QUATERNARY GLACIATIONS IN SOUTHERN VICTORIA LAND, ANTARCTICA

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Abstract. In the coastal mountain chain of southern Victoria Land approximately 4,000 km.^{2} of glacier-cut valleys and dividing ranges are almost completely ice-free, while the surrounding areas are fully glacierized.

In the ice-free Wright Valley and Victoria Valley systems evidence of four glaciations is recognized. The earliest two glaciations were the most extensive; glaciers flowed eastwards from the ice plateau through the coastal ranges and cut broad valleys extending to McMurdo Sound and the Ross Sea. The moraines of these glaciations are thin and highly weathered. The third glaciation was less extensive, consisting of advances by smaller glaciers derived from the inland ice plateau, the Wilson Piedmont Glacier and *névé* fields in the dividing ranges. The surfaces of moraines of this glaciation are now partly covered by saline lakes, evaporite deposits and extensive areas of desert pavements strewn with ventifacts. The fourth and youngest glaciation comprised small advances by remnants of the plateau-fed valley glaciers. Thick boulder moraines of this glaciation overlie earlier deposits.

During each glaciation the greatest volume of ice was derived from the inland ice plateau. The volume of ice entering the valleys was dependent on the difference in altitude between the plateau surface and subglacial rock thresholds at the valley heads. Decrease in the surface level of the inland ice plateau caused the rock thresholds to increasingly hinder the eastward flow of plateau ice until practically no ice could flow down into the valleys, thereby terminating the glaciation. Such a condition exists at the present time.

Résumé. Dans la chaîne de montagnes côtières du Sud de la Terre de Victoria il existe environ 4 000 km^2 de vallées d'érosion glaciaire et des chaînes de séparation, presque entièrement libres de glace, tandis que les régions environnantes sont complètement englacées.

Dans les systèmes des vallées de Wright et de Victoria, libres de glace, on a pu prouver le passage par quatre glaciations. Les deux premières glaciations étaient les plus étendues; les glaciers s'écoulaient du plateau glaciaire, vers l'est, à travers les chaînes côtières et découpaient de larges vallées s'etendant jusqu'au Détroit de McMurdo et la Mer de Ross. Les moraines de ces glaciations sont minces et très érodées. La troisième glaciation était moins étendue et consistait en l'avance de petits glaciers venant du plateau glaciaire de l'intérieur, du glacier de Wilson Piedmont et des zones de névé situées dans les chaînes de séparation. Les régions morainiques de cette glaciation sont maintenant partiellement recouvertes de lacs salins, de dépôts d'évaporation et de grandes étendues désertiques parsemées de cailloux érodés par le vent. La quatrième et dernière glaciation comportait de faibles avances des vestiges de glaciers de vallée s'écoulant du plateau. D'épaisses moraines de cailloux provenant de cette glaciation couvrent les dépôts antérieurs.

Au cours de chacune de ces glaciations la plus grande part du volume de glace était fournie par le plateau glaciaire de l'intérieur. Le volume de glace pénétrant les vallées était fonction de la différence d'altitude entre le niveau du plateau et les seuils de roches subglaciaires du fond des vallées. A mesure que le niveau du plateau glaciaire de l'intérieur baissait, les seuils rocheux empêchaient davantage l'écoulement vers l'est de la glace du plateau jusqu'à ce que celle-ci ne pouvait pratiquement plus se déverser dans les vallées; ainsi se terminait la glaciation. Une situation analogue existe actuellement.

Zusammenfassung. In der Küstengebirgskette des südlichen Victoria-Landes sind glaziale Taltröge und Zwischengrate mit einer Gesamtfläche von ca. 4 000 km^2 beinahe vollständig eisfrei, während die benachbarten Gebiete völlig vergletschert sind.

In den Systemen des eisfreien Wright- und Victoria-Tales konnten sichere Anzeichen für vier Vergletscherungen festgestellt werden. Die beiden älteren Vergletscherungen waren die ausgedehntesten; Gletscher flossen vom Eis-Plateau ostwärts durch die Küstenkette und tieften breite Täler aus, die sich bis zum McMurdo-Sund und zur Ross-See erstrecken. Die Moränen dieser Vorstösse sind spärlich und stark verwittert. Die dritte Vergletscherung war weniger ausgedehnt; sie bestand in Vorstössen kleinerer Gletscher aus dem Inlandeis-Plateau, dem Wilson-Piedmont-Gletscher und Firnfeldern auf den Zwischengraten. Die Oberfläche von Moränen aus dieser Vergletscherungsperiode ist heute teilweise von Salzseen, Verdunstungsrückständen und ausgedehnten, mit Windformen übersäten Wüstendecken verdeckt. Die vierte und jüngste Vergletscherung bestand aus kleinen Vorstössen der Überreste der aus dem Plateau gespeisten Talgletscher. Mächtige Blockmoränen aus dieser Phase liegen über älteren Ablagerungen.

Während jeder Vergletscherung floss die Hauptmasse des Eises vom Inlandeis-Plateau zu. Welche Eismenge in die Täler gelangen konnte, hing jeweils vom Höhenunterschied zwischen der Plateau-Oberfläche und der subglazialen Felsschwelle an den Talschlüssen ab. Beim Einsinken der Oberfläche des Inlandeis-Plateaus konnten die Felsschwellen dem Abfluss des Plateau-Eises nach Osten immer grösseren Widerstand entgegensetzen, bis schliesslich so gut wie kein Eis mehr in die Täler abfloss, womit die Vergletscherung abklang. Derartige Bedingungen herrschen auch gegenwärtig.

