ANTARCTIC INTERGLACIAL FEATURES

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Abstract. The upper 180 ft. (55 m.) of Lake Vanda in Wright Valley, south Victoria Land, is essentially potable, whereas that part below 200 ft. (61 m.) is more than three times as saline as sea-water. The salinity below 200 ft. (61 m.) resulted from the evaporation and freezing, mainly during interglacial (Loop-Trilogy) time, of a larger, less saline body of water.

An alluvial fan in Wright Valley has been dated as interglacial on the basis of (1) ice-marginal channels formed in Loop time that cut across it, and (2) the fjord-like longitudinal cross-section of the valley formed by the ice of the oldest glaciation or glaciations.

Fossils found in till and glacio-fluvial deposits in the McMurdo Sound region, south Victoria Land, date from both early and late Pleistocene interglacial time.

An ocean-bottom core sample obtained in the Ross Sea contained interglacial material. The presence in the sample of glacial marine sediments deposited in interglacial time suggests that the Antarctic Ice Sheet maintained itself throughout the Pleistocene.

Sub-surface efflorescences consisting of a layer of pure salts as much as 3 in. (7·6 cm.) thick are found 2–5 in. (5–13 cm.) below the surface in Loop deposits in Wright Valley. The absence of similar thick occurrences in Trilogy deposits indicates that the efflorescences are, in part at least, interglacial.

Interglacial cinder cones and lava flows are found in the McMurdo Sound area, and some of the widespread scoria present in moraines, glacio-fluvial deposits and beaches dates from interglacial time.

Résumé. *Formes interglaciaires antarctiques*. La couche supérieure de 55 m du Lake Vanda dans la Wright Valley, Terre Victoria du Sud, est essentiellement potable, alors que la partie en-dessous de 61 m est trois fois plus salée que l'eau de mer. La salinité en-dessous de 61 m résulte de l'évaporation et du gel, principalement pendant la période interglaciaire (Loop-Trilogy), d'une masse d'eau plus grande et moins salée.

Un cone de déjection de la Wright Valley a été daté comme interglaciaire parce que 1) des chenaux bordiers de la calotte de glace formés pendant le Loop l'ont coupé transversalement et 2) le profil longitudinal en forme de fjord de la vallée formée par la glace de la plus ancienne glaciation ou des glaciations.

Des fossiles trouvés dans les débris et alluvions de la région de McMurdo Sound, Terre Victoria du Sud, datent à la fois de l'interglaciaire du Pléistocène récent ou ancien.

Une carotte du fond de la mer de la Mer de Ross contenait du matériel interglaciaire. La présence dans cet échantillon de sédiments marins glaciaires déposés pendant l'interglaciaire suggère que l'Indlandsis Antarctique s'est maintenu lui-même pendant tout le Pleistocène.

Des efflorescences superficielles de couches de sel pur jusqu'à 7,6 cm d'épaisseur sont trouvées 5–13 cm sous la surface des Loop dépôts dans la Wright Valley. L'absence de strates d'épaisseur comparable dans les Trilogy dépôts indique que les efflorescences sont en partie tout au moins interglaciaires.

Des cones de cendres et de coulées de lave existent dans la région de McMurdo Sound, et quelques scories à large dispersion trouvées dans les moraines, les dépôts glacio-fluviatils et les plages datent de l'époque interglaciaire.

Zusammenfassung. *Interglaziale Bildungen in der Antarktis*. In den obersten 180 ft. (55 m) des Lake Vanda im Wright Valley, Süd-Viktorialand, ist das Wasser im wesentlichen trinkbar, während sein Salzgehalt im Bereich unterhalb von 200 ft. (61 m) mehr als dreimal so gross ist als der von Meerwasser. Die hohe Salinität unterhalb von 200 ft. (61 m) ist die Folge der Verdunstung und des Gefrierens eines grösseren, weniger salzhaltigen Wasserkörpers, vor allem während der Interglazialzeit (Loop-Trilogy).

Ein alluvialer Schuttfächer im Wright Valley wurde auf Grund folgender Beobachtungen als interglazial datiert: (1) Kanäle, die in der Loop-Ziet am Eisrand entstanden, durchschneiden ihn; (2) das Tal besitzt einen fjordartigen Längsschnitt, der durch das Eis der ältesten Vergletscherung oder Vergletscherungen gebildet wurde.

Fossilien im Tillit und in glazio-fluviatilen Ablagerungen des McMurdo Sound-Gebietes, Süd-Viktorialand, stammen sowohl aus der frühen wie aus der späten Interglazialzeit des Pleistozän.

Ein Bohrkern aus dem Ozeanboden der Ross-See enthielt interglaziales Material. Das Vorkommen glazialer mariner Sedimente, die in der Interglazialzeit abgelagert wurden, lässt annehmen, dass der Antarktische Eisschild sich durch das ganze Pleistozän erhalten hat.

Unterirdische Ausblühungen, bestehend aus einer Schicht reinen Salzes bis zu 3 in. (7,6 cm) Dicke, wurden 2–5 in. (5–13 cm) unter der Oberfläche in Loop-Ablagerungen des Wright Valley gefunden. Das Fehlen ähnlich dicker Vorkommen in Trilogy-Ablagerungen weist darauf hin, dass die Ausblühungen zum mindesten teilweise interglazial sind.

Interglaziale Aschekegel und Lavaergüsse wurden im Gebiet des McMurdo Sound gefunden. Desgleichen stammen einige der weitverbreiteten Schlacken in Moränen, glazio-fluviatilen Ablagerungen und Sandbänken aus der Interglazialzeit.

Introduction

Six different kinds of features that have been dated as interglacial are found in the south Victoria Land–Ross Sea sector of Antarctica. These include saline waters at the bottom of

Lake Vanda, an alluvial fan, fossil pectens, sub-surface efflorescences and volcanic rocks in Wright Valley, south Victoria Land; and some interglacial fossils are found in glacial deposits around McMurdo Sound, south Victoria Land. Ocean-bottom core samples from the Ross Sea contain interglacial sediments.

