I.G.Y. GLACIOLOGICAL WORK AT WILKES STATION, ANTARCTICA

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Abstract. The Wilkes Station area comprises 75 km.² of rock which form one of the most extensive exposures on this part of the East Antarctic coast. During 1957 and 1958 the continental ice sheet south-east of Wilkes Station was explored to a distance of 100 km. inland, and its form and behaviour studied by means of topographic, movement and gravity surveys. Surface stake measurements inland showed a net accumulation equivalent to 13·7 cm. of water in 1958. Sub-surface measurements of wetness, hardness, density, grain size, crystal size, shape and fabric and electrical conductivity were made at 60 locations and to depths which reached 62 m. at an auxiliary inland station. Meteorological observations were made and englacial temperatures measured. In summary, the ice sheet in this area provides a typical section of a polar glacier. The evidence for glacial fluctuations and the possibility of establishing a chronology for these are discussed.

Résumé. La zone de Wilkes Station, d'une superficie de 75 km² de roches, constitue une des plus grandes étendues déglacées de cette partie de la côte de l'Antarctique oriental. Au cours des années 1957 et 1958 l'indlandsis au S.E. de Wilkes Station a été exploré jusqu'à une distance de 100 km vers l'intérieur; sa forme et son comportement ont été étudiés par des mesures topographiques, dynamiques et gravimétriques. La lecture des balises d'accumulation donne une accumulation équivalente à 13,7 cm d'eau en 1958. Des mesures d'humidité, de dureté, de densité, de grosseur de grain, de grandeur, de forme et d'orientation des cristaux et de conductivité électrique ont été faites en 60 stations et jusqu'à 62 m de profondeur à une station auxiliaire de l'intérieur. Des observations météorologiques ont été faites et les températures de la glace mesurées. En résumé, cette partie de l'indlandsis constitue un cas type de glacier polaire. La mise en évidence des fluctuations glaciaires et la possibilité de fixer leur chronologie sont discutés.

Zusammenfassung. Die Wilkes Station umfasst einen Bereich von 75 km² Fels, der eines der ausgedehntesten Vorkommen an diesem Teil der antarktischen Küste darstellt. Während 1957 und 1958 wurde der kontinentale Eisschild auf eine Entfernung von 100 km nach Süden erforscht. Seine Form und sein Verhalten wurde auf Grund von topographischen Aufnahmen, Bewegungs- und Schweremessungen studiert. Messungen mit Stangen ergaben 1958 an der Oberfläche im Inlandeis eine reine Akkumulation von 13,7 cm Wasser. Unter der Oberfläche wurden Wassergehalt, Härte, Dichte, Korn- und Kristallgrösse, Form und Aufbau des Eises sowie seine elektrische Leitfähigkeit gemessen und zwar an 60 Stellen und bis zu Tiefen von 62 m an einer Hilfsstation im Inlandeis. Meteorologische Beobachtungen wurden gemacht und Temperaturen im Eisinneren gemessen. Im ganzen zeigt der Eisschild in diesem Bereich einen typischen Schnitt durch einen Polar-Gletscher. Der Beweis glazialer Fluktuationen und die Möglichkeit für diese eine Chronologie aufzustellen, werden diskutiert.

Introduction

Wilkes Station, on Clark Island (Fig. 1, p. 843), is situated in the northern part of the Windmill Islands group* (Fig. 2). These islands, on the east side of Vincennes Bay, at the western end of the Budd Coast, lat. 66° S., long. 110° E., were discovered and first photographed from the air in 1947. Australian, Russian and American parties visited them in 1956, but no sustained observations were begun in the area until February 1957, when Wilkes Station was established as part of the United States programme for the I.G.Y. This paper summarizes the glaciological work of the wintering over parties of 1957 and 1958. Glaciological data obtained at Wilkes Station in those two years is being compiled and published by the Ohio State University Research Foundation, and reports as they are issued [1, 2, 3] are made available through World Data Center A (Glaciology) at the American Geographical Society, New York 32, N.Y. Further analysis of the original data is expected to proceed for several years and will be published both in official reports and individual papers. Distances, heights and other figures in this paper are provisional, and final figures will be found in the reports mentioned.