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INTRODUCTION

Small ice-free areas occur around the margin of continental Antarctica; in the Larseman and Vestfold Hills (Christensen, 1939; Crohn, 1959) in Ingrid Christensen Land (lat. 69° S., long. 76–79° E.; area 350 km.^{2}); at the Amery locality (Crohn, 1959) (lat. 70° 30′ S., long. 68° 30′ E.; area 400 km.^{2}); in Alexander Island (Rymill, 1938) (lat. 72° S., long. 72° W.; area 400 km.^{2}) and in parts of Graham Land; in Neu Schwabenland (Ritscher, 1939) (lat. 71° 30′ S., long. 5° E.; area 100 km.^{2}); at Bunger's Oasis (Avsyuk and others, 1956; Shumskiy, 1957; Lebedev, 1959, p. 78–91) (lat. 66° S., long. 101° E.; area 600 km.^{2}); in southern Victoria Land west of McMurdo Sound, between the Koettlitz Glacier and the Royal Society Range (lat. 78° S., long. 164° E.; area 1,000 km.^{2}); and between the Miller and Ferrar Glaciers, the area discussed in this paper (Figs. 1 and 2). Similar ice-free areas occur within the limits of the Greenland inland ice (Lister and Wyllie, 1958).

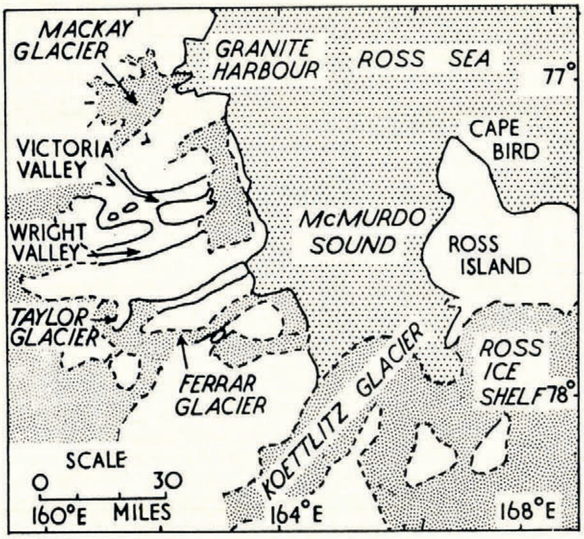

Fig. 1. General locality map of McMurdo Sound region

Parts of the ice-free areas west of McMurdo Sound were visited by field parties of Scott's expeditions of 1901–04 and 1910–13, and Shackleton's expedition of 1907–09. These parties carried out surveying, geological and glaciological investigations along the Ferrar and Taylor Valleys, along the coast between New Harbour and Granite Harbour, along the Miller and Debenham Glaciers and east of the Royal Society Range (David and Priestley, 1914; Taylor, 1922; Wright and Priestley, 1922).

However, the ice-free terrain bounded on the north by the Miller, Cotton and Debenham Glaciers and in the south by the Taylor Glacier was unknown to these expeditions. Aerial photographs taken in 1955–56 and 1956–57 by the U.S. Navy and the Commonwealth Trans-Antarctic Expedition (New Zealand party) showed that nearly all of this region is ice-free. During the summer of 1957–58 the New Zealand northern party of the Commonwealth Trans-Antarctic Expedition travelled around the borders of this area. Small expeditions from Victoria University of Wellington have investigated the area in the summers of 1957–58, 1958–59, and 1959–60 (Webb and McKelvey, 1959; McKelvey and Webb, 1959; McKelvey and Webb, in press; Bull, 1960; McKelvey and Webb, 1961).

Fig. 2. Map of the ice-free areas in southern Victoria Land

GENERAL GEOLOGY OF SOUTHERN VICTORIA LAND

Between the Miller, Cotton and Debenham Glaciers and the Taylor Glacier, the basement complex consists of folded and metamorphosed Precambrian–Cambrian sediments intruded by plutons of gneissic and porphyritic granites, granodiorite, and younger acid and basic dyke swarms (McKelvey and Webb, in press). This basement was peneplained during the Lower Palaeozoic and overlain unconformably by more than 1,500 m. of mid-Palaeozoic to mid-Mesozoic *Beacon Sandstone Group* sediments (Webb, in press). Upper Devonian (Woodward, 1921) and late Palaeozoic fossils (Seward, 1914; Edwards, 1928) have been described from the *Beacon Sandstone Group* sediments. *Ferrar Dolerite* sills and dykes (McKelvey, in press) up to 600 m. thick intrude the basement complex and the Beacon sediments.

The peneplain surface, the bedding of the *Beacon Sandstone* and the *Ferrar Dolerite* sills all dip regionally westwards below the ice plateau at a low angle (3–5°). The glacial landforms of the area are strongly influenced by the lithological and structural relationships of the various rock types.

PHYSIOGRAPHY OF THE ICE-FREE AREA

The high ice plateau of eastern Antarctica* is bounded at approximately long. 162° E. by a coastal mountain chain extending from lat. 70° S. to 85° S. North of lat. 79° S. this chain lies within Victoria Land.

The greater part of Victoria Land is completely glacierized; major glaciers flow eastwards from the inland ice plateau through the coastal ranges to the Ross Sea. Extensive *névé* fields in the coastal ranges feed alpine glaciers which flow to join the main valley glaciers.

However, in the area between the Miller, Cotton and Debenham Glaciers (lat. 77° S.) and the Taylor and Ferrar Glaciers (lat. 77° 45′ S.), similar east–west trunk glaciers have retreated, leaving approximately 4,000 km.^{2} of lowland valleys and the separating ranges almost entirely free of ice (Fig. 2).

1. *The inland ice plateau*

Westwards from the Victoria Land mountain chain the surface of the inland ice plateau rises from 2,000–2,500 m. to approximately 3,000 m. at long. 150° E. Farther west the plateau ice decreases in altitude and it has been suggested by Lebedev (1959, p. 10) that this ice flows westwards; the only plateau ice flowing eastwards through the Victoria Land ranges is that which accumulates between long. 150° E. and 160° E. The plateau surface in this region has a gentle relief except where it is pierced by nunataks or disrupted by shallow subglacial topography.

2. *The mountain ranges*

The Asgard, Olympus and St. Johns Ranges are units of the Victoria Land mountain chain (Fig. 2). They extend eastwards for 60 km. from the edge of the inland ice plateau, across the deglacierized region to the coastal piedmont.