Wright Valley trends approximately east–west (Fig. 1). Upper Wright Glacier, at the western end of the valley, is an outlet glacier which moves eastward down Wright Valley from the Antarctic Ice Sheet. Lower Wright Glacier, at the eastern end of the valley, is a channel glacier, the western part of which moves westward up Wright Valley. The 30 miles

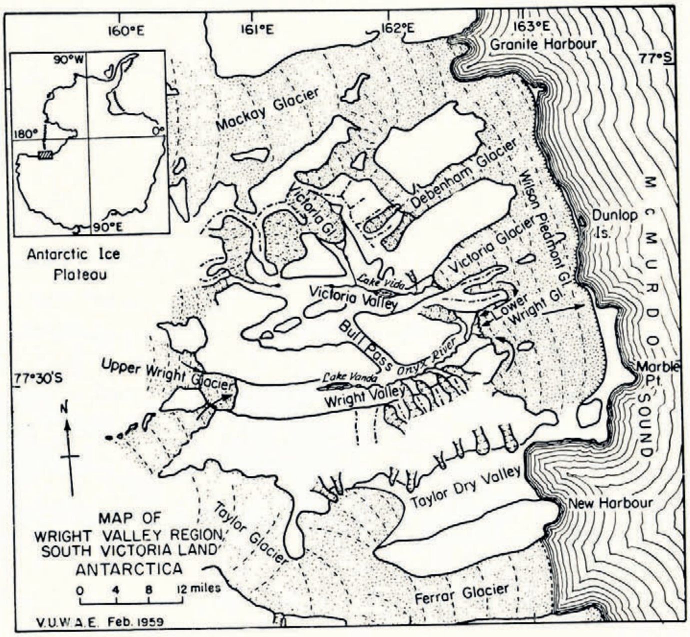

Fig. 1. Map of the Wright Valley region, south Victoria Land, Antarctica

(48 km.) of Wright Valley between these two glaciers are more or less ice-free due to deglaciation. The Onyx River, a melt-water stream that flows approximately 15 miles (24 km.) up Wright Valley, originates at the western terminus of Lower Wright Glacier and empties into Lake Vanda, which occupies an undrained bedrock basin. This bedrock basin and the slope responsible for this reversal of drainage were formed by an outlet glacier or glaciers that moved eastward down Wright Valley during the oldest glaciation or glaciations recognized in the eastern end of the valley by the writer. Three younger glaciations (Pecten, oldest; Loop; Triology, youngest), recognized in the eastern end of the valley, are marked by deposits from glaciers that moved from McMurdo Sound and the coastal mountains westward up the valley (Nichols, 1961[c]).

Chemical Stratification in Lake Vanda

Lake Vanda is approximately 17 miles (26 km.) west of the western terminus of Lower Wright Glacier and 11 miles (18 km.) east of the eastern terminus of Upper Wright Glacier in Wright Valley (Figs. 1 and 2). It is approximately 4 miles (6·4 km.) long, averages less than 1 mile (1·6 km.) wide and is 250 ft. (76 m.) or more deep (personal communication from Colin Bull). It is fed almost entirely by the Onyx River, the only river that empties into it. Lake Vanda is perennially frozen. Two ice corings gave a mean ice thickness of 11·5 ft. (3·5 m.) (Angino and Armitage, 1963, p. 91). During the warm season the ice at the margin of the lake thaws; in December 1960 the thawed area was less than 15 ft. (4·5 m.) wide. A larger body of open water is found during the warm season where the Onyx River enters the lake. Elevated beaches, silty offshore lacustrine deposits, deltas and lacustrine cliffs prove that Lake Vanda was once approximately 185 ft. (56·5 m.) higher (altimeter determination) (Figs. 3 and 4) (Nichols, 1962, p. 48).

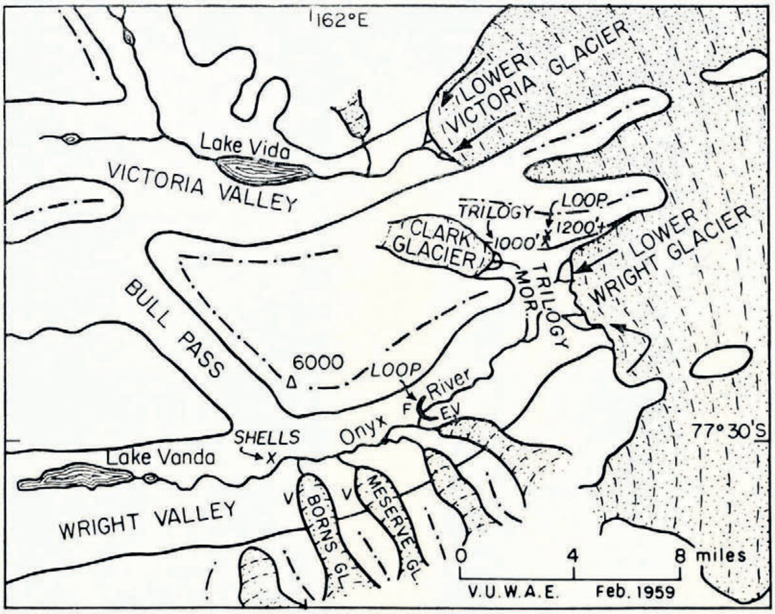

Fig. 2. Map of Wright Valley showing the positions of alluvial fan (F), sub-surface efflorescences (E) and volcanic rocks (V)

Angino and Armitage (1963) have published detailed chemical data for Lake Vanda (Wilson and Wellman, 1962, fig. 1). They show that the upper 180 ft. (55 m.) are essentially potable with less than 1,000 p.p.m. of dissolved salts, whereas that part below 200 ft. (61 m.) is more than three times as saline as sea-water, with more than 100,000 p.p.m. of dissolved salts (Table I). The origin of this chemical stratification is of interest; more than one process is probably involved.