The Windmill Islands

The Windmill Islands are the easternmost of three "oases" which are the major rock outcrops on sixty degrees of the East Antarctic coast between Prydz Bay in the west and the

* Place names have been taken from *Geographical names of Antarctica*, 1956 edition, published by the United States Board on Geographical Names.

Adélie Coast in the east. The other two are Bunger Hills (long. 101° E.) and Vestfold Hills (long. 78° E.). These three outcrops have much in common, and have been compared recently by Korotkevich.[4] The Windmill Islands occupy a rectangle roughly 15 × 30 km. and contain about 75 km.[2] of exposed rock. They were mapped geologically by Robertson in 1958, and comprise chiefly migmatites in the north and an intermediate igneous intrusion in the south.[2] Potassium-argon dating gives ages of between 950 million and 1,115 million years for these rocks.[5] Many of the outcrops labelled islands on maps of the area are actually peninsulas,

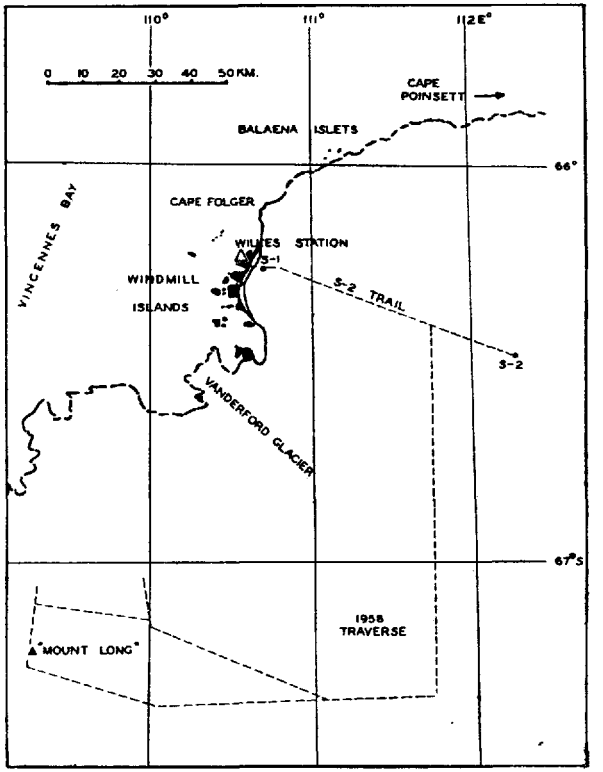

Fig. 2. The Windmill Islands area

abutting directly against the ice sheet and providing easy access to it. Clark Island, on which Wilkes Station lies, is one such peninsula. From Wilkes Station the other peninsulas are easily accessible by vehicle, either via the ice sheet, or over the sea ice, which provided poor travelling to the south in 1957, but good travelling to all the islands from June to December 1958. Sea-ice studies during 1958 have been described by Tressler.[6] The islands are rugged, particularly the southern ones, but their total relief is not great, and the highest summit in the group is only 113 m. above sea-level. This small relief contrasts sharply with the submarine topography offshore, where a 2,000 m. deep trench and other features suggest faulting and deep glacial erosion.

The Ice Sheet

In March 1957, an auxiliary station named "S-2" was established on the ice sheet 80 km. inland from Wilkes Station, at an elevation of 1,166 m. A Jamesway hut was allowed to drift over, and tunnels were excavated from it to various rooms hewn from the firn and to a 35 m.

deep pit (Fig. 3). Work on the ice sheet in 1957 was concentrated at this inland station and on a December journey over the sea ice to Cape Poinsett. The 1958 work included a 600 km. traverse to the south and west of the Windmill Islands, made with two "Weasels" and one "Sno-cat" from September to November. Work on the S-2 trail and on the actual Windmill Islands continued throughout the two years. The S-2 trail and the traverse route are shown in Figure 2. No rock outcrops were found anywhere in the interior.

