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GEOLOGIC FEATURES DEMONSTRATING ARIDITY OF McMURDO SOUND AREA, ANTARCTICA

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ABSTRACT. Glaciological observations and meteorological data indicate that Antarctica as a whole is an arid region; it receives less than 15 g/cm^2 of precipitation in an average year. The following geological features indicate that the deglaciated valleys and coastal areas around McMurdo Sound are arid: dry kettles and small saline lakes, surface and subsurface efflorescences of salts, calcite-veneered fragments, and undrained lakes that have very small areas in comparison to their basins. An analysis of these features suggests that this part of Antarctica has been arid for thousands of years.

GLACIOLOGICAL AND METEOROLOGICAL DATA

Although little is yet known about precipitation in Antarctica, all measurements and calculations indicate that it receives only a small amount of precipitation.

Using measurements made by the Australian National Antarctic Research Expeditions, Mellor (1959, p. 532) calculated the mean annual precipitation on 14,000,000 sq km of Antarctica to be 14 g/cm^2. Lister and Pratt (1959, p. 348), using data obtained by the Commonwealth Trans-Antarctic Expedition, calculated the annual net accumulation over the whole continent to be 13 g/cm^2. As the mean annual precipitation for Antarctica as a whole is approximately equal to the mean annual snow accumulation, the calculations of Mellor and Lister are in substantial agreement (see also Cameron and Goldthwait, 1961, p. 7-9). Earlier estimates of precipitation in Antarctica (Meinardus, 1938, p. 39-44; Loewe, 1957, p. 72-73) are somewhat lower.

Two stake fields were established at the Amundsen-Scott Station, South Pole, Antarctica, to permit the gathering of data on snow accumulation. A 50-stake field in which the stakes were relatively close together was set out near the station, and a 42-stake field in which the stakes were more widely distributed was set out about a mile from the station. Table 1 gives the snow-accumulation data.

TABLE 1

Snow-accumulation measurements at South Pole, Antarctica*

Average Annual Accumulation	42-stake Field	50-stake Field
November 10, 1959 to November 2, 1960	20.4 cm	24.2 cm
November 5, 1958 to November 2, 1960	18.47 cm	23.35 cm

* "October 1960 SITREP," Radio dispatch from Amundsen-Scott Station, November 5, 1960, on file at Polar Meteorological Research Project, U. S. Weather Bureau, Washington, D. C.

If 0.362 is taken as the mean density of the accumulated snow at the South Pole,[1] the average annual accumulation for the 42-stake field for the 2-year interval was 6.69 g/cm², that for the 50-stake field 8.45 g/cm².

Table 2 shows instrumental data for precipitation at the U. S. Navy Installation at McMurdo Sound, Antarctica.

TABLE 2

Precipitation at U. S. Navy Installation, McMurdo Sound, Antarctica*

Year	Water Equivalent
1957	17.45 g/cm² E
1958	6.05 g/cm² E
1959	6.63 g/cm² E
	E = estimated

* Unpublished data taken by U. S. Navy and supplied by the U. S. Weather Bureau.

The most arid region of the United States (southeastern California, southwestern Arizona, and western Nevada) receives approximately 12 cm of rainfall per year (Visher, 1954, p. 197), a figure comparable to the amount of precipitation that the Antarctic as a whole receives. The Antarctic is, therefore, from the point of view of deficient precipitation, also arid.

KETTLES AND SALINE PONDS

In view of glaciological and meteorological evidence for aridity in Antarctica as a whole, it is not surprising that geological features indicate long-continued aridity in the area around McMurdo Sound.

Kettles are common on the south side of the Wright Valley at approximately 1000 feet above sealevel in an area that extends westward from the western terminus of the Lower Wright Glacier for about 2 miles (77° 30′ S Lat, 162° 30′ E Long) (fig. 1). The largest one measured is approximately 1000 feet long, 500 feet wide, and 15 feet deep. Some kettles contain small undrained ponds, but most are dry. Lacustrine terraces, deltas, algal peat, calcite-veneered fragments, salinas, black muds, and outlet channels with boulder pavements prove that most of them have contained ponds. These ponds were fed at their high-level stages mainly by meltwater from the Lower Wright Glacier. When this source of water was cut off following glacial retreat, the ponds decreased rapidly in size, ceased to overflow, became increasingly saline, and finally most of them dried up.

