer to an arbitrary datum at the threshold end of the runway oriented 163°true.

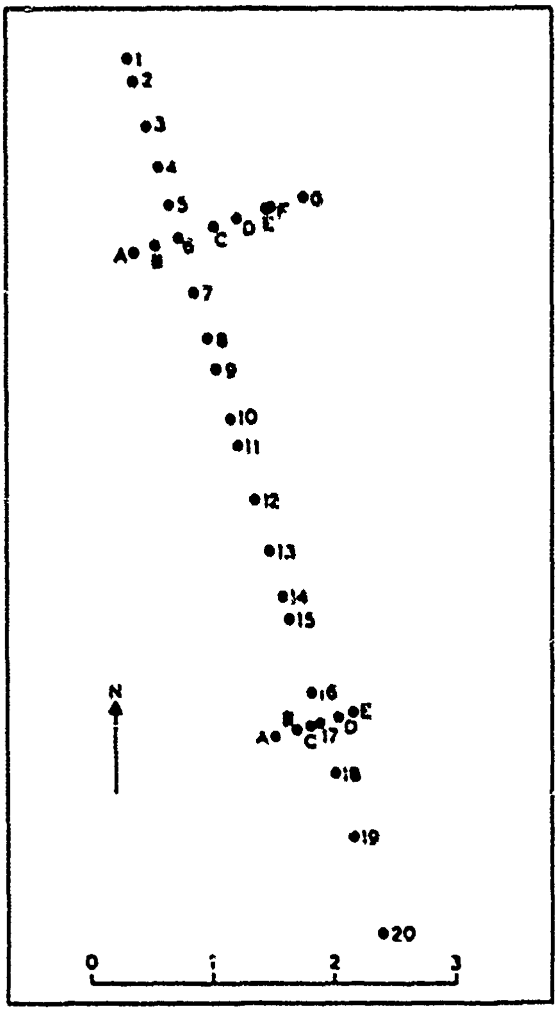

Figure 34. Location of bamboo markers set up to guide Mill icefield leveling survey. Each marker is numbered in pencil and topped with a green flag.

1989, so that ablation can be monitored. The exposed lengths of the stakes are given in Appendix A.

The air photographs of Figures 31 and 32 do not show any obvious surface features on the ice field site. The ice surface appears to rise gradually and steadily towards the south, with no major surface relief apart from a convex dropoff where the ice meets the lateral moraine. Flow bands can be seen faintly in Figure 31, and more clearly in the ground photograph of Figure 35. The color print of this photograph shows brown flow bands, which presumably contain low concentrations of rock dust. As at Mount Howe, there is no noticeable surface relief associated with the flow bands.

Figures 36–40 show the surface texture of the ice, which is covered by cup-shaped depressions about 15 cm (6 in.) in diameter and about 5 cm (2 in.) in maximum depth. Figures 37 and 40 show snow lodged in the pitted surface and smeared over the ice texture in a few small patches. Snow patches accounted for less than 1% of the surface area in January 1989. Apart from the ankle-twisting roughness of the scalloped surface, there are no noticeable bumps that would affect an aircraft or a wheeled vehicle (the few snow patches are not very thick).

The air photographs of Figures 31 and 32 illustrate the extent and the relief of the ice-free terrain alongside the runway site, but they do not give a

Figure 35. View across the Mill Glacier from Plunket Point, looking in the direction 77°true. The tents of the survey camp can be seen on the right of the picture. The proposed runway runs parallel to the flow bands, 300 m (1000 ft) from the tents towards the camera. (Photo by Charles Swithinbank, 9 January 1989.)

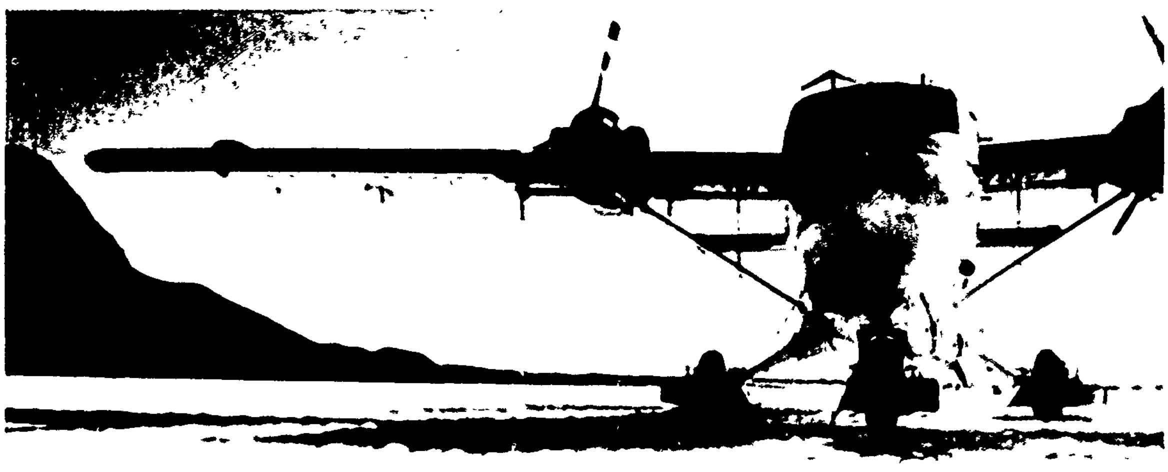

Figure 36. Twin Otter after a wheel landing at Mill Glacier. Note the scale of the ice ripples relative to the wheels of the aircraft. The photograph is taken looking northwest, with Plunket Point on the left. (Photo by Charles Swithinbank, 2 January 1989.)

Figure 37. Surface texture of the Mill Glacier icefield. This is a view looking NNW across the Plunket Point moraine, with the Beardmore Glacier in the background. (Photo by Malcolm Mellor, 22 January 1989.)

Figure 38. The Mill Glacier icefield, looking west towards the Meyer Desert. (Photo by Malcolm Mellor, 22 January 1989.)

Figure 39. Southern extension of the bluffs seen in Figure 38. (Photo by Mark Parent, January 1989.)

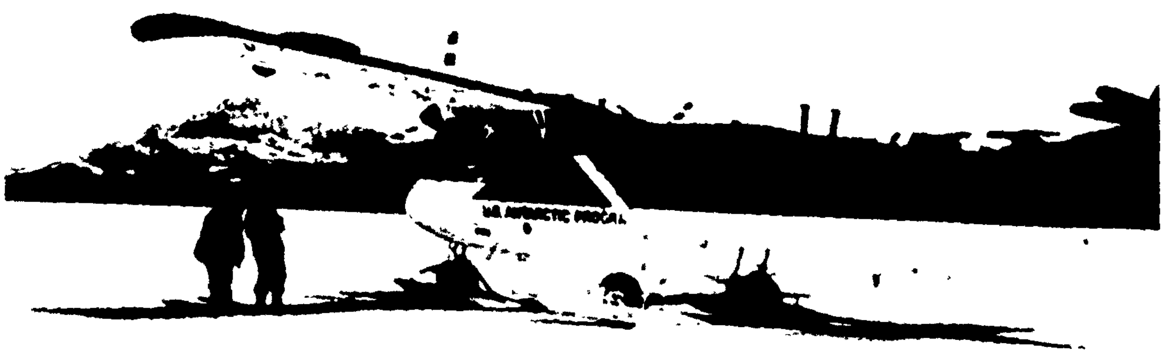

Figure 40. View to the south on the Mill Glacier runway. (Photo by Malcolm Mellor, 22 January 1989.)

Figure 41. One of the "giant rifts" that border the Mill Glacier icefield on its eastern side. These features can be seen in the air photographs of Figures 31 and 32. (Photo by Mark Parent, January 1989.)

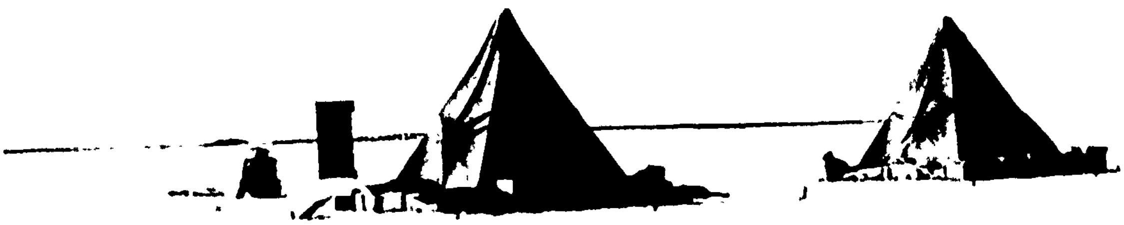

Figure 42. Survey camp on the Mill Glacier, looking northwest (330° true) across the Plunket Point moraine. The far side of the Beardmore Glacier, seen in the background, is 48 km (26 n.m.) from this camp. The contrail overhead, formed by an LC-130, is a reminder that this site lies on the direct air route from McMurdo to South Pole. (Photo by Charles Swithinbank, January 1989.)

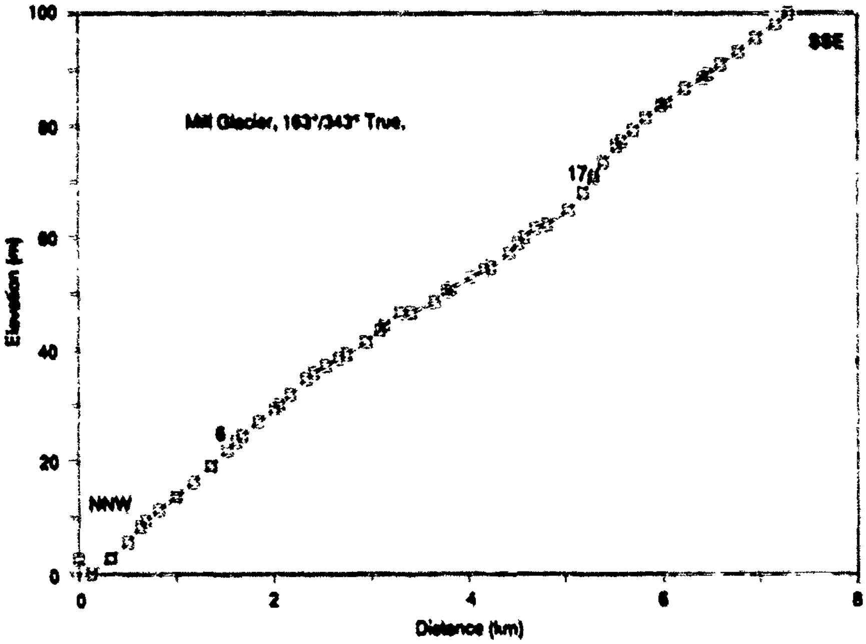

Figure 43. Profile along a line oriented 163°/343° true on the Mill Glacier icefield. The arbitrary datum for the levels is at the north end (see Fig. 33, 34).

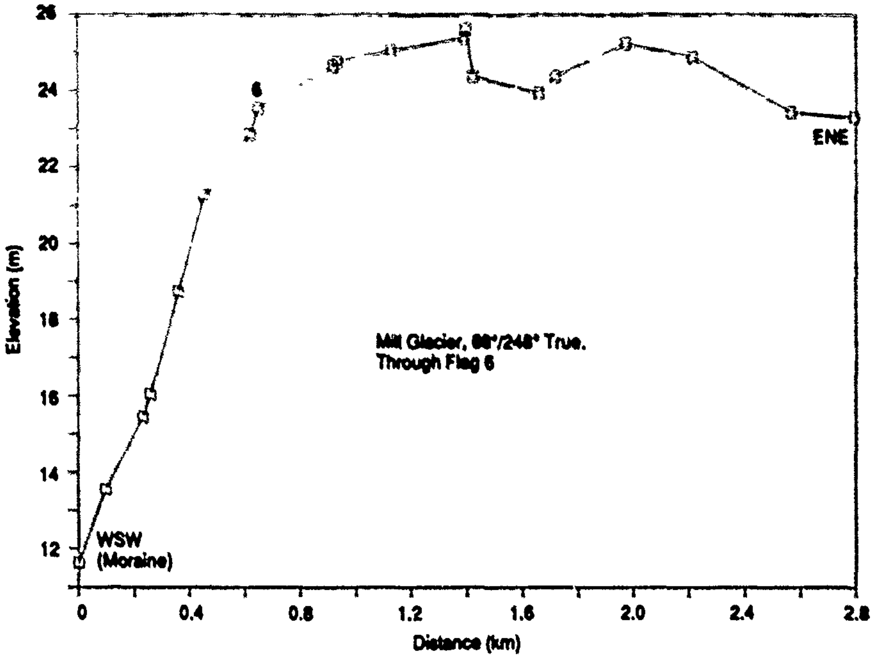

Figure 44. Profile of a cross-line on Mill Glacier. This line runs through flag 6 (Fig. 34) and has an orientation 68°/248° true. The arbitrary datum for the levels is that for the profile of Figure 43.

graphic impression of the scale. This is seen better in Figures 38 and 39, which show steep snow-free bluffs rising above the lateral moraine.

Figure 42, which shows a contrail over Plunket Point, emphasizes that this runway site lies on the direct flight route from McMurdo station to the South Pole (the 167° meridian). The straight-line distance to Pole is about 294 n.m.

During the exploratory survey in January 1989, a 7.3-km (23,900-ft) line was laid out in the esti-

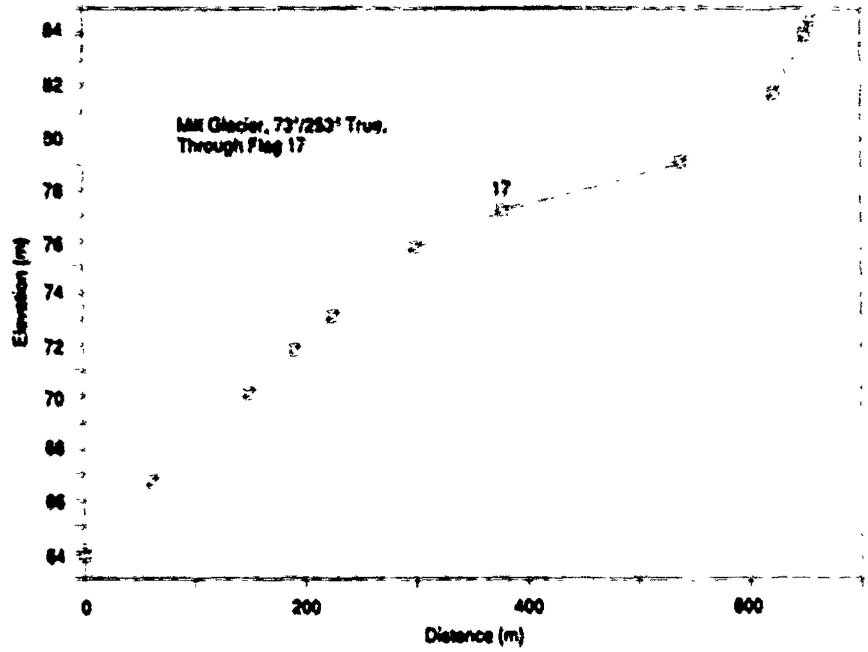

Figure 45. Profile of a cross-line on Mill Glacier. This line runs through flag 17 (Fig. 34) with an orientation of 73°/253°true. The arbitrary datum for the levels is that for the profile of Figure 43.

mated position for a long runway. The orientation of this line (shown in Fig. 33 and 34) is 163°/343° true. Over a 7-km length, the change of elevation is 100 m, for an average gradient of 1.4%. The ice has a smooth slope (Fig. 43), with no major humps or hollows.

Two cross-lines were surveyed (Fig. 33 and 34). The long one, running through flag 6 of Figure 34, was 2.8 km (9200 ft) long, with an orientation of 68°/248° true. The short one, running through flag 17 of Figure 34, was 655 m (2150 ft) long, with an orientation of 73°/253° true. The profiles of these lines are shown in Figures 44 and 45.

During the survey in January 1989, the wind blew consistently from 160° true, averaging about 10 knots (5.1 m/s). Conditions ranged from completely calm to a wind of about 30 knots (15.4 m/s). Snowdrift patterns in the area (see Fig. 31) suggest that 160° true is the prevailing direction of the surface wind.

The 163°/343° direction gives an exceptionally long runway that is parallel to both the glacier flow direction and the prevailing wind direction. Landings would be made upslope and into wind. In calm conditions, downslope takeoff would be available. On the normal approach across the Beardmore Glacier, shallow glide angles, as low as 1°, could be used on a long approach. On a normal takeoff to the SSE, a climb angle of 1° would clear the rising terrain.

Patriot Hills

Patriot Hills is the name given to an isolated ridge in the Heritage Range of the Ellsworth Mountains. The ridge is located at about 80°20'S, 81°20'W (Fig. 46). The highest point on the ridge, which trends WNW–ESE, is at an elevation of approximately 1250 m (4000 ft). The surface to the south of the ridge is at an altitude of about 1000 m, or 3300 ft (according to the USGS map, which may give elevations that are up to 250 m too high). The ice field immediately north of the ridge is at somewhat lower elevation. It has a flat and smooth area some 2 km by 8 km (6600×26,000 ft) in extent around the position 80°19'S, 81°16'W. The prevailing wind blows from 206° true, i.e. the smooth ice field is on the lee side of the rock ridge (Fig. 47). The ice surface has the characteristic ripples, or scallops, of a cold, windswept ablation area (Fig. 48 and 49).

Two runway lines were surveyed at Patriot Hills. The long line extended for 3414 m (11,200 ft) in the direction 130°/310° true, i.e. the crosswind direction. The approaches to this line from either end are unobstructed. There is a steady increase in elevation along the line, for a total change of 30 m in a distance of 3.4 km. The overall gradient is

Figure 46. Location of blue-ice runways at Patriot Hills. (From the USGS map "Liberty Hills," SU 16-20/2, 1:250,000.)*

Figure 47. Patriot Hills (left foreground), looking northwest. The blue-ice airfield site is on the right of the ridge, i.e. the lee side. Long-wave rolls in the ice surface can be seen. At the upper right of the photograph, the Vinson Massif can be seen 225 km distant. (U.S. Navy photo for USGS, TMA 897 F33 047.)

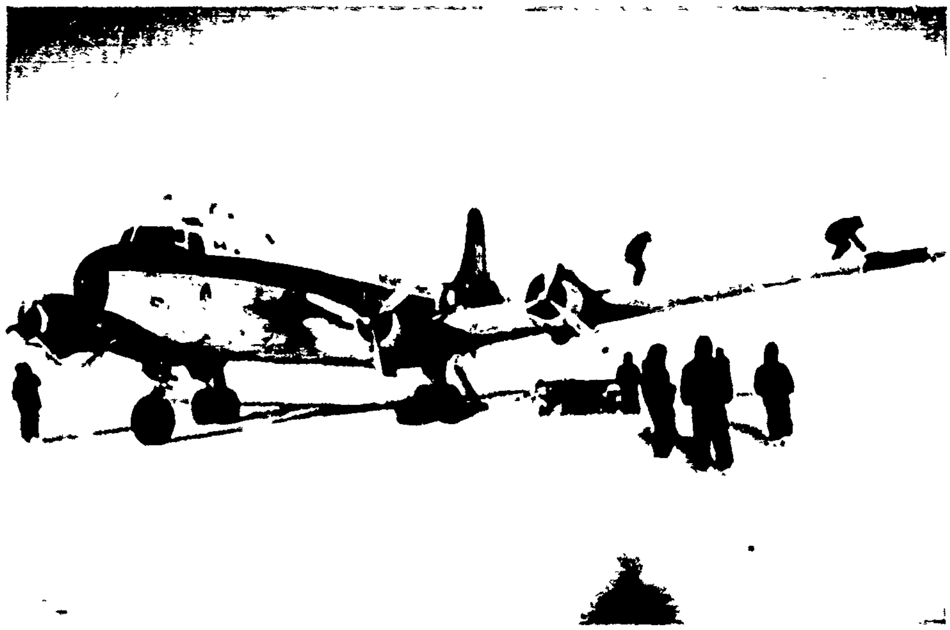

Figure 48. First wheel landing by a DC-4 at Patriot Hills. (Photo by Charles Swithinbank, 22 November 1987.)

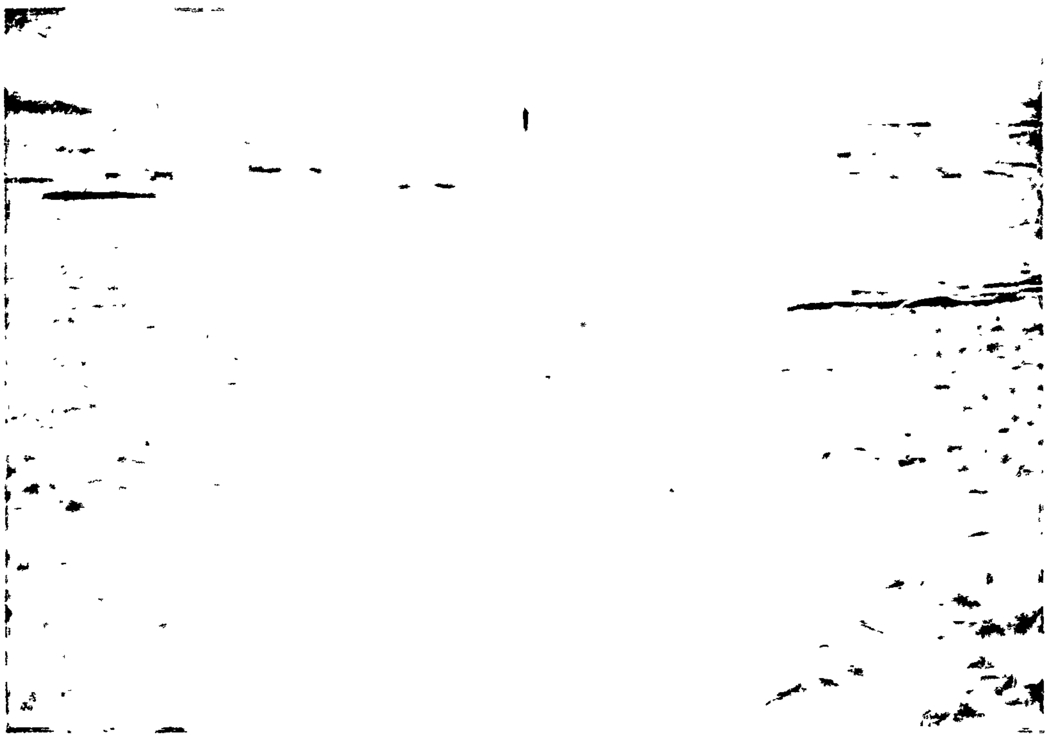

Figure 49. Surface texture of the icefield at Patriot Hills. Note the scattered patches of sastrugi (snow). The camera is looking in the direction 310°true, with the Patriot Hills off to the left of the picture. (Photo by Charles Swithinbank, December 1986.)

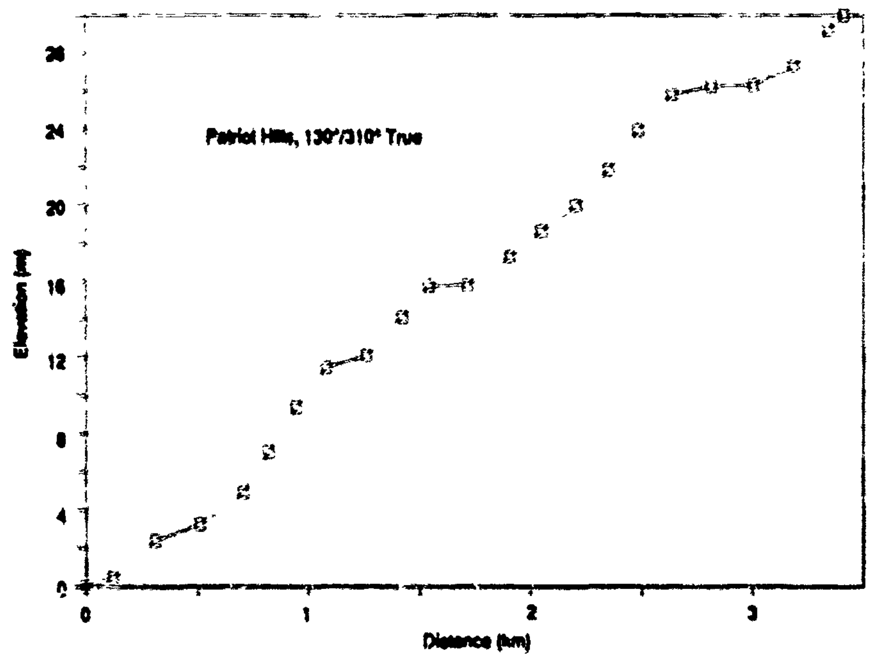

Figure 50. Profile along a 3.4-km line oriented 130°/310° true at Patriot Hills.

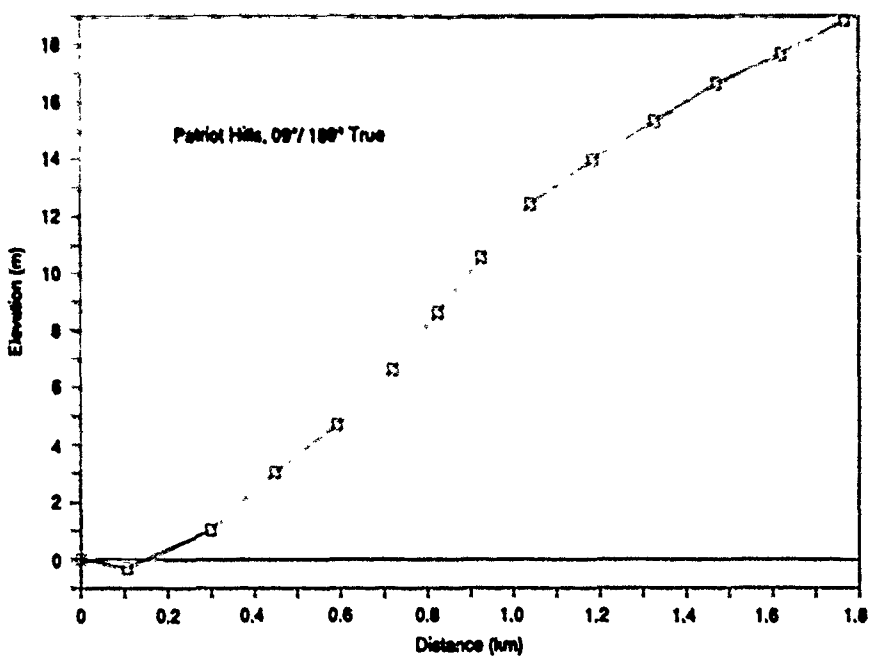

Figure 51. Profile along a line oriented 09°/189° true at Patriot Hills.

0.88%. The profile (Fig. 50) shows some long-wave undulations, which are also visible in the photograph of Figure 47.

The shorter of the two survey lines (Fig. 51) had a length of 1767 m (5800 ft) and an orientation of 09°/189° true, which puts it close to the prevailing wind direction of 206° true. The south end of this line is obstructed by the ridge, necessitating a 15:1 glide ratio for an approach from the south. The approaches from the north are completely unobstructed. The line slopes down from north to south, changing in elevation by 19 m over a distance of 1.7 km, with a mean gradient of 1.2%.