The form of the ice sheet in this part of Antarctica was determined by surveys carried out by the glaciological parties. Figure 4 is a surveyed profile of the trail from Wilkes Station to S-2. The profile is smoothly parabolic and the 80 km. trail unbroken by crevasses. At the

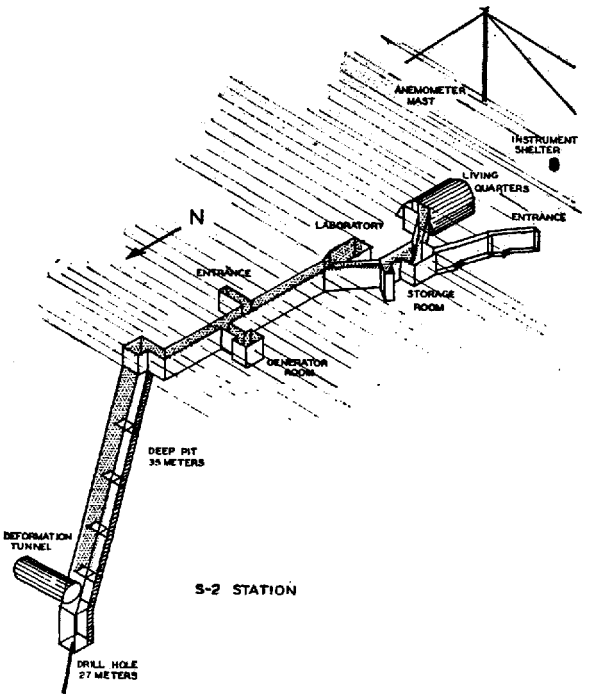

Fig. 3. Diagram of auxiliary station S-2

upper end, at S-2, the surface slope is in no direction more than 40′. A baseline and movement network roughly 20 km.[2] in area were surveyed here in March 1957 and resurveyed in January 1959. Down the trail the surface angle increases and averages a little over 2° in the upper part of the ablation zone, approximately 4 km. inland from the islands and 225 m. above sea level. The main topographic feature of the ablation zone of the ice sheet is a shear moraine a few metres wide and 25 km. long, approximately 120 m. above sea-level (Fig. 1). This moraine is composed of debris brought to the surface by the upward shearing of the ice sheet as it presses against "The Ramp" (see below) and the rock of the Windmill Islands. It provides a particularly fine example of a moraine type recently described from Thule, Greenland, by Bishop [7] and Schytt.[8] Between July and December 1958 the movement relative to rock of the ice immediately inland from the moraine was 69 cm. forward and more than 13 cm. upward. Below the shear moraine, and between it and the actual rock peninsulas, is an ice slope of 5° which averages one kilometre in length. This slope, "The Ramp" (Fig. 1), is composed of glacial ice and superimposed ice less active than that above the shear moraine. Down on the peninsulas the ice cover is no longer continuous, but patches of perennial snow and ice in the lee of rock eminences cover much of the area.

The profile described above is typical only of the ice sheet inland from the peninsulas of the Windmill Islands. Inland and south-south-west of the archipelago, in the area of the 1958 traverse, the ice sheet is much more undulating and often crevassed. In the area of "Mt. Long", a cartographic feature apparently non-existent, the ice sheet forms a series of crevassed domes with a relief of one or two hundred metres. A few kilometres to the north the ice overlooks the west side of Vincennes Bay, and drops to the sea in a slope broken by long parallel crevasses often over 10 m. wide. On the sea coast the forward movement of the ice sheet is much greater than where it abuts against the Windmill Islands. South-west of the islands the Vanderford Glacier,[9] 15 km. wide, moved forward in its centre more than 2 m. per day between March 1957 and November 1958. This ice stream must drain a large part of the area covered by the 1958 traverse. North-east of the islands, the ice sheet is not so well channelled. Ice movement at the tip of Cape Folger averaged only 15 cm. per day between March 1958 and December 1958.[6]

