Disruption of Sand-Wedge Polygons at McMurdo Station, Antarctica: An Indication of Physical Disturbance

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ABSTRACT

Sand-wedge polygons are a ubiquitous periglacial feature throughout the ice-free lowlands of McMurdo Sound, Antarctica. These features were once extensive in the ice-free areas on the southern tip of the Hut Point Peninsula on Ross Island. However, operations of McMurdo Station, which have supported scientific activities across the Antarctic continent since the late 1950s, have disturbed much of the local area. This physical disturbance has significantly reduced the extent of sand-wedge polygons in the area surrounding the station. With the exception of an area covering approximately 0.5 km^2 on Arrival Heights, a smaller area of 0.15 km^2 near Cape Armitage and other small scattered remnants, most sand-wedge polygons in the area have been disturbed during nearly 50 years of continuous human occupation. The disturbance of sand-wedge polygons was most extensive during the first 10 years of the station's history. Mapping the presence or absence of sand-wedge polygons at McMurdo through time is one means, although imperfect, of documenting changes in the station's "footprint" of physical disturbance through time. Monitoring future changes in their extent can aid in assessment of whether the spatial extent of physical disturbance at McMurdo continues to grow.

Keywords: Antarctica, periglacial, remote sensing, environment

INTRODUCTION

McMurdo Station, Antarctica, is the logistical hub of the United States Antarctic Program (USAP). Along with New Zealand's Scott Base it occupies a portion of the ice-free southern tip of the Hut Point Peninsula on Ross Island (Figure 1). McMurdo Station was established during the 1955–1956 austral summer in preparation for the 1957–1958 International Geophysical Year (IGY). Over its nearly 50-year history, human activities at McMurdo Station have considerably modified much of the ice-free area near the stations.

While permanent and continuous human occupation of the area did not begin until 1956, human occupation at the site is older, beginning in 1902 with the arrival of Robert Falcon Scott's Discovery Expedition. Scott selected Winter Quarter's Bay as the overwintering locale for the Discovery Expedition. In February 1902, the expedition constructed the area's first structure: the historic Discovery Hut on Hut Point. This hut served the subsequent British Antarctic expeditions

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of both Scott and Earnest Shackleton during the early part of the 20th century (Neider, 1974). As a base of operations for British Antarctic exploration, the local geomorphology and geology of the Hut Point Peninsula has been described in detail (e.g., Ferrar, 1969; Scott, 1969; Taylor, 1922). These early observations paint a picture of what the undisturbed conditions of the immediate vicinity of the station were like.

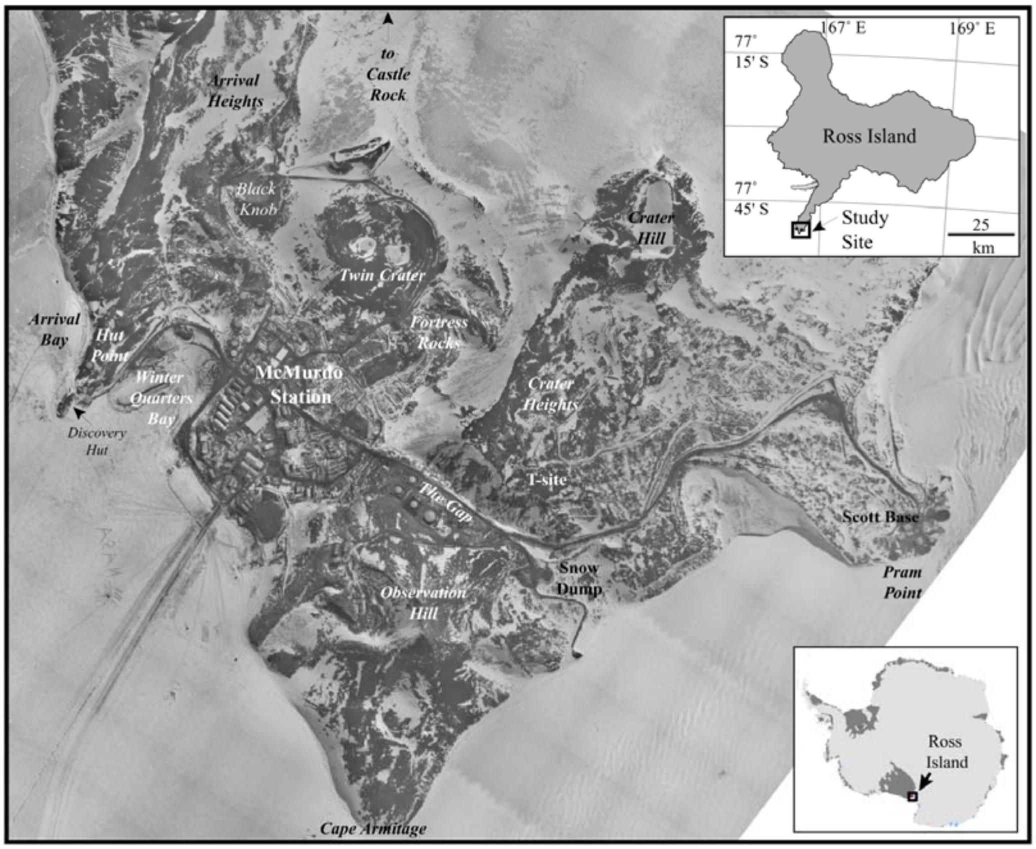

Figure 1. Location map of the southern tip of the Hut Point Peninsula.
Also shown are inset maps of Ross Island and Antarctica.

Much of the surface in the area now occupied by McMurdo Station was originally covered by sand-wedge polygons, which are ubiquitous periglacial features across the ice-free lowlands of McMurdo Sound. An example of these features is illustrated in Figure 2. Since the construction of McMurdo Station, significant physical disturbance of the local area has occurred. The surface has been impacted by a variety of activities, including preparation of building sites, road construction, and cargo and fuel storage. However, the most spatially extensive activity causing physical disturbance of the surface has been surface scraping to obtain fill material. In this process, a bulldozer is used to scrap the uppermost surface layer (Figure 3), which is then transported to other areas for use. Scraping has occurred even on fairly steep slopes with the material being pushed downhill, as is evident in Figure 3A. Unfortunately, these activities have resulted in the disturbance or disruption of many sand-wedge polygons. Areas impacted by this activity can sometimes be identified by the “windrows” that are left behind (Figure 3B). Figure 2 illustrates an example of how extensive the disruption of these periglacial features has been.