Table I. Chemical Analyses of Lake Vanda, Wright Valley, South Victoria Land, Antarctica (after Angino and Armitage, 1963, p. 92)

Depth		*Na*	*K*	*Ca*	*Mg*	*Cl*
ft.	m.	p.p.m.	p.p.m.	p.p.m.	p.p.m.	p.p.m.
20	6·1	28	10	46	9	150
40	12·2	41	9	69	17	250
60	18·3	100	32	148	48	700
80	24·4	26	9	43	11	150
100	30·5	29	10	47	11	200
120	36·6	120	40	190	47	600
140	42·7	142	39	413		950
150	45·7	151	44	298	77	1,900
160	48·8	185	80	1,070	293	3,350
180	54·9	38	12	61	15	300
200	61·0	5,120	690	20,534	7,039	64,500
217	66·2	6,761	766	24,254	7,684	75,869

The cations and anions found in Lake Vanda are also present in primary volcanic sublimates (Barth, 1952, p. 147). Several small cinder cones are found in Wright Valley and basaltic fragments are common and widely distributed. If volcanic vents were located beneath Lake Vanda, the salts could have been introduced by volcanic emanation, with little overturning if the process were gentle, and a saline layer could have been formed at the bottom of the lake. The chemical stratification of certain hot springs in Iceland may be due to this process (personal communication from Tom F. W. Barth). No field data supporting this hypothesis are

Fig. 3. Lake Vanda, Wright Valley, McMurdo Sound. The elevated beaches and lacustrine cliffs to the right of the lake extend 185 ft. (56 m.) above it. (U.S. Navy aerial photograph)

known to the writer, however, and the scarcity of volcanic activity in the valley makes it unlikely.

The presence of dry kettles and small saline lakes, surface and sub-surface efflorescences of salts, calcite-veneered fragments and other features (Nichols, 1963[a]) prove that Wright Valley is an arid area. The aridity is due to the dryness of the plateau air which, when it descends into the valley during the winter months, becomes still drier due to adiabatic heating. Wright Valley has been arid ever since Upper Wright Glacier first retreated westward leaving the valley deglaciated. It seems certain that evaporation resulting from aridity was one of the factors responsible for concentrating the salts in the bottom layer of Lake Vanda.

Whether Lake Vanda has existed continuously since its rock basin was first cut is not known. It might have dried up completely one or more times, or the basin might have been invaded by glacial ice. It seems reasonably certain, however, that it has existed continuously, perhaps ice-dammed at times, since the full-bodied stage of Loop glaciation (third oldest glaciation recognized in the eastern end of Wright Valley) because the western terminus of Lower Wright Glacier during Loop time was approximately 8 miles (13 km.) east of the lake and in Trilogy time still farther east. During the full-bodied stage of Loop glaciation Lake Vanda was saline; salts had been carried into it ever since its inception (Nichols, 1962, p. 49–52). It is not known, however, whether the salts were then uniformly distributed or whether the lake was chemically stratified as it is now. Nor is its height known, although very faint terraces, still higher than the prominent ones that extend up to 185 ft. (56·5 m.) above the present lake, may be lacustrine and date from late Loop time (Fig. 4).

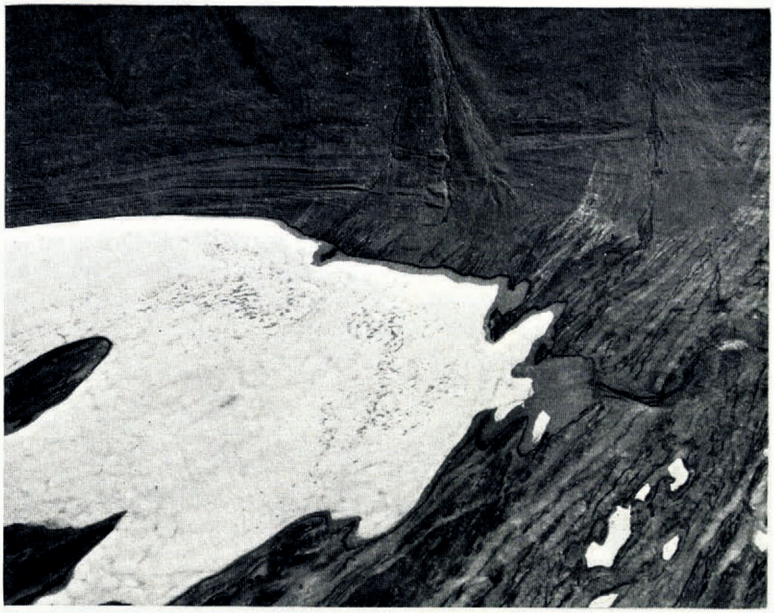

Fig. 4. Perennially frozen Lake Vanda, the narrow marginal moat of water which borders the lake during the warm season, and the elevated beaches and lacustrine cliffs above the lake. (U.S. Navy aerial photograph)

During late Loop time, because of an increase in temperature (Schell, 1961, p. 258) more melt water began to reach Lake Vanda, and it progressively rose and reached its highest level. Meanwhile, Lower and Upper Wright Glaciers and the local alpine glaciers progressively retreated and decreased in area. Still later, in late Loop time, there was increased evaporation and sublimation from the lake because of its greater area and perhaps because of still higher air temperatures, and more evaporation from the Onyx River because of its greater length. At the same time, progressively less melt water was furnished from the reduced area of the glaciers. Because of the new equilibrium between inflowing water and evaporation, Lake Vanda began to shrink and to increase in salinity. During Loop–Trilogy (youngest glaciation recognized in the eastern end of Wright Valley) interglacial time, the lake became still smaller and more saline. Finally, during the Trilogy glaciation, because the increased coldness further decreased the quantity of melt water reaching the lake, it was reduced to a still smaller saline pond, the waters of which are now near the bottom of the present Lake Vanda.

During late Trilogy time, because of a rise in temperature, more and more melt water reached Lake Vanda and it progressively rose as the glaciers progressively retreated. The presence of elevated beaches, deltas and silty offshore lacustrine deposits, weathered about as much as the Trilogy deposits at the eastern end of the valley, proves that Lake Vanda finally rose 185 ft. (56·5 m.) above its present level and was then more than 400 ft. (122 m.) deep.

The melt water flowed into the saline pond with little mixing because: (1) the saline water had a specific gravity of approximately 1·08 (Wilson and Wellman, 1962, p. 1172); (2) the velocity of the melt water that first reached the saline pond was low because its volume was small; (3) wind-driven turbulence in the lake waters was almost non-existent because the lake was probably perennially frozen; (4) the melt water initially flowed out on top of ice and not on top of the saline waters because the lake ice was probably frozen to the sides of its basin; (5) the fresh-water layer, as it grew deeper, inhibited mixing.