Ice Thickness

The chief geophysical efforts of the United States I.G.Y. programme were concentrated in West Antarctica, and no major traverses were planned from Wilkes Station. However, during his visit to the station in the summer of 1957-58, Mr. J. K. Sparkman of the University of Wisconsin measured the value of gravity at points on rock and on the ice sheet to 64 km. inland. Because in the interior these measurements could not be tied to seismic work or to measurements on a nunatak, the thickness of the ice near its margin has been calculated after extrapolating under the ice sheet the Bouguer anomalies obtained from the measurements on rock outside the ice sheet. In Figure 4 this extrapolation has been made for 9 km. and is probably quite accurate over this short distance.

Over this 9 km. the shear stress τ on the bed of the ice sheet, calculated after Nye [10] as approximately equal to $dgh \sin A$, varies only between 0·6 and 0·7 bars (d being the density of the ice, g the gravitational acceleration, h the thickness of the ice, and A the surface slope). This relatively low value is consistent with the apparently smooth base of the ice sheet, the small movement described above, and possibly high basal temperatures. It should be stressed, however, that the ice was not at the melting point at its margin, and that away from a few deep lakes the rock peninsulas are frozen to an unknown depth. As has been pointed out by various workers, the Antarctic "oases" are not a geothermal phenomenon.

Observations at the Surface

Stake observations of accumulation and ablation were made at 60 points along the S-2 trail. For the period February 1958 to January 1959, assuming a density of 0·4 g./cm.^{3}, the stakes show an average accumulation over the whole trail of 13·7 cm. of water. This figure actually represents the accumulation left after an unknown amount of original precipitation has been lost by subsequent sublimation or has been reworked and blown out to sea by the wind. On the lower part of the ice sheet the winter accumulation is ablated away each summer and a net loss occurs. Ablation at the coast obviously takes place by calving and probably by bottom melting. But where the ice ends on the Windmill peninsulas, and inland to S-2, the chief processes of ablation appear to be melting and evaporation in the summer and sublimation throughout the year. Large losses by sublimation were recorded in the superimposed ice and ablation zones.

Most of the familiar surface features of ice sheets were observed. In the superimposed ice and ablation zones, radiation hollows initiated in snow were gradually metamorphosed in late summer into ice which then took the form of ridges a few centimetres high facing the mid-day sun. These ridges were so ubiquitous and so strictly aligned that they were success-