The Patriot Hills airfield is at much lower eleva-

Figure 52. A camp on the moraine at Patriot Hills. The wind is blowing snow streamers from the right-hand end of the moraine towards the distant Twin Otter. (Photo by Charles Swithinbank, 25 November 1987.)

tion (perhaps 750 m, or 2500 ft) than the icefields at Mount Howe (2400 m, or 7900 ft) and at Mill Glacier (1800 m, or 5900 ft). It is about 580 n.m. from the South Pole.

Temporary camps capable of housing up to 40 people have been maintained during summer on the lateral moraine at Patriot Hills (Fig. 52). Tourists were flown in from Punta Arenas, Chile, on a DC-4 for transshipment to the South Pole by ski–wheel Twin Otters.

Rosser Ridge

Rosser Ridge is an east–west trending rock ridge at the northern edge of a small group of nunataks called Cordiner Peaks. The Cordiner Peaks are part of the Pensacola Mountains. The highest point on Rosser Ridge is mapped with a height of 1138 m (3734 ft).

The ice field that was surveyed (Kovacs and Abele 1977) lies immediately north of the ridge at 82°46′S, 53°40′W. Figures 53 and 54 show the location and the runway site. The surface elevation of the icefield is approximately 800 m (2600 ft). The prevailing wind blows from the east.

The exposed ice surface is covered with small cup-shaped depressions (Fig. 55 and 57). The ridges separating the cups are perhaps somewhat less sharp than corresponding ones at Mount Howe and Mill Glacier, possibly because of stronger ablation. Some parts of the icefield have a thin and patchy snow cover (Fig. 56), with some sastrugi up to 15 cm (6 in.) high. There is some evidence that rock fragments cause melting and sink into the ice (Fig. 58).

A runway line was laid out in an approximately east-west direction (85°/265° true) and a profile was measured over a length of 1.5 km (Fig. 59). It was estimated that a length of 2.4 km (7900 ft) is available for a runway with this alignment. A longer runway could perhaps be prepared with the aid of snow removal equipment. The overall gradient of the survey line was 0.6%, sloping up from west to east (i.e. upslope is into wind). The transverse gradient was about 1%. For a runway in this position, the approaches are unobstructed at both ends.

The runway is about 1 km (3300 ft) from the rock and moraine of Rosser Ridge. There are some reasonably level areas for camp construction near the edge of the ice, and gravel is abundant.

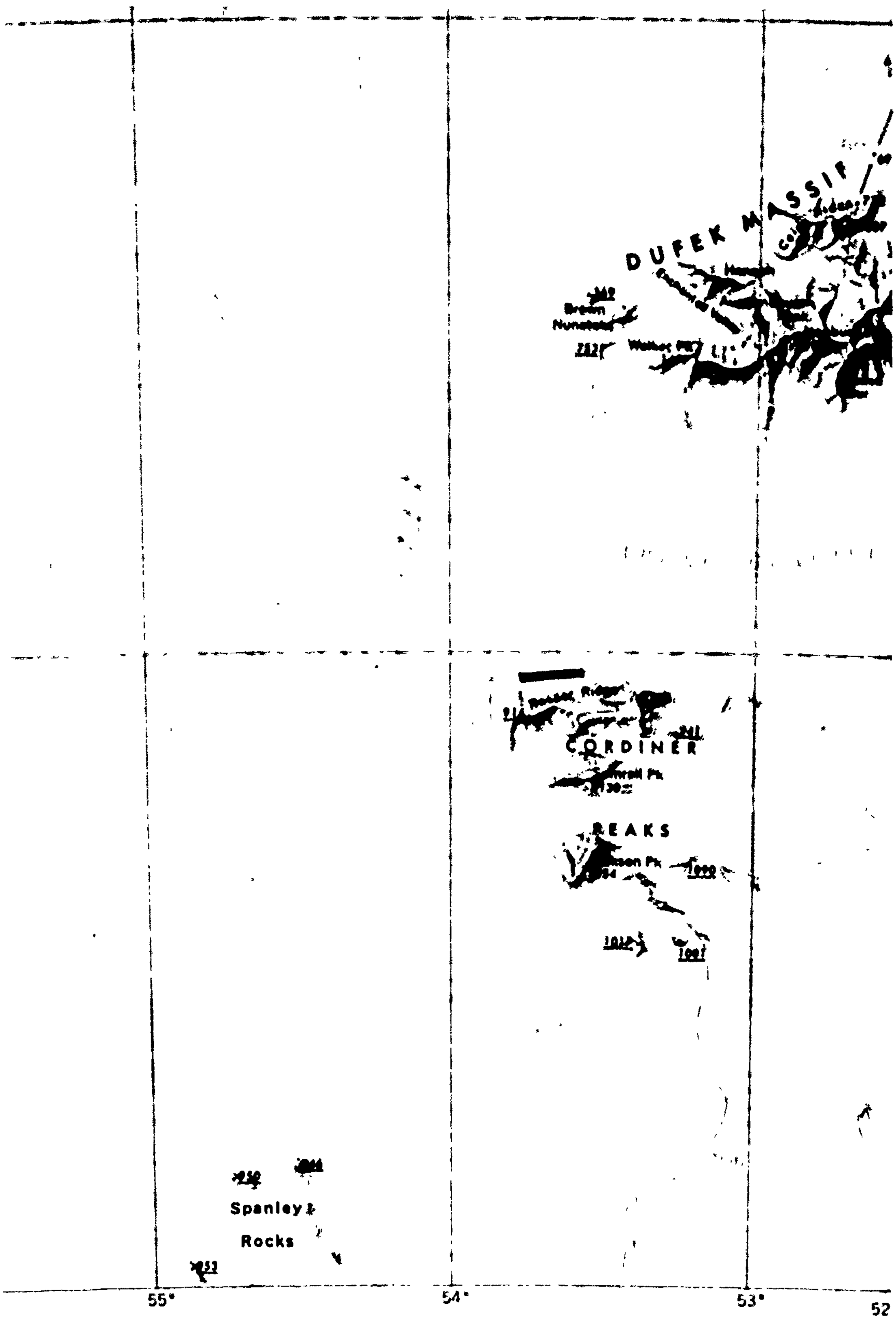

Figure 53. Location of blue-ice runway at Rosser Ridge. (From the USGS map "Cordiner Peaks," SU 21-25/9, 1:250,000.)

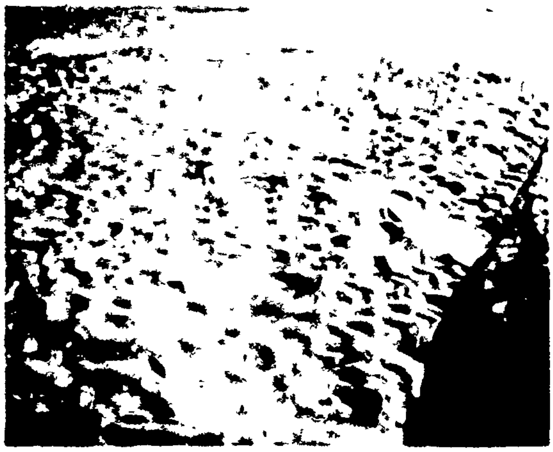

Figure 55. Ripples in the ice surface at Rosser Ridge. (Photo by Austin Kovacs.)

Figure 56. Thin, patchy snow cover on the ice at Rosser Ridge. (Photo by Austin Kovacs.)

Figure 54. The icefield and the proposed runway at Rosser Ridge. (Photo from Kovacs and Abele 1977.)

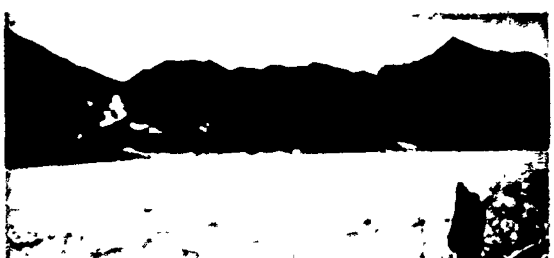

Figure 57. Small, snow-filled crevasses near the east end of the runway site at Rosser Ridge. (Photo by Austin Kovacs.)

Figure 58. Refrozen cryoconite holes on the icefield at Rosser Ridge. (Photo by Austin Kovacs.)

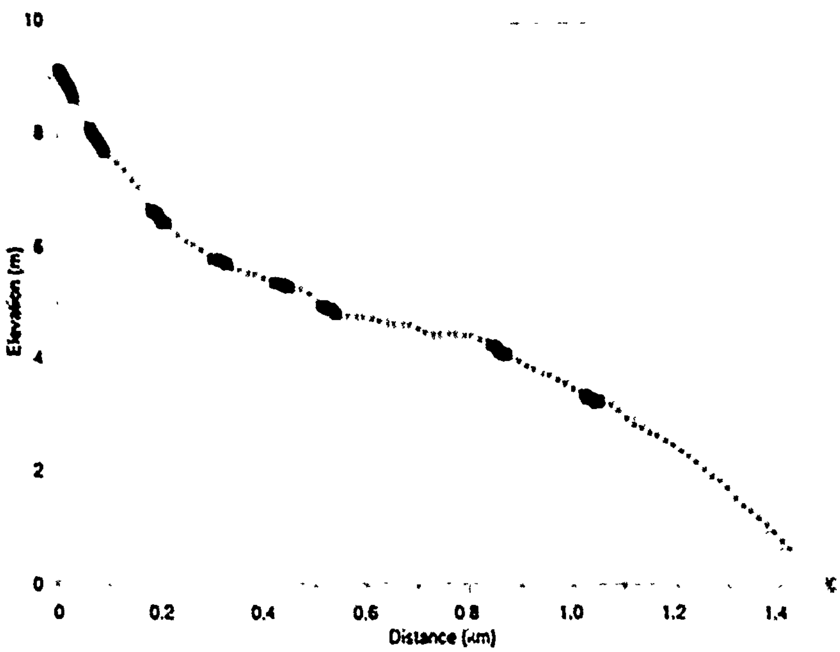

Figure 59. Profile along part of the proposed runway at Rosser Ridge. (Data provided by Austin Kovacs.)

Mount Lechner

Mount Lechner is a 2028-m (6600-ft) peak in the Forrestal Range. To the west of the mountain is an ice field which was chosen as a runway site by Kovacs and Abele (1977). The site is at 83°15'S, 51°14'W, with the ice surface at an elevation of about 1400 m (4600 ft). Surface winds at the site seem to blow from the east and the northeast. The location and situation of the site are shown in Figures 60 and 61.

A runway line was surveyed in a north-south direction (15°/195° true). The length of the survey

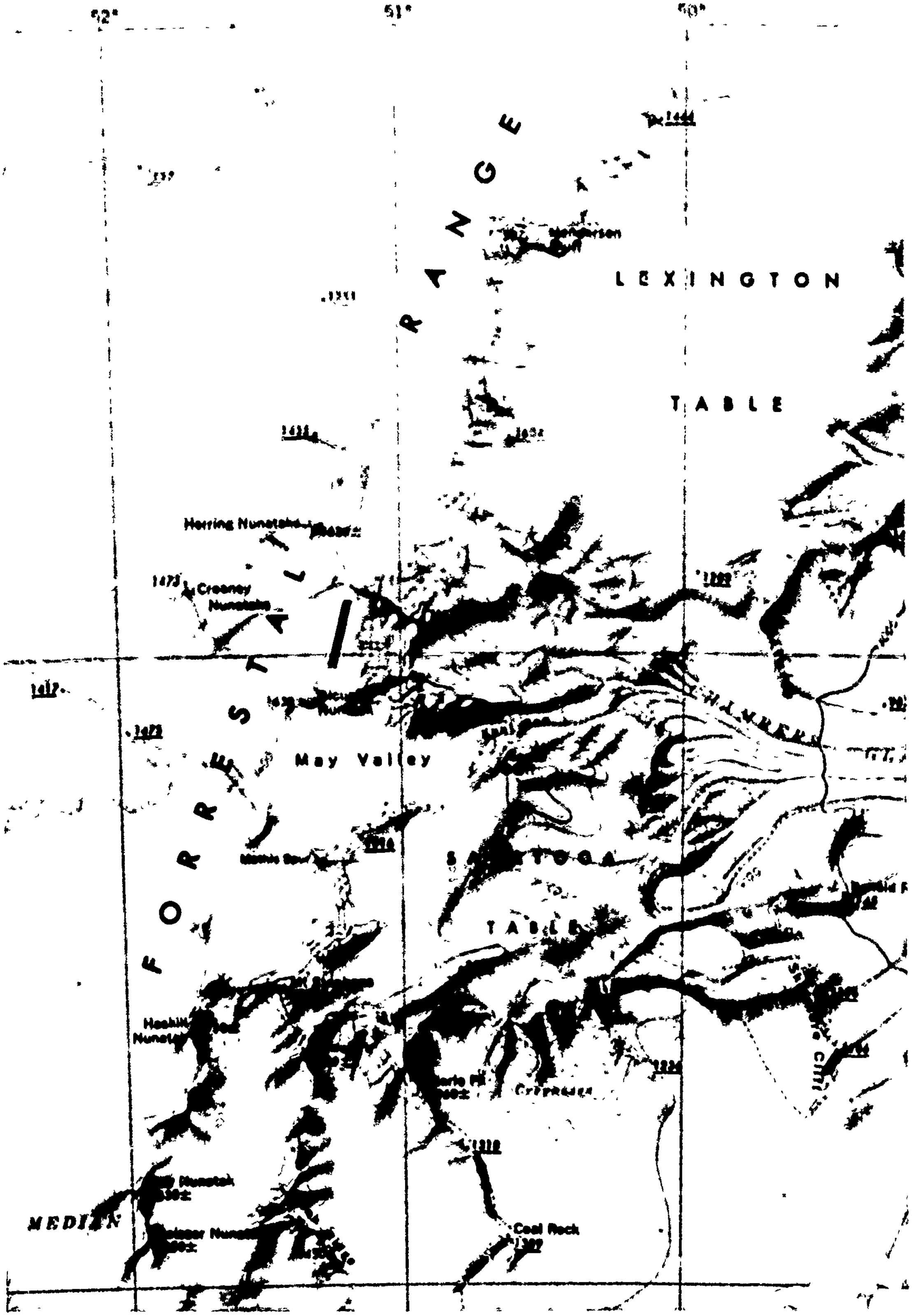

Figure 60. Location of blue-ice runway at Mount Lechner. (From the USGS map "Saratoga Table, [illegible] 21-25/14, 1:250,000.)

Figure 61. Aerial view of the icefield at Mount Lechner. Blount Nunatak is at the lower right. (Photo from Kovacs and Abele 1977.)

line (Fig. 62) was 1.5 km, but the estimated available length for a runway was 3 km (9800 ft). The general gradient along the survey line was 0.75%, sloping up towards the south (i.e. the upslope is in the downwind direction).

On the normal approach, heading about 15° true, there is a significant obstruction just left of the centerline. This is Blount Nunatak, which has a peak mapped at an elevation of approximately 1630 m (5350 ft), i.e. about 230 m (750 ft) above field elevation. The peak of Blount Nunatak is only about 500 m left of the surveyed centerline, and about 2 km (6500 ft) short of the threshold. In other words, the approach angle must be steeper than $\tan^{-1}(230/2000)$, or 6.6° (glide ratio 8.7:1). To the north, which would normally be the climbout direction, there is another, but smaller, obstruction. This obstruction takes the form of an ice ridge, with an emergent nunatak rising to about 1450 m (4700 ft), or some 50 m (160 ft) above field elevation. The obstruction is less then 1 km (3300 ft) from the end of the runway.

The ice surface at Mount Lechner is unusual in that it does not have a scalloped or furrowed surface. Where the ice is exposed, it is smooth to the degree that ice-skating would be possible. The 1974 survey line had an appreciable amount of snow cover, with snow thickness ranging from

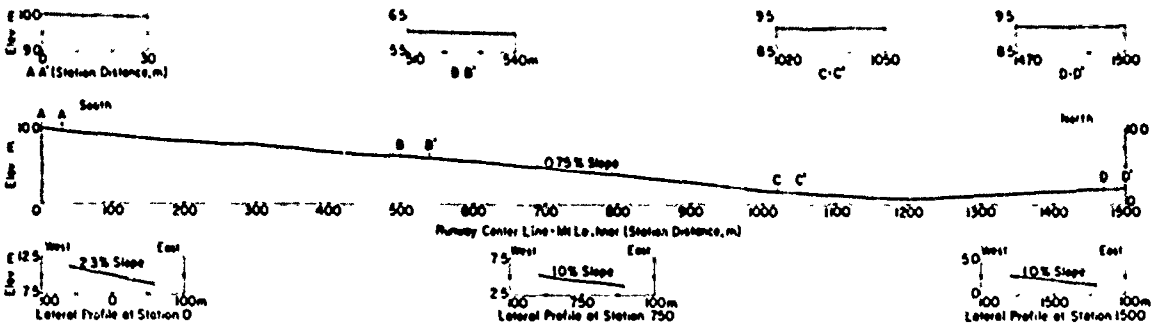

Figure 62. Profile along the proposed runway at Mount Lechner. (From Kovacs and Abele 1977.)

zero to 20 cm (8 in.). The mean snow thickness along the runway centerline was 4 cm (1.6 in.).

The location and orientation of a runway at Mount Lechner could be changed to improve the approach and climbout, but deeper snow cover would be encountered and maintenance problems would increase.

The S-1 site near Casey station

Close to the Australian Casey station (66°17'S, 110°32' E) there is a blue-ice runway site known as S-1 (see Fig. 1).

S-1 was a research site for the former U.S. Wilkes station (1956–59), which was handed over to Australia in 1959. Its location is approximately 66°16'S, 110°42'E, at an elevation of 262 m (860 ft), some 9 n.m. (16 km) south of Cape Folger, and about 2.5 n.m. (4.5 km) from the nearest coastline. The mean annual temperature is about –10.5°C, compared with –7.7°C at sea level. Blue ice is exposed at the site, with a density of 0.87 Mg/m³ (Cameron 1964). The site is surrounded by areas that have a small annual net accumulation of snow, and its ablation rate is negligible (not measurable during the period of U.S. occupancy).

The S-1 area was considered as a potential airfield site even before Australia took over Wilkes station, and preliminary site surveys were made on both snow and ice early in 1959 by Bruce Coombes of the Australian Department of Civil Aviation and by M. Mellor. Subsequent runway studies focused on compacted snow runway construction at a place called Lanyon Junction (Russell-Head and Budd 1989).

The first use of S-1 as an airfield was in November 1988, when a Twin Otter landed there on wheels after a non-stop flight from Hobart, Tasmania. There are now plans to develop the site for use by standard Lockheed Hercules (C-130) aircraft of the RAAF in 1989/90. Two trial flights will probably be made in early February of 1990.

The runway that was prepared for the Twin Otter in 1988 was located about 6 km (3¼ n.m.) east of Casey station at an elevation of about 300 m (1000 ft). The runway was on blue ice, with scattered patches of snow up to 5 cm (2 in.) deep. On each side of the runway were graded strips that received less preparation. The central runway was 30 m (100 ft) wide and 1.5 km (4920 ft) long. The adjacent graded strips were each 30 m (100 ft) wide, giving a total prepared width of 90 m (300 ft). For the new strip, consideration is being given to a construction procedure that depends on compacting the thin snow cover on the hard ice.

The McMurdo "Pegasus Site"

To the south and west of McMurdo station, a lobe of the Ross Ice Shelf flows into McMurdo Sound (Fig. 63). To the east and southeast of Cape Armitage, the surface of the ice shelf is a net accumulation area, with a permanent snow cover that is of great depth. Winds are relatively light in this area, as evidenced by the name "Windless Bight" for the area between Hut Point Peninsula and Cape Mackay. To the west and southwest of Cape Armitage, the surface of the ice shelf suffers very strong net ablation, with intense summer melting (Swithinbank 1970). This is a consequence of southerly winds which limit snow deposition and carry dark-colored dust onto the ice from Black Island and Brown Peninsula.

The Williams Field skiway, almost due east of Cape Armitage, is in the accumulation area, and it receives about 0.6 m (2 ft) of new snow per year. The water equivalent of this net accumulation is about 0.23 m of water. Traveling southwest from Williams Field, the annual accumulation gradually decreases, becoming zero at the transition from the accumulation area to the ablation area, probably under the influence of local surface winds (non-geostrophic) that funnel down from the south through the gap between White Island and Black Island. This transition zone is encountered at about longitude 166°35'E in latitude 78°S. Just to the west of the transition there is the wreck of an old C-121J Constellation which carried the name *Pegasus*. Since this aircraft, which crashed in October 1970, is the only landmark, the area immediately southeast of the wreck is known to us as the Pegasus site.

About 1 km west of the transition, and just within the zone of net ablation, is the site of the former Outer Williams Field (OWF). During the period when OWF operated as a backup airfield for McMurdo station (from 1966–67 to 1970–71), its nominal location was approximately 77°57.7'S, 166°28.5'E. According to old U.S. Navy drawings, the elevation of the ice surface was about 19 ft (5.87 m) above sea level, and the ice thickness at the site was approximately 114 ft (35 m). If accurate, these figures imply a low mean density for the ice (0.855 Mg/m³). The ice was moving slowly in the direction WNW at about 95 ft/yr (29 m/yr). The ice surface sloped down to the NNE at about 3 ft/mile (0.57 m/km); this is a gradient of only 0.06%.

When the field was first established (1966–67), the main runway was meant to be aligned with the prevailing wind, in a direction approximately 155°/335° true. There was also a crosswind runway aligned with the storm wind direction. No record

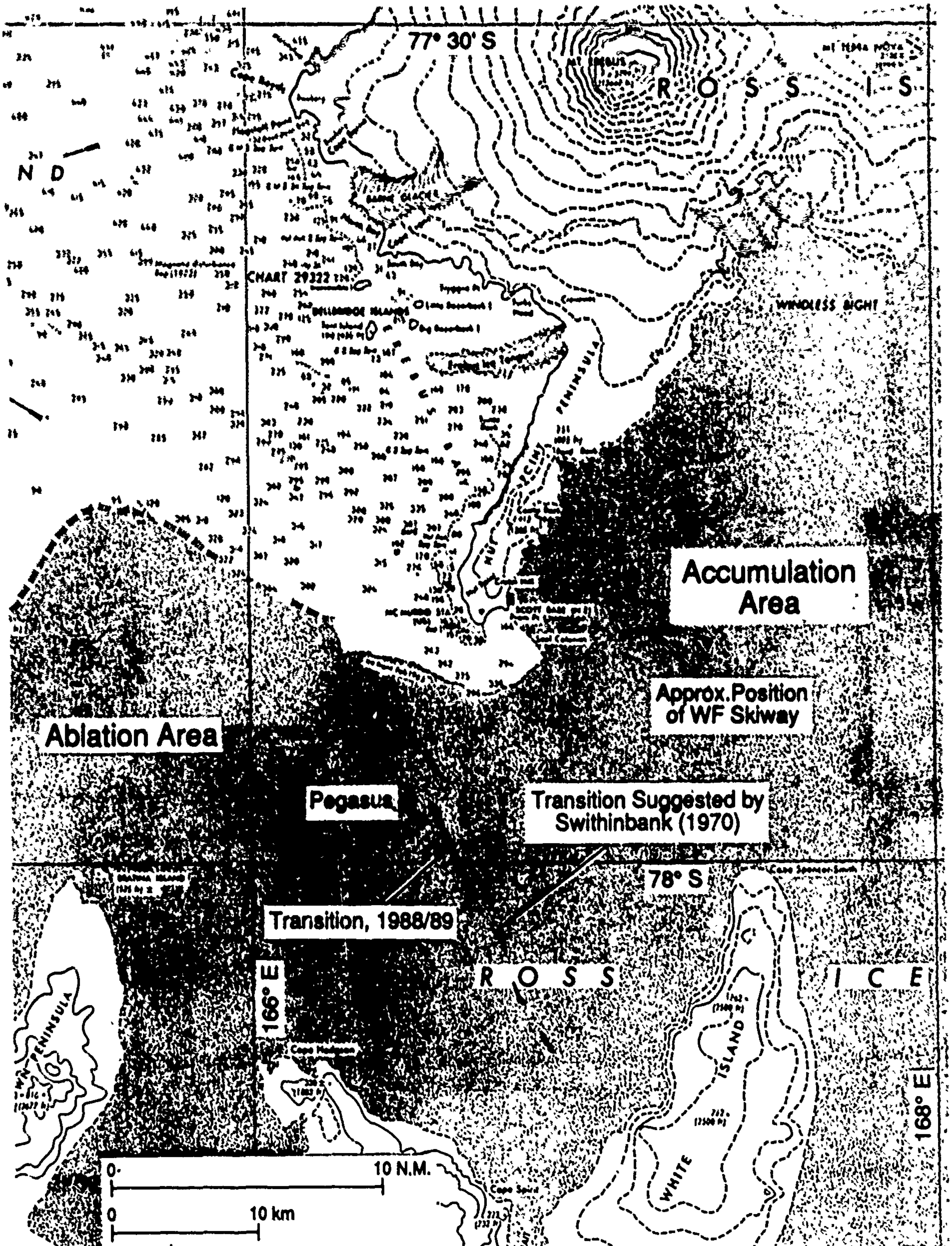

Figure 63. Location map for the Pegasus site.

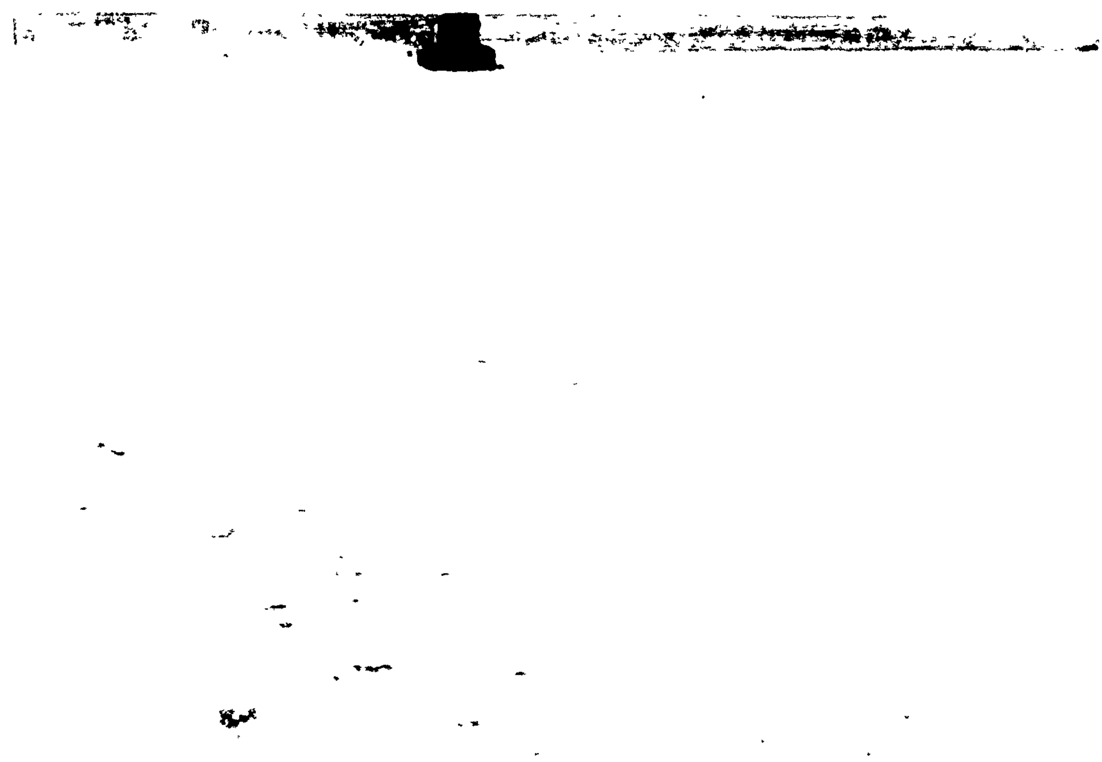

Figure 64. Smooth ice surface revealed by removing a thin snow cover with a 15-ft bulldozer blade at the Pegasus site. (Photo by Malcolm Mellor, November 1988.)

of the exact orientation has been found, but it was perhaps about 040°/220°. In 1967–68 the main runway was realigned about 15° closer to north-south, i.e. to about 170°/350° true. Drawings for the 1970–71 season indicate that it was changed again, to about 004°/184°.