Thompson and Nelson (1956, p. 235), in a study of a somewhat similar situation, concluded that: "Because of the marked differences in density, vertical mixing would occur only to a small extent at the immediate interface of the fresh water and the saline water." Bates (1953, p. 2136), in a study of the Mississippi River delta, writes: "The density contrast of 0·015 to 0·020 normally existing between inflowing river water (Mississippi) and entraining oceanic water (Gulf of Mexico) is sufficient to suppress vertical turbulence and mixing between these two layers." When fresh water flows out across Great Salt Lake from the surrounding high-lands, little mixing takes place. Objects too heavy to float in the fresh water and too light to sink in the saline water float along at the sharp interface between the heavy saline water below and the lighter fresh water above. Moreover, the fresh water maintains its identity for some time, as the lake sometimes freezes over at temperatures too high for the saline water to freeze (personal communication from Armand J. Eardley). The case for a minimum of mixing, therefore, is well substantiated.

Although the temperature may have continued to rise still later in late Trilogy and post-Trilogy time, finally, because the valley was arid and because the amount of melt water reaching the lake continued to decrease as the glaciers progressively retreated and the area of glacial ice supplying melt water progressively diminished, the lake level began to drop and continued to do so until it reached its present position. The salts in the upper potable part of the lake accumulated in late Trilogy and post-Trilogy time. They were carried into the upper part of the lake by the Onyx River and perhaps by other melt-water streams, and were probably also derived from the lower saline waters by mixing and diffusion. The layer between 140 and 160 ft. (42·5 and 49·0 m.) is more saline than any other layer above 180 ft. (55 m.) (Table I). This may be due to the mixing of younger fresh melt water with the older saline water or perhaps to the complexities of Trilogy glaciation.

The lower saline water is not concentrated sea-water formed by evaporation of an arm of McMurdo Sound that extended up into the valley and was later cut off by isostatic uplift following deglaciation, like the examples described from Canada and Norway by Williams, Mathews and Pickard (1961), and Strøm (1957, 1961). This statement is supported by the following: (1) The elevated marine beaches in the McMurdo Sound area, all of which are related to the Trilogy glaciation, are less than 70 ft. (21·3 m.) above sea-level (Nichols, 1961[b], p. 57). (2) The bedrock threshold at the eastern end of Wright Valley is approximately 1,000 ft. (305 m.) above sea-level (Fig. 5) (personal communication from Colin Bull). (3) This threshold would have been still higher if the Wilson Piedmont Glacier had not existed, a condition which would have had to be satisfied if an arm of the sea had extended up into Wright Valley.

As is well known, partial freezing of a solution will concentrate the solute in the unfrozen phase. This process may have been partly responsible for the chemical stratification in Lake Vanda.

As permafrost is known to extend to depths greater than 1,500 ft. (457 m.) in northern

Canada, it would be logical to expect that scores of feet of ice might form on Lake Vanda during a glacial period. The thickness of this ice can be roughly calculated. *Assuming that:*

the mean annual temperature was −20° C., approximately the mean annual temperature in Wright Valley at the present time (Ball and Nichols, 1960, p. 1705);

the average freezing point of the lake, because of its salinity, was −5° C. (the water found in Lake Vanda at a depth of 217 ft. (66 m.) is roughly equivalent to a solution containing 0·3 mole of NaCl, 0·6 mole of $CaCl_2$, and 0·33 mole of $MgCl_2$ all dissolved in 1,000 g. of H_2O. Such a solution will freeze at approximately −7° C. We will not be far from the truth, therefore, if we assume that the waters concentrated by freezing had an average freezing point of −5° C. (personal communication from Charles E. Messer);

the thermal conductivity of the ice was 0·005 cal. $cm.^{-1}$ $sec.^{-1}$ $°C.^{-1}$;

the specific heat of the ice was 0·5 cal. $g.^{-1}$ $°C.^{-1}$;

the water was everywhere at the freezing point,

then calculation shows (personal communication from Francis Birch) that if sufficient water

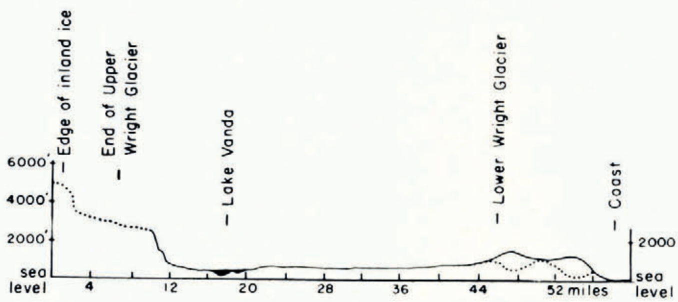

Fig. 5. Longitudinal profile of Wright Valley showing the undrained bedrock basin in which Lake Vanda is located and the bedrock surface which slopes downward up-valley for more than 15 miles (24 km.). (Profile made by Colin Bull, Victoria University of Wellington Antarctic Expedition)

were present approximately 250 ft. (76 m.) of ice could form in 1,000 yr. and approximately 800 ft. (244 m.) in 10,000 yr. If, however, following Schell (1961), it is assumed that the mean annual temperature in Wright Valley during a glacial period was −60° C., calculation shows that about 460 ft. (140 m.) of ice could form in 1,000 yr. and about 1,440 (439 m.) in 10,000 yr. As no allowance was made for surface ablation, geothermal or volcanic heat, the effect of solar radiation in the lake waters (Wilson and Wellman, 1962), or for the thermal energy that may have been brought into the lake by melt water, these figures are too high. Both calculation and observation show, however, that a layer of ice would form on the lake and that freezing was probably effective in concentrating the salts.