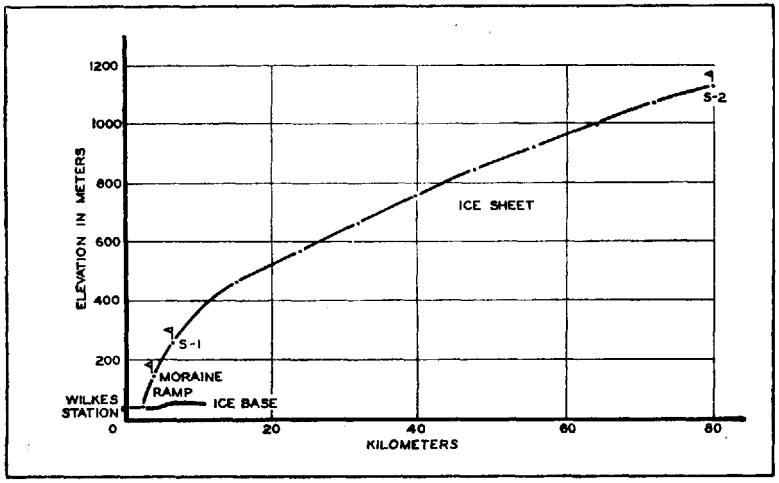

Fig. 4. Profile of the ice sheet between Wilkes Station and S-2

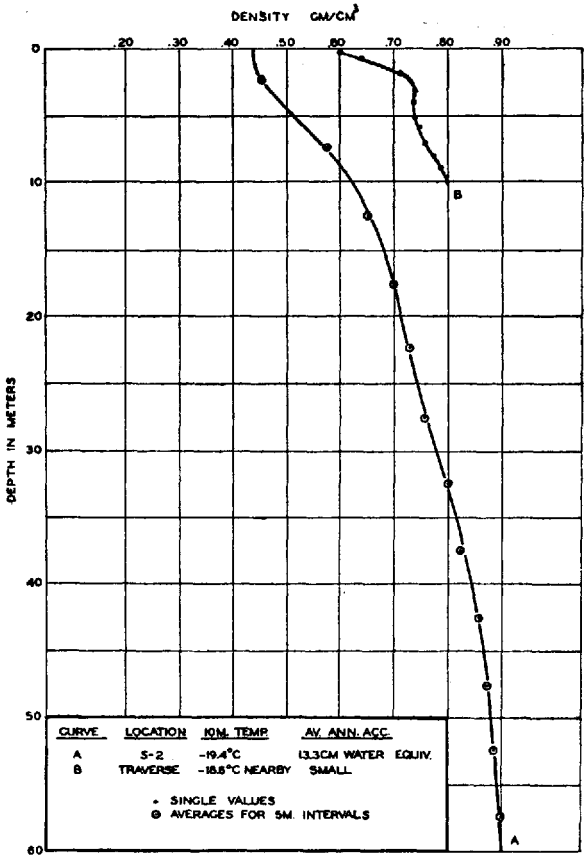

Fig. 5. Firn density curves at S-2 and in windy area of traverse

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fully used as directional guides for night-time "Weasel" journeys involving up to 40 km. of navigation over the lower ice sheet. In the firn zone, and particularly in the area of the 1958 traverse, surface forms could be grouped basically into those constructed by the blizzard winds and those eroded by katabatic winds, as at Mawson.[11] The predominant lineation of the former was 105°, and of the latter 150°. Sastrugi were not well developed in the area of S-2, but in domed and windy regions of the traverse they reached heights of 1 m. Whale-backed firn ridges, formed downwind from crevasse bridges, had a relief up to 10 m., and in poor light were often mistaken for nunataks.

Observations below the Surface

Observations below the surface were made at 60 locations by means of pit and core studies. Pits were normally 1 to 2 m. deep. Cores, 75 mm. in diameter, obtained with a SIPRE auger, were normally taken to a depth of 10 m. The deep pit at S-2 was dug to 35 m., and cores for an additional 27 m. to a total depth of 62 m. were obtained with the auger.[12] In most of these locations studies were made of wetness (summer only), hardness, density, grain size, crystal size and fabric, and electrical conductivity.

Densities recorded included 0·05 g./cm.^{3} (one of the few snowfalls in which crystals or grains were not rounded by wind action), 0·37 g./cm.^{3} (average value for winter snow on the lower ice sheet), and 0·48 g./cm.^{3} (wind-packed new snow in some lee locations). On the inland traverse unusually high densities of 0·6 g./cm.^{3} at the surface and 0·8 g./cm.^{3} at 10 m. were measured in an especially windy area of the dry firn zone.[13] At S-2 the complete transformation from snow (0·43 g./cm.^{3} at the surface) to ice (0·91 g./cm.^{3} at 61 m.) was plotted by means of 544 density determinations. Density profiles from both the windy area and S-2 are shown in Figure 5. Grain diameters in dry firn areas were normally less than 0·5 mm. in the case of new snow, but increased to more than 0·5 mm. after one summer and to the order of 1·0 mm. at a depth of 10 m. Crystal cross-sectional areas ranged from less than 0·1 mm.^{2} in new snow to 3 mm.^{2} at 37 m. in the deep pit, 6 mm.^{2} at 61 m. in the pit, 30 mm.^{2} in the shearing area of the ablation zone (much smaller in the actual shear planes) and 50 mm.^{2} at Cape Folger. Several individual crystals from the superimposed ice and ablation zones exceeded 7 cm. in length. Crystal fabric studies were made at 12 locations. Growth fabrics were generally random, but deformation fabrics included both girdles and isolated maxima. The electrical conductivity of melted samples of ice and snow was measured. The results fit into a definite pattern, in which snow and ice which has obviously originated near the coast and which presumably has a relatively high salt content has a much higher conductivity than that with an interior origin. This phenomenon proved a useful tool in the study of the local glacial history.