Human conduct in Antarctica is governed by the Antarctic Treaty (402 UNTS. 71), which went into effect on June 23, 1961. Three Antarctic Treaty conventions relating to protection of Antarctica’s environment have subsequently been adopted. A fourth, the Protocol on

Environmental Protection to the Antarctic Treaty (XI ATSCM/2), was adopted in October 1991 and went into force in 1998. This Protocol requires that activities in Antarctica be planned and conducted so as to limit adverse environmental impacts. Article 3 of the Protocol requires an environmental impact assessment prior to undertaking planned activities and environmental monitoring of ongoing and future activities. Antarctic Treaty documents are available online at (http://www.polarlaw.org/Treaty.htm).

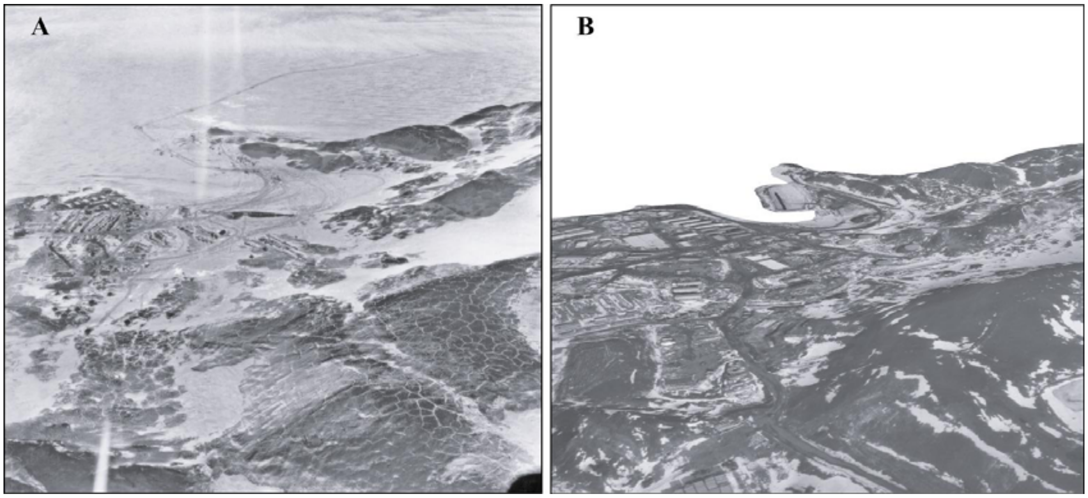

Figure 2. (A) An oblique trimetrogon aerial photograph of McMurdo Station taken in February 1956. Note the large areas of sand-wedge polygons as well as first structures in McMurdo Station. (B) A computer-generated perspective view of McMurdo using an aerial photograph taken on November 22, 1993. Note the disruption of sand-wedge polygons in the foreground between the two photographs

The disturbance of sand-wedge polygons, which can be identified in aerial photographs, provides one means of tracking temporal changes in the extent of physical disturbance associated with station activities. By mapping the extent of sand-wedge polygons through time, the historical reduction in their extent can be mapped. Monitoring of future changes in the extent of sand-wedge polygons can aid in assessing whether McMurdo's footprint of physical disturbance continues to grow or has stabilized.

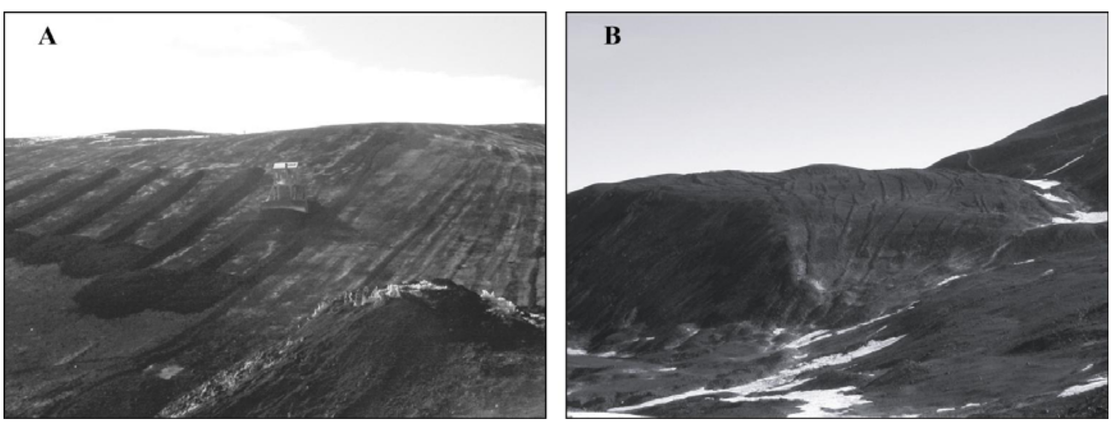

Figure 3. (A) Bulldozing of the slopes below Twin Craters to obtain fill.
(B) "Windrows" left by prior scraping activities on the slopes above Hut Point.

SAND-WEDGE POLYGONS

The Hut Point Peninsula extends approximately 25 km from the southern side of Ross Island (Figure 1), which is a volcanic island located in the eastern Ross Sea named after its discoverer, James Clark Ross. On the Hut Point Peninsula's southern tip is an ice-free area that now contains McMurdo Station and Scott Base. A Quickbird Satellite image acquired on November 20, 2001, shows that the snow and ice-free areas around the stations cover an area of approximately 4.0 km^2. The bedrock in this ice-free-area is entirely volcanic. With the single exception of a flow banded trachyte at Observation Hill, all rocks in the local McMurdo area are basaltic (Cole et al., 1971; Ferrar, 1969).

The ice-free areas of the Hut Point Peninsula were, as many other ice-free lowlands in the McMurdo Sound region remain, covered by a ubiquitous periglacial feature: a microrelief pattern of polygons. These periglacial features were first described in detail by Taylor (1922) who referred to them as "tessellations." He described them as generally being 3.5 to 9 m (12–30 feet) across, most typically in the form of pentagons or hexagons. He noted that an area near "the Gap" (Figure 1) contained one of the most typical areas of these features and that they were also present on Crater Heights. Petty Officer Edgar Evans, who later accompanied Robert Scott on his ill-fated trip to the South Pole, made the first excavation of these periglacial features in the Taylor Valley. His excavation revealed that the subsurface below the "gutters" between the tessellations was free of stones and partially filled with finer debris (Taylor, 1922).