During the advancing and full-bodied stages of Trilogy glaciation the climate was probably so cold that little or no melt water ran into the lake and a progressively thickening permanent layer of ice was formed on it. As the ice thickened, the solute was concentrated into deeper and deeper levels in the lake. During the retreat of Trilogy glaciers, when melt water due to amelioration of climate was again running into Lake Vanda, it seems certain that there was too little water in the lake for the ice to float and that the ice was probably frozen to the sides of the basin. The initial melt waters, therefore, probably flowed out over the ice and perhaps accumulated to a lesser extent in an empty moat which may have been formed by radiation between the upper part of the ice and the upper sides of the lake basin. Finally, after still more melt water had reached the lake, the layer of ice began to float. The melt water now accumulated between the ice and the saline layer. The melt water and saline layer, however, did not mix significantly because they differed in density and because the melt water was not turbulent. The layer of ice was therefore effective in concentrating the salts and inhibiting the mixing of melt water and saline water. It is difficult, if not impossible, to evaluate the relative importance of evaporation and freezing. The fact that the surface of Lake Vanda has dropped approximately 185 ft. (56·5 m.) since late Trilogy time suggests that evaporation was more important than freezing in concentrating salts in the bottom layer and that most of the evaporation took place in Loop–Trilogy interglacial time.

Alluvial Fan

An alluvial fan formed mainly in interglacial time is found in Wright Valley approximately 8 miles (13 km.) west of the western terminus of Lower Wright Glacier (Fig. 2, F). It is immediately beneath a hanging valley, adjacent to the prominent end moraine which is the type deposit of the Loop glaciation (Nichols, 1961[c]), and on the north side of the valley. The fan is several hundred feet high and is composed of alluvium that varies greatly in age and coarseness. Small melt-water streams are at present depositing sand and somewhat coarser material on the fan during the summer months. The main body of the fan, however, is composed of sub-angular fragments up to 9 ft. (2·7 m.) in diameter with a sandy, gravelly, brown-stained matrix. Most of the coarse-grained igneous and metamorphic fragments at the surface of the fan have been weathered and eroded down to ground level probably by a combination of frost action (Kelly and Zumberge, 1961) and deflation. The main body of the fan appears to have been more profoundly weathered than the nearby Loop deposits. The basalt and dolerite fragments, which in general do not disintegrate, are considerably wind-cut.

A small patch of till which, on the basis of its degree of weathering, is probably of Loop age was deposited on the fan near its apex by a glacier which originated in the hanging valley above the fan.

The most striking feature of the fan is a series of channels which do not run up and down the fan but cut across it. They are not low places between lateral moraines deposited on the fan but channels eroded into the fan. Some are several hundred feet long and up to 30 ft. (9 m.) deep, and all slope downward up the valley. They terminate at the western or down-channel side of the fan but in some cases do not start at the eastern or up-channel side of the fan (Fig. 6). They were cut by melt-water streams marginal to Lower Wright Glacier about

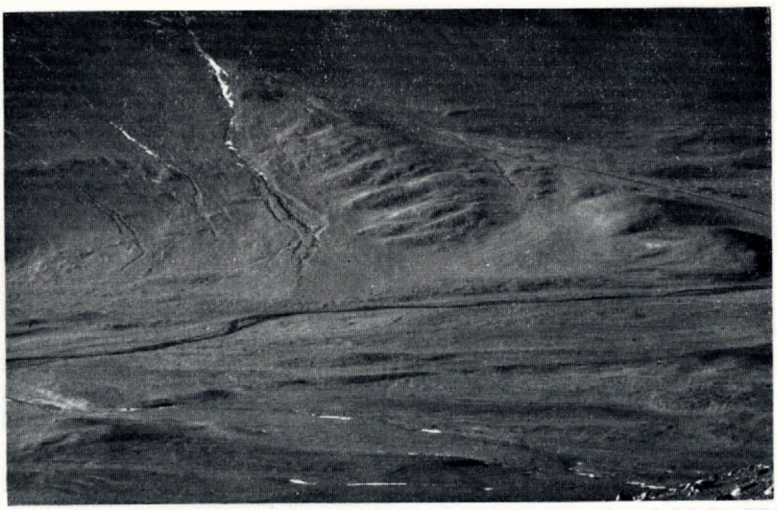

Fig. 6. The ice-marginal channels which are several hundred feet long and cut across an interglacial fan. Wright Valley, south Victoria Land

the time it started to retreat from its most advanced position during the Loop glaciation. The fan was not completely destroyed by glacial erosion because it was frozen, the glacier was thin and the fan was over-ridden by ice for only a short time. The presence of the marginal channels, the degree of weathering of the fan and the occurrence of glacial deposits of Loop age superimposed upon the fan prove that the main body of the fan is pre-Loop in age.

The floor of one of the hanging valleys in Wright Valley is approximately 2,500 ft. (760 m.) above the bottom of the valley. Some of this difference in elevation is undoubtedly due to differential glacial erosion, although some may be due to the pre-glacial history of the area. Truncated spurs are also found in Wright Valley and it seems likely that they have resulted from glacial erosion. The hanging valleys and truncated spurs were formed during the oldest glaciation(s), as some of them are found in those parts of Wright Valley which were not over-run by the ice of the three younger glaciations. The fact that the floor of Lake Vanda is approximately 1,000 ft. (305 m.) lower than the valley floor at the western terminus of Lower Wright Glacier, although it is more than 15 miles (24 km.) farther up the valley (Fig. 5) (Bull, 1960), is the best evidence of bedrock erosion by the eastward-moving ice of the oldest glaciation(s). The magnitude of the bedrock erosion proves that the fan was formed after the oldest glaciation(s). The fact that the fan was deposited on a bedrock surface which slopes downward up-valley also proves that the fan post-dates the oldest glaciation(s) and is in part of interglacial age.

Why the main body of the fan is composed of much coarser material than that deposited on it by melt-water streams during the 1959–61 field seasons is of interest. It is not known whether the main body of the fan was formed: (1) by the periodic drainage of ice-dammed lakes; (2) during a climate warmer than that at present when water was more abundant than now (this, in view of the interglacial age of the fan, seems logical); (3) by melt-water streams formed by volcanic heat; (4) by larger melt-water streams derived from more extensive glaciers; or whether the 1959–61 field seasons were not representative of hydrologic conditions in the valley.