The ablation area where OWF was located proved to have an unusual and disconcerting characteristic: subsurface melt cavities form in January, creating hummocks in the ice surface when they refreeze during the following winter (Paige 1968). The ice surface in this area usually remains at subfreezing temperatures throughout the summer, partly because of the persistent flow of cold air from the south. However, solar radiation is strong on clear days in December and January (up to 10.5 J/m^2), and the albedo of the bare ice is relatively low (Paige mentions 0.48 for very blue ice). Radiation thus penetrates through the cold surface and into the ice, where the radiant energy is absorbed, allowing internal melting to occur. At the time of the study by Paige (1968), melting at OWF began in mid-December, typically at a depth of 40 cm (16 in.) or more. The melting initiates, or perhaps concentrates, in scattered patches (it is not uniform in the horizontal plane). Eventually, lenticular water cavities develop and they grow, in both vertical and horizontal extent, until mid-January. Paige reported diameters up to 10–15 m, depths of 0.5 to 1.0 m (assumed to be below ice surface), and ice cover thicknesses decreasing from about 40 cm to 7 cm as the season progressed. During re-freezing the trapped water expands (about 8% by volume), the ice cover over the cavity heaves, and a cracked ice hummock is formed. Paige gave the size of these hummocks as 2–8 m in diameter and 0.3–0.6 m high at the site of OWF.

The 1988 proposal for a new airfield at the Pegasus site (Mellor 1988a) called for one or more runways to be laid out immediately east of the snow/ice transition instead of using the OWF site, which is west of the transition. In other words, whereas OWF was just in the ablation area, the Pegasus site was to be just inside the accumulation area. The intent was to maintain a thin snow cover over the ice in order to limit ablation problems.

A reconnaissance of the Pegasus site was made by Mellor in November 1988 and again in January 1989. Stakes were drilled into the ice to mark the snow/ice transition in November (brown and

Figure 65. Bulldozed swath at the Pegasus site, January 1989. To the left of the fresh swath can be seen the trace of a swath cut in November 1988, but subsequently filled-in with drifting snow. (Photo by Malcolm Mellor, January 1989.)

white checkered flags) and January (black flags). In November, the ice hummocks described by Paige for OWF could be seen on the bare ice at the transition. They were typically up to 0.4 m (16 in.) high, and some collapsed under the bulldozer tracks, leaving fragment-filled depressions up to 0.15 m (6 in.) deep. Long swaths were bulldozed through the thin snow cover, parallel to the transition inside the snow-covered area and in zig-zags across the transition (Fig. 64, 65). More hummocks were found under the thin snow cover (0.1 m, or 4 in.) and it was assumed that this was winter extension of the accumulation area. In Janu ry the transition appeared to have retreated ea ward by a few hundred metres but in some places there was hardly any change. Bulldozing tests were repeated, and subsurface melt cavities were found under bare ice and under the thin (0.1-m or 4-in.) snow cover near the transition (Fig. 66, 67). The 35-ton (32-tonne) LGP D-8 dozer was a reliable detector of the cavities, which were typically up to 10 m (33 ft) in diameter, with the deep part about 4 to 6 m (13–20 ft). The ice cover over the water was 0.1 to 0.15 m (4–6 in.) thick. The air bubbles in the ice were large, some several millimetres in diameter, suggesting local melting around the original small bubbles. The total depth, from general ice surface to the deep part of the cavity, was 0.25 to 0.46 m (10–18 in.), which is less than the depths reported by Paige for OWF. As the snow cover became thicker with increasing distance from the transition, the melt cavities became smaller and fewer. In areas where there was 0.25 to 0.3 m (10–12 in.) of snow over the ice the bulldozer ceased to reveal evidence of meltwater. Because it is hard to imagine significant penetration of solar radiation through more than 0.1 m (4 in.) of snow cover, it is suspected that the snow over the melt cavities was of recent origin.

Since the albedo and the extinction coefficient for snow are both high, it would be surprising if subsurface melt cavities could form under a stable snow cover that is 0.1 m (4 in.) or more thick. Paige (1968) indicated that a layer of ice chips with an albedo of 0.76 and a thickness of 3 cm (1.2 in.) or more was sufficient to prevent the formation of melt cavities. For now, we are assuming that the melt cavities formed in bare ice that was covered by new snow just before the January reconnaissance (there was a lot of snow at McMurdo during the 1988/89 summer).

Figure 66. Subsurface melt cavity broken open by a bulldozer blade. This cavity (0.43 m total depth with a 0.15-m ice cover) was under a patch of thin snow in a part of the Pegasus transition area where the proportion of snow to bare ice was about 60/40. (Photo by Malcolm Mellor, 17 January 1989.)

Further investigations of the Pegasus site are scheduled for 1989/90. The intention is to lay out a runway just inside the accumulation area, where a snow cover can be maintained throughout the summer. The runway will have to be plowed in late winter for the start of the flying season, and snow will probably have to be blown or pushed back onto the ice from time to time during summer. Any hummocks that are encountered will have to be planed flat. One of the primary goals is to develop procedures for preventing the formation of melt cavities.

At OWF, melt cavities were detected by towing a heavy load cart up and down the runway. The present intention is to prevent cavity formation, but to detect water pockets at the Pegasus site we propose to acquire a dual antenna radar unit of the type used earlier in this general area by Kovacs et al. (1982). The equipment will be towed along the runway in a series of parallel sweeps until the full area of the runway is covered. One design goal is to achieve a wide search path and to travel as fast as is reasonably possible. Preliminary discussion with a CRREL consultant (S. Arcone, pers. comm.) suggests that an appropriate system would be an impulse-type subsurface radar, such as is manufactured by the GSSI Company in Hudson, N.H. The control unit of the standard radar can operate two antennas at once, which helps in covering a wide search path. Each antenna unit contains separate transmit and receive antennas. The recommended antenna units are GSSI Model 3102; when placed on ice, these usually radiate a short 2- to 3-cycle wavelet with a frequency spectrum centered near 400 MHz. The estimated beam width in ice is about 70°, so that each antenna covers a 1-m swath at a depth of 0.7 m and a 0.5-m swath at a depth of 0.35 m. With a transverse separation of 1 m between the antennas, there would be continuous coverage across a 2-m swath at 0.7 m depth and two swaths of 0.5 m with a 1-m gap between them at 0.35 m depth. A realistic goal might be detection of water pockets when they reach a diameter of 1–2 m at 0.35 m depth. At a towing speed of 2 m/s (4.5 mph), data could be collected at a density of 13 echoscans for every metre. The antennas can be carried by a dielectric sled (metal-free) and need not be shielded from the weather. The control unit and the tape recorder should have an operating environment where the temperature is no lower

Figure C7. Subsurface melt cavity broken open by a bulldozer blade a short distance southeast of the Pegasus wreck. At the time, the proportion of this snow cover to bare ice was about 50/50. The maximum total depth of the opened cavity was about 0.46 m and the ice that covered it was about 0.15 m thick. In all the cavities that were broken open, the water level seemed too high when compared with the thickness of the original ice cover, perhaps because the bulldozer dropped a lot of snow from its blade when the cavity broke open. (Photo by Malcolm Mellor, 17 January 1989.)

than 2°C (35°F), but the equipment will operate down to −5°C (23°F). One or two operators would be needed. Microwave detection of cavities under pavements was studied by Kovacs and Morey (1983). Kovacs (pers. comm.) has a special antenna breakout box which permits the operation of five antennas side-by-side, covering a scanning swath that could be 6 m (20 ft) wide or more.

The ice shelf calves occasionally, producing major changes in the position of the ice front. In 1947 the ice front to the southwest of Cape Armitage was much further south than the present position, almost as far back as the current location of *Pegasus*. In siting a new airfield and camp facilities, periodic calving has to be taken into account.

SURFACE ROUGHNESS OF BLUE ICE

Blue ice ablation areas on glaciers and ice sheets are not perfectly smooth and level, like undeformed first-year sea ice. They have overall gradients, gentle waves and troughs, and small-scale surface irregularities.

Unless the ablation area is on a floating ice shelf, an overall gradient is to be expected, with an inverse relation between gradient and ice thickness (see eq 2). At the areas that are suitable for use as airfields, the overall gradient in the flow direction can be expected to be approximately 1% (±0.5%). Another type of surface disturbance produced by glacier flow takes the form of either long-wave undulations, their long axes usually perpendicular to the flow direction, or a rolling hill-and-valley relief. These undulations and humps represent a subdued expression of the subglacial terrain; the wavelength is typically of order 10^3 m at sites that are suitable for runways, and the trough-to-crest amplitude is quite small (in the range 1–10 m).

On a smaller horizontal scale, there are surface roughness elements produced by preferential ablation. At sites which are cold, dry and windy, the ice surface is commonly covered by a regular pattern of small (≈15 cm diam, ≈3–5 cm depth) bowl-

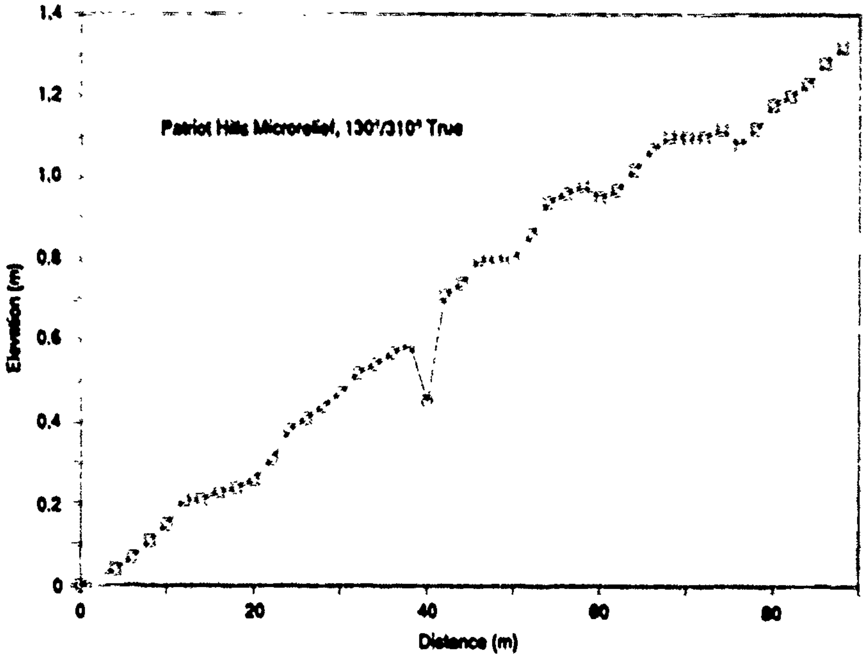

Figure 65. Microrelief of the ice surface at Patriot Hills. This profile is in the direction 130°/310° true.

shaped depressions (see "The Formation of Blue Ice Areas" and Fig. 5, 37, 49, 55). This scalloping of the surface is believed to be caused by evaporation into the turbulent boundary layer. There may also be small-scale furrows that form parallel to the wind direction (see Fig. 19), with a transverse spacing of 0.5 m (1.6 ft) or less. At some sites, the surface texture consists of small elongated bumps and valleys running parallel to the wind direction, with a maximum vertical relief of 5 to 10 cm (2–4 in.) and a transverse spacing of about 20 cm (8 in.).

At a wider and less regular horizontal spacing there are isolated bumps, typically gentle mounds where the width is greater than 10 times the height. At the cold, dry sites, these bumps seem to be associated with the scattered snow patches that accumulate on the ice from time to time. The snow cover blocks ablation (evaporation) from the ice surface so that, when the snow eventually disappears by erosion and/or evaporation, the ice that it covered is elevated relative to the surrounding ice.

At sites where there is both strong solar radiation and wind-transport of rock particles onto the ice, cryoconite holes can form in summer. Pebbles and/or dust pockets absorb radiation, melt the underlying ice, and sink into a small puddle of water, which itself then becomes a preferred absorber of radiation. The water-filled hole eventually refreezes as a plug of relatively clear ice, sometimes lifting and cracking the surface as the trapped water freezes and expands. In other circumstances, some liquid water can be lost from a cryoconite hole (perhaps by wind action or by drainage into a thermal crack), so that the refrozen hole leaves a small depression.

Ablation areas that are at low elevation and relatively low latitude can experience strong summer melting, to the extent that melt streams and lakes form. So far, areas of this nature have not been considered as sites for airfields, although landings have been made on refrozen melt lakes in various parts of Antarctica.

An ideal airfield site is one where the natural surface is smooth enough to accept standard transport aircraft, without a need for any significant surface preparation. The ice field near Plunket Point on the Mill Glacier appears to come close to this ideal. However, most sites are likely to need a certain amount of preparation, even if it only amounts to minor snow removal or snow grooming. To assess the roughness of ice surfaces in their natural state, microrelief surveys have been made and the resulting profiles have been analyzed for comparison with military specifications for various classes of runways.

Kovacs and Abele (1977) measured the microrelief in very short sections at various positions

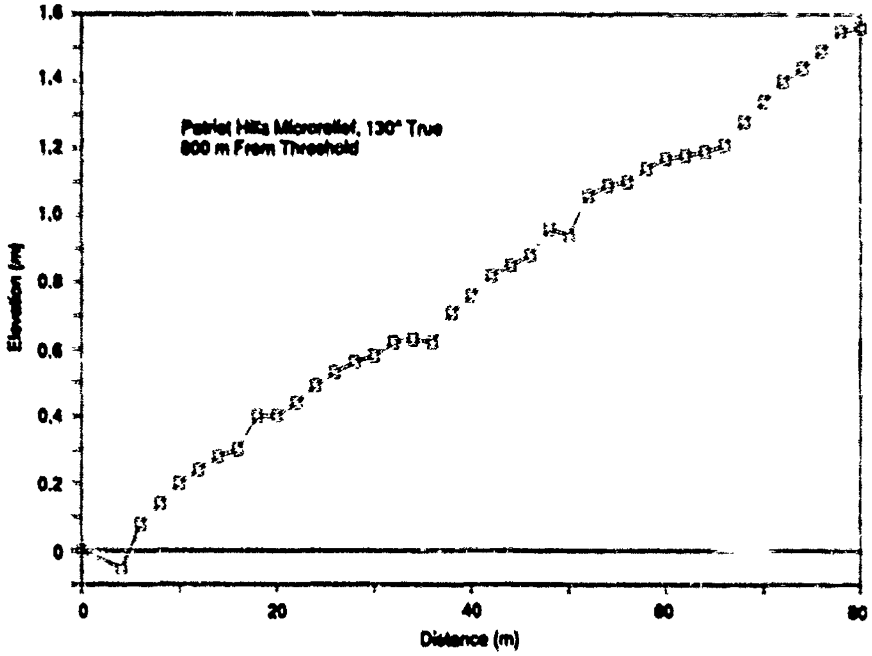

Figure 69. Microrelief of the ice surface at Patriot Hills. This profile is in the direction 130° true, starting 800 m from the threshold of "Runway 27."

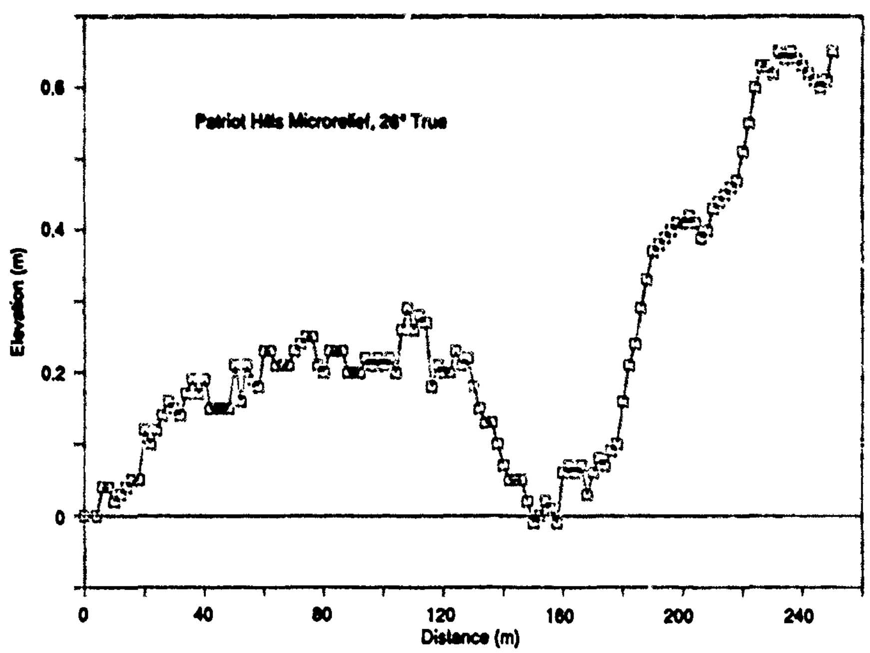

Figure 70. Microrelief of the ice surface at Patriot Hills. This profile is in the direction 26° true, parallel to the sastrugi.

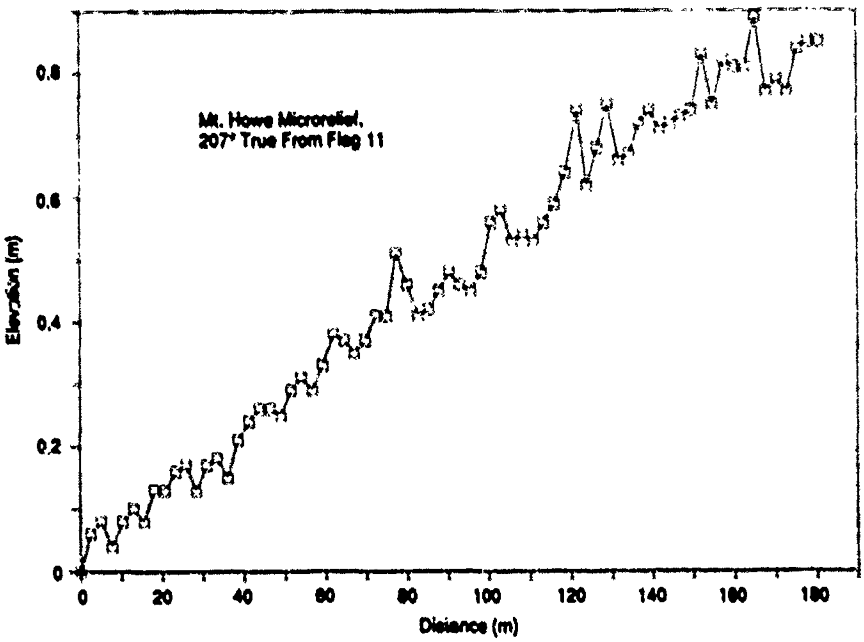

Figure 71. Microrelief of the ice surface at Mount Howe. This profile is in the direction 207° true from flag 11.

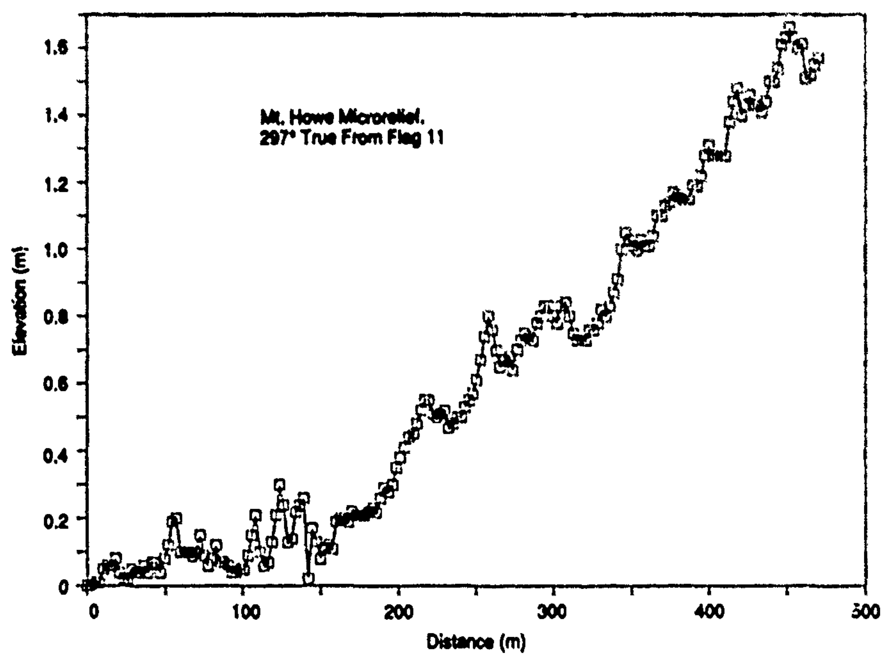

Figure 72. Microrelief of the ice surface at Mount Howe. This profile is in the direction 297° true from flag 11.

along their main profiles for Rosser Ridge and Mount Lechner, applying power spectrum analysis over the complete profiles. Non-uniform sampling intervals complicate the analysis and the form of the output from this work is hard to interpret. A different procedure has been adopted for the recent work.

Swithinbank (1987) measured three microrelief profiles at Patriot Hills, taking levels at 2-m intervals along lines that ranged in length from 80 m to 250 m (Fig. 68–70). At Mount Howe, Swithinbank (1989) measured microrelief profiles by taking levels at 2.58-m intervals along two lines of length 180 m and 470 m (Fig. 71, 72). No microrelief measurements were made at Mill Glacier.

Analysis and characterization of surface roughness

The microrelief profiles have been analyzed in order to compare the natural roughness of the ice surface with military specifications for the roughness limits on various types of runways (Appendix B). The overall slope of each profile was first removed by linear regression, leaving the oscillations about the general line of slope.

Two techniques were used in order to develop relations between "bump height" and wavelength: a) Fourier, or power spectrum, analysis and b) a two-point maximum bump height technique (see App. B for details). The power spectrum analysis gives an average of the bump height for each wavelength and therefore tends to underestimate the amplitude of the most extreme bump that is likely to be encountered. By contrast, the maximum half-cycle bump height technique gives conservative, or worst-case, estimates that tend to exaggerate the roughness of the ice. Given the quality of the data that are currently available, neither method gives meaningful estimates of critical wavelengths where bump amplitude is intense. The analysis cannot resolve the roughness at wavelengths shorter than twice the sampling interval of the level survey.

Figures 73 and 74 give envelopes for the relation between bump height and wavelength according to the power spectrum analysis. For each site, curves are given for the into-wind direction and the crosswind direction. It so happens that at both sites the into-wind direction is approximately transverse to the ice-flow direction, while the cross-

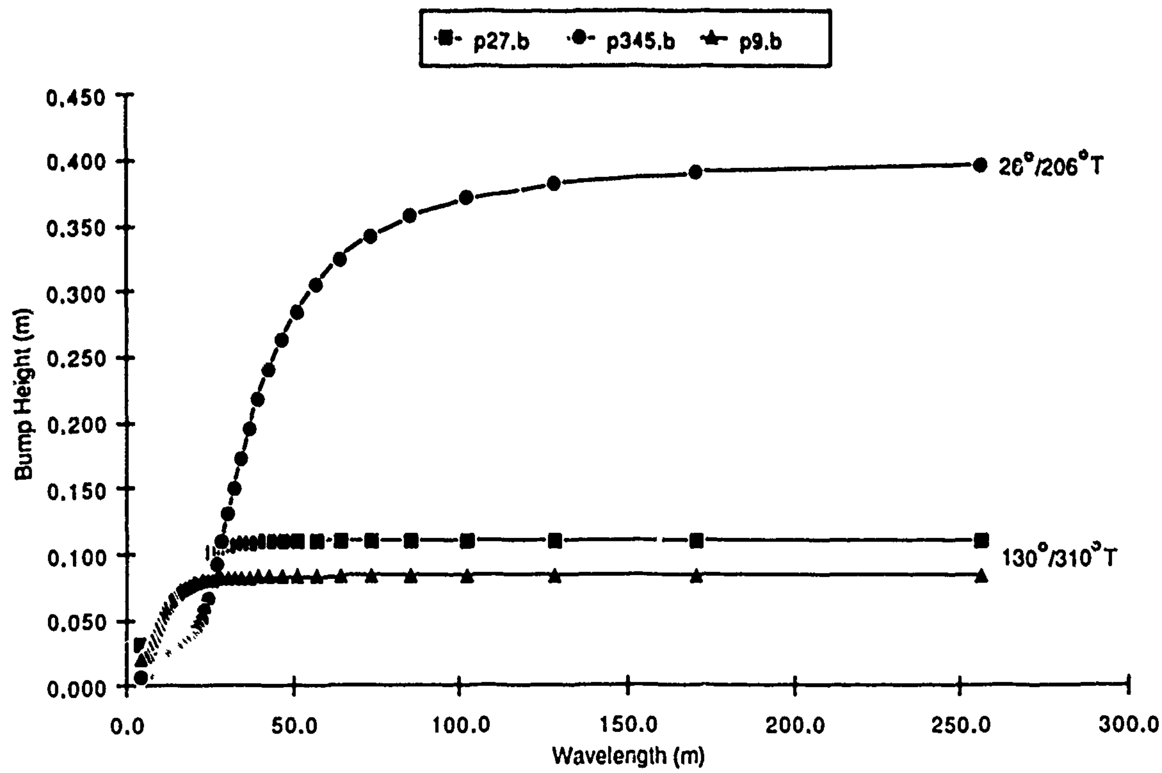

Figure 73. Spectral analysis of the surface roughness at Patriot Hills, using the power spectrum method described in Appendix B. The smooth direction is more or less at right angles to the direction of the prevailing wind. The rough direction is almost into wind (17° off the wind direction).