These features were subsequently studied and described in more detail by Péwé (1959) who proposed the term "sand-wedge polygon" to describe them. These polygons are typically 6 to 12 m (20 to 40 feet) in diameter and separated by a set of interlocking polygonal trenches 8 to 45 cm (3 to 18 inches deep) (Péwé, 1959). These polygons were found to form on all types of surfical materials including ablation moraine above stagnant ice as well as in stagnant glacial ice itself. Sand-wedge polygons were found to form on a wide range of slopes. Most polygons have upturned edges and are separated by furrows ranging in width from 0.1 to 1.8 m (4 in. to 6 feet). As Evan's original excavation revealed, a wedge-shaped mass of ice-cemented fine- to medium-grained sand underlies the furrows and extends to depths of 0.3–3 m (1–10 feet) (Péwé, 1959). The 1956 oblique aerial photograph that Péwé (1959) used to illustrate these features is shown in Figure 2A.

Originally, much of the surface around McMurdo, and of the surface of the sand-wedge polygons, was covered with a deflation lag. Its presence around Winter Quarters Bay was noted by H.T. Ferrar, who stated that "Around Winter Quarters the bare land surfaces were usually covered by a loose cloak of rock debris quite 6 inches thick." The presence of a thin basaltic rock debris was also noted by Taylor (1922), who commented that the rock fragments at the surface were angular and smaller than a foot in diameter with a great deal of the material being in the form of fine rock gravel. Taylor (1922) also observed that the rock debris layer extended a small distance up both Crater Heights and Observation Hill. Field observations and permafrost measurements across McMurdo Station, made during the 1999–2001 pilot phase of a long-term environmental monitoring program, indicate that in many areas this thin debris layer has been largely removed.

Much of the surficial gravel material in and around McMurdo station has been thinned or removed by scraping of the surface. This activity has resulted in the removal of the deflation lag and in the disturbance of the sand-wedge polygons. Mapping changes in the extent of sand-wedge polygons can help document the observed increase in extent of physical disturbance that has occurred over McMurdo Station's nearly 50-year history.

METHODOLOGY

Creation of Image Mosaics

Because McMurdo Station is the logistical hub of USAP Antarctic operations, an extensive archive of aerial photography for the station exists. The aerial photography used in this study is held by the United States Geological Survey (USGS). From its beginnings in 1946 until 1975, Antarctic aerial photography was collected using the trimetrogon method in which a horizon-to-horizon view was acquired from one vertical and two oblique (left and right) looking cameras. After 1975, most acquisitions dropped the oblique views; however, photographs in the collection continue to be referenced by their TMA (Trimetrogon Aerial photography) number (http://edc.usgs.gov/glis/hyper/guide/scar).

The aerial photography for McMurdo begins in February 1956, shortly after the station's inception (Figure 2A) and continues until present. The most recent photographs used in this study were acquired in 2000. A preliminary high-resolution satellite image from 2001 was obtained by the Quickbird Satellite over the station as well. However, this acquisition was during the statellite's commissioning phase and the publicly released images were not of sufficient quality to identify sand-wedge polygons. In the future, satellite imagery should be of suitable resolution to augment aerial photographs in monitoring future change in the extent of patterned ground near McMurdo.

All aerial photographs suitable to map disturbance at McMurdo were identified and digitized on a standard flatbed scanner at a resolution of 600 dots per inch (dpi). Depending on the scale of the original photographs, this scanning resolution resulted in pixel ground resolutions ranging from less than a meter to several meters. For days when multiple photographs were acquired over the study area, along-track mosaics were created through simple visual alignment of the digitized photographs. Individual photographs or image mosaics were then georeferenced to an ortho-photograph image mosaic created by the International Centre for Antarctic Information and Research (ICAIR) from aerial photographs taken on November 22, 1993.

Because of problems in locating ground control points in areas outside of the station, a conservative approach to gerectification was taken. Individual images or image mosaics were georegistered using a first- or second-order polynomial warp to enable inclusion of areas outside those where ground-control points could be identified. This geolocation technique resulted in a set of georegistered images where features in the center of McMurdo were correctly registered to within a few meters. Location errors in outlying regions may be higher. However, for the purposes of this study, the georectification results are adequate. The georegistered images used in the study are listed in Table 1, which also highlights those most useful for identifying patterned ground.

Mapping of sand-edge polygons

Once all images were georeferenced, the spatial extent of sand-wedge polygons throughout McMurdo Station's history was mapped within a Geographic Information System (GIS) using the georeferenced aerial photographs as a mapping base in the following manner. A hexagonal grid covering the study area was created. The grid's individual hexagons had diameters, as measured from the center to each edge, of 12.5 m and areas of 541 m^2.

All georectified photographs were examined in reverse sequential order (e.g., the most recent image was studied first). The acquisition date of the most recent aerial photograph showing evidence of sand-wedge polygons existing within an individual hexagon was then added as attribute information to that hexagon. In cases where ambiguity as to whether or not sand-wedge polygons existed, the original photographic prints were examined under magnification. Examination of all images yielded a map illustrating the date of last observation of sand-wedge polygons (Figure 4). As disturbance associated with the McMurdo Station was of primary interest, disruption of periglacial patterned ground in areas immediately adjacent to Scott Base was not considered.

In addition to mapping the date of last identification of sand-wedge polygons, a more generalized disturbance map was created in a manner somewhat analogous to that used to map the extent of sand-wedge polygons. In mapping disturbance, the acquisition date of the first aerial photograph showing tangible evidence of human disturbance was identified and recorded for a grid of 50-m-diameter hexagons covering McMurdo Station.

The mapping does have several limitations. Considerable variability exists in how distinct, and thus how identifiable, sand-wedge polygons are in the individual aerial photographs. While sand-wedge polygons were most easily identified on large-scale photographs, map scale is not the only factor affecting their identification. Sand-wedge polygons are most evident at times where snow fills the interlocking trenches but is absent on the polygon surface. Taylor (1922) noted that when this infilling occurred, the resemblance of the polygons to a Roman mosaic was striking. Thus, sand-wedge polygons are much easier to identify in aerial photographs taken when this infilling of the trenches by snow occurs. In particular, lack of snow in images acquired during the 1990s and in more recent years made it difficulty to identify the polygons, although these photographs are large scale and of high quality.