Interglacial Fossils

The type deposit of the Pecten glaciation (Nichols, 1961[c]), the oldest of the glaciations that moved westward up Wright Valley, is on the floor of Wright Valley approximately 25 miles (40 km.) from McMurdo Sound and 14 miles (22·5 km.) from the western terminus of Lower Wright Glacier in a gully cut by a melt-water stream that came from Bull Pass (Figs. 2 and 7). It is a stratified, essentially horizontal layer of sand and gravel about 1 ft. (0·3 m.) thick and 20 ft. (6·1 m.) long which has been weathered yellow; till is found immediately beneath it. It is buried by approximately 20 ft. (6·1 m.) of till and perhaps by other deposits, all probably belonging to the Loop glaciation, and it has been exhumed and eroded by a melt-water stream. The gravel contains a high percentage of pecten shells (Fig. 8). Only a single extinct undescribed species is present (personal communication from Ruth Turner). The writer believes that the shells are found in glacio-fluvial gravels, that they were initially transported by glacial ice from the floor of McMurdo Sound up into Wright Valley, and that they were later picked up and re-deposited by melt-water streams. When they were transported up into Wright Valley there was approximately 3,500 ft. (1,070 m.) of ice in McMurdo Sound. Similar deposits are found near Boston, Massachusetts, and elsewhere (Nichols and Lord, 1938, p. 324–25).

The presence of unweathered till below the fossiliferous gravels favors this interpretation. Moreover, as indicated above, there is no evidence that they are beach gravels formed during interglacial or interstadial time in an arm of the sea which might have extended from McMurdo Sound up into Wright Valley.

Although *Adamussium colbecki* (Smith), an abundant, fragile, light-weight pecten now living in McMurdo Sound is frequently blown hundreds of yards above sea-level, the pecten in Wright Valley is too heavy and its distance from the then-existing beaches too great to have been moved in this way, even if it did live in shallow water where it could have been washed up onto the beaches.

Fig. 7. An aerial photograph (U.S. Navy) looking eastward down Wright Valley. Lower Wright Glacier and beyond that sea ice and open water in McMurdo Sound in the distance. The locality where the shells were found is indicated by the letter S

A ^{14}C analysis (L-645) indicates that the shells are more than 35,000 yr. old; and a measurement of the isotopes of uranium and thorium suggests that they are more than 800,000 yr. old (personal communication from W. S. Broecker). The pectens may have been living in McMurdo Sound in the interglacial period that followed the oldest glaciation recognized in the eastern end of Wright Valley and preceded the Pecten glaciation.

Speden (1962) has recently described the Scallop Hill Formation. It consists of cemented tuffaceous sandstones, grits and conglomerates. It is found *in situ* only at the east corner of Black Island, McMurdo Sound, at an altitude of about 600 ft. (183 m.). Fragments, however, are found in moraine at eight localities on the east and south sides of McMurdo Sound. This formation contains the extinct thick-shelled lamellibranch *Chlamys* (*Zygochlamys*) *anderssoni* (Hennig). It has been glaciated and is, therefore, older than the last glaciation. Speden correctly concludes that during glacial epochs much of McMurdo Sound was filled

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with glacial ice and, therefore, that the shells in the Scallop Hill Formation must date from either pre-Pleistocene time or from an early interglacial period. He favors an early Pleistocene interglacial age.

The fossils in some of the south Victoria Land deposits which Speden (1962) has included in the Taylor Formation are probably Last Interglacial (Loop-Trilogy interglacial) in age.

Mud and sands at 160–180 ft. (48–54 m.) above sea-level half-way between Cape Royds and Cape Barne, Ross Island, contain Mollusca, Foraminifera, Ostracoda, Polyzoa, echinoids and sponge spicules (Speden, 1962, p. 768). Mud about 160–180 ft. (48–54 m.) above sea-level on the eastern shores of Backdoor Bay, Cape Royds, Ross Island, contains Foraminifera,

Fig. 8. The extinct undescribed interglacial pecten which is found in glacio-fluvial deposits in Wright Valley 25 miles (40 km.) from McMurdo Sound

echinoid spines and Serpulidae (Speden, 1962, p. 769). A similar deposit is found at Backstairs Passage at the mouth of Reeves Glacier south-east of Mount Gerlache (Speden, 1962, p. 769).

Although the writer has never had an opportunity to study these deposits, he believes that they are fossiliferous glacial deposits composed mainly of marine sediments and organisms scraped from the ocean bottom by glacial ice. Such deposits are common along glaciated coasts (Crosby and Ballard, 1894; Charlesworth, 1957, p. 630–32). If this theory is correct—and it was favored by David and Priestley (1914, p. 276) for the Backstairs Passage deposit—then these organisms, most or all of which are living today in Antarctic waters, probably date from the Last Interglacial epoch.

Interglacial Marine Sediments and Absence of Climatic Optimum

Hough (1950, p. 258) studied three ocean-bottom core samples obtained in the Ross Sea. One of these core samples penetrated nearly the whole of the Pleistocene sequence and therefore contained interglacial marine sediments. He found that glacial marine sediments with ice-rafted fragments were abundant in all three cores. He also found fine-grained well-sorted sediments, deposited particularly between 15,000 and 6000 B.P., that did not contain ice-rafted fragments. He concluded that these fine-grained sediments were deposited in a sea which was essentially ice-free when the climate was warmer than now, and that the period between 15,000 and 6,000 B.P. represented in Antarctica the climatic optimum of the Northern Hemisphere. He writes: "The 'climatic optimum' of the Northern Hemisphere has a counterpart in Antarctic history. Prior to 6,000 years ago, floating ice apparently was absent from the area of the Ross Sea represented by the core samples, for a period of several thousand years."

Thomas (1959, 1960), after studying these samples and three additional cores taken from the Ross Sea, concluded that the absence of ice-rafted fragments was not indicative of a warm climate but, on the contrary, represented a colder climate than the present one. He theorized that the debris-laden icebergs and sea ice of that time were immobilized and "frozen solid" close to the coast by an extensive and continuous cover of fast ice and that therefore no ice-rafted fragments reached the part of the Ross Sea where the cores were obtained.