A saline pond approximately 25 feet long, 10 feet wide, and 1 foot deep with no outlet occupies one kettle. U. S. Navy aerial photographs show that it varies in size from time to time as would be expected because of the absence of an outlet. Faint terraces prove that at one time it was as much as 400 feet long, 150 feet wide, and 6 feet deep. As no rain has ever been reported from this part of Antarctica (Simpson, 1919, p. 159), the pond is probably fed only by meltwater from snow, which is precipitated and which drifts into its drainage basin, and by meltwater derived from the active zone (the zone above

[1] Figure based upon the work of M. Giovinetto, glaciologist at Amundsen-Scott Station, South Pole, Antarctica, during 1958.

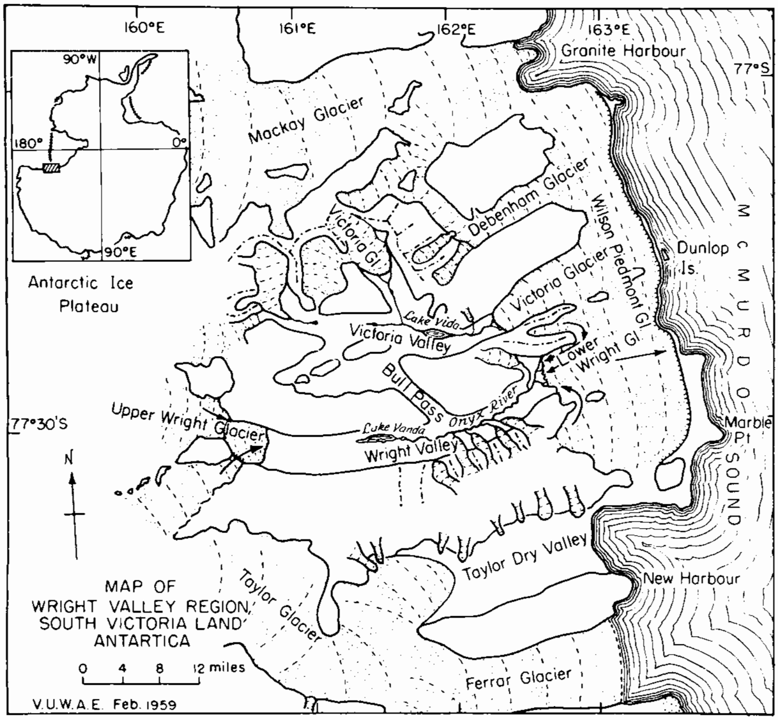


Fig. 1. Map showing the deglaciated valleys and coastal areas around McMurdo Sound, Antarctica.

permafrost that melts during warm periods). The water is not potable. Table 3 gives an analysis by the Water Analysis Laboratory of Metcalf and Eddy, Engineers. Boston, Massachusetts.

TABLE 3

Analysis of water from a saline pond, McMurdo Sound area, Antarctica

Substance	mg/l
Calcium as Ca	1,130
Magnesium as Mg	4,890
Sodium as Na	33,200
Sulfates as SO_4	16,150
Chlorides as Cl	58,000
Bicarbonates as CO_3	330
Sulfides as S	less than 0.1
Dissolved solids	132,620
pH	7.8

The salt concentration is approximately four times that of sea water. The principal dissolved salt is NaCl. $MgCl_2$, $CaSO_4$. $MgSO_4$, and $CaCO_3$ are also present. The salts probably originated in the same way as did those in a saline pond at Marble Point. Antarctica (Ball and Nichols. 1960, p. 1703-1704). and those in the saline lakes on Ross Island (David and Priestley, 1914, p. 147-148).

Very soluble white salts veneer an area approximately 250 feet long and 50 feet wide immediately around the present-day pond. The veneer has a maximum thickness of ¼ inch. It is not found at the bottom of the pond. Parts of algae projecting above the surface of the pond are covered with the white salts, whereas those parts beneath the surface are not covered. These facts, and the analysis, show that the water in the pond is not saturated with salts. The veneer owes its origin to the evaporation of water brought to the surface by capillarity in the lake sediments immediately adjacent to the saline pond.