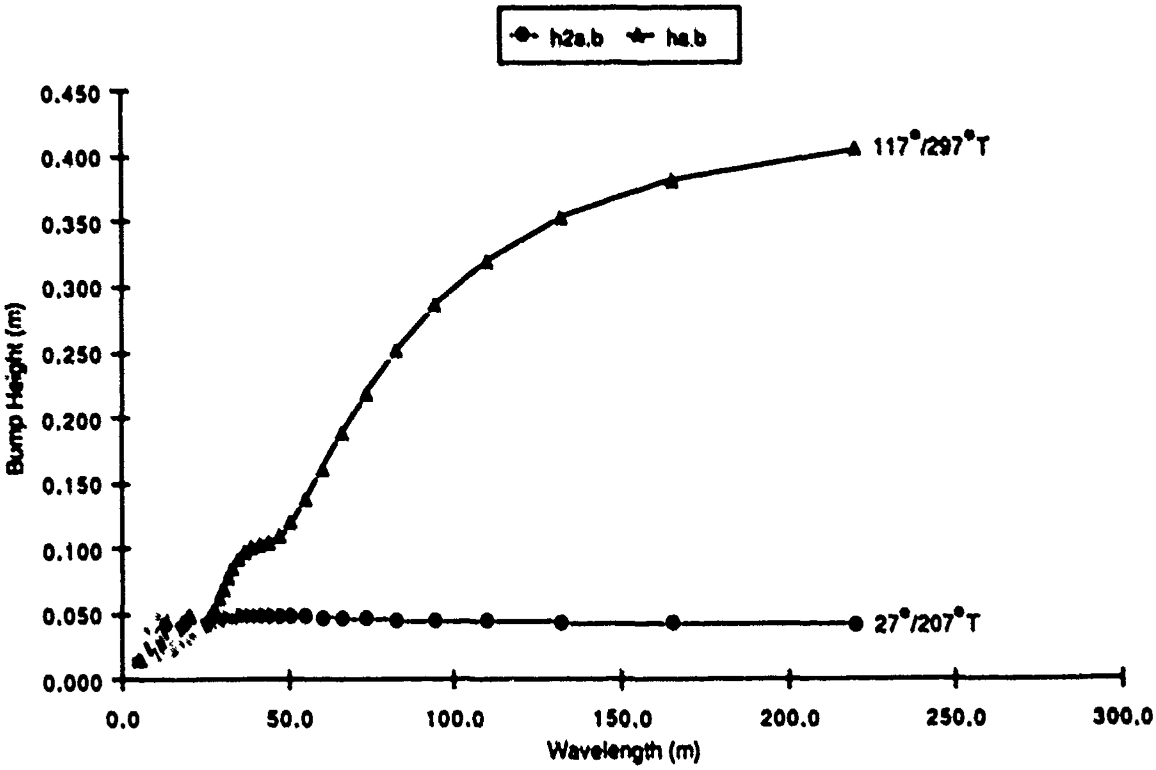

Figure 74. Spectral analysis of the surface roughness at Mount Howe, using the power spectrum method described in Appendix B. The smooth direction is parallel to the ice flow and more or less at right angles to the prevailing wind direction. The rough direction is across the flow lines and into wind.

wind direction is approximately parallel to the ice-flow direction. A remarkable feature of Figures 73 and 74 is the strong directionality of the long-wave roughness at both Mount Howe and Patriot Hills. At both sites the smoothest direction is the cross-wind (glacier flow) direction. At Patriot Hills, the short-wave roughness (< 20 m, or < 70 ft) is less in the wind direction than in the crosswind direction, as noted earlier by Swithinbank (1987). At Mount Howe, the roughness for wavelengths less than 20 m (70 ft) seems to be about the same in both directions. However, some people who have walked the site get an impression of greater roughness in the crosswind direction, perhaps because the isolated bumps tend to streamline along the wind direction.

Figures 75 and 76 give extreme bump height as a function of wavelength according to the maximum half-cycle bump technique. By this method the bump estimates are consistently bigger than those given by the power spectrum method. At the shortest wavelengths, the difference is great—about an order of magnitude. For both sites the long-wave roughness is still greater in the wind direction (i.e. the cross-glacier direction). At short wavelengths (< 20 m) the extreme bump height is about 0.12–0.22 m (5–9 in.) at Mount Howe and about 0.1–0.22 m (4–9 in.) at Patriot Hills.

U.S. military specifications for aircraft runways (MILSPEC MIL-A-8863B(AS), 6 May 1987) express the maximum acceptable bump height Δ as a function of the bump wavelength λ, typically in the form

$$\Delta = A + k\lambda \qquad (5)$$

where A and k are constants that depend on the required quality of the runway (see Fig. 77). In this relation, a bump is assumed to have shape that can be described by a cosine function. Although Figure 77 implies that the maximum acceptable bump height for a paved runway tends to zero as λ tends to zero, the relation can probably be ignored for wavelengths smaller than the footprint length for the aircraft tire. For example, with $\lambda = 0.15$ m (6 in.), there is no real problem (apart from tire noise) if $\Delta = \lambda/3 = 0.05$ m (2 in.).

When the MILSPEC envelopes are compared with the Fourier spectral distributions for Patriot Hills and Mount Howe (Fig. 78 and 79), it is seen

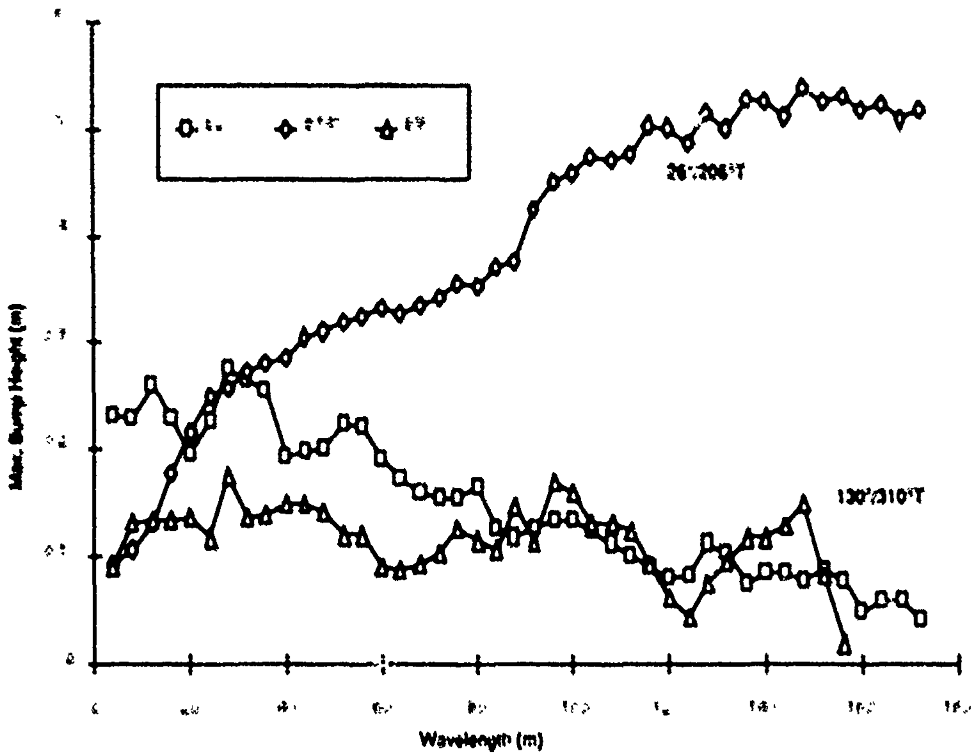

Figure 75. Extreme bump height at Patriot Hills according to the two-point method.

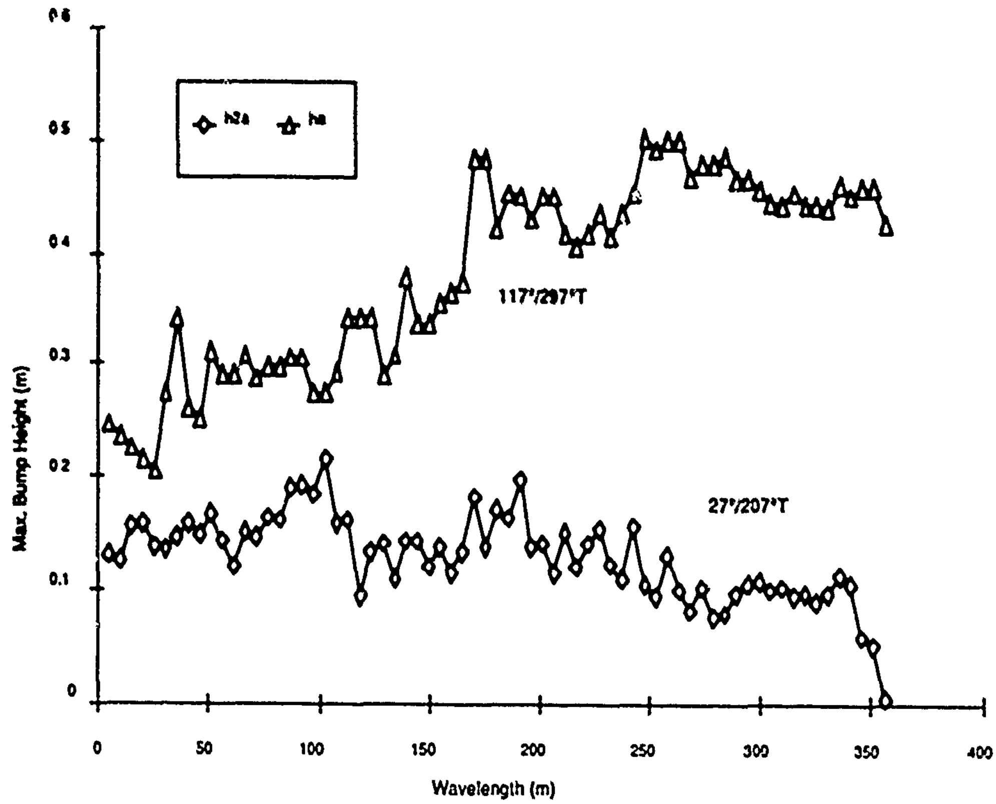

Figure 76. Extreme bump height at Mount Howe according to the two-point method.

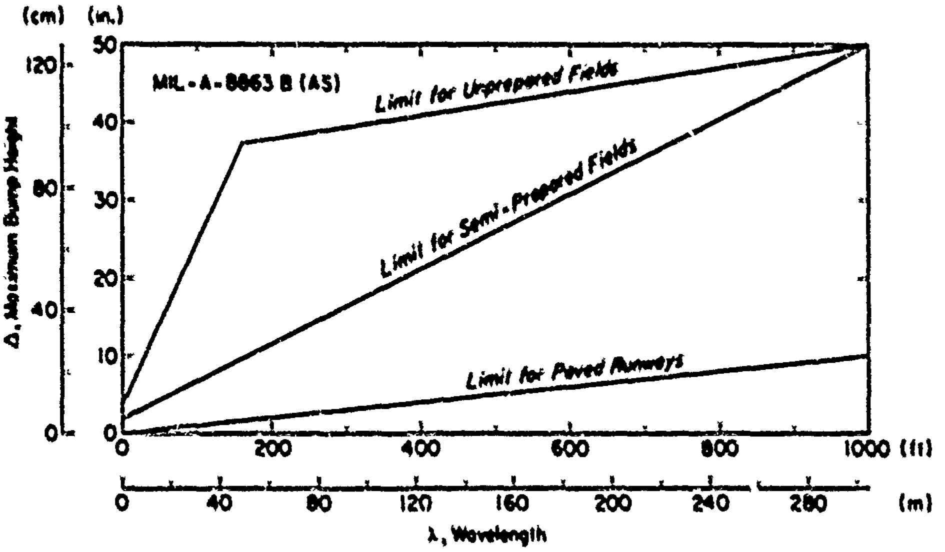

Figure 77. Military specifications for the roughness limits of runways. This is a plot of the equations given in Figure 1 of MIL-A-8863B(AS), 6 May 1987. The graph in Figure 1 of the MILSPEC is inaccurate for the "unprepared field" envelope.

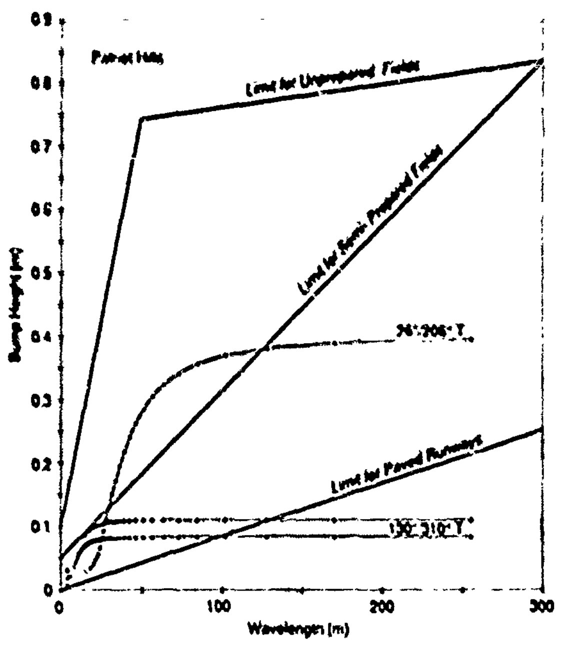

Figure 78. Comparison of the Fourier analysis for Patriot Hills with the military specifications for airfield roughness limits.

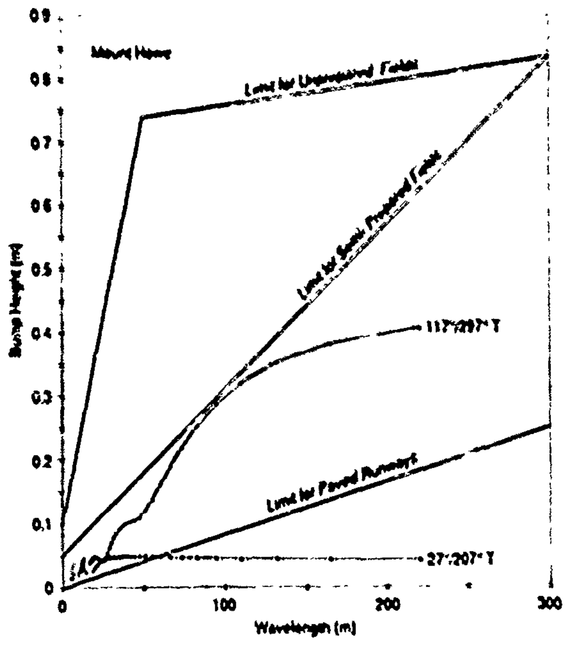

Figure 79. Comparison of the Fourier analysis for Mount Howe with military specifications for airfield roughness limits.

that the "long runway" at each site has a roughness that is within the limits for "semi-prepared" fields at short wavelengths and within the limits for "paved runways" at long wavelengths.

Comparing the MILSPEC envelopes with the "extreme bump" distributions for Patriot Hills and Mount Howe (Fig. 80 and 81), the roughness exceeds the limits for semi-prepared fields at short wavelengths, but it stays more-or-less within the limits for unprepared fields.

According to the available field data and the two types of analyses, the roughness at Mount

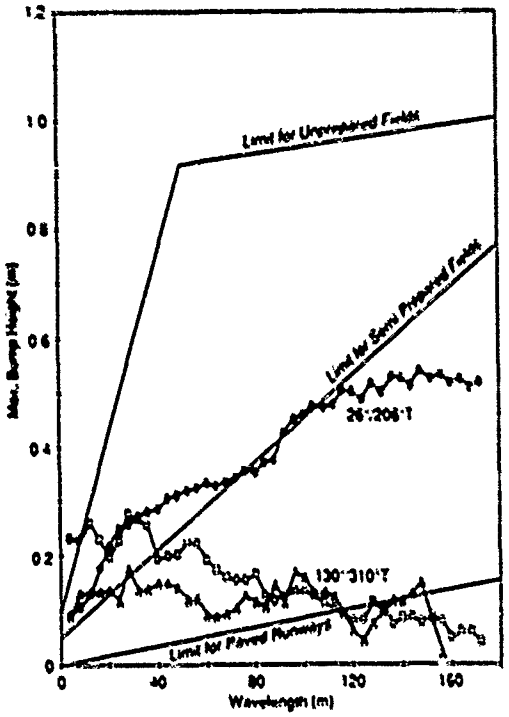

Figure 80. Comparison of the extreme-bump analysis for Patriot Hills with military specifications for airfield roughness limits.

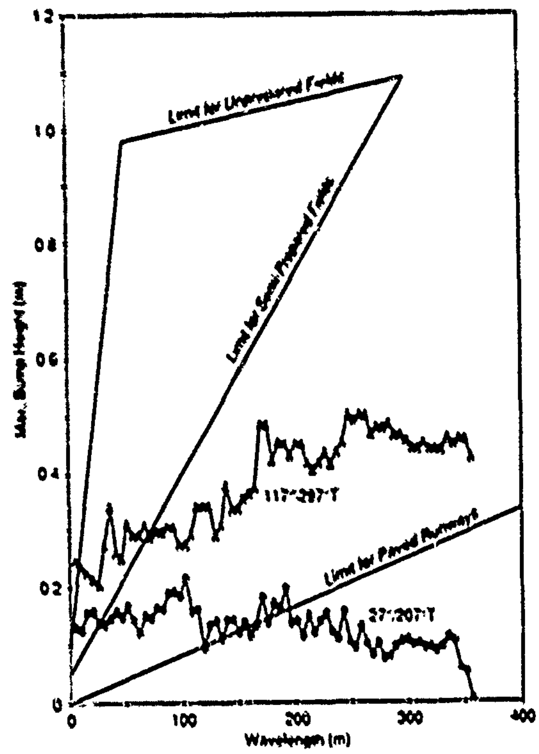

Figure 81. Comparison of the extreme-bump analysis for Mount Howe with military specifications for airfield roughness limits.

Howe is not significantly different from that at Patriot Hills, where the ice surface is being used fairly regularly by a DC-4.

Surface preparation to reduce ice roughness

At a well-chosen blue-ice site the long-wave roughness (Fig. 78–81) is well within the limits for "semi-prepared fields" (Fig. 77) and in certain directions it may be within the limits for paved runways. Comparisons for Patriot Hills and Mount Howe are given in Figures 78–81. The average short-wave roughness may also be within the limits for semi-prepared fields (Fig. 79), but the most extreme short-wave bumps, which appear to be more intimidating during a ground inspection, approach the specified limits for unprepared fields (Fig. 80, 81). Perhaps of more significance is the possibility of encountering some isolated bumps that do not show up in microrelief surveys and subsequent analyses. If there is any question of the adequacy of the surface for landings and takeoffs, then some kind of surface preparation has to be carried out.

One easy step is to remove isolated snow patches from the runway periodically. This takes away the bumps created directly by the snow and it prevents the formation of ice bumps by preferential ablation. On a typical windy day, snow removal from a blue-ice runway should be easy. With a suitable operating sequence, the wind will carry away the snow once the sintered patch is disaggregated and dislodged from the surface. A snowblower is the ideal tool. A runway broom might also be suitable for the job, but it may be too specialized to justify purchase and delivery for this application alone. A less expensive broom would be a rotary-broom attachment for a small tractor. An acceptable alternative for snow removal would be a scarifier, or possibly a light snowplow blade or grader blade fitted with a serrated edge. If a runway is laid out across an area that has a substantial snow cover, say 50% coverage or more, then a snowblower would certainly be more suitable than a scarifier or blade. The strategy with a blower is to start on the upwind side of the runway (assuming a crosswind component), maximizing the casting distance by taking advantage of the wind.

To remove ice bumps of any wavelength there are two basic problems: 1) to cut the relatively hard ice, and 2) to plane the surface as flat as possible.

Ice bumps can be scraped down in increments by successive passes of a very sharp serrated grader blade or scraper blade. The carrier vehicle must have inherent pitch stability or servo blade control in order to avoid vertical oscillations that could *amplify* the surface roughness. The objection to scraping with fixed cutters is the high force on the blade. A self-propelled wheel vehicle may not have enough traction, even with chains; a towed vehicle has to be able to withstand high pulling force and its prime mover has to develop a large drawbar pull.

To estimate the pulling force for a fixed-blade scraper machine, assume that well-designed drag-bit teeth can cut ice with a specific energy consumption of 100 in.-lbf/in.^{3} (i.e. lbf/in.^{2}), or about 0.69 MJ/m^3. This value is based on tests of various ice-cutting machines, from small rotary drills to large rotary saws and milling drums. The specific energy E_s is the energy needed to remove unit value of ice or, alternatively, the cutting power P divided by the volumetric removal rate for the ice $\dot{v}$:

$$E_s = P/\dot{v} \quad . \tag{6}$$

If the scraper blade removes 1 in. (25.4 mm) of ice across a blade width of 10 ft (3.05 m) while traveling at 2 mph (176 ft/min, or 0.894 m/s), the ice-cutting process consumes 64 horsepower (47.7 kW). For a 2-mph forward speed, this translates to a horizontal resistance of 12,000 lbf (6 tons, or 53.4 kN). To this must be added the pulling resistance of the carrier vehicle, which should be about 10% of the vehicle weight if it is ski-mounted. Thus, to take a 1-in. (25-mm) skim off the ice, we require a drawbar pull of about 7 tons (62 kN). If the drawbar coefficient of the towing vehicle is 0.25, that vehicle has to weigh about 28 tons (25 tonnes) in order to develop the necessary drawbar pull. This is about the size of a Caterpillar D7H dozer or a 973 loader. If a scraper blade suddenly runs into a high spot, so that the cutting depth increases abruptly, then the resistance increases sharply and a high impulsive load can be thrown onto the system. Breakage of the carrier frame or the blade mount can result.

For blade widths other than 10 ft and for cutting depths other than 1 in., the power and the towing resistance change in direct proportion to blade width and cutting depth.

The static forces and the towing demands can be reduced by using a planing machine that has a powered rotary drum for milling the ice bumps. Ideally, this would be a self-contained machine with its own power source, self-propulsion, and a capability for producing a specified surface profile (e.g. by laser control). However, it could be something simpler, such as a rotary-drum miller fitted to a long carrier frame and towed by a tractor.

To develop some technical specifications for a power planer, we again assume a specific energy consumption of 100 lbf/in.^{2} (0.69 MJ/m^3), and again set a design speed of 2 mph (176 ft/min; 0.894 m/s) for the planing operation (i.e. one pass down a 10,000 ft runway every hour). To remove a 1-in. (25-mm) ice layer across a drum width of 10 ft (3.05 m) the power consumed is, as before, 64 horsepower (47.7 kW). However, the horizontal force on the machine is much lower than in the case of the scraper blade. For a fixed scraper blade, the cutting power P_s has to be supplied by a horizontal force F traveling at horizontal velocity U, i.e.

$$P_s = FU. \tag{7}$$

For a rotary miller, the cutting power P_d is supplied by the drum torque T with a rotation speed of f:

$$P_d = 2\pi fT. \tag{8}$$

The calculation of the horizontal resistance to drum motion is fairly complicated (Mellor 1977b), but for present purposes we can assume sharp cutting teeth, shallow cutting depth relative to drum radius, and an upmilling drum, obtaining an estimate of the horizontal resistance as approximately equal to T/R, where T is torque from eq 8 and R is the drum radius.

In principle, drum torque T can be reduced without limit simply by increasing the rotational speed f. In reality, however, the specific energy for cutting increases as the chipping depth decreases (producing ever-finer cuttings) and an increasing amount of power is consumed in accelerating the cuttings to high tangential velocities and thus imparting kinetic energy. Practical experience indicates that the tangential velocity of the cutters on the milling drum should be kept within the range 300 to 1000 ft/min (1.5 to 5 m/s). Thus the estimate of horizontal resistance F is

$$F \approx T/R \approx P_d/2\pi fR \tag{9}$$

in which $2\pi fR$ is the tangential tool speed, likely to be in the range 300 to 1000 ft/min (1.5 to 5 m/s). This means F is likely to be of the order of 2000 to 7000 lbf (9.4 to 31 kN). The total towing resistance for a ski-mounted device might be about 4 tons (3.6 tonnes) so that, with a tow vehicle that has a draw-

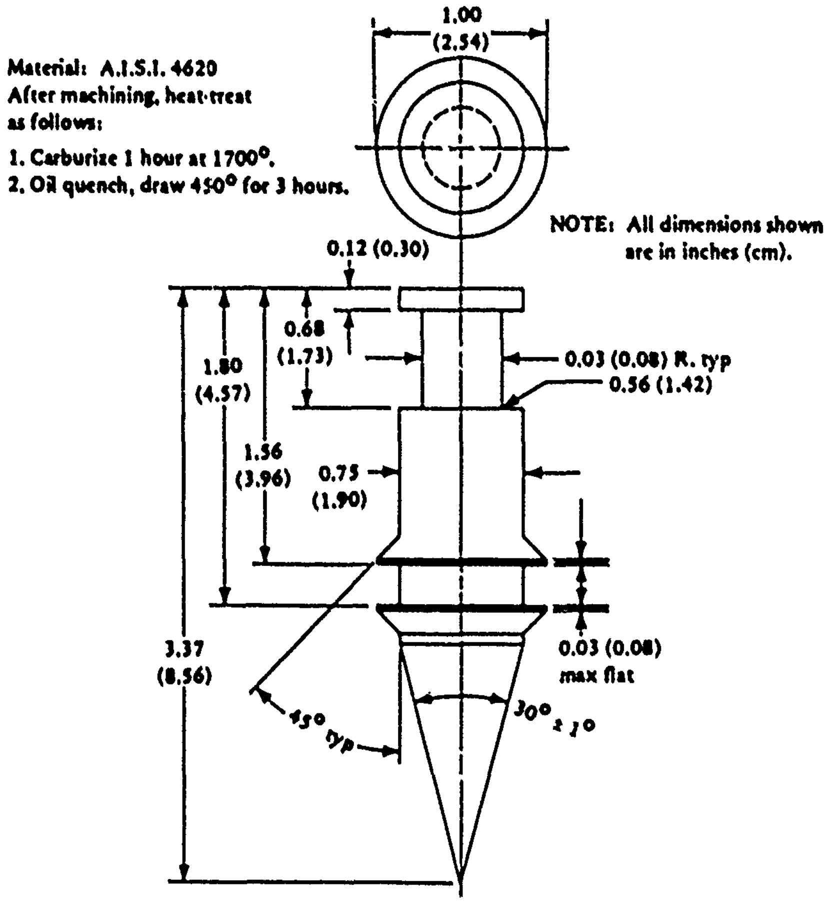

Figure 82. Special conical bit developed by NCEL for use on ice-cutting machines. (*From* Engineering Manual for McMurdo Station.)

bar coefficient of 0.25, the necessary drawbar pull can be developed by a vehicle weighing about 16 tons (14.5 tonnes). This is about the size of a Caterpillar Challenger, a D5H dozer, or a 943 loader.

The required drum power is directly proportional to the cutting depth and the drum width. However, the towing resistance does not increase in proportion to the cutting depth. The drum can mill to greater depth in a single pass without significantly increasing the towing force. The estimate made above will suffice for any chipping depth that is likely to be needed at a good runway site.

The next step is to develop some kind of picture of a power planer for use at blue-ice runways.

A milling drum of large diameter is desirable theoretically, but we have to set a practical limit. As a design goal, we can specify 4-ft (1.2-m) diameter, with an acceptable lower limit of 3-ft (0.91-m) diameter. The required rotational speed f depends on the drum diameter D, measured to the tips of the cutting teeth. It is suggested that f should be in the range

$$f = 300/\pi D \text{ to } 1000/\pi D \text{ rev/min}$$

when D is in feet. In other words, with a 4-ft-diameter drum, the required rotation speed is in the range 24 to 80 rev/min. With a 3-ft-diameter drum, the required rotation speed is in the range 32 to 106 rev/min.

The actual available cutting power at the drum should be about 6.4 hp per foot of drum width. The input drive power needed to operate the drum is greater, depending on the efficiency of the transmission system (high for mechanical, fairly low for hydraulic).

Ideally, we would like to have a very wide drum to minimize the number of passes needed to cover the width of the runway, but again there are practical limits. A width of 12 ft (3.66 m) is a realistic, but slightly optimistic, design goal. The minimum useful drum width is about 8 ft (2.44 m).

The drum has to be fitted with cutting teeth in

Table 1. Characteristics of some rotary-drum planers that could be adapted for planing ice surfaces. (Compiled by D. Garfield.)