The present writer believes that Hough has not demonstrated the existence of the "climatic optimum" in Antarctica and that the "frozen solid" mechanism is the best explanation of the absence of ice-rafted fragments in the fine-grained well-sorted sediments. This conclusion is based on the following:

1. The climatic optimum did not occur between 15,000 and 6000 B.P. (Flint, [1947], p. 487–99).

2. The increase in temperature represented by the climatic optimum would not have been sufficient to eliminate ice from the Ross Sea.

3. Thomas found that radiolarian tests are associated with the glacial marine sediments but are absent or scarce in the fine-grained well-sorted sediments, free of ice-rafted fragments, which Hough thought were deposited when the Ross Sea was ice-free. Thomas concluded that the fast ice, which immobilized the icebergs, was snow-covered; that the solar energy reaching the sea-water was cut down to such a degree by the fast ice that phytoplankton could not exist beneath it; and that, therefore, the radiolarians, which depend upon phytoplankton for food, are absent from these sediments.

4. The writer's field work indicates that glacial ice was more extensive and icebergs probably more common in this part of Antarctica between 15,000 and 6000 B.P. than now. The facts on which this statement is based are as follows:

A beach at Marble Point, McMurdo Sound (Fig. 1), approximately 44 ft. (13·5 m.) above sea-level, is about 4,600 ± 200 yr. old as determined by a ^{14}C analysis (L-594; personal communication from W. S. Broecker) (Nichols, 1963[b], p. 211). The highest beaches at Marble Point, approximately 66 ft. (20 m.) above sea-level, are therefore perhaps 7,000 yr. old. The highest beaches at Marble Point roughly correlate, on the basis of their degree of weathering, with the deposits laid down in the eastern end of Wright Valley during the Trilogy glaciation, the youngest glaciation recognized in the valley (Nichols, 1961[c]). During the full-bodied stage of Trilogy glaciation Lower Wright Glacier extended approximately 5 miles (8 km.) farther up Wright Valley than at present and was about 1,000 ft. (305 m.) thick at its present terminus.

The greater extent of Lower Wright Glacier in Wright Valley during Trilogy time, considered together with the present proximity of the highest elevated beaches and the terminal positions of the glaciers around McMurdo Sound, makes it certain that these glaciers at many places must have advanced out into McMurdo Sound beyond the positions of the highest elevated beaches during the most extensive stage of Trilogy time. The highest beaches around McMurdo Sound were not formed, therefore, until the Trilogy glaciers had retreated considerably from their most advanced positions out in McMurdo Sound. The full-bodied stage of Trilogy glaciation occurred, therefore, more than 7,000 yr. ago, and it seems certain that there was more glacial ice around McMurdo Sound and the Ross Sea between 15,000 and 6000 B.P. than at present. Moreover, because of the more advanced positions of the glaciers at that time, ice-cliff shorelines must have been present along a greater length of the coast than now and icebergs were common. The glacial geology and geomorphology of south Victoria Land give no support for the existence of a warm ice-free period between 15,000 and 6000 B.P., but on the contrary indicate that land ice was more extensive than now and that icebergs were common.

5. The work of Schell (1961, p. 258) indicates that the greater extent of glacial ice at this time was the result of lower temperatures than those of the present. The fast ice at this time, therefore, must have been more extensive and permanent than now.

Why the sediments which do not contain ice-rafted fragments were apparently formed only during the last 35,000 yr. is puzzling (core N-3). The glacial history of south Victoria Land indicates nothing unusual about this period and consequently one would expect these sediments to be distributed throughout the core.

Glacial marine sediments were found at the tops of cores N-3, N-4 and N-5 studied by Hough (1950) and core N-8 studied by Thomas (1959). These sediments were continuously deposited during the last 6,000 yr. where core N-5 (studied by Hough) was obtained and during the last 4,000 yr. where core N-3 (studied by Hough) was taken. They indicate that there was open water here during these times and that material was deposited by moraine-laden icebergs and perhaps by debris-laden sea ice. This correlates reasonably well with the evidence for open water during the last 6,000 or 7,000 yr. along the west side of McMurdo Sound as shown by the excellently developed raised beaches (Nichols, 1961[a], 1963[b]).

Sub-surface Efflorescences of Salts

A layer of white salts is found immediately below the surface of the ground in many places in Wright Valley (Figs. 2, E and 9). The layer is commonly 2–5 in. (5–13 cm.) below the surface. Above it is 1–3 in. (2·5–7·6 cm.) of yellow sand or granule-gravel and above this 1–2 in. (2·5–5·0 cm.) of deflation pavement (Nichols, 1963[a], p. 28–30). In places a layer of pure salts as much as 3 in. (7·6 cm.) thick is present. In other places the salts impregnate

Fig. 9. A sub-surface efflorescence of salts in Wright Valley, McMurdo Sound. The salts are interglacial as they are, in general, more abundant in Loop deposits than in Trilogy ones

and loosely consolidate 4–7 in. (10–18 cm.) of silt, sand and gravel. Sodium chloride and sodium sulfate are the principal salts, although magnesium sulfate, calcium sulfate and calcium carbonate are also present.

This layer may have been formed by the evaporation of water, containing dissolved salts, that moved upward by capillarity. Any upward-moving solutions and leaching must have occurred in thawed material. The active layer where the white salts are found is less than 3 ft. (0·9 m.) thick. It is extremely unlikely that the salts were derived from the leaching of material only a few feet thick. Perhaps the white salts were formed in interglacial time by upward-moving solutions when the climate was warmer and the active zone thicker. In any event, a Loop-Trilogy interglacial age for part of the layer is indicated by the fact that in the writer's experience* it is in general thicker in Loop deposits than in Trilogy ones.

Interglacial Volcanic Rocks

Several cinder cones are found in Wright Valley, and basaltic fragments re-distributed by glacial ice and melt-water streams are common on till and outwash deposits.