Table 1. Aerial photographs and satellite images used in the study

Date	TMA	Altitude	Orientation	Source	Patterned Ground
2/1/1956	467/457	Unknown	Oblique	USGS	
11/14/1959	549	6,000	Vertical	USGS	
11/14/1959	554	16,000	Vertical	USGS	
2/15/1960	590	1,300	Vertical	USGS	√
1/27/1962	950	2,800	Vertical	USGS	√
11/9/1962	1095/1097	5,000	Vertical	USGS	
12/31/1962	1124/1130	5,000	Vertical	USGS	
11/2/1963	1208	15,000	Vertical	USGS	
11/4/1963	1219?	15,000	Vertical	USGS	
11/10/1964	1454	5,000	Vertical	USGS	
1/22/1965	1592/1593/1594	2,800	Vertical	USGS	
1/26/1965	1565/1567/1568	2,800	Vertical	USGS	
2/18/1965	1615	2,800	Vertical	USGS	
2/18/1965	1648	15,000	Oblique	USGS	
10/27/1965	1703	9,700	Oblique	USGS	
1/19/1967	1842	12,000	Oblique	USGS	
11/20/1967	2044	32,000	Vertical	USGS	
11/28/1969	2225	9,000	Vertical	USGS	
1/25/1970	2256	2,500	Vertical	USGS	
1/21/1971	2306	5,000	Vertical	USGS	
1/27/1974	2371/2428/2429/2430/2431/2432	2,500	Vertical	USGS	
2/5/1975	2330/2331/2332/2333	3,200	Vertical	USGS	√
2/9/1980	2458	4,500	Vertical	USGS	√
1/22/1983	2491	4,500	Vertical	USGS	√
12/9/1983	2373	2,000	Vertical	USGS	
12/9/1983	2573	3,200	Vertical	USGS	
12/15/1983	2690	26,000	Vertical	USGS	
12/28/1983	2691	4,500	Vertical	USGS	√
11/12/1984	2821	15,900	Vertical	USGS	
1/16/1985	2772	4,300	Vertical	USGS	√
11/6/1989	2865	5,000	Vertical	USGS	√
1/11/1989	2980	15,000	Vertical	USGS	
11/22/1993		2,500	Vertical	ICAIR	√
11/22/1993		10,000	Vertical	ICAIR	
11/23/1993	3101	3,000	Vertical	USGS	
2/2/1999	3199	3,000	Vertical	USGS	√
1/1/2000			Vertical	USGS	√
11/20/2001		Satellite	Vertical	DIGITAL GLOBE	

A more subtle limitation to the developed history is that the extent of photographic coverage varies from year to year. While sand-wedge polygons may have existed in a certain year, and could have been identified, or even were identified over part of the study site, they potentially could have been missed in some areas simply because of the extent of available photographs.

No large-scale vertical photographs of the station were taken prior to February 15, 1960. Unfortunately this makes it impossible to map the extent of sand-wedge polygons prior to the station's inception or during the earliest four years of its history. However, oblique aerial photographs taken in February 1956 and terrestrial photographs taken during the British Antarctic (Terra Nova) Expedition of 1910–1913 (Taylor, 1922) indicate that sand-wedge polygons were extensive in areas of McMurdo that were disturbed before 1960.

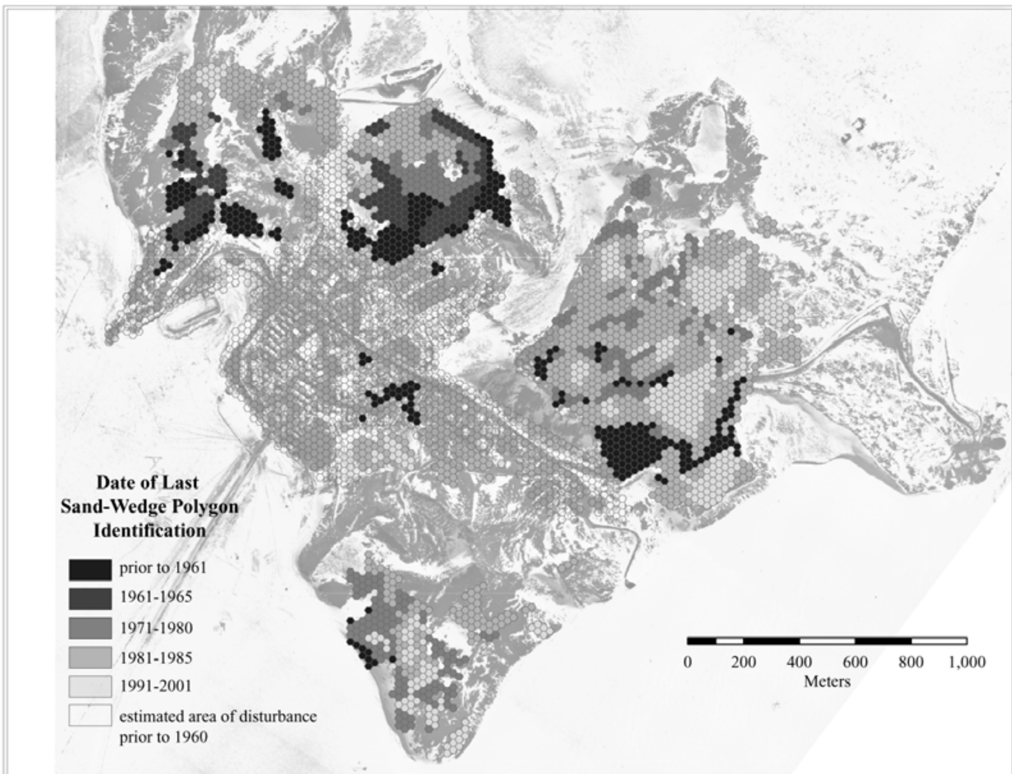

Figure 4. Last date in which sand-wedge polygons can be identified within individual hexagons. Unfilled hexagons indicate areas that may have contained sand-wedge polygons disrupted prior to February 1960. Grayscale in the remaining polygons indicates date of last identification.