In the western parts of these ranges, cirque erosion in the horizontal *Beacon* sediments and dolerite sheets has carved accordant mesa-like peaks with summits at 2,300 m., separated by passes at 1,500 m. (Fig. 3). In the eastern parts of the ranges the *Beacon* sediments and most of the dolerites have been removed by erosion. In these localities cirques have cut arête-like peaks ranging up to 1,500 m. in the steeply dipping metasediments and intrusives of the basement complex.†

From *névé* fields in the eastern parts of the ranges, wasting alpine glaciers descend to the

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* Eastern Antarctica is that part of the continent on the Atlantic Ocean–Indian Ocean side of the line between the Ross Ice Shelf and the Filchner Ice Shelf. *See* Editor's note in the *Journal of Glaciology*, Vol. 3, No. 26, 1959, p. 455.

† Unless otherwise stated, all heights in this article are given in m.a.s.l.

Wilson Piedmont Glacier and towards the floors of the ice-free valleys. In the western parts of the ranges the cirques are either free of ice or contain only small amounts of static ice.

3. *The ice-free valleys*

Wright Valley. The floor of the Wright Valley is ice-free for 50 km. (Figs. 4, 5 and 6). At the western end of the valley ice flowing eastward from the inland ice plateau is channelled between nunataks and subglacial extensions of the Asgard and Olympus Ranges. This ice flows over high rock shelves flanking Mt. Fleming and coalesces to form the 10 km. long Upper Wright Glacier at an altitude of 1,400 m. (Fig. 3). At the eastern end of the valley the almost stagnant Lower Wright Glacier extends 11 km. westwards into the valley from the Wilson Piedmont Glacier.

The ice-free valley floor descends westwards for 30 km., from a height of approximately 400 m. at the snout of the Lower Wright Glacier to about 70 m. (Bull, 1960) on the floor of Lake Vanda. This ice-covered lake is at present 7 km. long and about 70 m. deep but beaches cut in the moraine and scree surrounding the lake indicate a greater extent in the past (Fig. 6). West of Lake Vanda the valley floor rises and is divided by a flat-topped feature, Dais, into two parallel forks which contain thick moraines. Over a distance of 8 km. the moraine-mantled floors of the forks undulate considerably and then rise steeply to about 1,000 m. and unite again in a flat doleritic scabland (Cotton, 1952, p. 348), the Labyrinth (Fig. 3). This feature, carved in a 100 m. thick dolerite sill, occupies the whole width of the valley floor at this point and extends westwards beneath the Upper Wright Glacier.

Melt water derived from cirque ice, the alpine glaciers and the Lower Wright Glacier, forms the Onyx River, which meanders 30 km. across the valley floor flood plains to Lake Vanda (Figs. 4 and 5). No water flows out of Lake Vanda, since all water loss is due to evaporation and sublimation.

The valley walls display a series of benches cut by former glaciers in Wright Valley. The greater part of these older benches has been destroyed by later glacial undercutting of the valley sides. Remnants of the oldest benches notch the valley walls at between 1,200–1,500 m. and these slope back gently to the floors of bordering cirques. The flat top of Dais is a remnant of the original floor of Wright Valley cut during this glaciation.

A younger series of benches cut at 800 m. occurs in the North and South Forks and at the eastern end of Dais. These benches are considered to be contemporaneous in age with the present valley floor farther eastwards.

Victoria Valley system. The Upper Victoria, Barwick and McKelvey Valleys converge at the eastern end of Insel Range to form the Lower Victoria Valley which extends eastwards towards the Wilson Piedmont Glacier. Another tributary valley, the Balham Valley, enters the southern side of Barwick Valley (Fig. 7).

The floors of these valleys are all higher than that of Wright Valley east of Dais, due in part to their thicker deposits of ground moraine. The lowest part of the valley system is occupied by the 5 km. long, ice-covered Lake Vida, with a surface altitude of approximately 350 m. Melt water flows into this lake from the Lower Victoria Glacier (a lobe of the Wilson Piedmont Glacier analogous to the Lower Wright Glacier), from the Upper Victoria Glacier (a retreating alpine glacier analogous to Clark Glacier (Fig. 2)), and from a few cirque glaciers in the eastern Olympus and St. Johns Ranges.

At the western end of the Barwick Valley, the Webb Glacier now receives nearly all of its ice from an extensive *névé* field south of Skew Peak, although some plateau ice still flows through a pass in the Willett Range down to the glacier. Glaciers of plateau ice formerly flowed through other higher passes in the Willett Range but a fall in the ice plateau level has starved these glaciers and their courses are now ice-free.

The walls of the valleys display remnants of glacial benches at approximately 800 m. and between 1,200 and 1,500 m. The higher set slope back gently to the accordant floors of ice-free

Fig. 3. *Aerial view from above North Fork of Wright Valley looking towards the inland ice plateau and showing:* (1) *The inland ice plateau;* (2) *Western Asgard Range;* (3) *Mt. Fleming;* (4) *Ice falls in the course of Upper Wright Glacier;* (5) *Snout of Upper Wright Glacier;* (6) *Labyrinth;* (7) 1,500 *m. glacial bench;* (8) *Olympus Range with accordant cirques opening onto the glacial benches*

Fig. 4. *View east from the mouth of Wright Valley showing:* (1) *Beaufort Island;* (2) *McMurdo Sound;* (3) *Wilson Piedmont Glacier;* (4) *Lower Wright Glacier;* (5) *Onyx River, meandering westward along valley to Lake Vanda;* (6) *King Pin Nunatak;* (7) *Mt. Erebus, Ross Island*