	Bomag MPH100	*Dresser SP-750*	*Caterpillar RR-250*	*Caterpillar PR-450*	*Speicher 3600*	*Broken Bow 300, w/38-ll auger*
Operating wt (lb)	33,360	53,416	39,300	57,000	15,500	22,246
Shipping wt (lb)	32,360					
Overall width (in.)	120	96	116	182 est.	122	168
Overall height (in.)	140	120	103	126	121	117
Height (less rops) (in.)	101	99	103	126	204	240
Overall length (in.)	336	296	337	264	204	240
Wheels or tracks	wheels	wheels	wheels	tracks	wheels	wheels
Ground clearance (in.)	20	15				22
Engine	Detroit diesel	Detroit diesel	Cat diesel	Cat diesel	4-71 GM diesel	Cummins diesel
Horsepower/rpm	304/2100	322/2100	335/2100	450/2100		177/2500
Electrical system (V)	24	24		24		12
Propulsion system	hydrostatic	hydrostatic	hydrostatic	hydrostatic	hydrostatic	hydrostatic
Min/max speeds						
Working (fpm)	0/176	0/120	0/200	0/176	0/?	0/128
Travel (mph)	0/11.9	0/24.2	0/15	0/2	0/17.5	0/18
Fuel capacity (gal.)	120	170	110	200		78
Hydraulic capacity (gal.)	60	78	53	60		40
Rotor location	rear	middle	middle	middle	front	front
Drive type	hydraulic	hydraulic	mechanical	mechanical	mechanical	hydraulic
Drum diameter (in.)	48	37	43	40	36	38
Cutting width (in.)	79	78	96	144	122	168
Cutting depth (in.)	12	7	13	10		
Rotor speed (rpm)	0 to 135	0 to 13	124 to 389	95 to 115		0 to 140
Type of teeth	bullet	bullet	bullet	bullet		
No. of teeth	167	135	188	144		
Cross slope adjustment	yes	yes	no	available	no	yes
Up/climb milling	upmilling	upmilling	upmilling	upmilling	upmilling	upmilling

such a way that there is complete and efficient removal of the ice. The relevant design principles are well understood (Mellor 1975). The teeth themselves must be sharp tools set on the face of the drum at appropriate angles. Again the relevant principles have been studied (Mellor 1977a). In practice, it is unlikely that a milling drum will be designed and built specially for this project. The drum will probably be a modification of an existing commercial product, with receptacles to accept commercial "bullet bits." For ice-cutting, the standard bullet bits should be replaced by specially sharpened conical steel bits (Fig. 82). Carbide inserts are not necessary for cutting clean ice.

An experimental machine with a milling drum for planing ice surfaces was designed and built by the U.S. Naval Civil Engineering Laboratory in the early sixties (Gifford 1964, 1966). Some years later a commercial pulvimixer made by the former Bros company (SPRM-84B Rota-Mixer) was modified for ice-chipping and used by NCEL for maintenance of a runway on glacier ice at the old Outer Williams Field near McMurdo station in 1969 (see *Engineering Manual for McMurdo Station*, 1979 revision, p. 10–12, 20–23). An experimental ice-planing machine was also built by CRREL in the early sixties (Frankenstein 1965). In the early seventies, CRREL experimented with rotary-drum graders for planing frozen ground (Mellor 1972). These machines, built in Germany and England, were forerunners of the present-day commercial road planers. CRREL then designed and built a large milling drum attachment for heavy bulldozers, the primary purpose being the grading of frozen ground for roads and runways (Garfield and Mellor 1976). One of the present authors also designed a heavy-duty ice cutter for preparing roads across rough sea ice in 1972, and a modified version was built by the Sun Oil Company.

When proposals for blue-ice runways were put forward in 1988 (Mellor 1988a), it was expected that there would be a substantial budget for the acquisition of special-purpose machines, including ice planers. Thus the initial emphasis was on self-propelled power planers (see Table 1), with large scrapers as an alternative (see Table 2). For a power-planer, various types of commercial road planers were considered, and some modifications

Table 2. Characteristics of some towed scrapers that could be adapted for planing ice. (Compiled by D. Garfield.)

	Miskin SP-408	*Miskin SP-410*	*Miskin SP-412*	*Miskin SP-313*	*Miskin SP-315*	*Miskin SP-318*
Overall length (in.)	236	236	236	257	257	257
Overall width (in.)	86	86	86	181	205	241
Overall height (in.)	40	40	40	60	60	60
Weight (lb)	7925	8457	9955	12,950	13,942	16,866
Cutting width (in.)	96	120	144	156	180	216
Bucket cap. (yd³)	10	12	15	15	17	21
Clearance (in.)				18	18	18
No. hydraulic circuits req'd	3	3	3	3	3	3
Suggested DBHP	90	105	130	140	160	190
Laser level	available	available	available	available	available	available
Ripper	no	available	available	available	available	available
No. of shanks		11	13	14	16	19
Ripper clearance (in.)		9	9	9	9	9
Tooth construction	2-in.-wide hardened steel					

of standard machines were examined with the aid of Caterpillar Inc. (Mellor 1988b). The most appealing machines in the study group were modifications of the Cat PR-450 pavement profiler, either with a standard 8-ft drum or with a special 12-ft-wide drum, and the Cat RR-250 road reclaimer with only minor modifications. Comparable machines from other manufacturers were also considered (Table 1).

In 1989, these plans were cut back, partly in the interest of economy and partly to develop a device that would be transportable by air. Interest then switched to modification of a "detachable" snowblower, a commercial item that is normally fitted to a front-loader for snow plowing. For work on glacier ice, the unit would be center-mounted on a snow plane or similar carrier vehicle.

GROUND FACILITIES

At inland blue-ice areas, most of the ground facilities can be placed on rock or on moraine. Bedrock poses no significant problems for construction and maintenance. The moraines in these areas are not expected to be much affected by ablation, and semi-permanent installation can be built on pads of rock-fill and gravel gathered locally. The required thickness for a gravel pad is expected to be small, perhaps as little as 0.3 m, or 1 ft.

Fixed facilities set directly on the ice should be kept to a minimum, since they will tend to produce differential ablation, either causing melting in summer or becoming elevated on glacier tables. However, buildings or facilities could be set on elevated platforms that themselves are supported on piles. Runway markers will probably be required; these can be framed plywood sheets elevated above the ice surface on stout timber supports that have been set in drill holes.

If aircraft are to stay at an inland airfield for more than a few hours, tie-downs will be needed, and it might be advisable to provide a screen fence. Tie-downs present no problems; strong ice anchors can be set in drill holes as required. For smaller aircraft an open-mesh barrier, with upwind guys, could be built.

The level of facilities and staffing will depend on the operating scheme for the airfield. If the field is used only as a freight-transfer depot for a brief period each year, simple facilities should suffice. Minimum services might include weather reports, emergency firefighting capability, and emergency medical facilities. Electronic landing aids are not essential if incoming aircraft can divert to an alternate.

Some activities will inevitably take place on the ice, e.g. cargo handling, fuel transfer and runway maintenance. To avoid problems from contamination or littering of the ice surface, strict discipline should be enforced. Any spills should be cleaned up without delay.

Some blue-ice areas are too far from rock exposures to permit construction on rock or moraine (e.g. the Pegasus site). At such places it is likely that permanent structures will have pile, pier, or post foundations (movable buildings on sleds can also be used). There is no lack of bearing strength, but structures need to be separated from the ice to prevent heat transfer, and elevation eases the problems of snow drifting. A more serious concern is how to limit the buildup of meltwater and other fluids below and around the buildings. Even with very good insulation, snow that accumulates against, or on top of, buildings will melt in summer, refreezing on the ice surface. It will probably help to have the buildings sited in a permanently snow-covered area so that the snow reduces the albedo of the surroundings and provides some absorbing capacity for spills and meltwater. However, it still may be necessary to have periodic removal of contaminated snow and maintenance cutting of ice stalagmites.

Water supply can be provided by in-situ melting of the ice in subsurface c ·ities, which need not be very deep in impermeable ice. With appropriate planning, empty water supply cavities can be used for disposal of sewage. At the Pegasus site, where the shelf is only 35 m thick, sewage can be discharged directly into the sea. Some of the solid wastes (paper, wood, plastics) can be burned in a high-temperature incinerator. Wastes that cannot be burned (thick metal, glass) can be compacted for shipment to an approved disposal site.

At some of the inland blue-ice areas there are no drainage systems for the disposal of liquid wastes and net ablation precludes the use of burial pits for solid waste. Ideally, all wastes should be removed from the site, a procedure that may be feasible when large aircraft are returning empty from a small airfield facility. If local disposal is necessary, burnable trash can be consumed in an incinerator, preferably a high-temperature shipboard type. Wastewater, or at least the sewage component of wastewater, should discharge into disposable containers. Non-burnable solid waste should be compacted and packaged for disposal. Containers of frozen wastewater and packages of solids can be taken to an accumulation area for burial, or possibly taken to a suitable crevasse near the downstream limit of the ablation area. The remnants of fuel in the containers used for refueling aircraft can probably be salvaged and filtered for use in the station heaters, generators and vehicles.

GROUND TRANSPORT

At this stage, some blue-ice sites are seen primarily as freight transfer depots, not as final destinations. Some sites, e.g. Pegasus site and Casey S-1, are final destinations, intended to serve permanent stations via local ground transport.

At blue-ice sites, conventional four-wheel-drive vehicles can be used on flat areas where there is exposed ice or a thin snow cover over hard ice (studs or chains might be needed). If conventional wheeled vehicles can be used they are faster, less expensive and easier to maintain than tracked vehicles.

In favorable situations, it may be possible to use wheeled vehicles beyond the limits of the airfield site. At McMurdo, a direct ice road between the main station and the Pegasus site should be feasible from late winter until mid-December, crossing first-year sea ice (7–8 ft, or 2–2.5 m, thick), old sea ice (say 20 ft, or 6 m, thick), and the ice shelf itself (up to 120 ft, or 35 m, thick). A road across the sea ice could be used for a longer period, perhaps until late January, given suitable vehicles and ice-monitoring facilities. The problems of mid-summer roads on the sea ice include the following:

a) The land/ice transition becomes difficult. (Tide cracks become active; melting and flooding intensifies. Bridges of some kind are needed.)

b) There is a danger of breaking through the first-year sea ice. (Amphibious vehicles, or vehicles with flotation, may be needed. Frequent scanning of ice thickness, preferably by subsurface radar, is certainly needed.)

c) Puddles and potholes can form on the road. (Wheeled vehicles may need traction aids, such as chains.)

d) The first-year ice usually breaks out in late summer, moved by strong local winds or by penetration of long-wave ocean swells. (Observation, forecast and warning services are required.)

The alternative for wheeled vehicles traveling between McMurdo station and the Pegasus site is a variant of the present road system which goes to the Williams Field skiway via Scott Base. An ice road can be plowed out for some distance northeast from the Pegasus site, but for much of the way to Pram Point a compacted snow road would be required.

In general, wheeled vehicles are unsuitable for use outside the limits of a blue-ice site. Tracked vehicles and sleds (or possibly tracked trailers) are the logical choice.

For travel between the Pegasus site and McMurdo station, fast sled trains running to Pram Point should be suitable, both for freight and for passenger service. The Caterpillar Challenger, which has a novel rubber-belt track system, is geared to travel at a top speed of 18.2 mph (29.3 km/hr). It should be able to maintain 15 mph (24 km/hr) over a dragged snow trail between the

Pegasus site and Pram Point. The distance is close to 13 miles, giving a trip time of about 50 minutes. At Pram Point, passengers and freight would transfer to wheeled vehicles, the passengers to buses or vans, the palletized freight to trucks. Large sleds provide a smooth ride; with a heated cabin and bus seats, passengers would travel in comfort.

For passengers and priority freight traveling between the Pegasus site and McMurdo station, summer travel on the direct route across sea ice is tempting, but potentially hazardous. Hovercraft can provide all-season service on the direct route, but the vehicles are rather expensive. For the period when the ice shelf is intact but rotting, wheeled or tracked vehicles with limited amphibious capability could be used; if the vehicle breaks through the ice it floats until it can be retrieved. The BV 206 might be a suitable amphibious vehicle for passengers and light cargo.

The ground transport considerations for Mount Howe are of a very different nature, since Mount Howe is seen as a support facility for the South Pole station. The idea is to fly heavy freight and fuel to Mount Howe in conventional aircraft, while passengers and priority freight continue to be delivered to Pole by ski–wheel LC-130 aircraft. Freight and fuel are intended to go by ground transport from the Mount Howe depot to Pole, a straight-line distance of some 160 n.m. The obvious choice is to use sled trains over a well-marked trail. The Caterpillar LGP D-8, which was developed for polar use 35 years ago, would still be an excellent workhorse for this job, but new machines of this type are not available. The alternative is to use another kind of steel-track construction tractor, such as the LGP D7H, or else a tractor with higher speed potential, such as the Challenger. A realistic goal for sustained travel speed is perhaps 8 mph (13 km/hr). With a straight-line distance of some 185 statute miles and some extra distance to snake between crevasse areas in the first 35 miles of the trip, the idealized trip time might be about 24 hours. With a wannigan for messing and berthing, no stops are needed for eating or sleeping, but some kind of maintenance stops are likely. A realistic trip duration is therefore two work days and one night. Allowing for loading, unloading, maintenance and crew rest, one round trip per week seems realistic. Science projects could be integrated into these journeys, and Mount Howe itself could be a useful research site.

At this stage Mill Glacier is thought of as an emergency alternate for Mount Howe (it has very smooth ice and a very long runway directly into wind). The airfield is probably too far from the South Pole to be attractive as a staging depot. However, Plunket Point might be attractive as a base for research.

CONCLUSIONS AND RECOMMENDATIONS

Antarctic ablation areas can provide airfields for large conventional transport aircraft, and the cost of development should be very low.

So far, only a few good airfield sites have been discovered and surveyed, but it seems likely that there are enough suitable sites to provide a well-distributed system of Antarctic airfields for use by conventional aircraft.

Currently, the main barriers to rapid development of such a system are unfamiliarity and conservatism on the part of aircraft operators. However, innovative operators are expected to make more use of blue-ice airfields in the future, and others can probably be won over by site visits and ground inspections.

The Twin Otter (12,500 lb, 60-knot stall) can land with standard wheels at many blue-ice locations in Antarctica. For larger aircraft, and aircraft without STOL capability, there are at least six known sites that can be developed as glacier-ice airfields. The first to be used operationally was Patriot Hills, where landings have been made on the natural ice surface by a Douglas DC-4, an old low-wing aeroplane which is not particularly well-suited for rough field operation.* A Douglas DC-6 is to be used in 1989–90, so there can be no serious doubt that the icefield at Patriot Hills is usable by military tactical transports such as the C-130.

According to our preliminary surveys and analyses, the surface roughness of the icefield at Mount Howe is very similar to that of the operating airfield at Patriot Hills. Actually, the Fourier analyses for the long runway at each site suggest that Mount Howe is a bit smoother than Patriot Hills. This suggests that Mount Howe might be usable in its natural state by the C-130, especially if tire pressures are reduced from the standard 96 lbf/in.^{2}. However, we have developed plans for planing the ice in order to bring it closer to the quality of a paved runway.

The icefield near Plunket Point, on the Mill Glacier, ought to be usable without any preparation

*The DC-4 is a civilian version of the WWII C-54 Skymaster; Douglas delivered the last one in 1947. The DC-4 has the advantage of a moderate wing-loading (50 lbf/ft max.) and low stall speed (under 80 knots with landing flaps).

other than installation of runway markers. It should be a useful place for familiarization and training flights.

The place known to us as the Pegasus site can provide an all-season wheel runway for McMurdo station, but it will require some preparation (plowing and planing) and there will be a continuing need for some maintenance work (sustaining a thin snow cover). The main objection to this site is the length of the journey to McMurdo station when the sea ice cannot be used for direct travel. The attraction is that it can provide all-season capability for conventional aircraft at a more-or-less permanent location. Annual deployment and demobilization on the sea ice could be eliminated, periodic relocation of the Williams Field facilities would become unnecessary, and there would be no need to rely on the LC-130 for transport to and from New Zealand. The runway site is close to SSSI No. 18 (White Island), but not prohibitively so. (The letters SSSI indicate a Site of Special Scientific Interest designated under the Antarctic Treaty Recommendations. The designation of SSSI No. 18 is due to expire on 31 December 1991.)

It is suggested that the USAP should adopt the concept of using glacier-ice airfields for conventional aircraft. By supplementing the transport operations with readily available conventional aircraft of various types, the specialized ski-wheel LC-130 aircraft would have much more time to fly the missions where their unique capabilities are essential. For routine freight-hauling in mid-summer, a conventional aircraft can lift more payload than a ski version of the same aircraft.

Surveys and construction experiments at the Pegasus site are recommended. A simple ice-planing machine should be acquired as soon as possible.

Steps should be taken to develop airfields at Mount Howe and Mill Glacier. Pilots of VXE-6 and MAC should be given the opportunity to make ground inspections at these sites, to experience landings on the ice, and to make trial landings with light loads at Mill Glacier. Automatic weather stations should be installed at these sites.

LITERATURE CITED AND SELECTED REFERENCES

Annexstad, J.O. (1983) Meteorite concentrations and glaciological parameters in the Allan Hills Icefield, Victoria Land, Antarctica. Doctoral dissertation, Johannes Gutenberg-Universitat, Mainz.

Annexstad, J.O. and F. Nishio (1979) Glaciological studies in Allan Hills, 1978–79. *Antarctic Journal of the U.S.*, 14(5): 87–88.

Annexstad, J.O. and F. Nishio (1980) Glaciological studies in Allan Hills, 1979–80. *Antarctic Journal of the U.S.*, 15(5): 65–66.

Annexstad, J.O. and L. Schultz (1982) Triangulation survey of the Allan Hills icefield, 1981/1982. *Antarctic Journal of the U.S.*, 17(5): 57–58.

Ashton, G.D. (1972) Ripples on underside of river ice covers. *Journal of the Hydraulics Division, ASCE*, HY 9(Paper 9191): 1603–1624.

Brunk, K. and R. Staiger (1986) Nachmessungen an Pegeln auf einem Blaueisfeld im Borgmassiv, Neuschwabenland, Antarktis. *Polarforschung*, 56 (1/2): 23–32.

Cameron, R.L. (1964) Glaciological studies at Wilkes station, Budd Coast, Antarctica. In *Snow and Ice Studies* (M. Mellor, Ed.). Antarctic Research Series, Publication 1197, American Geophysical Union, vol. 2, p. 1–35.

Cassidy, W.A. and J.O. Annexstad (1981) Antarctic search for meteorites, 1980–1981. *Antarctic Journal of the U.S.*, 16(5): 61–62.

Day, C.F., R. Sweeney and W.T. Towles (1973) Zero base II analysis. Report UR-213, RMC Research Corporation, for Office of Polar Programs, National Science Foundation, Contract NSF-C681.

Frankenstein, G.E. (1965) USA CRREL ice chipper. USA Cold Regions Research and Engineering Laboratory, Special Report 73.

Garfield, D. and M. Mellor (1977) Permafrost excavating attachment for heavy bulldozers. In *Proceedings of the Second International Symposium on Cold Regions Engineering, University of Alaska, Fairbanks, 12–14 August 1976*, p. 144–151.

Gifford, S.E. (1964) Ice grading equipment—Development of an experimental rotating-drum cutter. U.S. Naval Civil Engineering Laboratory, Port Hueneme, California, Technical Report R-346.

Gifford, S.E. (1966) Ice grading equipment—Icedozer for pioneering in rough ice. U.S. Naval Civil Engineering Laboratory, Port Hueneme, California, Technical Report R-468.

Hoffman, C.R. et al. (1979) Engineering manual for McMurdo Station. U.S. Naval Civil Engineering Laboratory for U.S. Naval Support Force, Antarctica.

Kovacs, A. and G. Abele (1977) Runway site survey, Pensacola Mountains, Antarctica. USA Cold Regions Research and Engineering Laboratory, Special Report 77–14.

Kovacs, A., A.J. Gow, J.H. Cragin and R.M. Morey (1982) The brine zone in the McMurdo Ice Shelf, Antarctica. USA Cold Regions Research and Engineering Laboratory, CRREL Report 82-39.

Kovacs, A. and R.M. Morey (1983) Detection of cavities under concrete pavement. USA Cold Regions Research and Engineering Laboratory, CRREL Report 83-18.

Mellor, M. (1958) Australian glaciological contributions in Antarctica. *Journal of Glaciology*, 3(4): 279–285.

Mellor, M. (1961) The Antarctic ice sheet. USA Cold Regions Research and Engineering Laboratory, Cold Regions Science and Engineering Monograph I-B1, .

Mellor, M. (1967) Mass economy of Antarctica: Measurements at Mawson, 1957. ANARE Scientific Reports, Series A(IV) Glaciology, Antarctic Division, Department of External Affairs, Melbourne, Publication no. 97.

Mellor, M. (1972) Cutting frozen ground with milling drums. USA Cold Regions Research and Engineering Laboratory, Technical Note (unpublished).

Mellor, M. (1975) Mechanics of cutting and boring. Part I: Kinematics of transverse rotation machines. USA Cold Regions Research and Engineering Laboratory, Special Report 226.

Mellor, M. (1977a) Mechanics of cutting and boring. Part IV: Dynamics and energetics of parallel motion tools. USA Cold Regions Research and Engineering Laboratory, CRREL Report 77-7.

Mellor, M. (1977b) Mechanics of cutting and boring. Part VI: Dynamics and energetics of transverse rotation machines. USA Cold Regions Research and Engineering Laboratory, CRREL Report 77-19.

Mellor, M. (1988a) Hard-surface runways in Antarctica. USA Cold Regions Research and Engineering Laboratory, Special Report 88-13, for Division of Polar Programs, National Science Foundation.

Mellor, M. (1988b) Planing machines for building runways on ice. USA Cold Regions Research and Engineering Laboratory, report for Division of Polar Programs, National Science Foundation (unpublished).

Military Specification (1987) Airplane strength and rigidity: Ground loads for Navy acquired airplanes. Naval Air Engineering Center, Systems Engineering and Standardization Department, Lakehurst, New Jersey, MIL-A-8863B(AS) (available from Global Engineering Documents, 2805 McGaw Ave., Irvine, California 92714).

Nagata, T. (1978) A possible mechanism of concentration of meteorites within the Meteorite Ice Field in Antarctica. *Memoirs, National Institute of Polar Research (Japan), Special Issue*, 8: 70–92.

Naruse, R. (1979) Dynamical features of the Meteorite Ice Field, Antarctica. *Memoirs, National Institute of Polar Research (Japan)*, 12: 19–24.

Nishio, F. and J.O. Annexstad (1979) Glaciological survey in the bare ice area near the Allan Hills in Victoria Land, Antarctica. *Memoirs, National Institute of Polar Research (Japan)*, 15: 13–23.

Nishio, F. and J.O. Annexstad (1980) Studies on the ice flow in the bare ice area near the Allan Hills in Victoria Land, Antarctica. *Memoirs, National Institute of Polar Research (Japan)*, 17: 1–13.

Nishio, F., N. Azuma, A. Higashi and J.O. Annexstad (1982) Structural studies of bare ice near the Allan Hills, Victoria Land, Antarctica: A mechanism of meteorite concentration. *Annals of Glaciology*, 3: 222–226.

Paige, R.A. (1968) Sub-surface melt pools in the McMurdo Ice Shelf, Antarctica. *Journal of Glaciology*, 7(51): 511–516.

Russell-Head, D.S. and W.F. Budd (1989) Compacted snow runways: Guidelines for their design and construction in Antarctica. USA Cold Regions Research and Engineering Laboratory, Special Report 89-10, for Division of Polar Programs, National Science Foundation.

Swithinbank, C. (1970) Ice movement in the McMurdo Sound area of Antarctica. International Symposium on Antarctic Glaciological Exploration (1968). International Association of Scientific Hydrology, Publication no. 86, p. 472–487.

Swithinbank, C. (1987) Ice runways in the Heritage Range, Antarctica. Report for Adventure Network International, Inc. and Fuerza Aérea de Chile (unpublished).

Swithinbank, C. (1988a) Location of blue-ice runway sites: Report on air photo search. USA Cold Regions Research and Engineering Laboratory, report for Division of Polar Programs, National Science Foundation (unpublished).

Swithinbank, C. (1988b) Antarctic Airways: Antarctica's first commercial airline. *Polar Record*, 24 (151): 313–316.

Swithinbank, C. (1989) Ice runways near the South Pole. USA Cold Regions Research and Engineering Laboratory, Special Report 89-19, for Division of Polar Programs, National Science Foundation.

Thomas, R.M. (1979) Size of scallops and ripples formed by flowing water. *Nature*, 277(5694): 281.

Whillans, I.M. (1982) Meteorite concentration mechanism near the Allan Hills and the age of the ice. In *Proceedings of Workshop on Antarctic Glaciology and Meteorites* (C. Bull and M. Lipschutz, Ed.). Lunar and Planetary Institute, Houston, LPI Technical Report 82-03, p. 35.

Yoshida, Y. and S. Mae (1978) Some information on topographic features and the characteristics of the ice sheet around the Yamato Mountains. *Memoirs, National Institute of Polar Research (Japan), Special Issue*, 8: 93–100.

APPENDIX A: SURVEY DATA FOR PATRIOT HILLS, MOUNT HOWE AND MILL GLACIER

(From Swithinbank 1987 and 1989.)