To help offset this limitation, an estimate of maximum extent of sand-wedge polygons that may have existed prior to human disturbance was determined as follows. From the map of generalized physical disturbance occurring at the station, all 50-m-diameter hexagons showing evidence of disturbance on or before February 15, 1960, were identified. The hexagons in the sand-wedge polygon map intersecting these disturbed hexagons were then selected. In a small number of these selected polygons it was obvious that sand-wedge polygons could never have existed, either because the surface was ice-covered or slopes within the hexagon were near vertical. These hexagons were discarded. The remaining hexagons cover an area of approximately 828,000 m^2 and represent the maximum extent of sand-wedge polygons that could possibly have been disrupted by station activities prior to 1960.

In calculating the total area covered by sand-wedge polygons, the area of sand-wedge polygons mapped near Cape Armitage (Figure 4) required special treatment. Compared to other portions of the study area, access to this area is difficult. Interpretation of all aerial photographs and field observations indicate that very little human disturbance of the area has occurred. Observed changes in the area covered by sand-wedge polygons is probably not due to their disruption, but primarily due to variable snow conditions and snow extent and lack of photographic coverage for the area after 1993.

As there is no reason to believe these sand-wedge polygons have been disrupted in more recent years, the calculated sand-wedge polygons area for all dates includes the total area of sand-wedge polygons observed on Cape Armitage (Figure 5). Despite these limitations, a spatially and temporally consistent map of the disruption of sand-wedge polygons in the area surrounding McMurdo Station emerges.

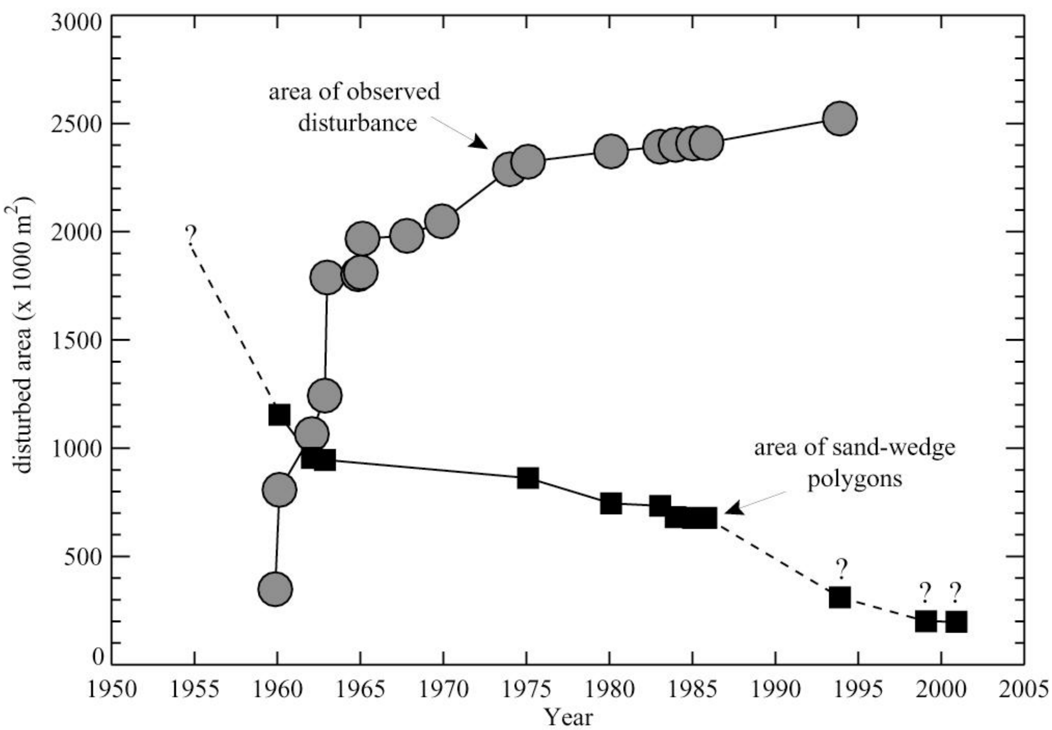

Figure 5. Extent of sand-wedge polygons (black squares) and disturbed areas (gray circles) in the study area through time.

Measuring the depth to a frozen layer

Measuring the depth to a frozen layer, or in some cases bedrock, offers an independent assessment as to the presence or absence of a deflation lag at McMurdo today. As part of a 3-year terrestrial environmental sampling program, the depth at which frozen ground or bedrock was encountered was measured at over 1000 locations in and around McMurdo. At each site, a meter-long stainless-steel permafrost probe was forcefully inserted into the subsurface to the maximum depth possible. This penetration depth was then measured at 3 points in a 1-m^2 area and their average calculated. While this penetration depth is influenced by soil temperature, and can be expected to increase during the austral summer, it does provide a measure of the depth of the active permafrost layer at McMurdo. Similar measurements were also made at four undisturbed control sites in the McMurdo Sound region: Bratina Island, Cape Evans, Cape Bird, and Marble Point. Because Marble Point's lithology differed greatly from that at McMurdo, only measurements from the remaining three control sites are considered here. All measurements at McMurdo Station and the control sites were made during the same time period.

RESULTS AND DISCUSSION

The impetus for this research originated while searching the SCAR aerial photography collection housed at the U.S. Antarctic Resource Center (USARC) in the U.S. Geological Survey (USGS), Reston, Virginia. The recognition that disruption of sand-wedge polygons could help track the expansion of physical disturbance associated with the growth of McMurdo station came from examination of a trimetragon aerial photograph of the station taken in February 1956, only a few months after the station's inception. Extensive sand-wedge polygons were clearly visible where recent photographs and extensive fieldwork indicate none presently exist. Later it was discovered that the photograph that inspired this research was selected by Péwé (1959) to illustrate the sand-wedge polygons found in the McMurdo Sound region. Figure 2 compares this photograph to a computer generated 3-D perspective view of the station created from a digital elevation model (DEM) and a 1993 aerial photograph. The disruption of sand-wedge polygons used by Péwé (1959) to illustrate these ubiquitous McMurdo Sound periglacial features is clearly evidenced.

While certainly not all areas surrounding McMurdo Station, especially rocky steep slopes, were covered with sand-wedge polygons prior to station construction, this early oblique photograph indicates they were extensive. Terrestrial photography taken during the Terra Nova Expedition also shows extensive sand-wedge polygons in the area now occupied by the McMurdo Station (Taylor, 1922). These photographs contrast strongly with the small area of sand-wedge polygons visible today.