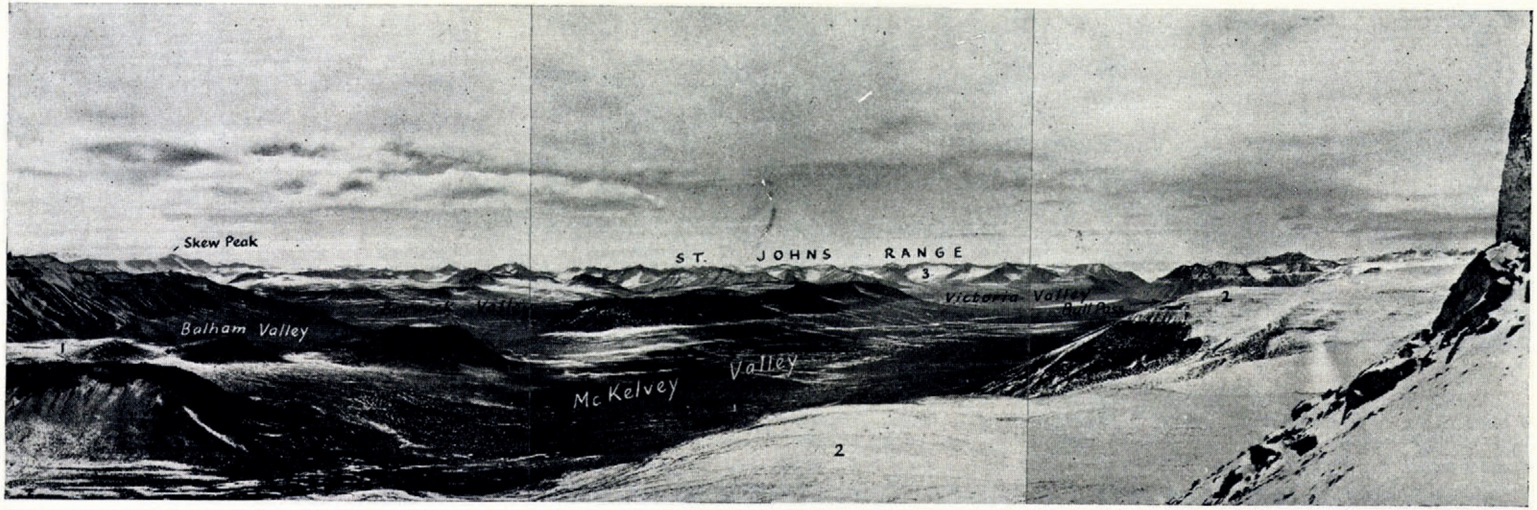

Fig. 7. Panoramic view north from Mt. Boreas, Olympus Range showing the old and now partly dissected erosion surface (1) on Insel Range, the glacial bench (2) on the northern wall of Olympus Range, and accordant cirques (3) in St. Johns Range

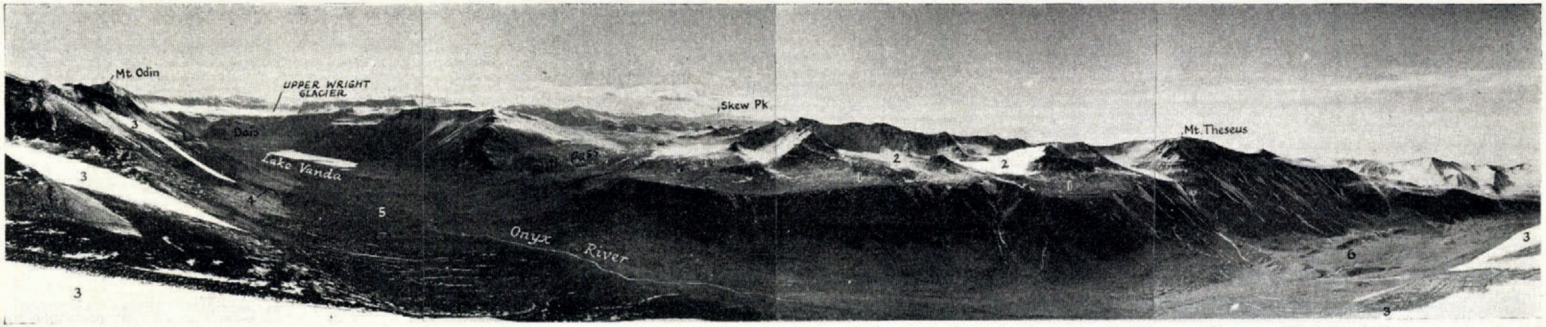

Fig. 5. Panoramic view from Mt. Valkyrie, Asgard Range, showing the broad glacier-cut Wright Valley flanked by the Asgard and Olympus Ranges. High-level (1,500 m.) glacial benches (1) are incised in both the northern and southern walls. Accordant cirques (2), some containing small alpine glaciers (3) open onto these glacial benches. Dark moraines overlying bedrock and older moraines (4) were deposited during an advance (fourth glaciation) of the alpine glaciers. The floor of Wright Valley is covered by a thin veneer of highly weathered moraines (5) of the second glaciation. In the extreme right (6), terminal and lateral moraines of the third glaciation occupy the eastern part of Wright Valley