Gray calcite encrusts the rock fragments immediately upslope from the white salts and some distance below the highest lake terraces. In general the encrustation adheres strongly to the fragments. It is commonly less than 1/16 of an inch thick, but globular masses in places are as much as ⅛ of an inch in diameter. It is found on those parts of the fragments that are above ground level and not on those parts that are buried. It is found on fragments that barely project above ground level and on blocks 3 and more feet above ground level. The distribution of the encrustation proves that it was precipitated when the water of the pond was saturated with calcium carbonate, after considerable desiccation had taken place but before the white salts were deposited. Such a sequence is normal, as carbonates are among the first salts to be precipitated when saline waters evaporate (Twenhofel, 1950, p. 376). Many other kettles in the Wright Valley have similar deposits.

Subsurface drainage of the kettles does not occur, since permafrost is only a few feet below the surface. The dry kettles and the saline ponds prove that evaporation is considerably greater than precipitation and that the climate is arid (Thornthwaite, 1948, p. 56).

The dissolved salts, the white salts, and the calcium carbonate did not begin to accumulate until the ponds ceased to overflow. Their abundance indicates that it took a considerable period of time to accumulate them and that the aridity, therefore, has had considerable duration.

The saline ponds and dried pond basins in the Wright Valley are not isolated examples. In the lower end of Miers Valley, McMurdo Sound, Péwé (1960, p. 512) has recorded a 2-inch-thick deposit of gypsum and a ¼-inch-thick layer of $CaCO_3$ which he thinks were perhaps deposited as Glacial Lake Trowbridge evaporated. David and Priestley (1909, p. 304, 319; 1914, p. 44, 152-155, 164, 166) have reported saline lakes and dried-up lake basins at Cape Royds and Cape Barne, Ross Island. Ball and Nichols (1960, p. 1703-1704) reported a saline lake at Marble Point, McMurdo Sound.

LAKE VANDA AND ITS BASIN

Lake Vanda, an undrained lake, occupies a bedrock basin in the Wright Valley approximately 17 miles west of the western terminus of the Lower Wright Glacier and 10 miles east of the eastern terminus of the Upper Wright Glacier (fig. 1). It is approximately 4 miles long and averages less than a mile in width. The Onyx River, which originates at the western terminus of the Lower Wright Glacier, is the only river that empties into Lake Vanda.

Undrained lakes are found only in arid regions where evaporation exceeds precipitation. They generally have small areas compared to their basins. The lakes in the Lahontan Basin of Nevada occupy approximately 1900 square miles, whereas the basin is approximately 45,000 square miles; the ratio of the two areas is approximately 1:24 (Broecker and Orr, 1958, p. 1029). Great Salt Lake in 1940 occupied about 1500 square miles, the basin about 54,000 square miles (Gilbert, 1890, p. 20), and the ratio was about 1:36. The Dead Sea is approximately 340 square miles in area, the basin approximately 10,000 square miles, and the ratio approximately 1:29 (Irwin, 1923, p. 430).

The area of the deglaciated part of the basin of Lake Vanda is considerably more than 50 times that of the lake (fig. 1). A reconnaissance study of Lake Vanda and an analysis of the U. S. Navy aerial photographs indicate that the Onyx River probably supplies more than 80 percent of the lake water. The Onyx River is fed almost entirely by meltwater from the Lower Wright Glacier and by tributaries fed by meltwater from the alpine glaciers on both sides of the valley. These facts indicate that if Lake Vanda were fed only by the present-day precipitation of the deglaciated area, the ratio of the area of Lake Vanda to that of its drainage basin would be a very large one. This high ratio indicates that the present-day precipitation yields no significant runoff and that the area is very arid. Lakes with similar ratios are found elsewhere in the McMurdo Sound area.

U. S. Navy aerial photographs and the writer's field observations (discontinuous snow cover in the winter, the scarcity of permanent snowdrift ice slabs, the disappearance of almost all the snow during the early part of the summer) indicate that the mean annual snowfall in the Wright Valley is very small. Potential evaporation is considerably in excess of precipitation, and the area is arid (Thornthwaite, 1948, p. 56).