These sub-surface observations had various objectives, and in the firn zone the chief of these was the determination of past accumulation. At S-2 this was determined by Cameron chiefly on the basis of density and grain size differences and crust occurrences. One hundred and seventy-four annual layers were traced between the surface and 35 m., so that the firn at that depth must have been deposited in approximately 1783. The average annual accumulation since then equals 13·3 cm. of water. Checks on this value may be provided by pit data from 1958, $^{18}O/^{16}O$ studies, the application of Sorge's law,[14] and the deformation recorded by the relative movement network mentioned earlier. Compaction of the deep pit (roofed over and laddered) is being measured on a wire from the top to the bottom and by pegs inserted in the walls. At the 30 m. level of the pit a horizontal deformation tunnel 2 m. in diameter and 6 m. long was completed in October 1957. The closure of this tunnel and its movement relative to the pit shaft is being measured by pegs at various distances inside and by a deformation grid on the end wall. Up to January 1959 the closure at the tunnel midpoint was 2·9 cm. vertically, 2·2 cm. diagonally and 1·6 cm. horizontally.

Meteorological Observations and Temperatures in the Upper Ice

For future studies of the heat balance on the ice sheet, meteorological observations are available from three stations. At the main base a full meteorological programme which included twice daily upper air soundings was conducted from the beginning of 1957 by aerologists of the U.S. Navy. At S-1 (Fig. 4), 7·5 km. inland from the base and 263 m. above sea-level, a thermograph was operated throughout the two years and wind speed observations were made during December 1958 and January 1959. At S-2 three-hourly observations of temperature, cloud cover, wind speed and direction and snow surface conditions were made continuously from May 1957 to January 1958 and occasionally afterwards. Intermittent radiation measurements were made at both Wilkes Station and S-2.

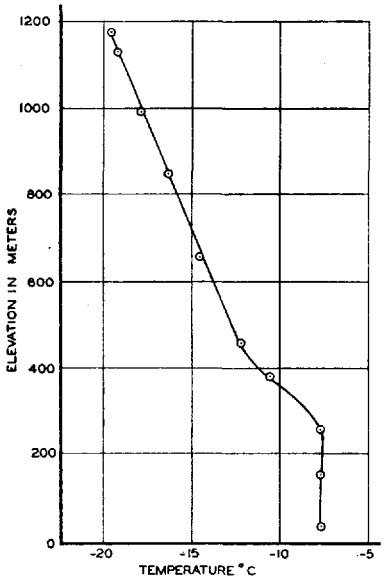

Fig. 6. Altitude vs. temperature at 10 m. depth

Because summer there normally includes one or two months with mean temperatures above 0° C., the base and its immediate area fit into the tundra category of most climatic classifications. At the base the highest temperature recorded was 8° C. in January 1958 and the lowest −38° C. in July 1958. Temperatures were generally lower in 1958 than they were in 1957, and the snowline in the summer of 1958-59 was 350 m. lower than in 1957-58. The mean wind speed at Wilkes, 18 km./hr. between March 1957 and January 1958, was the lowest recorded at any East Antarctic station. However, the generally calm weather of Clark Island was regularly interrupted by storms, and gusts of at least 95 km./hr. were experienced during every month between March 1957 and December 1958. In April 1958 the wind mast was blown down whilst recording a gust of 214 km./hr. During one of these storms rain fell as late in the year as 17 May in 1958. At S-2 the highest temperature recorded was 4° C. in December 1957 and the lowest −48° C. in June 1957. Unlike the base, with its usual calm and occasional high winds, S-2 was normally windy, but never experienced such extreme winds as the base. The mean wind speed at S-2 between March and December 1957 was 40 km./hr. Mean wind speeds in the area of the 1958 traverse are probably even higher than at S-2. On the traverse the average of twice daily wind observations for 61 days was 47 km./hr.