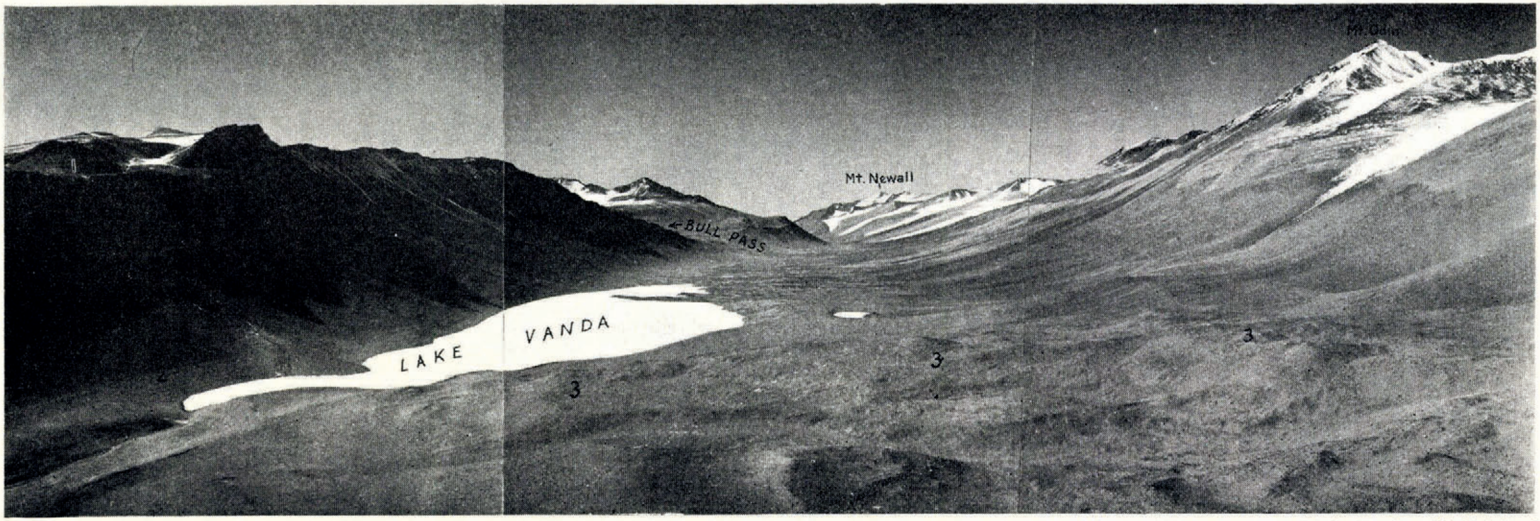

Fig. 6. View east from Dais, down Wright Valley, showing a high-level glacial bench cut along the contact between granite and a dolerite sill (1); ice-covered Lake Vanda with high-level shorelines (2) cut in second glaciation moraine, and scree, exposed only on the northern side of the lake; thick moraines (3) of the third glaciation filling the western part of Wright Valley. Note the undulating boulder-strewn surface of these moraines and the large channel passing from the South Fork. In the middle distance, the valley floor moraine cover is thin or entirely absent. Thin screes of dolerite cover the basement rocks on the southern wall of the valley. In the distance four alpine glaciers extend almost to the floor of Wright Valley

cirques bordering the valleys. The flat top of Insel Range is a remnant of the valley floor cut by a glacier which occupied the area of the present Balham and McKelvey Valleys when the 1,200–1,500 m. benches were cut throughout the valley system.

The valley floors are thickly mantled with moraines. These contain large areas of sand dunes and well-developed desert pavements strewn with ventifacts. Melt water from the remnant glaciers has reworked much of this moraine in the Lower Victoria Valley into extensive flood plain areas.

4. *The coastal piedmont area*

For 60 km. north of Cape Bernacchi the coastal piedmont of the Victoria Land mountain range is covered by the Wilson Piedmont Glacier. It blocks the entrances to the Wright and Lower Victoria Valleys (Fig. 4) and in the north merges with the Debenham Glacier. The piedmont glacier varies in width between 5 and 16 km. and an east–west traverse has shown it to be up to 300 m. thick east of Wright Valley (Bull, 1960).

Alpine glaciers from the eastern Olympus and Asgard Ranges, and the Debenham Glacier now carry insufficient ice to the Wilson Piedmont Glacier to maintain a positive regime. As a result the piedmont has retreated inland to expose coastal ice-free areas between Taylor Valley and Gneiss Point, at Dunlop Island and at Cape Roberts. Most of the piedmont is stagnant but at a few places the glacier still flows seawards, for example, near Gneiss Point the movement is about 7 m./yr. (personal communication from R. L. Nichols).

MECHANISMS OF DEGLACIERIZATION

Mechanisms that have been proposed to explain local deglacierization in Antarctica include volcanism, settling of dust particles, underground coal fires, and heating by radioactivity in the basement rocks. None of these are acceptable as an explanation for the development of this ice-free region.

The deglacierization of the region discussed in this paper was caused by a decrease in the surface level of the inland ice plateau with consequent emergence of high *rock thresholds* at the western ends of the valleys, cutting off the supply of plateau ice to the valley glaciers. A similar mechanism has been proposed to explain the starvation of the trunk glaciers in Dronning Louise Land, north-east Greenland (Lister and Wyllie, 1958).

The floors of the Wright, McKelvey, Balham and Barwick Valleys rise steeply to more than 1,800 m. along the margin of the inland ice. The relief of the rock surface beneath the ice plateau farther west is not known with any certainty. However, the lack of nunataks and the gentle relief of the ice plateau surface tends to indicate that the altitude of this rock surface falls to the west. This view is supported by data from recent field traverses in southern Victoria Land.

Geophysical studies (Wilson and Crary, 1961) have been made along the Skelton Glacier which flows through the Victoria Land mountain chain 40 km. south of the Wright Valley. Under the Skelton Glacier a high subglacial rock threshold at long. 158° to 160° E. allows little flow of ice from the plateau to the Ross Ice Shelf. Over the threshold the ice is about 200 m. thick; to the west the thickness increases to 3,000 m. A decrease of 200 m. in the altitude of the ice plateau surface would completely disrupt the supply of ice from the plateau to the Ross Ice Shelf by way of the Skelton Glacier.

The suggestion that the height of the sub-plateau land surface west of the Wright Valley and the Victoria Valley system decreases to the west is also supported by the results of a gravity traverse along the Wright Valley (Bull, 1960). The traverse extends from the coast near Marble Point to the Labyrinth. A major north–south fault zone occurs at or near the coastline and the variation of the acceleration due to gravity along the Wright Valley is consistent with the Victoria Land mountain chain being a horst, the centre line of which in this area is at about long. 161° E. A second north–south fault is expected to occur west of the inland ice margin, and the subglacial surface should resemble that found west of the Skelton Glacier.

A similar threshold effect occurs at the heads of the Taylor and Ferrar Glaciers. Extensive ice falls break the upper slopes of the glaciers, whilst the plateau ice flowing towards the valley heads shows considerable undulating relief.

The volume of plateau ice flowing into the valleys is small and in the case of the Taylor Glacier is not sufficient to maintain a glacier extending to the coast. This glacier now terminates approximately 30 km. inland from the coast. Any further decrease in the level of the inland ice plateau would result in complete disruption of the supply of ice to the glacier. Ablation would then cause the Taylor Glacier to retreat to the threshold at the valley head.

At the heads of the Mackay Glacier (lat. 77° S.) and other trunk glaciers crossing the mountain chain the rock threshold is much lower or is absent and plateau ice still flows unhindered through the valleys.