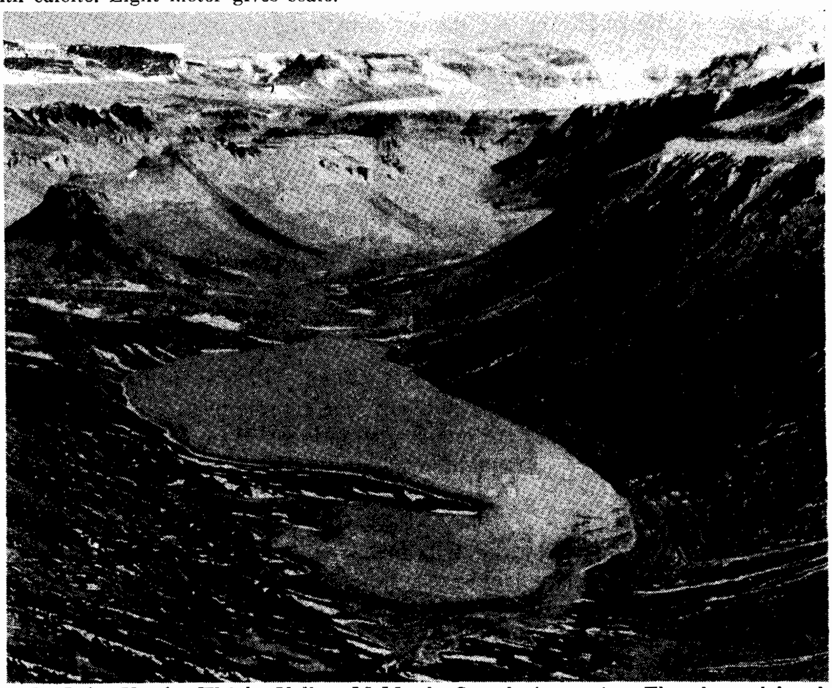
As it seldom if ever rains in the valley (Simpson, 1919, p. 159), and as the ablation is due mainly to evaporation of snow (Ball and Nichols, 1960, p. 1704), little water is added to the ground. The valley is therefore not only meteorologically arid but also arid from the point of view of soil-forming processes.

Elevated beaches, silty offshore lacustrine deposits, deltas, and lacustrine cliffs prove that Lake Vanda was once approximately 185 feet higher (pl. 1-B). These deposits are weathered about as much as the deposits of the youngest glaciation in the eastern end of the valley. The terminus of the Lower Wright Glacier has retreated approximately 5 miles since the full-bodied stage of the youngest glaciation. During this retreat the level of the lake dropped 185 feet primarily because, as the Lower Wright Glacier and the small alpine glaciers in the valley retreated, the area of ice in the zone of wastage progressively decreased and the amount of meltwater furnished to the lake from the glaciers therefore progressively decreased. The runoff from the annual precipitation that fell on the deglaciated areas in the Wright Valley during this interval was not great enough to maintain the size of the lake, and something like the present degree of aridity existed, therefore, during this interval.

A beach at Marble Point on McMurdo Sound (fig. 1) approximately 44 feet above sealevel is about 4450 $\pm$ 150 years old as determined by a C^{14} analysis (L-594. W. S. Broecker, personal communication). The highest beaches at Marble Point, approximately 66 feet above sealevel (Nichols, 1961a,

PLATE 1

A. A calcite-veneered diorite fragment at Marble Point, McMurdo Sound, Antarctica, which was partly buried in till until excavated. The part which was buried is veneered with calcite. Light meter gives scale.



B. Lake Vanda, Wright Valley, McMurdo Sound, Antarctica. The elevated beaches and lacustrine cliffs to the right of the lake extend 185 feet above it.

p. 67), are therefore perhaps 6000 to 7000 years old. The highest beaches at Marble Point on the basis of their degree of weathering roughly correlate with the deposits of the youngest glaciation in the eastern end of the Wright Valley and with the beaches above Lake Vanda. Something like the present degree of aridity has therefore existed for several thousand years in the Wright Valley.

Probably the Antarctic has been arid whenever the continental icecap has been about as large as it is at present.