The pervasiveness of physical disturbance in the areas adjacent to McMurdo Station is illustrated by the small extent of patterned ground that can be recognized in recent aerial photographs. Figure 6 illustrates the extent of sand-wedge polygons visible in the 1993 ICAIR orthophotograph mosaic. On the slopes facing the station proper only one small remnant (approx. 3,700 m^2) of patterned ground remained below the buildings on Observation Hill in 1993. Two smaller areas (under 700 m^2) still existed in 1993 on and below Twin Craters. More extensive areas of sand-wedge polygons can be observed at the T-site and near Cape Armitage in 1993.

By far the most extensive area of sand-wedge polygons in 1993 was a 0.5-km^2 area of sand-wedge polygons in the ice-free areas on Arrival Heights north of McMurdo Station. Under the Protocol on Environmental Protection to the Antarctic Treaty, this area has been designated an Antarctic Specially Protected Area (ASPA No. 122) (http://www.era.gs/resources/apa/introduction/index.html). Under previous Antarctic conservation agreements, this area was designated as a Site of Special Scientific Interest (SSSI No. 2). The reason for this special conservation status is that this area has been designated as an electromagnetically quiet zone where sensitive instruments for upper atmospheric studies can be installed. As an Antarctic Specially Protected Area, permits are required for entry and movement of vehicles and people in the area is limited. Although some roads have been constructed in the area, the special conservation status of this area has provided some degree of protection from physical disturbance, which has been much more limited than in ice-free areas found closer to the station.

Figure 4 shows the date of last identified occurrence of sand-wedge polygons in the area immediately adjacent to McMurdo Station while Figure 5 illustrates the reduction in their area through time. Distinct temporal and spatial patterns in the disruption of sand-wedge polygons at McMurdo are evident. Not surprisingly, an increase in the physically disturbed area through time is accompanied by a concomitant decrease in the area covered by sand-wedge polygons. Indeed, a major indication of human disturbance was disruption of sand-wedge polygons.

There appear to be three major phases of disruption of sand-wedge polygons at McMurdo captured in the aerial photography derived history. The period from the station's inception to 1962 saw a dramatic reduction in the extent of sand-wedge polygons at McMurdo with a concurrent increase in disturbed area (Figure 5). The area of sand-wedge polygons at McMurdo rapidly decreased from a maximum estimated area of approximately 2 km^2 prior to McMurdo's establishment to 0.95 km^2 in 1962. As can be seen in Figure 5, prior to 1961, this disruption occurred primarily at the lower altitudes of central McMurdo and in "the Gap," where most of the early, and current, station activities are concentrated. By 1961 disruption had already occurred on portion of the slopes below Twin Craters as well as on portions of Hut Point.

From 1962 and continuing through the mid 1980s, the extent of snow-wedge polygons continued to decrease, but at a much reduced rate. The area of sand-wedge polygons decreased to 0.68 km^2 in 1985. By the end of the 1960s, all but the highest slopes above Hut Point had been scraped, as had large portions of Twin Craters nearest the station. Unfortunately, only one acquisition of aerial photographs, but one of high quality, exists from the mid-1970s. During the 1970s the Twin Craters area continued to be impacted by scraping activities; more scattered disturbance continued to occur on Crater Heights. By 1985 most of the Twin Crater area had been scraped. Scraping activities also continued to move higher on the slopes above Hut Point towards Arrival Heights. By the end of the 1980s few areas of sand-wedge polygons remained in the western half of the study area.

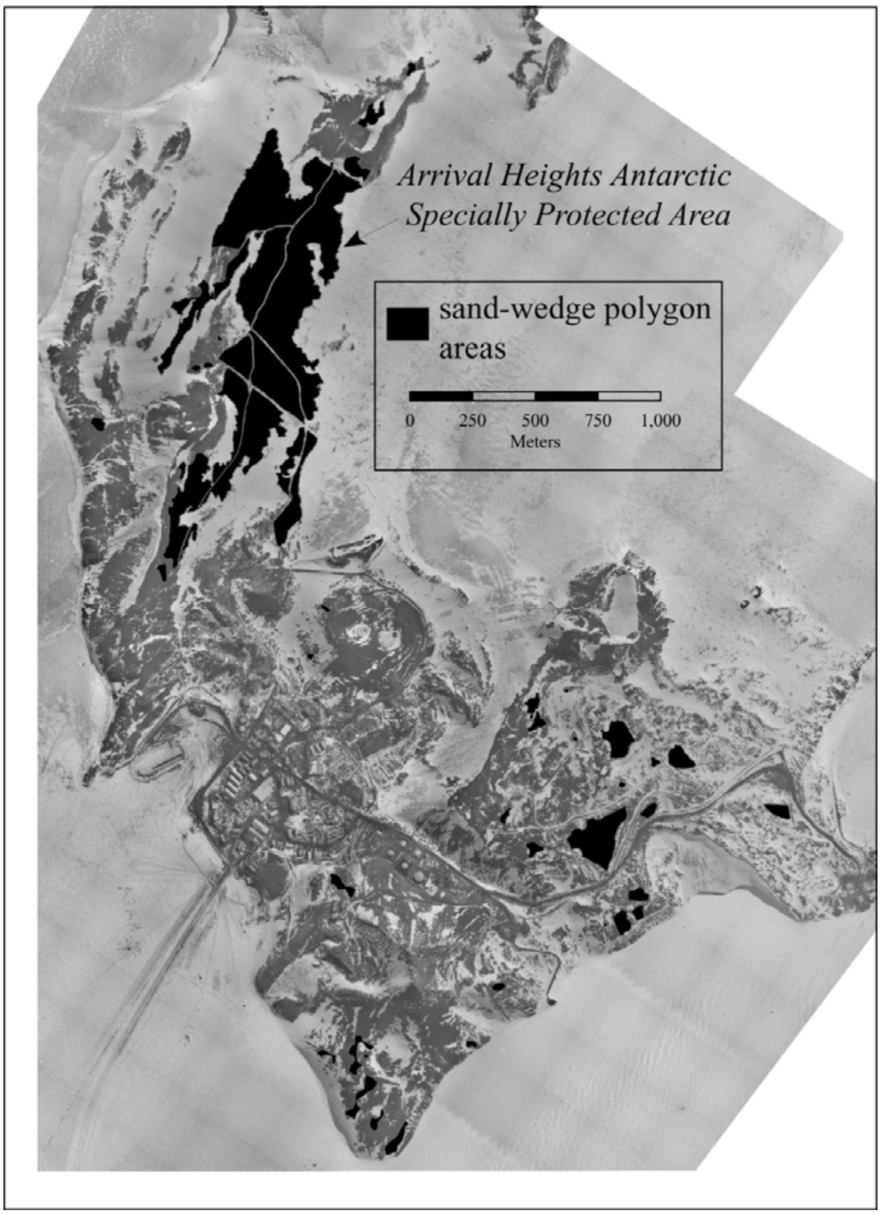

Figure 6. Areas of sand-wedge polygons existing on November 22, 1993.