Glacial History

Glacio-geomorphological evidence indicates that at least four glaciations* occurred in the Wright Valley and in the Victoria Valley system (Fig. 8). The *first* glaciation is represented by high-level glacial benches strewn with thin deposits of fine drift. The *second* glaciation is represented by a lower series of benches in the western reaches of the valleys and by subdued moraines on the middle reaches of the valley floors. Thick moraines of the last two glaciations overlie older deposits on the valley floors. Fluvio-glacial phenomena associated with the latter two glaciations have often resulted in the reworking of valley floor moraines into low flights of river terraces. This process continues to the present day.

The formation of the inland ice

For a similar physiographic setting in Greenland, Cailleux (1952) suggested that with a deterioration of climate, ice first accumulated on the high coastal ranges. The ice flowing inland from these ranges coalesced to form inland piedmont glaciers, which, with continued alimentation from the ranges, thickened to evolve into a continental ice sheet.

It is probable that a similar process occurred in the Victoria Land mountain ranges to produce the inland ice. The time interval between this onset of glaciation and the oldest glaciation discussed below is unknown.

First glaciation

During the oldest glaciation recognizable in the valleys inland ice spilled eastwards through the coastal ranges of Victoria Land into McMurdo Sound to join the Ross Ice Shelf. Downcutting at this initial stage established the course of the present valleys (Fig. 8).

Lowering of the plateau ice level and westward retreat of its margin due to decrease in snow accumulation caused mountain ranges and nunataks to emerge progressively farther inland. Plateau ice channelled eastwards between these ranges and nunataks, extending the downcutting of the valleys progressively farther inland towards their present limits. Continued lowering of the plateau ice level finally resulted in highlands piercing it near the valley heads. The *rock thresholds* gradually cut off the supply of plateau ice to the valleys, causing glaciers to lose their cutting power and eventually stagnate and retreat.

The 1,500 m. benches and accordant cirque floors bordering the Wright Valley and the valleys of the Victoria system, and the flat erosion surfaces of Dais and the Insel Range (Figs. 5 and 7) are remnants of the valley profiles cut during this glaciation. Sparse areas of weathered drift, now having no morainal form, lie on these erosion levels.

There is no evidence that the ice disappeared completely from the valleys at the end of this glaciation.

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* In this article the term "glaciation" includes both the advance by down-cutting glaciers followed by their retreat with the deposition of moraines, and the advance by down-cutting glaciers followed by stagnation. Thus, static ice masses may have remained in the valleys between successive glaciations.

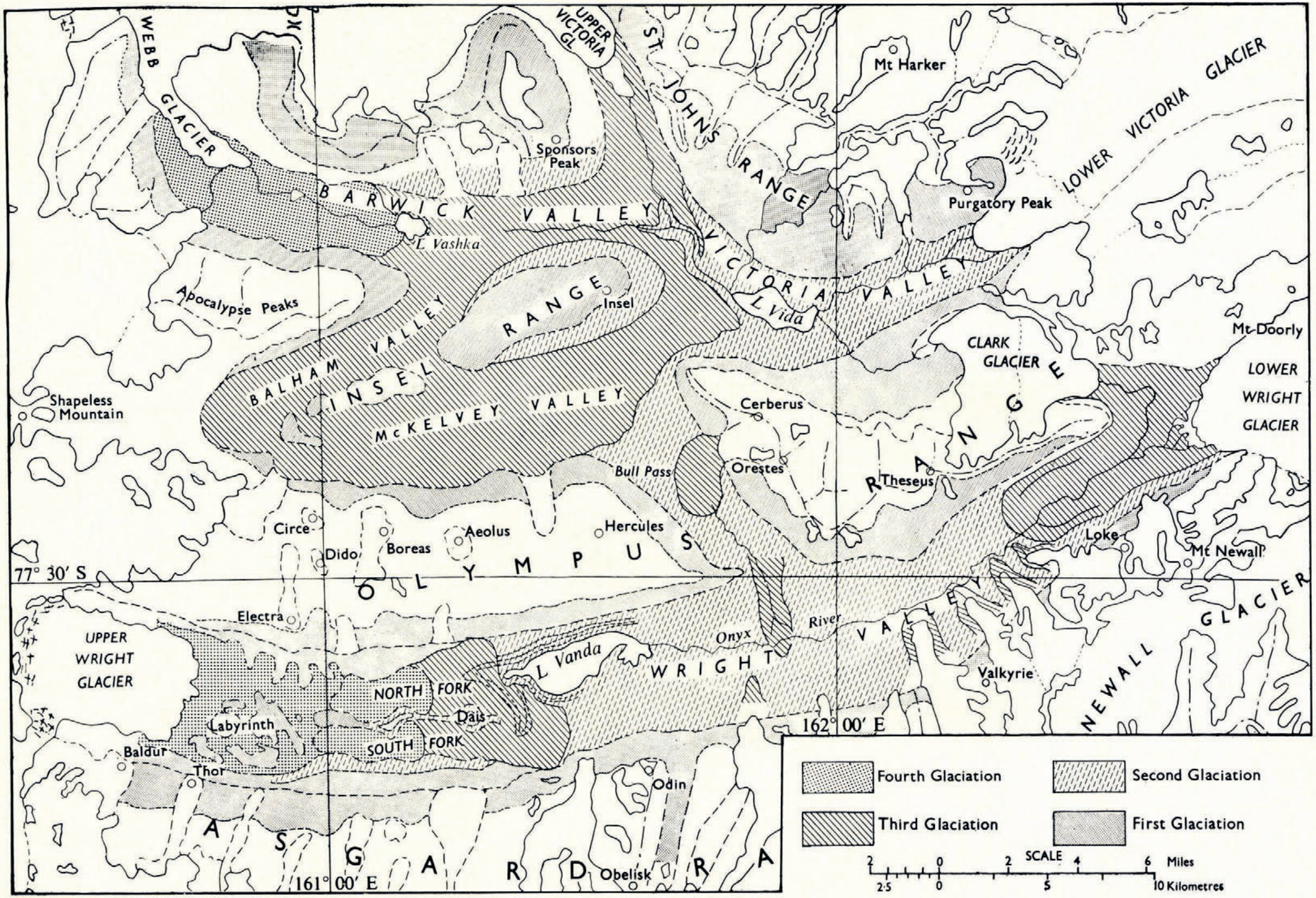

Fig. 8. Map showing the distribution of erosion surfaces, glacial benches and moraine deposits of the four glaciations proposed for the Wright Valley and Victoria Valley system