VENEERS ON SUBSURFACE PORTIONS OF FRAGMENTS

The buried portions of many fragments at Marble Point and other deglaciated areas around McMurdo Sound have a thin, smooth veneer of gray calcite. The veneer stops abruptly at or near the surface of the ground (pl. 1-A). It is usually less than 1/16 of an inch thick. It has been found extending down as much as 25 inches. It coats granite, diorite, basalt, and other rocks and is found in till and in beach, outwash, and solifluction deposits.

For the formation of the veneer the following are necessary: (1) a source of $CaCO_3$; (2) water; (3) evaporation. Calcite-marble crops out at Marble Point and elsewhere in the area, and marble is undoubtedly present in both the coarse- and fine-grained fractions of the mantle-rock deposits. This marble probably is the source of most of the calcite coating. Melting snow and ice supply moisture. The veneer is formed in the active zone where water is present during the summer but not in the permafrost. If it had been found in the permafrost, it would have proved the existence of a climate warmer than that of the present. Although the air temperature rarely exceeds 40°F in these areas, soil temperatures of 70°F are undoubtedly reached at the surface of the ground. Evaporation is therefore effective.

The fact that the veneer is not found on the upper surfaces of the fragments and that the veneered fragments are not found where either ponds or streams exist proves that the veneer is not formed by the evaporation of surface water. The abrupt termination of the veneer at the ground level, the more or less uniform thickness of the veneer up to the ground level, and the fact that meltwater, which moves from the surface downward, tends to remove and not to concentrate calcite at and near the surface suggest that the veneer was formed mainly by the evaporation of water that moved upward in fine-grained sediments because of capillarity.

These veneers do not form in a wet climate, for the water in the soil moves mainly downward, and the soil does not commonly dry out. The concentration of salts at and near the surface of the ground due to evaporation of upward-moving water is common in arid and semiarid regions (Twenhofel, 1950, p. 39-41).

Millar, Turk, and Foth (1958, p. 437) have noted somewhat similar calcite-veneered fragments in the hot, arid regions of southwestern United States. They write: "Stones buried at shallow depths are coated on the underside with calcium carbonate, deposited by upward-moving water, and those at greater depths may be entirely covered with lime." Calcite-veneered stones completely buried in the active zone no doubt occur in the Antarctic. Stones identical to those in Antarctica are found in New Mexico and other semiarid areas in the United States. The veneer indicates that arid conditions existed in the McMurdo Sound area during the period of its formation.

The rate of formation of these calcite coatings is unknown. The small amount of precipitation in the area, the fact that the soil is frozen for most of the year, and measurements on the rate of solution of limestone in other parts of the world (Bryan, 1929, p. 207-208) suggest that hundreds of years were necessary for their formation. Overturned calcite-veneered fragments are common on solifluction lobes and sheets. None of these fragments had a veneer on the newly buried surfaces, indicating that the time necessary to form the veneer is much longer than the interval since the fragments were overturned.

SURFACE EFFLORESCENCES OF SALTS

A surface efflorescence is commonly found veneering till and outwash, beach, and lake deposits in the deglaciated areas around McMurdo Sound. It is usually very thin but in some places it is a few millimeters thick. It is friable, soft, soluble, and has a strong taste. In places it is approximately 50 percent halite ($NaCl$) and 50 percent thenardite (Na_2SO_4). The halite was probably derived from the ocean. The thenardite may have been formed by the action of H_2SO_4, resulting from the oxidation of pyrite, on minerals containing sodium (Ball and Nichols, 1960, p. 1703).