The area of remaining sand-wedge polygons appears to have been halved in the period from 1985 to 1993. Part of this reduction may be caused by the lower quality and limited spatial extent of the available aerial photography after 1993. While snow made sand-wedge polygons relatively easy to map on the aerial photographs from November 6, 1985, they are somewhat harder to identify in subsequent years. Despite this limitation, it is clear that the remaining area of sand-wedge polygons on Twin Craters definitely disappeared from 1985 to 1993, as did small remnants left on the northwestern slopes of Observation Hill. Most of the decrease in the area of sand-wedge polygons between 1985 and 1993 occurred on Crater Heights. Some of this may be due to the difficulty in identifying the polygons in the 1993 image, but disruption of polygons did occur in conjunction with the construction in the area during this period.

It should be noted that the presence of sand-wedge polygons visible in recent aerial photographs does not mean that these areas remain unimpacted. In some areas where sand-wedge polygons were still visible during the 1990s, evidence of surface disturbance was also evident; however, the polygons were not entirely disrupted. Likewise, on the plateau below Crater Hill (T-Site) and a very small patch on Observation Hill, sand-wedge polygons still remain, but field observations shows that disturbance of this area of patterned ground has also occurred.

Like the aerial photography mapping, the depth at which a frozen layer or ground is encountered supports the assertion of extensive disruption of the surface at McMurdo. The difference in depth to a frozen layer at McMurdo and the three control sites is shown in Figure 7, which depicts two normalized histograms of the depth to a frozen layer, one from McMurdo and the other from the three controls sites. The three undisturbed sites tend to have penetration depths of 10 cm or more, while the distribution of penetration depths made at McMurdo is more bimodal, with a large number of measurements of less than 5 cm. Most of the scatter in the controls sites comes from observations made at Cape Bird, while measurements at Cape Evans and Bratina Island are more uniform, with most penetration measurements being between 10 and 20 centimeters (Figure 8). The Bratina Island control site, in particular, contained quite distinct sand-wedge polygons, and of all control sites is probably most representative of the depth of the active layer in areas where sand-wedge polygons are present. Of the 20 depth measurements made at Bratina, only 3 were less than 15 cm, with the remaining 17 clustered between 15 and 22 cm.

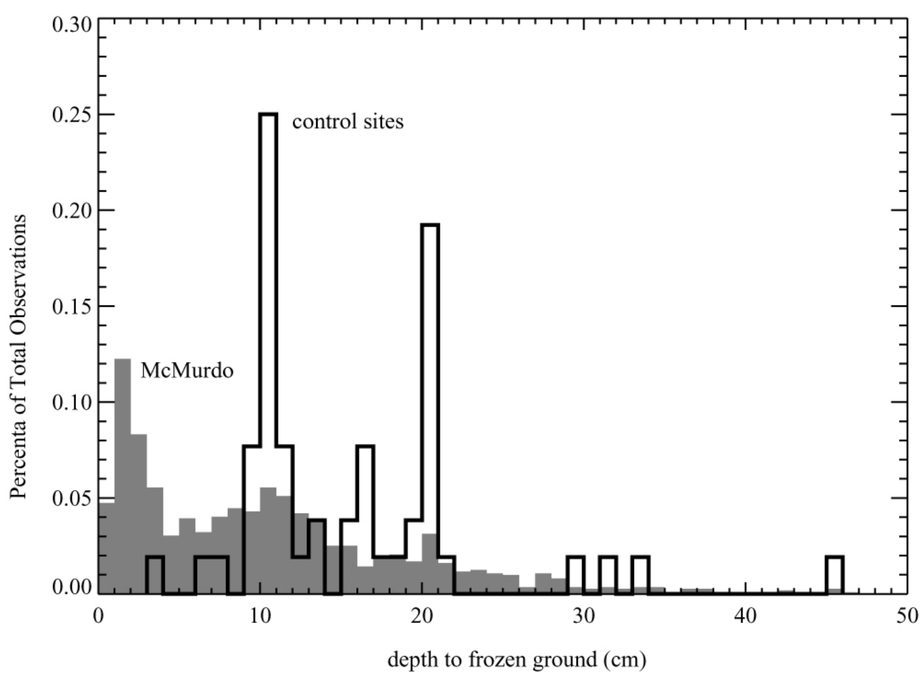

Figure 7. Normalized histograms of measured depth to frozen ground made at McMurdo (filled) and control sites (unfilled) from 1999 to 2002.

Figure 9 illustrates penetration depths greater and less than 15 cm for sites at McMurdo sampled in the austral summers of 1999–2000 and 2001–2002. Over much of McMurdo proper these penetration depths are less than 15 cm. Many areas at the stations with concentrations of permafrost depths in excess of 15 cm are areas that either have been recently remediated (Hut Point), covered (the Landfill to the west of Winter Quarters Bay) or have had fill brought in to level the surface (fuel tanks above Winter Quarters Bay and the Gap). Overall, however, the shallow depth to a frozen layer is an indication that the loose debris cover noted by early British expeditions has been removed in many locations. This is also consistent with the disruption in the "sand-wedge" polygons over much of McMurdo.