Second glaciation

An increase in plateau accumulation allowed plateau ice to cross the thresholds and rejuvenate the valley glaciers, which then recommenced downcutting. However, considerably less ice flowed into the valleys than in the *first glaciation*, so that they narrowed as the downcutting proceeded (Fig. 8). The valley glaciers were thinner and in some cases divided into smaller streams. The Wright Glacier divided into two streams on either side of Dais but re-united farther east and continued flowing to McMurdo Sound. Similarly, the thinning glacier occupying the Balham–McKelvey Valleys area was divided into two streams by the Insel Range. This glaciation is recorded by erosion benches at approximately 800 m. in the western Wright Valley and in the valleys of the Victoria system. Deposits formed during the final retreat of the valley glaciers are represented by a thin veneer of highly weathered moraine in the central parts of Wright Valley and the lower Victoria Valley. The moraine now comprises undulating coarse gravels scattered with boulders and extensive areas of dune sand. In the western and eastern ends of the Wright and the lower Victoria Valleys these moraines are overlain by younger glacial deposits.

Again, decrease in snow accumulation on the plateau resulted in a lowering of its surface level and the reappearance of *rock thresholds* at the valley heads. The Wright Glacier, now inadequately supplied by only the alpine glaciers from the Asgard and Olympus Ranges, became stagnant and its central part melted to form the ancestral Lake Vanda. The central part of the glacier in the Victoria Valley also melted to form the ancestral Lake Vida.

Third glaciation

This glaciation was much less extensive than the preceding two (Fig. 8). An increase in plateau accumulation caused ice to spill once more over the valley head thresholds. However, the volume of ice was sufficient to maintain a glacier in the Wright Valley extending only as far as the western shores of Lake Vanda and in the Victoria Valley system only as far as the eastern end of the Insel Range.

Extremely thick terminal, lateral and ground moraines of this glaciation extend from Lake Vanda westwards into the North and South Forks (Fig. 6).

At the eastern end of Wright Valley, the Lower Wright Glacier, fed by the Wilson Piedmont Glacier and the Clark Glacier, flowed westwards up Wright Valley to a point between Mt. Theseus and Mt. Loke (Fig. 5). Here thick terminal, lateral and ground moraines were deposited and these extend eastwards to the present snout of the Lower Wright Glacier (Fig. 4). During this glaciation alpine glaciers flowed from the Asgard and Olympus Ranges into the ice-free central part of the Wright Valley. These glaciers deposited loops of moraine over the deposits of the *second glaciation* (Fig. 5).

In the Victoria Valley system thick deposits of this *third glaciation* extend from the coastal end of the Insel Range along the floors of the McKelvey, Barwick, Upper Victoria and Balham Valleys. These moraines are the thickest in the area. They range from boulder fields to sand dune areas and desert pavements strewn with polished ventifacts. The moraines are hummocky and contain fresh and saline lakes. In many cases the lakes have evaporated to leave extensive salt deposits (Fig. 9).

The size of Lake Vanda at this time can be determined from the extent of the beaches cut in the moraine and scree around the lake (Fig. 6). The highest well-defined shoreline, 60 m. above present lake level, is cut in *second glaciation* moraine. This shoreline is continuous along the northern side of the lake, but it is not cut in the *third glaciation* terminal moraines at the western end of the lake. A pronounced lower shoreline, 20 m. above present lake level, *is* continuous in the terminal moraines of the *third glaciation*. Thus, at some time following the *second glaciation* but before the deposition of the *third glaciation* moraines, Lake Vanda was approximately 130 m. deep and possibly more than 20 km. in length. During the glacial retreat which followed the maximum advance of the *third glaciation*, the lake shallowed to approximately 90 m.

Fourth glaciation

A slight increase in plateau level and hence re-establishment of the ice supply over the threshold caused the Upper Wright and Webb Glaciers to rejuvenate and recommence downcutting.

Moraines of this glaciation occur in the western ends of the North and South Forks (Figs. 8 and 9) and between Lake Vashka and the present snout of the Webb Glacier. Ground moraines close to the sides and fronts of the Upper and Lower Victoria Glaciers, Lower Wright Glacier and the alpine glaciers may be contemporaneous with, or younger than, the *fourth glaciation*.

Fig. 9. View looking west along the South Fork of Wright Valley. The terminal moraine of the fourth glaciation borders an evaporite- and boulder-covered lake floor, occurring as a depression in third glaciation moraines

The moraines are coarse and angular, and lack ventifacts and sand dune areas. Frost heaving is extremely pronounced. A few frozen tarns and saline pools, often rimmed by salt encrustations, occur in these moraines. Following this *fourth glaciation* Lake Vanda has been lowered by evaporation and sublimation to its present depth of 70 m.

Climatic Factors

Measurements of the yearly heat balance have been made at Scott Base (Thompson and Macdonald, 1959) (lat. 78° 20′ S., long. 164° 30′ E.), at Mirnyy (Rusin, 1958) (lat. 66° 33′ S., long. 93° E.), and at Maudheim (Liljequist, 1956–57) (lat. 71° S., long. 9° W.). From these results it is calculated that with the cloud cover and temperatures which exist in the ice-free area, the heat lost by a snow-covered surface is about 4,000 cal. $cm.^{-2}$ $yr.^{-1}$, while at a rock surface (albedo 20 per cent) the heat gain is about 19,000 cal. $cm.^{-2}$ $yr.^{-1}$. At sea-level an ice surface will lose about 20 g. $cm.^{-2}$ by summer melting as long as the melt water can escape.

From the discussion of the glacial history it is recognized that recession and lowering of the inland plateau brought about both the disruption of major glaciers and the exposure of increasingly large areas of rock. In such conditions solar radiation can slowly ablate any remaining stagnant ice mass and ensure that the region does not become reglacierized, as long as the winter snow accumulation is not sufficient to substantially increase the mean albedo. Photographs taken at the end of five recent winters show that very little snow settles in the area, even on high land.