Patriot Hills

RUNWAY 27 ELEVATION PROFILE

Distance m	Reduced level m	Gradient per cent	Transverse gradient per cent
0	0.00		
121	+0.48	0.40	
310	2.43	1.03	+0.08
508	3.27	0.42	+0.54
705	4.92	0.84	+0.48
820	7.05	1.85	-0.05
942	9.40	1.93	-0.29
1078	11.47	1.52	+0.02
1259	12.09	0.34	+0.73
1421	14.14	1.27	+1.03
1540	15.80	1.39	+0.27
1712	15.81	0.01	+0.13
1905	17.32	0.78	-0.16
2047	18.67	0.95	-0.28
2204	20.00	0.85	+0.46
2350	21.90	1.30	+0.73
2484	23.97	1.54	+0.81
2634	25.86	1.26	+0.39
2812	26.29	0.24	+0.64
3003	26.33	0.02	+1.67
3187	27.32	0.54	+2.32
3343	29.22	1.22	+2.05
3414	30.00	1.10	+2.00

RUNWAY 33 ELEVATION PROFILE

Distance m	Reduced level m	Gradient per cent	Transverse gradient per cent
0	0.00		
105	-0.28	-0.27	-0.61
297	+1.03	+1.68	-0.93
448	3.03	1.32	-0.93
591	4.71	1.17	-0.65
721	6.63	1.48	-0.15
824	8.63	1.94	-0.19
924	10.57	1.94	-0.46
1041	12.44	1.59	-0.25
1184	13.99	1.08	+0.17
1326	15.34	0.95	-0.08
1470	16.65	0.91	-0.25
1621	17.66	0.67	-0.09
1767	18.85	0.81	-0.81

RUNWAY 27 MICRORELIEF SURVEY

800 m from threshold. Direction 27

Distance m	Reduced level m
0.0	0.0
4.0	+0.04
6.0	0.07
8.0	0.11
10.0	0.15
12.0	0.21
14.0	0.21
16.0	0.23
18.0	0.24
20.0	0.26
22.0	0.31
24.0	0.38
26.0	0.41
28.0	0.44
30.0	0.47
32.0	0.52
34.0	0.54
36.0	0.57
38.0	0.59
40.0	0.45
42.0	0.71
44.0	0.74
46.0	0.80
48.0	0.80
50.0	0.80
52.0	0.86
54.0	0.94
56.0	0.96
58.0	0.98
60.0	0.95
62.0	0.97
64.0	1.02
66.0	1.07
68.0	1.10
70.0	1.10
72.0	1.10
74.0	1.12
76.0	1.08
78.0	1.12
80.0	1.18
82.0	1.20
84.0	1.23
86.0	1.28
88.0	1.32

RUNWAY 27 MICRORELIEF SURVEY

800 m from threshold.
Direction 09

Distance m	Reduced level m
0.0	0.0
4.0	-0.05
6.0	0.08
8.0	0.14
10.0	0.20
12.0	0.24
14.0	0.28
16.0	0.30
18.0	0.40
20.0	0.40
22.0	0.44
24.0	0.49
26.0	0.53
28.0	0.56
30.0	0.58
32.0	0.62
34.0	0.63
36.0	0.62
38.0	0.71
40.0	0.76
42.0	0.82
44.0	0.85
46.0	0.88
48.0	0.96
50.0	0.94
52.0	1.06
54.0	1.09
56.0	1.10
58.0	1.14
60.0	1.17
62.0	1.18
64.0	1.19
66.0	1.21
68.0	1.28
70.0	1.34
72.0	1.40
74.0	1.44
76.0	1.49
78.0	1.55
80.0	1.56

MICRORELIEF SURVEY OFF RUNWAY 27

800 m from threshold

In sastrugi direction (345° magnetic)

Distance (m)	Reduced level (m)	Distance (m)	Reduced level (m)	Distance (m)	Reduced level (m)
0.0	0.0	86.0	0.23	170.0	0.06
4.0	0.0	88.0	0.20	172.0	0.08
6.0	+0.04	90.0	0.20	174.0	0.07
8.0	0.04	92.0	0.20	176.0	0.09
10.0	0.02	94.0	0.22	178.0	0.10
12.0	0.03	96.0	0.21	180.0	0.16
14.0	0.04	98.0	0.22	182.0	0.21
16.0	0.05	100.0	0.21	184.0	0.24
18.0	0.05	102.0	0.22	186.0	0.29
20.0	0.12	104.0	0.20	188.0	0.33
22.0	0.10	106.0	0.26	190.0	0.37
24.0	0.12	108.0	0.29	192.0	0.38
26.0	0.14	110.0	0.26	194.0	0.39
28.0	0.16	112.0	0.28	196.0	0.40
30.0	0.15	114.0	0.27	198.0	0.41
32.0	0.14	116.0	0.18	200.0	0.41
34.0	0.17	118.0	0.21	202.0	0.42
36.0	0.19	120.0	0.20	204.0	0.41
38.0	0.17	122.0	0.20	206.0	0.39
40.0	0.19	124.0	0.23	208.0	0.40
42.0	0.15	126.0	0.21	210.0	0.43
44.0	0.15	128.0	0.22	212.0	0.44
46.0	0.15	130.0	0.18	214.0	0.45
48.0	0.15	132.0	0.15	216.0	0.46
50.0	0.21	134.0	0.13	218.0	0.47
52.0	0.16	136.0	0.13	220.0	0.51
54.0	0.21	138.0	0.10	222.0	0.55
56.0	0.19	140.0	0.07	224.0	0.60
58.0	0.18	142.0	0.05	226.0	0.63
60.0	0.23	144.0	0.05	228.0	0.63
62.0	0.23	146.0	0.05	230.0	0.62
64.0	0.21	148.0	+0.02	232.0	0.65
66.0	0.21	150.0	-0.01	234.0	0.64
68.0	0.21	152.0	0.00	236.0	0.65
70.0	0.23	154.0	+0.02	238.0	0.64
72.0	0.24	156.0	+0.01	240.0	0.63
74.0	0.25	158.0	-0.01	242.0	0.62
76.0	0.25	160.0	0.06	244.0	0.61
78.0	0.21	162.0	0.07	246.0	0.60
80.0	0.20	164.0	0.06	248.0	0.61
82.0	0.23	166.0	0.07	250.0	0.65
84.0	0.23	168.0	0.03		

Mount Howe

HOWE RUNWAY 09 (207°true, 057°grid)

Distance (m)	Reduced level (m)	Flag	
0	0.0	1	(on steep ice slope)
82	+1.75	2	
168	2.99		
336	4.65		
484	5.88	3	
630	6.49		
856	7.10	4	
1080	7.15		
1408	8.40	5	
1707	10.21		
1807	11.69	6	
1892	12.49		
1997	13.52	7	
2191	14.09	8	
2473	12.41		
2589	12.82	9	
2747	12.73		
2895	15.48		
3036	18.25		
3046	18.43	10	
3258	20.97		
3334	21.40	11	
3420	21.69		
3520	22.23	12	
3625	22.57		
3839	22.77	13	
3960	22.15		
4075	21.60	14	
4286	20.47		
4576	19.03		
4927	17.98		
5107	17.35	16	
5236	16.91		
5450	15.77	17	
5720	14.46		
5922	14.00	18	
6044	13.56		
6321	11.54	19	
6407	9.92	20	
6528	7.49		
6657	5.69		
6747	4.51	21	
6816	1.29		
6888	2.71	(at edge of moraine)	

HOWE CROSS LINE through flag 7 (180°magnetic, 297°true, 147°grid)

Distance (m)	Reduced level (m)	Flag
0	+6.95	
216	6.41	
316	9.21	
425	10.78	7A
606	12.69	
674	13.52	7B
830	14.32	
1085	16.37	
1170	17.50	7C
1326	18.04	7D
1748	18.35	7E
2049	17.24	
2341	16.17	
2642	13.83	(into small crevasses)

HOWE VALLEY LINE from flag 9 (180°magnetic, 297°true, 147°grid)

0	12.82	9
216	13.54	
282	14.30	9A
365	15.53	
504	16.93	9B
799	17.80	9C

HOWE CROSS LINE through flag 13 (180°magnetic, 297°true, 147°grid)

0	15.70	(backsight to edge of moraine)
289	17.31	
421	18.41	13A
520	19.53	
632	20.60	
712	21.71	
896	22.77	13C
1009	23.02	13D
1175	23.48	13E
1292	23.59	
1448	22.66	13F
1522	22.12	
1598	21.25	13G
1724	20.33	
1991	18.54	
2047	18.36	13H
2216	18.02	
2312	18.95	13I (at crevasses 30 cm wide)

HOWE MICROPRELIEF SURVEY

Reduced levels (m) 2.58 m apart along 090°magnetic from flag 11

(Read columns down and from left to right)

Level	Level	Level	Level	Level	Level	Level	Level	Level	Level	Level
0	+0.13	+0.15	+0.31	+0.41	+0.48	+0.54	+0.68	+0.72	+0.81	+0.85
+0.06	0.13	0.21	0.29	0.41	0.46	0.53	0.75	0.73	0.89	
0.08	0.16	0.24	0.33	0.51	0.45	0.56	0.66	0.74	0.77	
0.04	0.17	0.26	0.38	0.46	0.48	0.59	0.67	0.83	0.79	
0.08	0.13	0.26	0.37	0.41	0.56	0.64	0.72	0.75	0.77	
0.10	0.17	0.25	0.35	0.42	0.58	0.74	0.74	0.82	0.84	
0.08	0.18	0.29	0.37	0.45	0.53	0.62	0.71	0.81	0.85	

The same along 180°magnetic from flag 11

0	+0.04	+0.04	+0.26	+0.22	+0.52	+0.70	+0.76	+1.10	+1.44	+1.63
0	0.08	0.04	0.21	0.26	0.47	0.73	0.76	1.13	1.48	1.60
+0.01	0.12	0.05	0.17	0.29	0.48	0.75	0.78	1.14	1.48	1.61
0.01	0.19	0.05	0.13	0.29	0.50	0.74	0.82	1.17	1.40	1.51
0.05	0.20	0.09	0.08	0.28	0.50	0.73	0.80	1.16	1.43	1.52
0.06	0.10	0.15	0.11	0.30	0.53	0.78	0.83	1.15	1.46	1.55
0.06	0.10	0.21	0.12	0.35	0.55	0.80	0.87	1.15	1.43	1.57
0.08	0.10	0.10	0.11	0.38	0.57	0.83	0.91	1.15	1.43	
0.04	0.09	0.06	0.19	0.41	0.61	0.83	1.00	1.19	1.41	
0.02	0.10	0.07	0.20	0.44	0.67	0.80	1.05	1.19	1.44	
0.02	0.15	0.13	0.20	0.45	0.74	0.78	1.03	1.22	1.46	
0.05	0.09	0.21	0.19	0.48	0.80	0.83	1.01	1.28	1.44	
0.04	0.06	0.30	0.22	0.52	0.76	0.84	1.00	1.31	1.50	
0.04	0.08	0.24	0.21	0.55	0.70	0.80	1.03	1.28	1.50	
0.06	0.12	0.13	0.21	0.55	0.65	0.75	1.01	1.28	1.54	
0.04	0.07	0.14	0.21	0.51	0.67	0.73	1.01	1.28	1.61	
0.07	0.07	0.22	0.22	0.50	0.68	0.73	1.04	1.28	1.63	
0.07	0.06	0.24	0.23	0.51	0.64	0.73	1.10	1.38	1.66	

MILL RUNWAY 36 (003°magnetic, 163°true, 329°grid)

Distance (m)	Reduced level (m)	Flag	Distance (m)	Reduced level (m)	Flag
0	+2.66		3654	48.43	
134	0	1	3780	50.40	12
321	+2.64		3821	50.89	
334	2.80	2	4040	52.89	
504	5.68		4165	54.06	13
633	8.50		4230	54.66	
684	9.52	3	4427	57.20	
823	11.44		4523	59.04	14
985	13.59		4585	60.13	
1011	13.95	4	4699	61.64	15
1176	16.32		4817	62.27	
1347	19.04		5038	64.83	
1363	19.30	5	5185	67.95	
1519	22.03		5286	70.61	
1614	23.56	6	5305	71.21	16
1677	24.60		5391	73.45	
1839	27.06		5526	76.43	
2010	29.39		5573	77.21	17
2056	30.04	7	5695	79.17	
2176	31.89		5831	81.33	
2341	34.71		5992	83.48	18
2416	35.86	8	6037	84.03	
2543	37.12		6233	86.67	
2678	38.45	9	6423	88.56	
2753	39.18		6467	89.17	19
2953	41.37		6595	90.88	
3095	43.55	10	6778	93.16	
3131	44.21		6964	95.59	
3305	46.45	11	7167	98.20	
3414	46.57		7295	99.93	20

MILL CROSS LINE through flag 6 (268°magnetic, 068°true, 234°grid)

Distance (m)	Reduced level (m)	Flag	
0	11.64		(backsight to edge of moraine)
98	13.55		
232	15.46		
259	16.05	6A	
361	18.74		
456	21.26	6B	
621	22.88		
648	23.56	6	
918	24.66		
934	24.78	6C	
1127	25.06	6D	
1393	25.39		
1398	25.63	6E	
1423	24.40	6F	
1657	23.94		
1718	24.39	6G	
1974	25.24		
2213	24.89		
2563	23.45		
2794	23.30		(at giant rift)

MILL CROSS LINE through flag 17 (273°magnetic, 073°true, 239°grid)

0	63.90	17A	(on steep ice slope)
62	66.75		
149	70.14		
190	71.81	17B	
225	73.13		
299	75.80	17C	
377	77.21	17	
537	79.07	17D	
622	81.72		
650	83.99		
655	84.57		(at giant rift)

ABLATION STAKES

1. Exposed length of stakes placed at Mount Howe on 28 December 1988.

Flag	Height (cm)	Flag	Height (cm)
1	150	13	153
2	148	13A	150
3	160	13B	147
4	147	13C	150
5	149	13D	148
6	149	13E	143
7	146	13F	161
8	158	13G	147
9	145	13H	155
9A	147	14	148
9C	148	15	153
10	149	16	147
11	155	17	163
12	145		

2. Exposed length of stakes placed at Mill Glacier on 6 January 1989.

Flag	Height (cm)	Flag	Height (cm)
1	148	18	146
3	155	19	154
4	127	20	150
5	152	6A	147
6	150	6B	155
7	152	6C	160
8	152	6D	152
9	145	6E	145
10	150	6F	154
11	147	6G	156
12	147	17A	143
13	150	17B	146
14	152	17C	158
15	144	17D	147
16	146	17E	136
17	147		

APPENDIX B: ANALYSIS OF SURFACE ROUGHNESS AT BLUE-ICE SITES

ROBERT H. WILLS

Introduction

A measure of roughness is needed to evaluate a runway's condition and its suitability for use by various types of aircraft. Estimates of roughness can also be used to compare, as in this report, the attributes of different sites.

Raw elevation traverse data are shown in Figures B1 and B2 for the Mount Howe and Patriot Hills sites. Measurements were taken at regular 2.58-m intervals for the Mount Howe data and 2.0-m intervals for the Patriot Hills data. It can be seen that it is difficult to visually evaluate bump height and wavelength from raw elevation data.

Military Specification MIL-A-8863B defines an envelope of maximum bump height versus wavelength for the categories of unprepared fields, semi-prepared fields and paved runways (Fig. B3). It assumes a raised cosine bump shape.

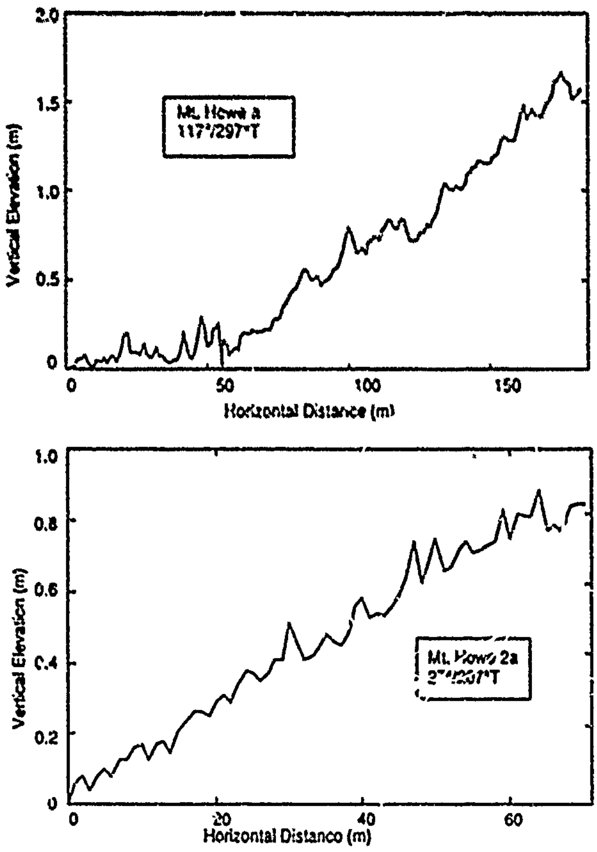

Figure B1. Raw elevation data for Mount Howe traverses.

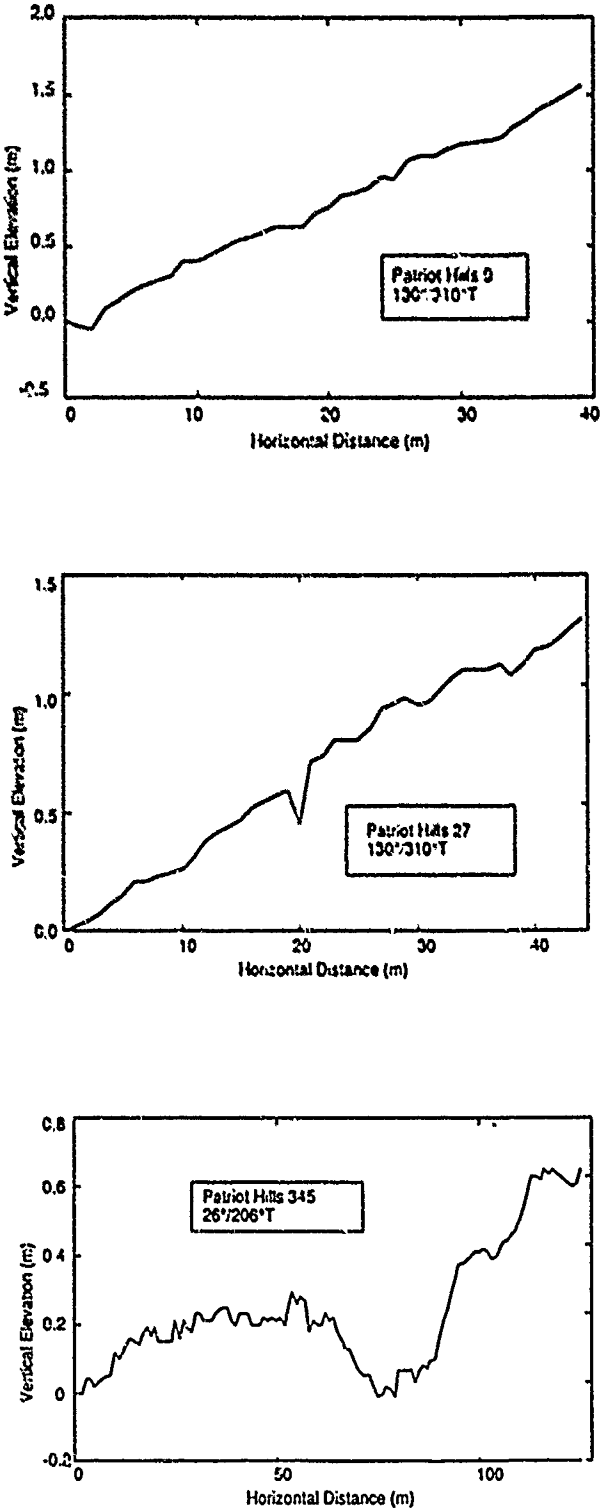

Figure B2. Raw elevation data for Patriot Hills traverses.

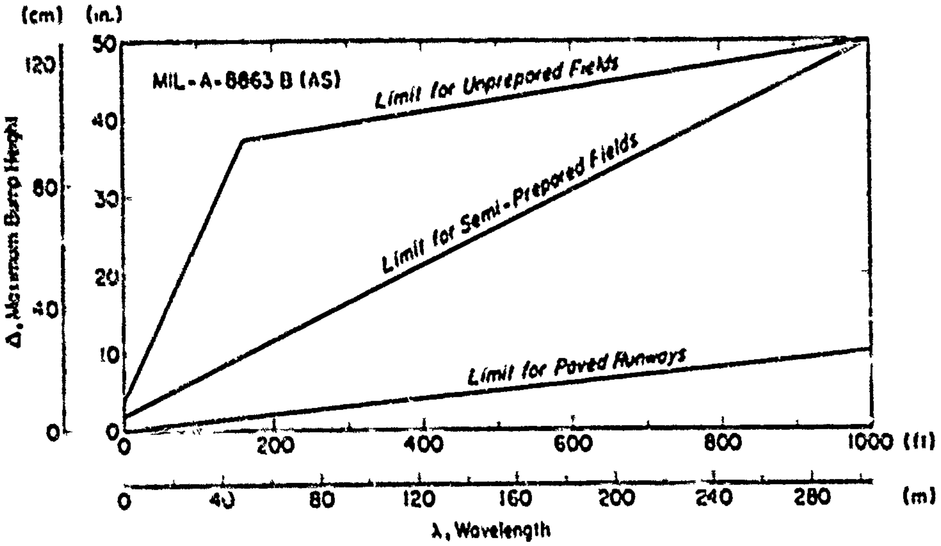

Figure B3. Mil-A-8863B maximum bump height specification.

In order to compare field measurements to this standard, it is necessary to develop data processing techniques for determining bump height versus wavelength from the raw data. Two techniques are investigated here: Maximum Half-Cycle Bump Height and Fourier Analysis.

Maximum bump height

One way to measure maximum bump height versus wavelength is to find the maximum height difference in the field data for various horizontal spacings. This may be considered a peak-to-trough or two-point measurement, so the corresponding wavelength is equal to the spacing times two.

The algorithm is:

For spacing = 1 to N-1,
  For each (N-Spacing) case
    Find the maximum difference in height (absolute value)
    Output: Wavelength = Spacing ×2
    Output: the Maximum Value for this wavelength

The results of such an analysis are shown in Figures B4 and B5.

The salient points are that there is a significant change in roughness with direction for both sites. Traverses running across the ice-flow direction are rougher. The two 130°/310°T traverses at Patriot Hills showed reasonable consistency.

Fourier analysis

The raised cosine bump shape used by MIL-A-8863B suggests that the elevation data can be analyzed as the superposed sum of cosine-shaped

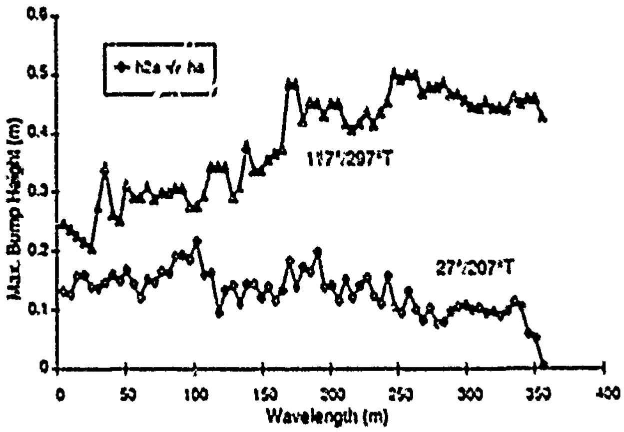

Figure B4. Two-point maximum bump height for Mount Howe traverses.

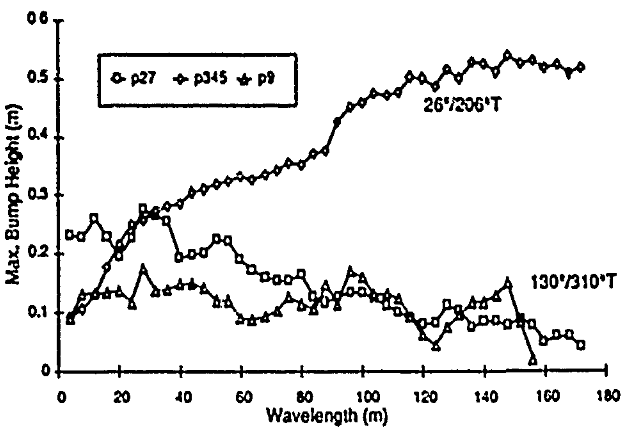

Figure B5. Two-point maximum bump height for Patriot Hills traverse.

bumps of different wavelengths. This decomposition of a data series to a set of weights for sinusoidal (or equivalently, complex exponential) basis functions is known as *Fourier analysis*. Methods of analyzing intensity or power versus wavelength or frequency are known as *spectral analysis*.

The elevation data, $x(n)$, may be represented by the weighted sum:

$$x(n) = \frac{1}{N} \sum_{k=0}^{N-1} X(k)\, e^{j(2\pi/N)nk},$$

The spectral coefficients, $X(k)$, may be found from:

$$X(k) = \sum_{n=0}^{N-1} x(n)\, e^{-j(2\pi/N)nk},$$

This form of analysis, however, cannot be used directly as the effects of finite input data length and superimposed slopes on the data cause distortion of the spectral estimate. The Fourier transform also has the property of giving poorer (noisier) spectral estimates for longer input sequences. (The variance of the spectral estimate increases with the input sequence length.)

To overcome these problems:

1. The input data are generally de-trended to remove any underlying slope.
2. The data are split into many sub-sequences whose spectra are averaged to reduce the variance of the estimate.
3. Each sub-sequence is windowed (multiplied by a raised cosine or other envelope) to reduce the effect of the ends of the sequence.

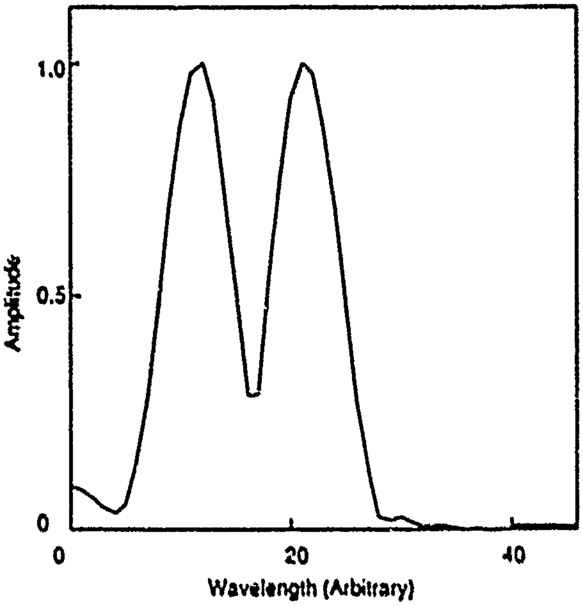

Figure B6. Spectrum of synthetic test data.

This methodology was proved with a synthetic data set that consisted of two sine waves superimposed on a linear ramp. The output of the Fortran spectral analysis program (with two sub-sequences being averaged) is shown in Figure B6. The two sinusoidal components are clearly visible. Less averaging results in narrower peaks, but more noise when analyzing real data. The peak amplitudes correspond to the test sinusoid amplitude of 0.5, or a peak-to-trough bump height of 1.0.

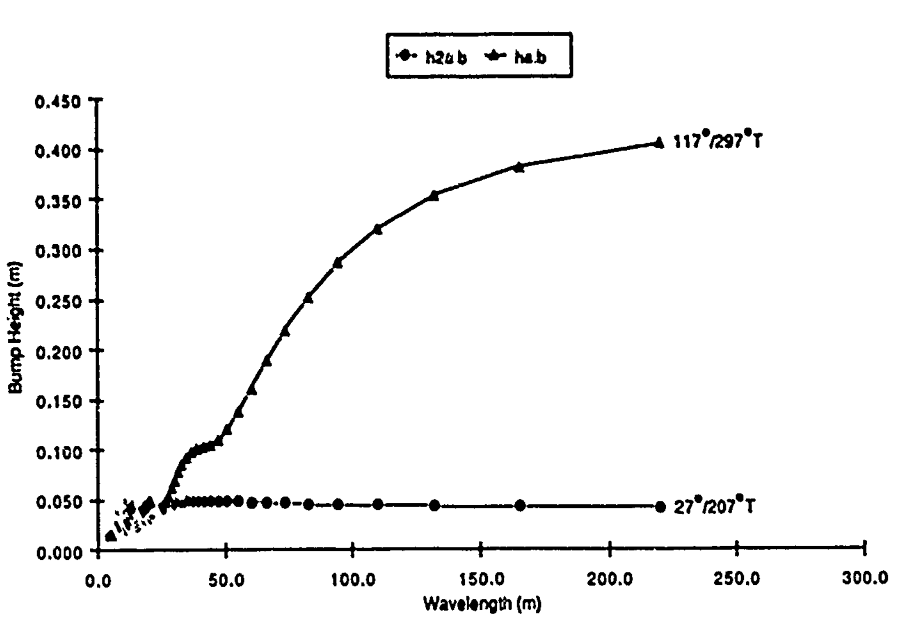

Figure B7. Bump height spectra for Mount Howe traverses.