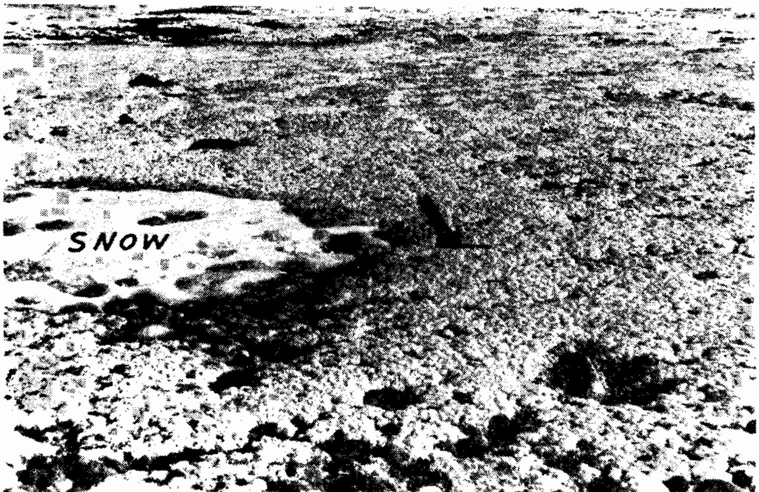
The most extensive occurrence seen by the writer covers somewhat less than an acre on the southeast corner of Dunlop Island (pl. 2-A). The salts are concentrated in roundish mammalary shapes a few inches in diameter and ½ inch to 1 inch high, on fine-grained sediments.

Although salts were deposited in the McMurdo Sound area by the evaporation of saline lakes, these salts were not deposited in this way because: (1) they are found on sloping areas where standing water could never have existed; (2) the absence of lacustrine terraces, sediments, basins, and other features indicates that ponds have never existed on the flat areas where the salts are found; (3) the surfaces of fragments that are lower than the salts are salt-free (pl. 2-A). Such a distribution would be expected if the salts were brought to the surface of the fine-grained sediments between the fragments by capillarity; it would not be expected if the salts were precipitated from saline lakes.

Phenomena resulting from bulldozing and excavating by the U. S. Navy Construction Battalion Reconnaissance Unit at Marble Point during the 1957-1958 and 1958-1959 field seasons support the idea that the salts were deposited by the evaporation of water that moved upward in fine-grained sediments due to capillary action. An efflorescence formed on freshly excavated, piled-up material. It could have been formed only by the evaporation, at the surface, of water which came from within the freshly bulldozed material.

Several areas 30 to 40 feet in diameter in the Wright Valley remain damp for most of the summer. The wetted material had a strong taste. The dampness resulted from the solution of thin surface efflorescences by meltwater from nearby patches of snow. The areas remain damp because of the low vapor pressure of the concentrated solutions. Most of them probably dry up by the end of the summer. These efflorescences indicate that the area is currently arid (Twenhofel, 1950, p. 488-489) and was arid during their formation and existence.

PLATE 2



A. A surface efflorescence at Dunlop Island, McMurdo Sound, Antarctica, formed by the evaporation of water which moved upward because of capillarity. There is snow to the left of the ice axe.

B. A subsurface efflorescence of salts in the Wright Valley, McMurdo Sound, Antarctica. The great solubility of the salts proves that the area has been arid since their formation.

SUBSURFACE EFFLORESCENCES OF SALTS

Recent field work by the writer indicates that a prominent end moraine approximately 8 miles up the Wright Valley from the western terminus of the Lower Wright Glacier (fig. 1) was formed by ice that moved westward up the valley from the coastal mountains during a glaciation that immediately preceded the youngest glaciation in the Lower Wright Valley. Glacial deposits roughly contemporaneous with the end moraine have a layer of white salts immediately below the surface of the ground. The salts are on the south valley wall above the end moraine and approximately 500 to 900 feet above the Onyx River.

The layer is 2 to 5 inches below the surface. Above it is 1 to 3 inches of yellow sand or granule-gravel, and above this 1 to 2 inches of deflation pavement. In places a layer of pure salts as much as 3 inches thick is present. In other places the salts impregnate and loosely consolidate 4 to 7 inches of silt, sand, and gravel. The layer varies in thickness from one part of a pit to another and from pit to pit, and it may be found in one pit but not in another. The salts are very soluble and white when pure (pl. 2-B). Prof. Cornelius S. Hurlbut, Jr., of Harvard University made an X-ray analysis and microscopic examination of some of the efflorescence and found it to be predominantly halite (NaCl).

The Water Analysis Laboratory of Metcalf and Eddy, Boston, Massachusetts, analyzed the salts and identified sodium chloride, sodium sulfate, magnesium sulfate, calicum sulfate, and calcium carbonate. Table 4 shows that sodium chloride and sodium sulfate are the principal salts.