The Wilson Piedmont Glacier contrasts with the area farther west. Only a small number of nunataks protrude through the ice so that the area's albedo is high, the annual heat balance negative and the summer melting small.

Correlation of Glacial Phenomena

Harrington and McKellar (1958) have suggested that the Quaternary history of the Antarctic continent is similar to that of the Northern Hemisphere in having "several major glaciations separated by long interglacials".

Péwé (1960) has recorded evidence for at least four major Quaternary glaciations in the McMurdo Sound region, each successively less extensive than the former. The localities described by Péwé are all within 80 km. of Wright Valley, so that the Quaternary history should be broadly comparable with that of the area described above. In Table I the basic glacio-geomorphological criteria for distinguishing the glaciations in each area are cited and a tentative correlation with Péwé proposed. It must be emphasized, however, that minor fluctuations within each glaciation certainly occurred and that the late Quaternary history is considerably more complex than shown.

Age of Glacial Phenomena

It is not yet possible to date accurately the stages of glacial recession in this ice-free area, as little information of past Antarctic climatic variations and few useful absolute dates are available.

Hough (1950) has described a sea-bottom core from near Scott Island (lat. 68° 26′ S.) in the Ross Sea. From this he recognized marked climatic variations over the last 300,000 yr. and, with less certainty, climatic variations which could be traced back to 1,000,000 yr. ago, to fully span the Pleistocene.

Speden (1960), describing fluvio-glacial features from Cape Chocolate (lat. 77° 58′ S., long. 164° 35′ E.), suggests they are younger than 16,000 yr., having formed during a post-glacial "warm" period, stated by Hough as lasting from 15,000 to 6,000 yr. ago.

Péwé (1960) has dated algal deposits from ablation moraines (*Koettlitz Glaciation*) at the snout of the Hobbs Glacier as 5,900 ± 140 yr. old and from Garwood Valley as 2,480 ± 120 yr.

Glacio-geomorphological features, analogous to those described by Péwé (1960) and Speden (1960) (i.e. lake sediments, former lake shorelines, river terraces and ablation moraines), formed during and following the *fourth glaciation* of the Wright Valley and Victoria Valley system, and are perhaps contemporaneous with Hough's "warm" period (15,000 to 6,000 yr. ago) and Péwé's *Koettlitz Glaciation* (6,000 + yr. ago).

Investigations of other ice-free areas in eastern Antarctica indicate similar ages for late Quaternary deglacierization. Shumskiy (1957) has estimated that parts of the low-lying Bunger's Oasis area have been ice-free for more than 10,000 yr. and Tressler (1960) estimates that Clark Island (lat. 66° 30′ S., long. 110° E.) has been ice-free for 12,000 yr.

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TABLE I. GLACIAL HISTORY AND GLACIO-GEOMORPHOLOGICAL FEATURES

	McMurdo Sound Region (Péwé, 1960)		*Wright Valley and Victoria Valley System* (this paper)
KOETTLITZ GLACIATION	Advances by plateau glaciers and shelf ice were more extensive than advances by alpine glaciers. Ice-cored moraines with knob and kettle topography. Lake and delta silt beds common. Radiocarbon dating of dried algae from ablation moraine in front of Hobbs Glacier gives an age of 5,900 ± 140 yr., indicating a minimum age of 6,000 yr. for the Koettlitz Glaciation.	FOURTH GLACIATION	The *fourth glaciation* was characterized by minor advances of the plateau outlet glaciers in the western part of the area. The glaciation is represented by thick boulder moraines in which intense frost heaving is most apparent. Ventifact fields are not developed. Depressions in these moraines contain small ice lakes. Ground moraines close to the sides and snouts of present-day alpine glaciers and the Lower Wright and Victoria Glaciers may be contemporaneous with other *fourth glaciation* moraines.
FRYXELL GLACIATION	Fryxell Glaciation less extensive than preceding glaciations. Dissected moraines with well-developed ventifacts and glacial lake shorelines. Alpine glaciers expanded onto floor of Taylor Valley depositing moraine loops.	THIRD GLACIATION	Following the *second glaciation* land-locked lakes were reduced in area by evaporation and sublimation leaving the Wright-Victoria area largely deglacierized. The *third glaciation* was marked by glacier advances into the valleys from the inland ice plateau and from the Wilson Piedmont Glacier. Alpine glaciers descended from the ranges to the valley floors. This glaciation is represented by thick terminal and lateral moraines often covered with a surface veneer of ventifacts. Depressions in the moraine are filled by evaporite deposits and lake silts. Glacial melt lakes were less extensive compared with those associated with the preceding glaciation. Moraines of the *third glaciation* have been deeply dissected by later fluvio-glacial action.
TAYLOR GLACIATION	Subdued moraine blanket extending up to 1,000 ft. (330 m. approx.) above sea-level in Taylor Valley and other localities on the western side of McMurdo Sound. Well-developed ventifacts and desert pavements. Ice-dammed lakes left high shorelines and laminated silts.	SECOND GLACIATION	The second glaciation was less extensive than the preceding glaciation. However, as with *first glaciation*, plateau glaciers flowed through this area to McMurdo Sound. New glacier courses were cut and old ones further entrenched. Deposits of this glaciation are preserved as dune sands, gravels, polished boulders, ventifact fields and as scattered drift on erosion levels up to 800 m. (2,400 ft. approx.) above sea-level. During the retreat of the *second glaciation* ice-dammed lakes flooded the central parts of Wright Valley, cutting high-level lake shorelines.
McMURDO GLACIATION	Scattered and highly weathered drift with morainal form lying on deeply etched bedrock benches up to 3,000 ft. (1,000 m. approx.) in Taylor Valley and around McMurdo Sound.	FIRST GLACIATION	A major glaciation, responsible for the cutting of benches, accordant cirques and floors up to 1,500 m. (4,500 ft. approx.) above sea-level across the entire width of the present day deglacierized area. Sparse, highly abraded moraines lie on these levels. These features are prominently developed along the Asgard, Olympus and St. Johns Ranges, and on the tabular summits of Insel Range, Dais and Labyrinth. More recent glacial erosion has dissected these features at many localities.

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