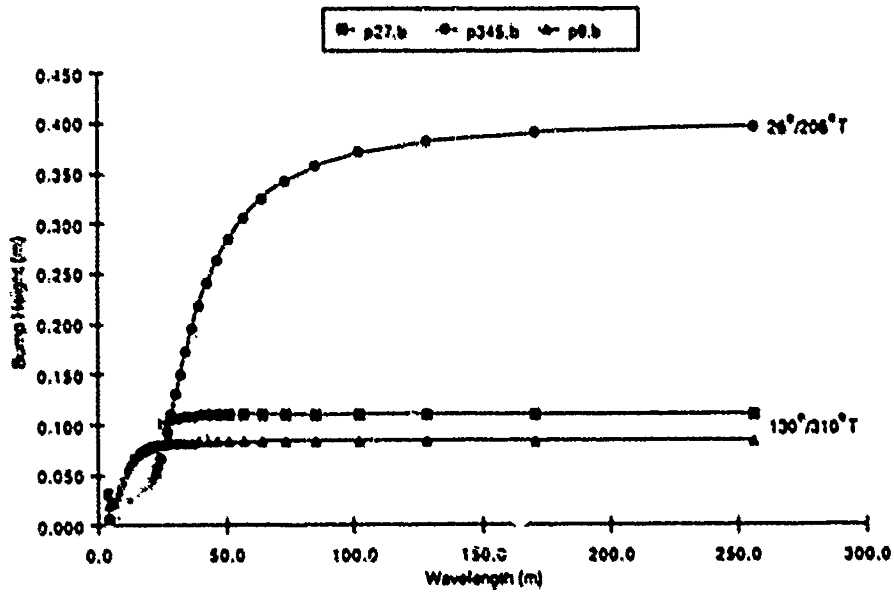

Figure B8. Bump height spectra for Patriot Hills traverses.

Analysis of the Mount Howe and Patriot Hills data using this technique gave the results shown in Figures B7 and B8. These show quite close correspondence with the maximum bump height analysis. The indicated bump heights, being averages rather than maxima, are lower in value.

Discussion

The two-point maximum bump height technique is a straightforward measure of the worst case bump height. Using this measure, both the Mount Howe and Patriot Hills sites appear to meet the MIL-A-8863B(AS) specification for unprepared fields in the ice-flow direction and, for all but the smallest wavelengths, in the cross-flow direction.

The spectral technique gives similar results, with all traverses analyzed in this manner meeting the specification. As it is an average rather than a maximum measure, it will naturally show lower values. The spectral intensity is of interest as it is a true representation of the mechanical excitation given to a vehicle traversing the runway. (It is equivalent to the spectrum of an electrical waveform exciting an electronic circuit.)

A problem with the spectral technique is that the amount of averaging applied (i.e. the number of segments that the input data are divided into) greatly affects the result. Little or no averaging results in noisy spectral estimates with false peaks and dips. Too much averaging results in a highly smoothed version of the spectrum. (There is an inherent tradeoff between noise and resolution.) There are no obvious spectral peaks in the data that would indicate the presence of periodic structures.

MIL-A-8863B(AS) specifies *maximum* bump heights, so the two-point maximum technique is the most appropriate of the two for this use.

One problem with the maximum technique is that a single high point can dominate the measure of roughness of the surface. For example, a 0.5-m measurement on an otherwise flat surface would show 0.5-m bump height for all wavelengths. Also, the specification assumes a cosine rather than a two-point bump shape. Because of this, the two-point maximum technique will generally overestimate the surface roughness with respect to the MIL-A-8863B(AS) specification.

There are other ways to measure surface roughness that could be investigated. For example, using a maximum three-point measurement may better approximate a cosine bump. Averaging the absolute two-point height differences could provide another approach. In the end, it is the aircraft and its response to runway roughness that matters. From this viewpoint, wheel acceleration and the path of a wheel traversing the surface become significant and indicate a possible direction of further research.

APPENDIX C: METEOROLOGICAL CONDITIONS TO BE EXPECTED IN SUMMER IN THE TRANSANTARCTIC MOUNTAINS

AUSTIN W. HOGAN

Executive summary

1. I have reviewed my notebooks, papers and photographs relating to conditions observed in the vicinity of the Transantarctic Mountains. I do not have any specific surface observations at Plunket Point or Mt. Howe; the observations noted are intended to provide insight and reference to meteorological conditions which may impact on establishing a wheeled aircraft runway at high southern latitude in the Transantarctic Mountains.

2. This work is heavily influenced by Schwerdtfeger (1984), and some credit is due him for every idea and analysis expressed.

3. Flight Following records (P_1, P_2, P_3 reports) were archived for several years, and at least two years' records are available from the NSFA Met Detachment. These would provide an extended series of wind, temperature and cloud observations made above the Transantarctic Mountains. Observations from Beardmore South Camp (BMG) may also be archived; POC: LT Vayda, Naval Support Force, Antarctica (NSFA).

4. Bob Writner of Scripps has archived satellite photos showing down-glacier katabatic flows in the Transantarctic Mountains since 1985 and has prepared a paper on the subject.

5. The sources of the data used in the following report are notebooks recording my surface observations at South Pole (NPX) and Beardmore South (BMG); airborne observations from instrumented aircraft XD03 (147131) in Jan 77, Oct/Nov 77, Nov/Dec 78, and Oct/Nov 80; P_1, P_2, P_3 reports provided by LCDR M.S. Foster, NSFA, 1980; and soundings provided by NOAA/NWS (NPX, South Pole) and NSFA (ZCM, McMurdo). Some of this information has been previously published.

6. It is my opinion that good flying weather, equal to that at South Pole, will be present on most "summer" days (mid-November through early February) at both Plunket Point and Mt. Howe. Some strong winds may occur in spring (October through early November). Reduced visibility and lowered cloud bases may accompany advection of "warm highs" onto the Ross Ice Shelf and/or Marie Byrd Land in summer, reaching Mt. Howe on some occasions. An enhanced Antarctic science capability may accompany establishment of an airfield at either of these sites. Flights over the Transantarctic Mountains in spring of 1977–78 indicated that stratosphere–troposphere exchange is mountain-enhanced in this area, providing access to atmospheric circulation and air chemistry research sites (ozone hole etc.) not attainable from McMurdo.

7. It would probably be possible to conduct a critical analysis of potential hazardous flying weather at these sites based on existing data. Stationing automatic weather stations at or near these sites would provide verification of the analysis.

Introduction

The Transantarctic Mountains are a "climate divide" within Antarctica. They act as a barrier, separating the extremely cold and dry continental Antarctic (cA) air from the maritime Antarctic (mA) air of the Ross Ice Shelf and sea-ice-covered areas, and from maritime Polar (mP) air of the surrounding seas (Dalrymple 1966, Schwerdtfeger 1984). These air masses may gently mix while passing over the interior of Antarctica, but rarely appear at the surface as a front on the polar plateau.

Schwerdtfeger (1984, also many individual papers) describes precipitation enhancement on the Antarctic Peninsula and on the windward side of the Transantarctic Mountains due to "barrier winds." The mountains form a nearly impassable barrier to the cold, stable air within 2 km of the surface, and the momentum of the wind flowing towards the mountains causes lift and turning, which produces cloudiness and snowfall before the mountains and a surface wind flow parallel to them.

Additionally, strong katabatic winds may flow down the slopes and onto the shelf at the base of the Transantarctic Mountains (Mather and Miller 1967, Swithinbank 1973, Parish and Bromwich 1987). These are seen, as a result of adiabatic heating, in IR satellite images, and seem to occur most frequently when a low center is seaward over the Ross Ice Shelf near Ross Island.

The two proposed high southern latitude aerodrome sites are indicated in Figure C1. The elevation of the Mt. Howe site is approximately 2.4 km, and that of Plunket Pt. is approximately 1.8 km. There appears to be only occasional snow accumulation at these sites. This is probably the result of persistent subsident flow from the South Polar Plateau, similar to the circulation in the dry valleys farther north. The question we seek to answer is

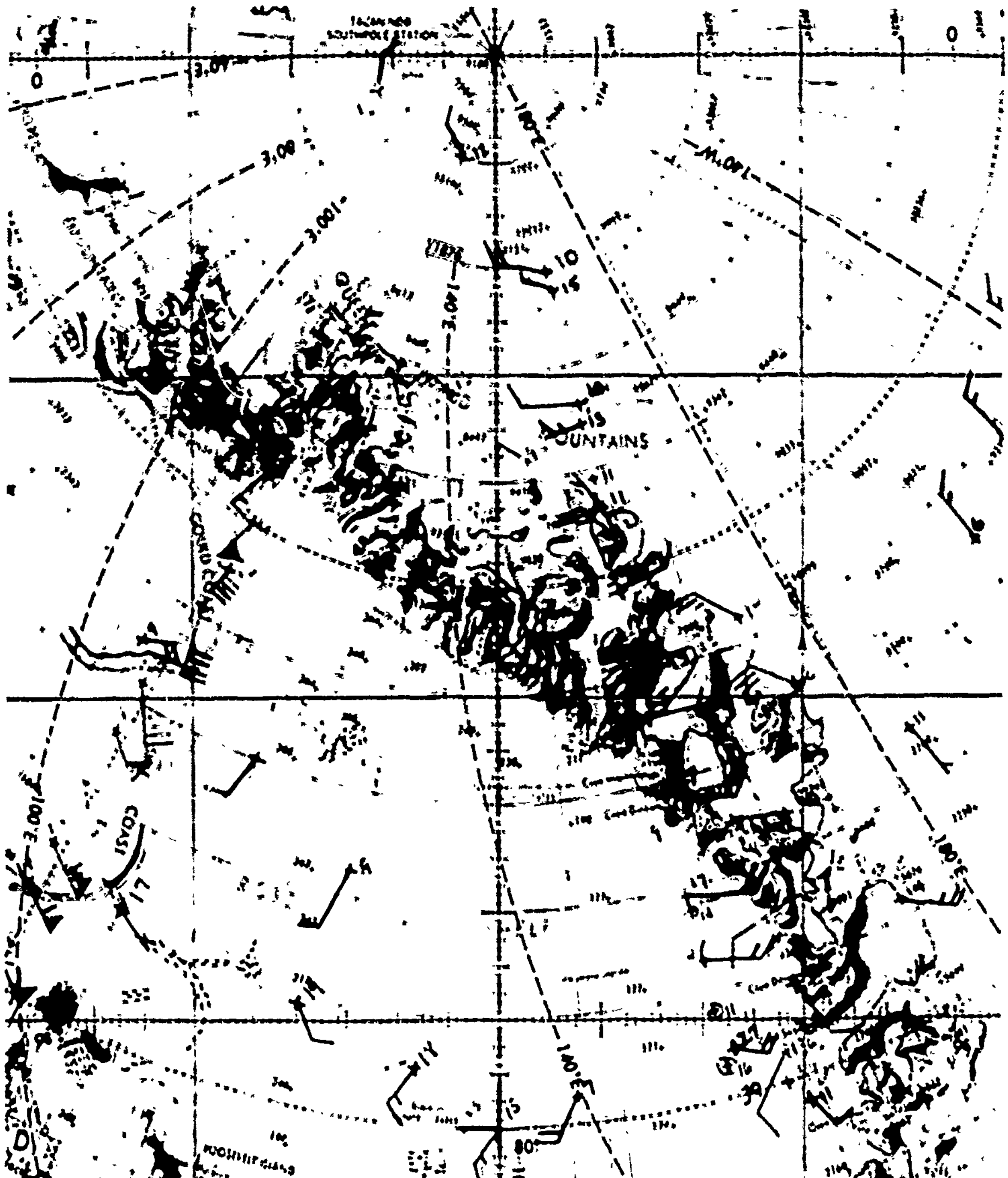

Figure C1. Winds observed in mid-troposphere (500- to 400-mb levels) over Antarctica in November, during instrumented meteorological flights. Repetitious data are not plotted. The Transantarctic Mountains constitute a boundary between the continental Antarctic (cA) and maritime Antarctic (mA) air masses.

whether the apparently benign summer weather observed at Plunket Pt., Mt. Howe and nearby at Beardmore South Camp begins sufficiently early in spring to facilitate establishing a wheeled aircraft aerodrome capable of carrying out logistic support to scientific activities on the South Polar Plateau.

Analysis

The center of a Global Navigation Chart (GNC 26) showing the location of Mt. Howe and Plunket Point is provided for reference (Fig. C1). Mid-tropospheric winds, observed at the 500- and 400-mb levels during continental transects by instrumented meteorological flight missions of 1977 and 1978 (Hogan 1986), are plotted. Tropospheric winds inland of the Transantarctic Mountains (i.e. over the Polar Plateau) are usually weak, and flow parallel to the 045°W–135°E meridian of longitude. The troposphere is generally cold, dry, stable and slightly subsident, providing the clear, cold surface associated with the Polar Plateau and the cA air mass (Hogan 1986). Tropospheric winds over the Ross Ice Shelf and Marie Byrd Land, seaward of the Transantarctic Mountains, are much more variable with respect to both direction and speed, as organized systems (usually cold lows or warm highs, according to Schwerdtfeger) are frequently able to spread over this lower lying area. A slightly more temperate mA air mass is generally found over the ice shelf, or seaward of the Transantarctic Mountains.

Examination of the winds along the McMurdo (ZCM) to South Pole (NPX) flight track (165°E longitude) indicates variability of wind direction in the vicinity of Plunket Point. Although only two transects are plotted in Figure C1, a chronology of navigators' reports taken at the reporting points "Papa One" (79°34'S, 166°50'E), "Papa Two" (83°57'S, 166°50'E) and "Papa Three" (88°19'S, 166° 50'E) by M.S. Foster in 1980 showed a weak front to be present in 50% of cases (Anon. 1988). A cross section of wind and temperature along 165°E taken in early November 1977 is given in Figure C2. This cross section shows the dissimilarity between ZCM and NPX atmospheric structure in spring, and the indistinct "front" separating the air masses.

The existence of a persistent "front" between cA and mA air masses at the 500- to 400-mb levels

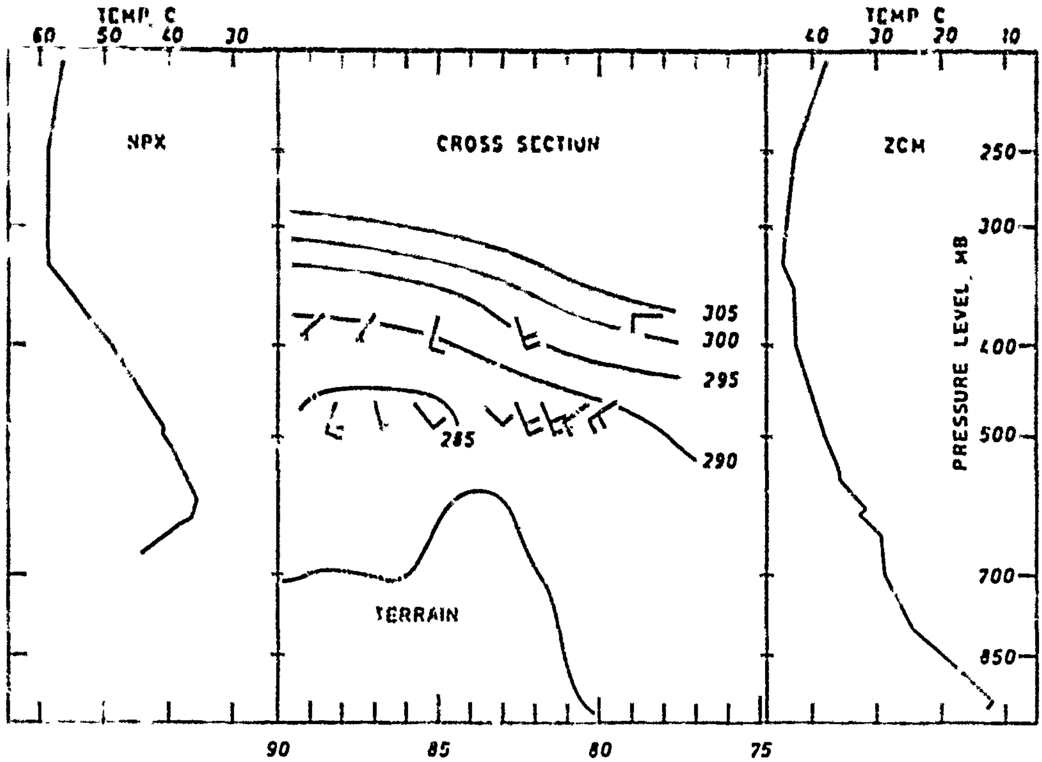

Figure C2. Cross-sectional analysis of winds and potential temperatures along 165°E longitude from McMurdo to South Pole, November 1978. The slope of the isotherms indicates air mass difference. Concurrent soundings from McMurdo (ZCM) and South Pole (NPX) show differing vertical temperature profiles in the air masses.

over the Transantarctic Mountains seems well established. Reports of fine, benign summer weather by most field parties in the Transantarctic Mountains indicate that this front is not only dry, but decoupled from the surface over the mountains, as it is over the Polar Plateau.

Surface and aircraft observations of meteorological conditions in the vicinity of Plunket Point and Mt. Howe are tabulated in Attachments 1 and 2. Dated cloud ph[illegible]raphs are the source of some of these observations. Persistent banks of water clouds were observed on the "southern" horizon (i.e. in the dateline direction) from South Pole during cloud physics experiments conducted in 1974, 1975 and 1977 (Kikuchi and Hogan 1976, 1979, Sato et al. 1981). Frequent heavy contrailing by inbound and outbound aircraft was also noted along the 165°E flight track. Examination of South Pole (NPX) upper air data on several of the days when these clouds were observed showe[illegible] [illegible] flow along the International dateline in the m[illegible]-troposphere but only a slight influence at the surface of the plateau. Aircraft observations and photos of the Beardmore/Plunket Point area at this time (mid-1970s) showed it to be snow-free during mid-summer. The same area was observed from the air to be covered with deep, fresh snow on 5 Jan 1984 en route to South Pole, concurrent with other unusual meteorological events that polar summer (Egan and Hogan 1986).

Mt. Howe lies off the usual air track. Benign surface conditions were observed inland of the Transantarctic Mountains on most of the continental transects of 1977–78. Blowing snow was observed on the surface at 87°S, 174°E on 7 Nov 1977, although winds at flight altitude were weak. Strong katabatic flows down the glaciers of these areas were seen in infrared satellite images during the flight experi-

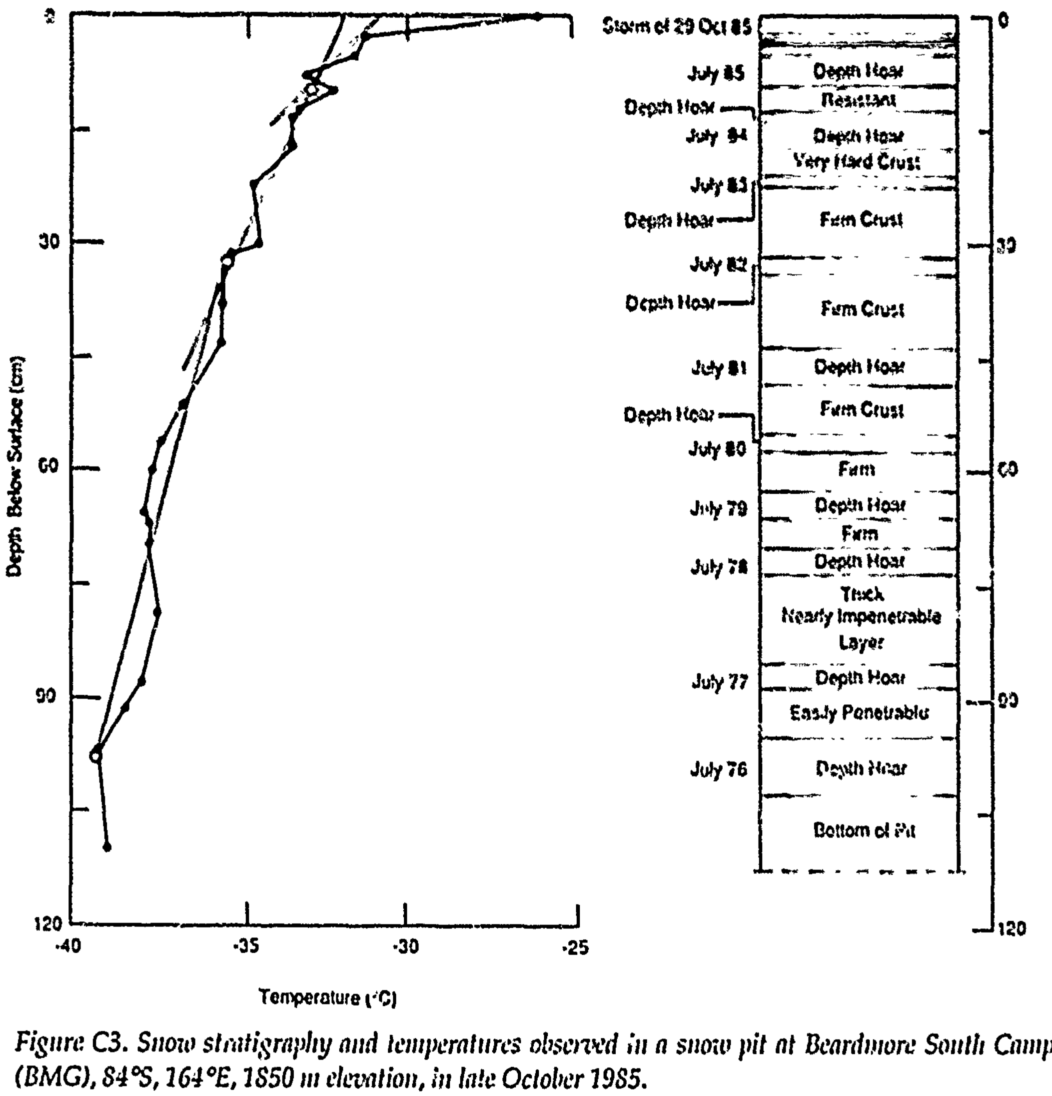

Figure C3. Snow stratigraphy and temperatures observed in a snow pit at Beardmore South Camp (BMG), 84°S, 164°E, 1850 m elevation, in late October 1985.

ments of 1978 and 1980. Stratosphere–troposphere exchange was found to be limited to the air above mountain ranges (Robinson et al. 1983, Hogan 1986) in these experiments as well.

I proposed to study this exchange, and examine the nature of this katabatic down-glacier flow, and was able to do the experiment at Beardmore South Camp (BMG) in October–November 1985. I arrived at BMG as a member of the opening party at 1000 CUT 26 October 1985. The snow surface was an extremely fine-grained wind crust, and settling of this crust into the previous winter's depth hoar was nearly continuous. Camp elevation was barometrically established as 1845 m (6050 ft) above mean sea level. Other estimates have placed the camp at 1815 m altitude. Recently (December 1988), LCDR Leninski, VXE6 Herc Ops Officer, placed a field party near this site and recorded 5700±100 ft (1740 m) at 84.01°S, 164.12°E inertial. Similar variations exist in the published elevations of Plunket and Mt. Howe.

I examined the snow, firn and depth hoar in a pit about 1 km south (true) of camp to avoid possible disturbances. The annual strata were quite apparent, separated by distinct depth hoar layers representing the cooling season (March–July). The crusts were extremely hard and fine-grained. I was able to mark the crusts with lumber crayon for photos. I uncovered 10 depth hoar layers in the upper meter. The temperature at 1-m depth was –39°C. I extracted cylinders from each layer and melted and weighed them. The mean accumulation was 10.7 cm of snow, yielding 3.6 cm water, per year over the period 1976–1985. I drove a pipe an additional 4 m below the pit floor and lowered a thermistor into the hole. Pit strata and temperature profiles are given in Figures C3 and C4. Temperatures of –39.5° to –40.0°C were measured below the pit floor. As this temperature was quite constant with depth below 1 m, I interpret it as representative of the annual mean temperature of the location.

Figure C5 shows the mean annual instrumental temperatures measured at Plateau, Vostok, Dome C (AWS) and South Pole (NPX) plotted against station elevation. A dry adiabat (9.8°/km) passes through the points representing Plateau, Vostok and South Pole; the Beardmore South snow temperature also lies along this adiabat. Points representing Siple, and Byrd (NBY) are also shown. They receive warmer mA more frequently, and do not lie on the dry adiabat.

Consideration of Figure C5 indicates that stations at elevations of 1700 m (5700 ft) and above in

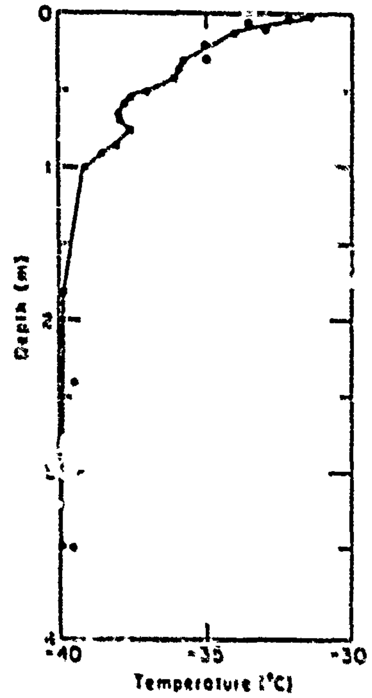

Figure C4. Temperature profile from BMG snow pit and in hole driven to 3.5 m. Near-constant temperatures of –39.5°C ±0.5° observed below 1 m are interpreted to indicate mean annual temperature.

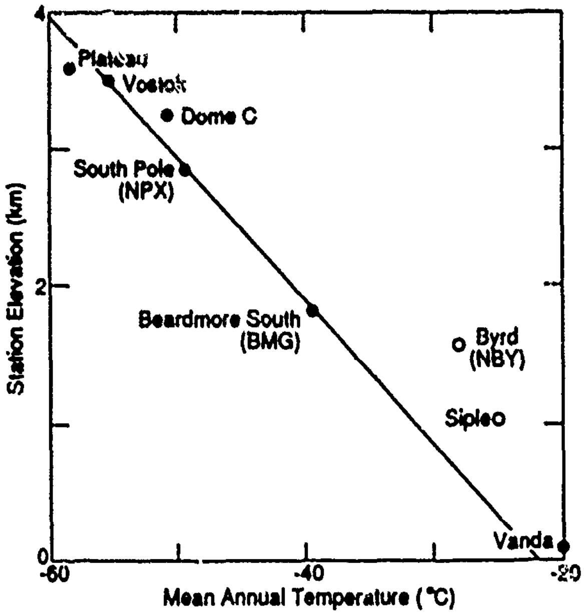

Figure C5. Mean annual temperatures at several Antarctic stations (from Schwerdtfeger 1985) plotted against station elevation. The line is a dry adiabat (9.8°C/km). This indicates that BMG primarily receives cA air subsiding from the polar plateau. This is in agreement with the small annual accumulation of snow shown in Figure C3.