TABLE 4

Analysis of a subsurface efflorescence in the Wright Valley, Antarctica

Substance	mg/l
Calcium as Ca	520
Magnesium as Mg	1,990
Sodium as Na	81,500
Alkalinity as CO_3	9.3
Sulfates as SO_4	38,750
Chloride as Cl	109,000

Yellow sand and gravel are found below the efflorescence. Similar subsurface caliche was found on both sides of the Onyx River in the vicinity of Bull Pass (fig. 1). It seems certain that further field work will show that it is widespread in the Wright Valley.

A small patch of the efflorescence is commonly found on the underside of stones where the layer is absent. The patch may be as much as 4 inches in diameter and is usually less than ¼ of an inch thick. It is found beneath stones that are buried a few inches beneath the surface as well as beneath those at the surface.

It is not known for certain how the white salts originated. Five possibilities suggest themselves. First, the salts may have been originally interbedded in the Beacon Group, which crops out in the Wright Valley (McKelvey and Webb, 1961, p. 546). Second, the salts may be related to volcanic activity (Palache, Berman, and Frondel, 1951, p. 5, 406). Two small cinder cones are found a few hundred yards from the white salts and cinder cones are found in the upper part of the Taylor Valley (Hamilton and Hayes, 1960, p. B376). Ross Island and Mount Discovery are of volcanic origin, and Mount Erebus is an active volcano. Third, the salts may have been concentrated by the freezing of salt water trapped in some way by the glacier that moved from McMurdo Sound up the Wright Valley (Nichols, 1961b) and transported from the ocean up the Wright Valley (Debenham, 1919). Fourth, an arm of the sea may have extended from McMurdo Sound up the Wright Valley during interglacial and/or interstadial time. This seems unlikely, however, as the elevated beaches in the McMurdo Sound area, all of which are related to the most recent glaciation, are less than 70 feet above sealevel (Nichols, 1961a, p. 57), and the bedrock threshold at the western end of the Wright Valley may be 1000 feet above sealevel (Colin Bull, Ohio State University, personal communication). Fifth, the salt may have been transported from McMurdo Sound up the Wright Valley as finely divided salt spray and/or salty snow by onshore winds (Jackson, 1905, p. 10-11).

Small patches of silty material of lacustrine origin prove that small ponds were once located on the slope where the white salts are found. The white salts are similar chemically to those that surround the saline ponds previously described. As these ponds must have been dammed by glacial ice, it is unlikely that they were ever saline, and it seems certain that the white salts were not formed by evaporation and precipitation in and around these small ponds.

It is certain that 3 inches of salts could not have been leached by downward-moving solutions from only 5 inches of deflation pavement and glacial deposits. Several feet of glacial deposits may have been removed by wind action in the formation of the deflation pavement. Numerous well developed ventifacts are found on the deflation pavement. More than 1 foot of rock has been removed by sand blasting in the formation of some of the larger ventifacts, and wind cutting took place as much as 3 to 4 feet above the ground. This suggests vigorous wind action, and it seems likely that the deflation pavement was formed not long after glacial retreat. It seems doubtful, therefore, that enough time was available for the formation of the white salts by the leaching by downward-moving solutions of the glacial deposits from which the deflation pavement was formed before their removal by the wind.

Because the surface efflorescence was formed by the evaporation of water that contained dissolved salts and moved upward by capillarity, it seems logical, especially in view of the failure of other mechanisms to explain the white salts, to consider whether this process was not also responsible for them. The presence of the white salts immediately beneath stones definitely favors this origin (Millar, Turk, and Foth, 1958, p. 437). Any upward-moving solutions and leaching must have occurred in thawed material. The active layer where the white salts are found is definitely less than 3 feet thick and probably less than 2 feet. Considering the density and thickness of the white salts and the chemical composition and intensity of weathering of the deposits below them, it seems extremely unlikely that the salts were derived from the leaching of material only a few feet thick. Perhaps the white salts were formed by upward-moving solutions when the active zone was thicker and the climate warmer than now.

The great solubility of the white salts regardless of their origin, however, proves that the area has been arid since the time of their formation, and their thickness demands a considerable period of time for their formation.

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