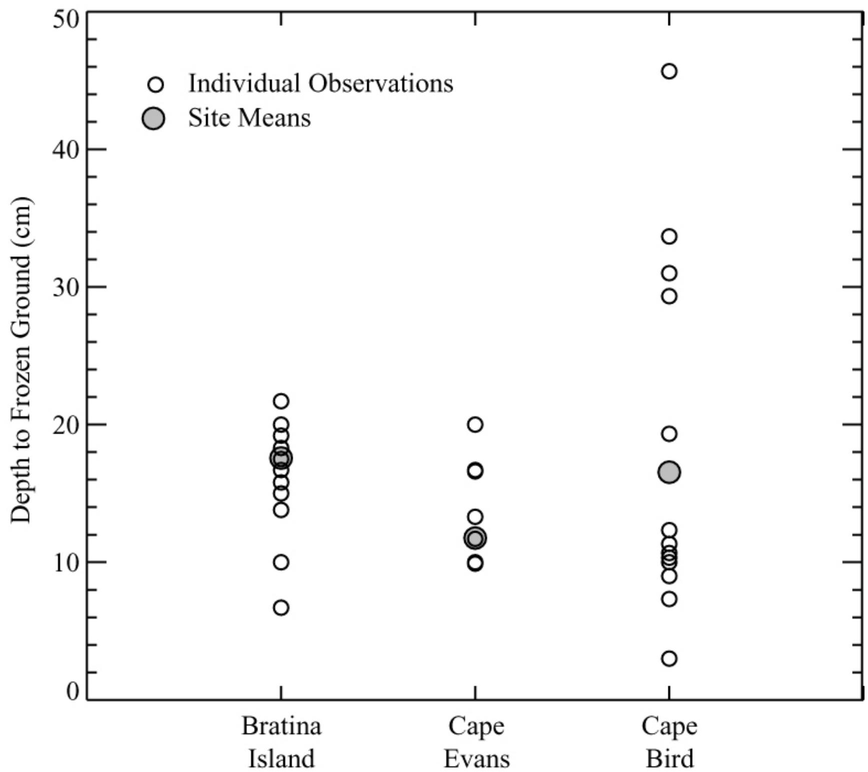

Figure 8. Individual measurements of depth to frozen ground observations and site means for control sites on Bratina Island and at Cape Evans and Cape Bird.

CONCLUSIONS

Sand-wedge polygons, a ubiquitous periglacial feature in the McMurdo Sound region, once covered a significant fraction of the ice-free portion of Hut Point Peninsula's southern tip prior to the construction of the area's two bases. However, human activities at McMurdo Station that began in the 1955–1956 austral summer have resulted in extensive physical disturbance of the surface, which has significantly reduced their extent. This reduction in area has not been uniform over time, but occurred most dramatically early in the station's history. With the exception of an area covering approximately 0.5 km^2 on Arrival Heights, a smaller area of 0.15 km^2 near Cape Armitage, and small scattered remnants, most sand-wedge polygons in the area have been disrupted in nearly 50 years of continuous human occupation. Most, if not all areas, of patterned ground that remain near the station are no longer "pristine," but have experienced some level of disturbance.

Although snow conditions do impact their visibility, the unique character of sand-wedge polygons makes them easy to identify on aerial photographs. Their disruption provides one means of tracking growth in the station's "footprint." Mapping their presence or absence at McMurdo through time has resulted in an important, although imperfect, measure of the stations "footprint" of physical disturbance. Monitoring future change in the extent of sand-wedge polygons can aid in monitoring whether the spatial extent of terrestrial physical disturbance at McMurdo continues to grow.

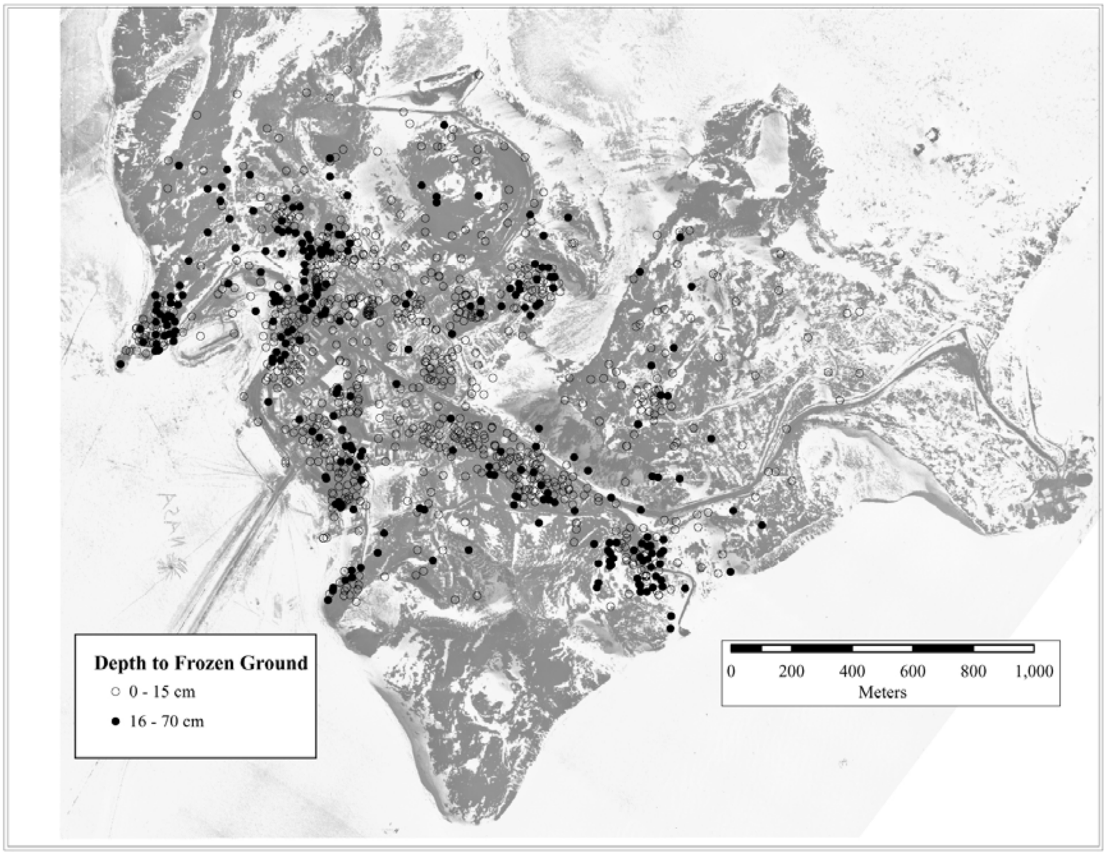

Figure 9. Measured depth to frozen ground at McMurdo Station.

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