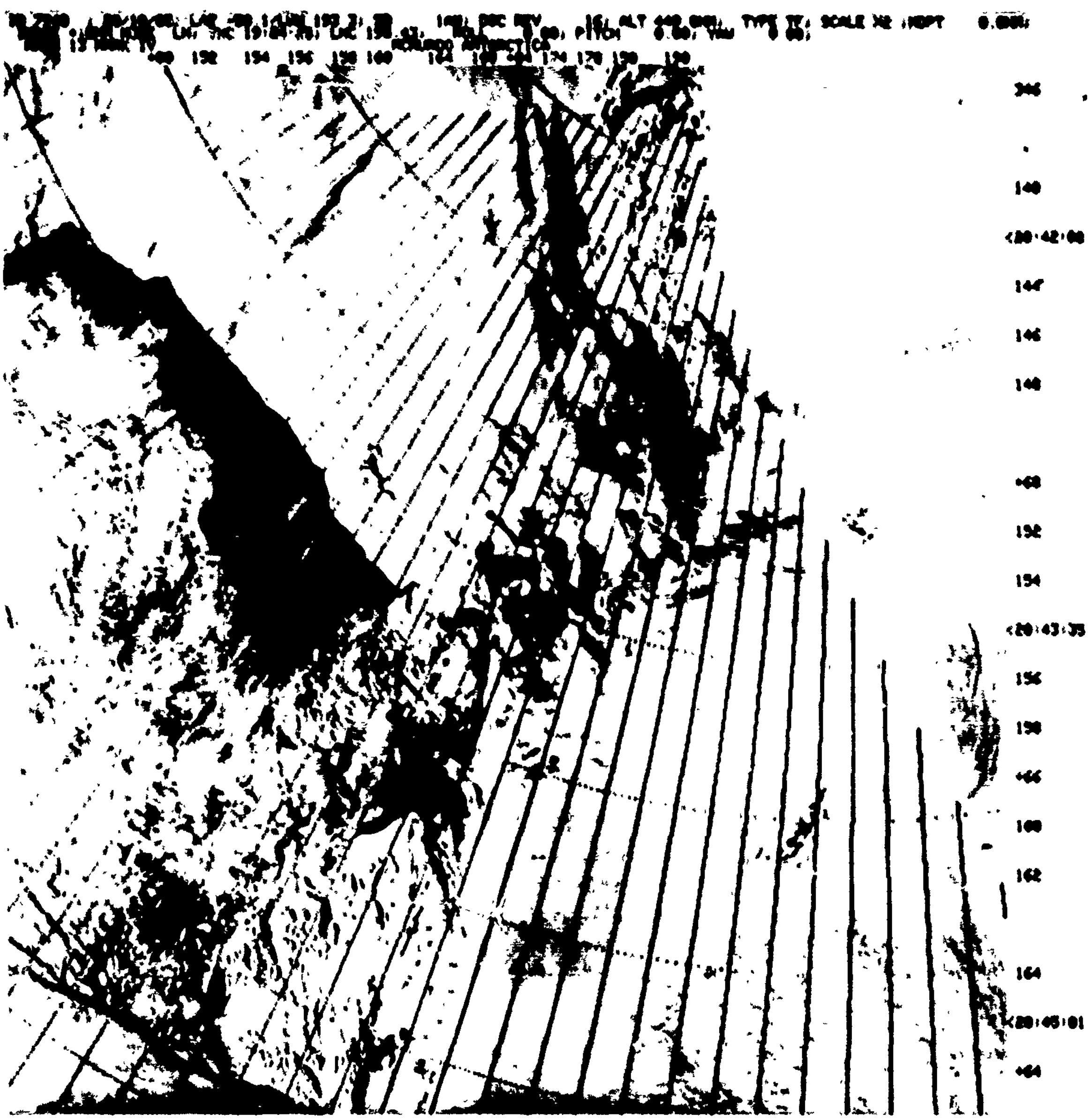

Figure C6. IR satellite image (courtesy Bob Writner), 28 October 1985, 1924 CUT. The dark streaks south of 84°S are adiabatically warmed streams flowing down-glacier, similar to those which produced strong surface winds at BMG a few hours later.

the Transantarctic Mountains are almost continuously under the influence of the cA air mass, as are the plateau stations. Precipitation is very slight, due to the downslope subsidence of the air from the cA source on the plateau to the station. The stations in west Antarctica and nearer the coast more frequently receive mP air and consequently lie along a warmer adiabat with a lapse rate nearer moist adiabatic.

On 29–30 October 1985, strong downslope katabatic winds and blowing and drifting snow were experienced at Beardmore South. Surface winds were sustained at more than 20 m/s for several hours during the period. Satellite analyses of similar events have been noted by Swithinbank (1973) and Writner (pers. comm.). Blowing snow was observed distant from camp at other times during the period. Katabatic winds at this time show as dark streaks in the satellite image (Fig. C6) at around 84.3°S, 170.0°E, in the upper part of the glacier.

Discussion

The South Pole and Beardmore South field camp temperatures appear to lie along a dry adiabat. Cloudiness over Mt. Howe coincides with tropospheric flow along the dateline at South Pole. This indicates that the number of flying days at South Pole per season are probably quite close to the number of flying days to be expected near Mt. Howe or Plunket Point. Two major questions cannot be uniquely answered from this analysis:

1. Does katabatic flow down glaciers in the Transantarctic Mountains accelerate air at their origins at the edge of the plateau to speeds sufficient to cause blowing snow? How late into the "summer" flying season will these winds persist?

2. Does occasional upslope flow along the dateline result in lower-based cloudiness at Mt. Howe (or Plunket Point) than at South Pole?

It will be necessary to extract some additional summer camp, satellite and pilot report data and perhaps obtain dedicated automatic weather station or satellite data to properly answer these questions.

Conclusions and recommendations

1. Flying weather at Mt. Howe and Plunket Point should be very similar to that at South Pole. However, with a short flying season small differences might be operationally significant.

2. A dedicated satellite study is a possible technique for analysis of the frequency of katabatic winds which might halt aerodrome operations.

3. Automatic weather station surveys would provide a unique calibration of the frequency of strong winds, riming, clouds, and fog at the stations relative to satellite and regional synoptic data.

4. An additional meteorological benefit of a Transantarctic station is that it lies under a region of stratosphere–troposphere exchange in spring (Fig. C8). Establishment of such a station would facilitate such exchange studies, which can rarely be accomplished at McMurdo or South Pole.

Acknowledgment

The data reported are drawn from published and unpublished work, supported through NSF/DPP grants to Dr. A.W. Hogan during the period 1973–85. The draft was reviewed by Dr. C. Ryerson and Dr. E Andreas.

Literature cited

Anonymous (1988) McMurdo forecaster's handbook. U.S. Naval Support Force, Antarctica (NSFA), Port Hueneme, California.

Dalrymple, P. (1966) a physical climatology of the South Polar Plateau. In *Studies in Antarctic Meteorology* (M.J. Rubin, Ed.). American Geophysical Union Antarctic Series, **9**: 195–231.

Egan, W. and A. Hogan (1986) Meteorological variation of atmospheric optical properties in an Antarctic storm. *Applied Optics*, **25**: 1155–1165.

Hogan, A. (1986) Aerosol exchange in the remote troposphere. *Tellus*, **38B**: 197–213.

Kikuchi, K. and A. Hogan (1976) Snow crystal observations in summer season at Amundsen–Scott South Pole Station, Antarctica. Hokkaido University, *Journal of the Faculty of Science of Hokkaido University*, **VII**: 1–19.

Kikuchi, K. and A. Hogan (1979) Properties of diamond dust type ice crystals observed in summer season at Amundsen–Scott South Pole Station, Antarctica. *Journal of the Meteorological Society of Japan*, **57**: 180–190.

Mather, K. and G. Miller (1967) Notes on topographic factors affecting surface wind in Antarctica. VAG-R-189, Fairbanks, Alaska.

Parish, T. (1988) Surface winds over the Antarctic continent: A review. *Reviews in Geophysics*, **26**: 169–180.

Parish, T. and S. Bromwich (1987) The surface windfield over the Antarctic ice sheets. *Nature*, **327**: 51–54.

Robinson, E., D. Clark, D. Cronn, L. Bamsberger and A. Hogan (1983) Stratospheric–tropospheric ozone exchange in Antarctica caused by mountain waves. *Journal of Geophysical Research*, **88**: 10,708–10,720.

Sato, N., K. Kikuchi, C. Barnard and A. Hogan (1981) Some characteristic properties of ice crystal precipitation in the summer season at South Pole Station, Antarctica. *Journal of the Meteorological Society of Japan*, **59**: 772–780.

Schwerdtfeger, W. (1984) *Weather and Climate of the Antarctic*. Amsterdam: Elsevier.

Swithinbank, C. (1973) Higher resolution satellite pictures. *Polar Record*, **16**: 739–741.

Attachment C1

Observations extracted from field notes. Entries are in Coordinated Universal Time (CUT) unless otherwise noted. Photos are dated 35-mm slides. Grid directions originate at north, defined as the Greenwich Meridian.

Flight observations and photos, 23 Jan 1974: Supercooled water clouds were observed over the Ross Ice Shelf from McMurdo to near the foot of the Beardmore Glacier. The Beardmore Glacier and Plunket Point were clear, with an exposed (snow-free) band of rock paralleling the glacier. Ice crystal clouds were observed over the Polar Plateau. Upon landing at the South Pole at 0930 CUT, 23 Jan 1974, the ice crystals appeared as a low overcast.

10 Jan 1975: Observations made on a flight from McMurdo to South Pole found supercooled water clouds over the Ross Ice Shelf, and clean air from Beardmore Glacier to the South Pole. Bare rock was again observed along the Beardmore.

11 Jan 1975: A sky observation made at South Pole at 1130 CUT, 11 Jan 1975, showed altostratus over the interior plateau (grid north) and on the horizon in the vicinity of Mt. Howe, although it was clear directly overhead.

12 Jan 1975: An altostratus and altocumulus bank was watched on the horizon near Beardmore and Mt. Howe while conducting cloud physics experiments, 0900–1200 CUT, 12 Jan 1975.

15 Jan 1975: A C-130 (JD 130) generated a persistent spreading contrail along the flight track, from the horizon over the Transantarctic Mountains to the South Pole.

17 Jan 1975: An altostratus bank was observed on the horizon over the Transantarctic Mountains at 1000 CUT, 17 Jan 1975.

17 Jan 1975: Cirrostratus originated from a C-130 contrail spread over the South Polar Plateau, from the area of the Transantarctic Mountains, covering $^3/_{10}$ of the sky by 1625 CUT, 17 Jan 1975.

17 Jan 1975: Two new contrail clouds on horizon. Surface wind 155° grid at 05 knots at 2040.

20 Jan 197[illegible] [illegible]ltostratus on southern horizon over Transantarctic Mountains at 1155.

23 Jan 19[illegible] [illegible]stratus on southern horizon at 1338.

23 Jan 197[illegible] [illegible]ure spreading up from direction of Beardmore. Large Cs bank there; clouds dissipating before reach[illegible] station. Wind 130° grid, 06 knots, temperature –29°C at South Pole surface.

24 Jan 1975: Cirrus on southern horizon.

24 Jan 1975: Cirrus spreading toward South Pole from south, at 1600 CUT winds above Polar Plateau are 140° grid at 09 m/s (from general Ross Sea direction).

25 Jan 1975: Sky $^6/_{10}$ covered by As. Opening is around 120° grid, wind shifted 190°–90°–120° grid at surface around 1000, speed diminished and air temperature increased 2°C in one-half hour.

27 Jan 1975: Liquid water clouds spreading over station from grid south—$^6/_{10}$ As at 1530.

28 Jan 1975: As bank to grid south, southern horizon obscured.

29 Jan 1975: Straight line clouds on grid south horizon look like contrails, but there are no airplanes on the ice.

1 Feb 1975: Nearly clear but Cs or As on south horizon. This condition continues.

2 Feb 1975: Persistent contrail from C-130 remains on grid south horizon.

3 Feb 1975: Clear over South Pole, except few bands on grid south horizon.

4 Feb 1975: Clear over South Pole but fog bank on grid southeast horizon.

Aerial observations

The reporting points along the McMurdo–Pole flight route are designated as Papa One, Two, and Three; the locations are:

P_1 = 79°34'S, 166°50'E
P_2 = 83°57'S, 166°50'E
P_3 = 88°19'S, 166°50'E

Aircraft observations, November 1977

0047	7 Nov 77	79°S×161°E	Solid deck below Papa One.
0127		82°S×160°E	Clear over Ross Ice Shelf and mountains. Over Transantarctic Mountains wind 240° at 15 kt at 500 mb level.
0200		84°S×160°E	$^6/_{10}$ Cs scattered above Papa Two, wind light and variable at flight level.
0530		87°S×174°E	Blowing snow below. Cs ahead at flight level.
0553		85°S×173°E	Very slight turbulence noted.
0636		81°S×169°E	Over solid As deck.
0505	8 Nov 77	81°S×161°E	Peaks and nunataks protruding through unbroken low cloud deck.
0516		82°S×161°E	Nimrod Glacier, Papa Two.
0541–0542		84°S×161°E	Very clear below, no clouds or blowing snow, sharp view of Beardmore Glacier, P_2 wind 340° grid at 05 kt.
0555		85°S×160°E	Blowing snow visible on surface, wind 160° at 18 kt at flight level.
0604		85.5°S×161°E	Ice fog, blowing snow on surface below.
0654		89°S×161°E	Entering top of ice crystal layer, 1400 ft AGL over Polar Plateau.
1019		82°S×171°E	Peaks protruding through cloud deck, wind light and variable at flight level.
0538	10 Nov 77	80°S×159°E	Wind 266° at 18 kt at 20,000 ft.
0620		83.5°S×159°E	Wind 139° at 17 kt at 20,000 ft, enter moister air.
0638		84°S×159°E	Papa Two wind 167° at 21 kt, very slight turbulence noted.
0650			Over Beardmore, wind 157° at 10 kt, clear below.
0745		89°S	Just above ice fog (or Cs) layer at 2370 ft AGL over Polar Plateau. Aircraft contrails heavily on ground after landing.
1029		85°S×169°E	Clearing at edge of plateau, wind 350° at 08 kt.
1120		81°S×170°E	Low cloud deck beginning below, unbroken over northern shelf, tops at around 10,000 ft.
1148			Mt. Erebus and smoke plume protruding above cloud deck.
1603	20 Nov 78	86.5°S×167°E	Wind 105° at 11 kt.
1103	21 Nov 78	83.5°S×166°E	Wavy, near lenticular As; slight turbulence near Beardmore.
1144		86°S×167°E	Diffuse deck just above surface on Polar Plateau.
1224		89°S×163°W	Very thin deck on surface.
1312		87°S×71°W	Over crevassed area; clear but Cs deck ahead.
1334			Nunataks ahead, Cs thickening.
1345		85.5°S×64°W	

3 Jan 83: Flight to South Pole

Ross Ice Shelf cloud-covered.

Much cloud around Transantarctic Mountains.

Beardmore visible, St on flanks of mountains, water clouds over Polar Plateau.

5 Jan 84: Flight to South Pole

Deep cloud bank over Ross Ice Shelf, tops at 20,000 ft.

Some water clouds over Transantarctic Mountains.

Deep, fresh snow visible along glaciers.

Very deep hoarfrost layer on the surface on arrival at South Pole.

14 Jan 84: Surface observation at South Pole

Blizzard. Winds 015° at 20 kt, gusting 22.

Visibility one-fourth mile at surface.

Lower tropospheric flow along northwest grid direction.

Beginning of very warm period.

17 Jan 84

A real snowstorm, dendritic snowflakes, several inches of fresh snow on ground, –20°C, wind 330° at 04 kt.

Attachment C2

Beardmore Glacier Camp		*"Beardmore South"*
		Put in 1300/26 Oct 85
0000	27 Oct 85	Surface wind 160° grid at 10 kt, temperature –30°C. Most mountain tops in clear, 3/10 AsCs clouds. Remarks: Surface wind aligns with light winter drifting around Jamesways, which are aligned N–S grid. Ice shelf cloud-covered, clouds intrude up-glacier slightly from shelf. Clear over plateau.
0130	28 Oct 85	–25°C, wind 270° grid at 3 kt, strong mirages visible in all quadrants. As over shelf, 2/10 Cs overhead. South Pole reports same. Mirage up-canyon towards plateau. Willy Field closed at McMurdo due to bad weather.
2000		Nearly calm. Temperature –20°C in calms, –27°C in wind runs. Cloud deck over Ross Ice Shelf. Wave clouds over mountains. At 2145 a large wave cloud forms and blowing snow is visible coming downslope. The wind accelerated to 12–17 kt, then at 2200, nearly calm again. A large lenticular cloud or fog bank is "parked" near the plateau.
0000	29 Oct 85	Calm at BMG. Some standing wave clouds around mountain peaks, streaks of cloud are coming off plateau, and ice crystal patches appear "parked" upslope.
0030	29 Oct 85	Blowing snow across the basin to grid southeast. Wind here is 180° grid at 3 kt in the upslope direction.
0115		Wind 360° grid at 7–12 kt, occasional blowing snow; fog or mirage in basin, lull here, williwaw visible across the basin.
0500		–19°C, wind rises from calm to 060° grid at 12 kt. Williwaw begins here. Sustained wind 340° grid at 24–35 kt by 0600; gusts may have reached 40 kt.
0925		0/10 overhead, blowing snow at surface. 24 kt sustained wind with gusts to 35. Strong wind continues through 1500.
2100		–28°C, wind 240° grid at 5–7 kt, few waves and cap clouds on peaks. As creeping up-glacier from shelf. No surface accumulation of blowing snow, even in tracks. Downslope wind is apparently associated with cessation of "onshore" wind from shelf at base of glacier.
2115		–29°C, 330° grid at 03 kt. 1/10 As over peaks, deck over shelf extends well above horizon. No snow accumulation downwind of camp from blowing snow. Some loose snow in tracks. No extension of existing drifts. Baro rose 0.19 in. last 12 hours to 28.50 in.
0445	30 Oct 85	Dig snow pit to winter 1976, 10 depth hoar layers in 1 meter. Spectacular wave and cumuliform clouds all sectors.
2345		–26°C, 240° grid at 07 kt, 8/10 AsCs translucent clouds, aligned along axis of mountains. Blowing snow visible over ridge to grid east. McMurdo town was in condition one this morning.
0230	1 Nov 85	Aircraft landed. The aircraft did not produce a contrail until reaching cloud base after takeoff. –40.2°C, scattered AsCs. Snow pit day. Much mirage. AcCs spread over BMG from shelf.
0435		Sun's disk visible through AsCs clouds. As quite thick over shelf. Low ceiling on shelf end of basin, –30°C, 340° grid at 05 kt.
1000		–25°C, 360° grid, 05 kt, 28.30 in. Hg, CcCs passed 2 hours ago. Looked like mid-latitude warm front. Jet? Vortex break? Still cloudy overhead, but blue east and west.
2040		–20°C, 135° grid at 05 kt, snowing lightly. Needles, dendrites and occasional graupel fall from fairly high cloud base. Cloud deck appears solid, but sun shafts are visible.
0115	2 Nov 85	135° grid at 10 kt, –22°C, visibility less than 1 km. Snow blowing in air but not drifting at surface.
0550		Snow stops. This light snowfall covers more tracks than previous blizzard.
0045	3 Nov 89	–23°C, 180° grid at 01–03 kt, 9/10 AsCs overcast, thickening.
0400		Light snow, –23°C, visibility 3 km, 180° grid at 01 kt.

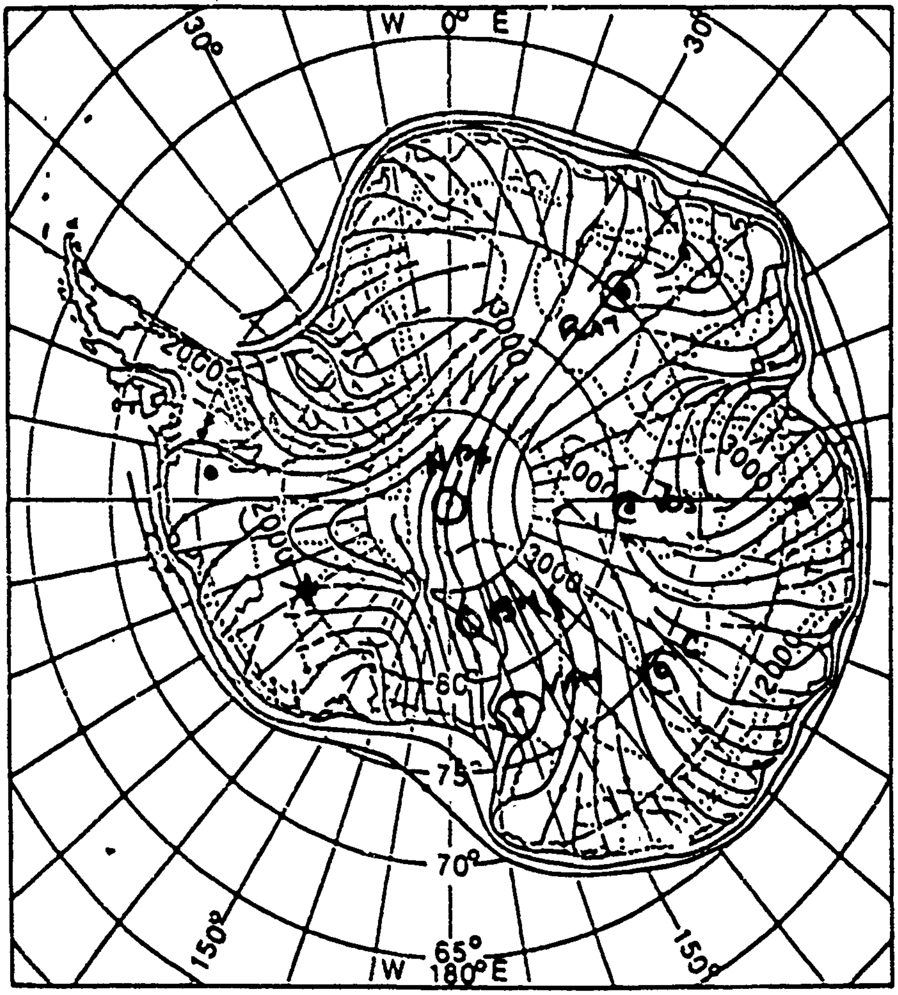

Figure C7. Surface winds over Antarctica (fromMather and Miller 1967). This shows flow from the plateau dominating Mt. Howe area, Plunket Pt. and BMG, in agreement with Figure C5.

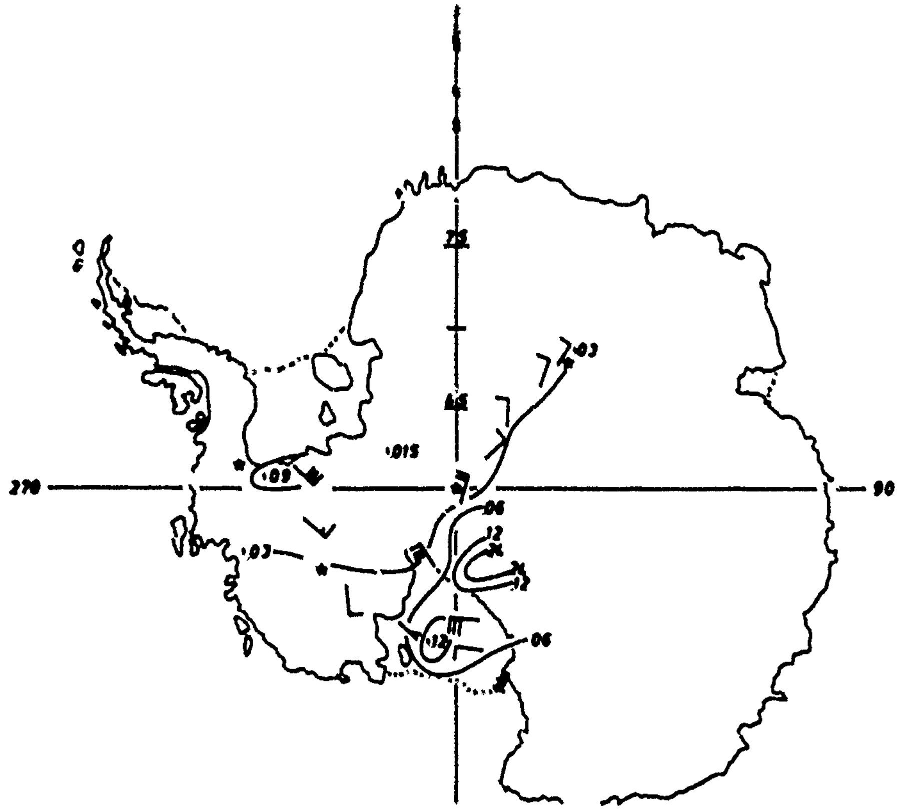

Figure C8. Isopleths of upper tropospheric ozone concentration observed over Antarctica, November 1977 and November 1978. Mountain-induced mixing over the Transantarctic Mountains produces the strongest ozone exchange into the troposphere over Antarctica.

Beardmore South Camp

1. The 6500 ft elevation of Beardmore Camp is high enough above the ice shelf to be characterized by good weather and bypassed by most low pressure systems.

2. Overcast low cloud layers on the Ross Ice Shelf and over Beardmore Glacier are often confined to the base of the Transantarctic Mountains. The same cloud mass over the Plateau becomes either broken or scattered. This information is useful to pilots because Beardmore Camp often can be more easily approached from the Plateau than from the Ross Ice Shelf.

Thumb Rules

a. Beardmore Camp is protected between two mountains with mostly light and variable winds.

b. Restrictions to visibility are rare. Beardmore rarely gets snowfall after November in the summer season.

c. Cloud layers are often 3000 scattered, 8000 scattered and 14000 scattered.

d. Fog developing in the lower valleys to GRID south normally will not move in unless winds are steadily blowing up the glacier. Similarly, a steady downslope wind will cause fog developing on the Plateau to move over Beardmore Camp.

e. A low pressure system along the mountain base will sometimes cause an upslope wind from GRID south.

f. A ridge built into the Ross Sea can steer low pressure systems over the mountains towards the Plateau. This system combined with orographic lifting of the clouds is a cause for snow and fog.

g. Inclement weather moves in rapidly and barometric pressure changes rapidly.

Plateau Station

1 Plateau Station was established in December 1965 and is locat at 79°28'S 40°35'E at an elevation of 11,500 ft. It has not been regularly occupied since 1967. Plateau Station is characterized by good weather with low temperatures, mostly clear skies and rare occasions of poor visibility below 1/4 mi.

2. Prevailing winds are GRID northwest to northeast. These winds are primarily katabatic and make up 75% of the observations. Wind speeds average between 6-9 kt. Minimum surface temperatures are above -54°C between mid-November to mid-February. Average temperatures and temperature ranges are given below.

Figure C9. Page from McMurdo forecast guide giving insight relative to Beardmore area.

A facsimile catalog card in Library of Congress MARC format is reproduced below.

Mellor, Malcolm

Airfields on Antarctic glacier ice / by Malcolm Mellor and Charles Swithinbank. Hanover, N.H.: U.S. Army Cold Regions Research and Engineering Laboratory; Springfield, Va.: available from National Technical Information Service, 1989.

v, 105 p., illus., 28 cm. (CRREL Report 89-21.)

Bibliography: p. 69.

1. Airfields. 2. Antarctica. 3. Blue ice. 4. Cold regions. 5. Ice. 6. Ice runways. 7. Land ice. 8. Polar cap. 9. Polar regions. 10. Runways. I. Swithinbank, Charles. II. United States Army. III. Corps of Engineers. IV. Cold Regions Research and Engineering Laboratory. VI. Series: CRREL Report 89-21.