The firn temperatures at a depth of 10 m. (where the range of the annual temperature wave is reduced to less than 1° C.) were obtained whenever cores were taken from the ice sheet. Ten-metre temperatures on the S-2 trail are plotted against altitude in Figure 6.

Above 375 m., in the firn zone, the straight line of the plot probably represents a direct relationship between air temperature and firn temperature. Below 375 m., in the superimposed ice and ablation zones, factors such as melting and differing albedos alter this relationship and, as can be seen from Figure 6, have a net warming effect. At S-1 ice temperatures at depths of $\frac{1}{2}$, 2, 4, 7, 11 and 16 m. were recorded every week for two years.

The Regimen

The sub-surface observations on the trail from S-2 to the main base provide a typical section of a polar glacier and its accumulation and ablation zones.[13] In the firn zone of accumulation, S-2, 1,166 m. above sea-level, is probably slightly below the upper limit of summer melt infiltration on the ice sheet. Down-slope from S-2 ice laminae and layers produced by summer melting increase rapidly in thickness. For example, at 850 m. elevation continuous ice layers observed in pits are frequently 4 cm. thick. Still further downhill, at approximately 375 m. elevation, nearly all of each year's net accumulation is transformed into ice by summer melting and subsequent refreezing; and this elevation represents the upper limit of the superimposed ice zone of accumulation. From this level the superimposed ice zone extends for 5·5 km. down the trail and provides a strikingly smooth and regular surface for travel. Tentative criteria have been established for distinguishing annual layers in this zone. Features of the superimposed ice were groups of extremely thin, hexagonal, plate-like cavities, usually 1 or 2 mm. across, and always parallel to the basal plane of the containing ice crystal. These cavities differ from true vapour figures in that they are filled with gas, but they do appear to be formed by solar radiation. They may, therefore, be of stratigraphic value since they must form primarily near the top of any given layer of superimposed ice. At the lower limit of the superimposed ice zone at approximately 225 m. elevation summer melting and run-off become greater than accumulation, and the ablation zone is entered. At a little below this elevation, shallow melt stream gullies appear.

The ablation zone above is not confined to the area of the Windmill Islands only, but extends along the coast on either side of the archipelago. Strongly preferred bubble and crystal orientations in ice from the Vanderford Glacier and Cape Folger show that net ablation is occurring in those places also. In other words the ablation here is not merely a local warming effect produced by the low albedo of the Windmill Islands. Climatically and glaciologically, therefore, it is misleading to call this area an "oasis". However, the term is certainly accurate in a biological sense and, because it is convenient and expressive, it may survive. It should be stressed that the regimen described here is not common to all of the Antarctic coast in the same latitude, and that in areas such as the West Ice Shelf (long. 85° E.) closely interrelated topographic, meteorological and oceanic factors can bring the accumulation zone down to sea-level.

Glacial Geology

Glacial geological observations included studies of the small amount of fluvial erosion in the area, of lake sediments, and of physical and chemical weathering phenomena. The main feature of this area is the 25 km. long shear moraine previously described. End moraines are rare, and most of the drift has the form of a thin and patchy cover of ground moraine or till. Below a well defined line identified by Løken [1] at approximately 30 m. elevation this cover has been swept away or into hollows by the sea, which must have previously been higher relative to the land. The vegetation of the area has been described by Llano,[15] and the marine life by Tressler.[6]

Historically, little evidence of multiple glacial stages can be expected from such a small and low-lying area. However, a sequence of four events has been traced. (1) The occurrence of striae and erratics everywhere on the islands shows that they have been completely covered

by ice at some time, and the amount of weathering suggests that the ice last retreated across the islands at least several thousand years ago. (2) Subsequently, probably isostatically, the land has been uplifted 30 m. in relation to the sea. (3) Since the uplift the ice may have readvanced. This is suggested by the position of the ice sheet only a few metres away from completely intact raised shoreline sequences (wave-washed rocks from 30 m. down to sea-level) on the Balaena Islets and Lewis Islet (long. 134° E.). (4) Most recently a thinning of perennial snow and ice patches by at least 1·5 m., probably in the last few score years, is shown by a well marked lichen and moss trim-line on Clark Island.