Two small basaltic cinder cones are located on the south wall of Wright Valley a few hundred yards above the prominent steep-sided end moraine which is approximately 7 miles (11 km.) west of Lower Wright Glacier (Fig. 2, V). They are completely surrounded by morainal material of Loop age and neither has a crater. One cone is 6 ft. (1·8 m.) high and averages 30 ft. (9 m.) in diameter. A well-developed boulder train, easily traced for 150 ft. (45 m.), is associated with it. The cone, therefore, was over-run by the Lower Wright Glacier of Loop time and is pre-Loop in age. The cone was built on a bedrock surface which in general slopes downward up-valley. It therefore post-dates the glaciation responsible for this reverse slope. The area where the cone is found was also over-run by the Lower Wright Glacier of Pecten time and the cone is, therefore, interglacial.

Three very small closely spaced volcanic areas are found on a lateral moraine of Loop age on the west side of Borns Glacier (Fig. 2, V). One is an embryonic volcano about 6 ft. (1·8 m.) high, 100 ft. (30 m.) long and 50 ft. (15 m.) wide. It contains an indistinct crater and is composed of basaltic fragments up to 2 ft. (0·6 m.) in diameter. Most of the fragments are black but some are red. They are fresh and unweathered, and some are wind-cut. Several small cones 3–5 ft. (0·9–1·5 m.) high and 30 ft. (9 m.) or more in diameter are found in another area about 100 yd. (91 m.) in diameter. There is no evidence indicating that these cones were formed beneath, on top of, or in contact with the glacier. Basaltic fragments are common on and within a younger lateral moraine of Trilogy age about 200 ft. (61 m.) away. These volcanic rocks were apparently formed in Loop-Trilogy interglacial time.

The glacial deposits in Wright Valley are usually light-colored because light-colored rocks predominate in the valley. However, the older lateral moraines on the south side of the valley and on the west side of Meserve Glacier, which are probably of Loop age (Fig. 2, V), are very dark as they contain an abundance of basaltic fragments. The younger moraines on the west side of Meserve Glacier contain less basalt and are lighter-colored, and the youngest moraine is light-colored and contains no basalt. A dark alluvial fan below the moraines also contains abundant basalt. The source of the basalt was not found but it was undoubtedly in areas now covered by Meserve Glacier. The distribution of the basalt suggests an episode of vulcanism in pre-Loop time, when Meserve Glacier was less extensive than now. This was followed by progressive destruction of the volcanic rocks by glacial erosion with complete destruction some time before the formation of the basalt-free youngest moraine. These moraines are also found in that part of the valley which slopes downward up-valley and the basalt is, therefore, interglacial.

The abundance of basaltic fragments everywhere in Wright Valley suggests that many

* Confirmed by Dr. F. C. Ugolini, Rutgers University, New Jersey.

cones must have been over-ridden and destroyed by the successive glacial advances and re-advances.

Volcanic areas are common on the mainland side of McMurdo Sound (Prior, 1907, p. 101–60; Debenham, 1921; Taylor, 1922; Smith, 1954; Harrington, 1958; Gunn and Warren, 1962).

McCraw (1962, fig. 1) studied the scoria cones in Taylor Valley. More than 20 distinct cones were counted. One was 300 ft. (91 m.) high and about 1,200 ft. (366 m.) in diameter. McCraw concluded that they were erupted between the McMurdo and Taylor glaciations of Péwé (1960). Angino and others (1960) have also reported interglacial cones and flows in Taylor Valley, and Hamilton and Hayes (1960) also believe that the volcanic activity in Taylor Valley is interglacial in age. Near the terminus of Wolcott Glacier, approximately 40 miles (64 km.) south of the terminus of Ferrar Glacier (Fig. 1), there are five lava flows which are interglacial in age, as they are interbedded with morainal deposits. In addition, three other flows, stratigraphically below the five, may also be interglacial (personal communication from Colin Bull).

A study of Mount Erebus, Hut Point peninsula, Mount Discovery, Mount Morning, and the other volcanic areas around McMurdo Sound will probably demonstrate that some of these volcanic rocks are also interglacial.

Interglacial Lacustrine Deposits

Péwé (1960, p. 506–07) has described the interglacial lacustrine deposits in Taylor Dry Valley, south Victoria Land. He writes: "Many glacial lakes were formed when the 'dry valleys' on the west side of McMurdo Sound were blocked by ice or moraines from the huge outlet glaciers during and immediately after the Taylor glaciation. A large lake 1,000 ft. [305 m.] deep formed in Taylor Dry Valley when the glacial ice in the valley began to recede. The water was held in by the glacial ice or ice-cored moraine which filled the sound and blocked the valley. . . . Many dissected deltas and a thick deposit of laminated lake silt and clay are widespread in the valley bottom and attest the former presence of the lake. . . . The lake deposits were subsequently dissected and over-ridden by later glacier advances."

Amount of Deglaciation during Interglacial Times

Because of the scarcity of data on interglacial stratigraphy and paleontology, little is definitely known about the extent of the Antarctic Ice Sheet during interglacial times. Assuming, however, that the present climate in Antarctica is roughly similar to those of interglacial times (a crude assumption often made of present and interglacial climates in the Northern Hemisphere), then one may logically conclude that during interglacial times there was a great deal of ice on the Antarctic continent.

Hough's study of ocean-bottom cores from the Ross Sea indicates that throughout most of the Pleistocene, glacial marine sediments were being deposited here (Hough, 1950, p. 258, core N-3). Moreover, the kinds of sediments deposited during 95 per cent of Pleistocene time were similar to those deposited in the last 5,000 yr. The extent of ice on the Antarctic continent during the last 5,000 yr. was essentially the same as at present (Péwé, 1958, 1960; Nichols, 1961[c]). This suggests that the extent of ice in existence on the Antarctic continent throughout the Pleistocene was about the same as it is now, and that, therefore, glacial and interglacial times do not differ greatly in Antarctica.

Zeuner (1959, p. 274), after a study of the summer radiation for lat. 75° S., concluded that: "Glacial conditions persisted throughout the Pleistocene on the Antarctic continent, and the variations from the present ice volume never exceeded one-third either way."

Schell's (1961, p. 258) calculations have shown that the temperature at the South Pole during interglacial times should be approximately −30° C., low enough for the Antarctic Ice Sheet to maintain itself during the entire Pleistocene.

Thus the available evidence suggests that the Antarctic Ice Sheet maintained itself throughout the entire Pleistocene.

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