In an attempt to provide a chronology for the events above, various samples are being dated by different means. The period of deglaciation on the islands may be determined by the ^{36}Cl method,[16] despite the complication of contamination by marine chlorine. Specimens collected for ^{14}C dating of post-glacial events include coralline algae, marine shells, penguin bones from long abandoned rookeries, bones from the mummified bodies of elephant seals and whalebones. On the raised beaches search was made for both driftwood and pumice but neither was found. As dates are supplied, and as field work is further extended and correlated, it is hoped that our insight into the history and process of glaciation in Antarctica will develop rapidly.

ACKNOWLEDGEMENTS

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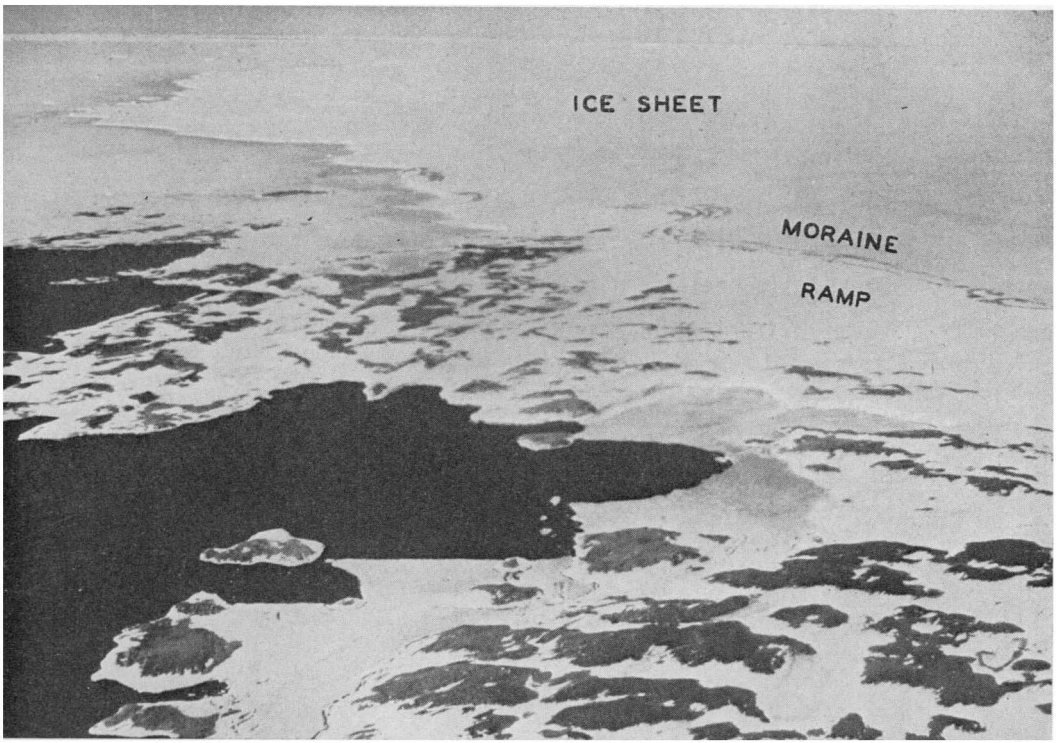

Fig. 1. Aerial view of ice sheet, shear moraine and Ramp east of Clark Island. Clark Island, approximately 5 km. long, is the rock peninsula in the centre of the photograph. Wilkes I.G.Y. Station lies on the western tip of the peninsula, just outside the photograph. Photograph by C. Cronk, February 1959

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