Journal of Glaciology, Vol. 27, No. 95, 1981

LARGE SALT BEDS ON THE SURFACE OF THE ROSS ICE SHELF NEAR BLACK ISLAND, ANTARCTICA

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ABSTRACT. An extensive system of mirabilite ($Na_2SO_4 \cdot 10H_2O$) beds has been mapped on the Ross Ice Shelf near Black Island. The salt beds are normally underlain by a thin layer of mud and their surface is covered by a non-marine algal mat and boulder lag. These authors suggest the salt has been formed by the displacement of sub-ice-shelf brines to the ice-shelf surface. Evidence also suggests that other terrestrial mirabilite beds in the McMurdo Sound area were formed in the same manner and deposited by the Ross Ice Shelf during its Wisconsin retreat from McMurdo Sound. Mirabilite salt in the dry valleys, southern Victoria Land, may have also originated from melt waters which dissolved ice-shelf mirabilite beds.

RÉSUMÉ. *Grands bancs de sel á la surface du Ross Ice Shelf près de Black Island, en Antarctique.* Un système étendu de bancs de sel de Glauber ($Na_2SO_4 \cdot 10H_2O$) ont été cartographiés sur le Ross Ice Shelf près de Black Island. Les bancs de sel sont normalement supportés par un mince niveau de boue et leur surface est couverte par une natte d'algues non marines et un niveau de caillou. Les auteurs font l'hypothèse que la glace a été formée par le déplacement de la saumure sous-glaciaire jusqu'à la surface de la couverture de glace. On a aussi des preuves que d'autres barres terrestres de sel de Glauber dans la région de McMurdo Sound ont été formés de la même manière et déposés par le Ross Ice Shelf pendant son retrait du McMurdo Sound au Wisconsin. Les sels de Glauber dans les vallées sèches, au Sud de la Victoria Land, peuvent également avoir leur origine dans les eaux de fusion qui ont dissous les bancs de sel de Glauber de la couverture glaciaire.

ZUSAMMENFASSUNG. *Grosse Salzablagerungen auf der Oberfläche des Ross Ice Shelf nahe Black Island, Antarktika.* Ein ausgedehntes System von Mirabilit-Ablagerungen ($Na_2SO_4 \cdot 10H_2O$) wurde auf dem Ross Ice Shelf nahe Black Island kartiert. Die Salzablagerungen sind gewöhnlich von einer dünnen Schmutzschicht unterlagert; ihre Oberfläche ist mit nichtmarinen Algen und Gesteinsresten bedeckt. Die Verfasser vermuten, dass das Salz durch Verlagerung von Sole aus dem Eisuntergrund zur Oberfläche gebildet wurde. Auch andere Mirabilit-Vorkommen auf Böden der McMurdo-Sound-Region scheinen auf diese Weise entstanden und vom Ross Ice Shelf bei dessen Rückzug aus dem McMurdo Sound nach der Würm-Eiszeit abgelagert worden zu sein. Mirabilit-Salz in den Trockentälern von südlichem Victoria Land dürften ebenfalls aus Schmelzwassern entstanden sein, die Mirabilit-Ablagerungen des Schelfeises auflösten.

THE discovery of large mirabilite ($Na_2SO_4 \cdot 10H_2O$) beds up to 1 200 m long, 30 m wide, and 1 m deep on the surface of the western Ross Ice Shelf near Cape Spirit, Black Island (Fig. 1), may shed new light on continental mirabilite deposits. It is suggested that at least some of them, such as the deposits near Hobbs Glacier, southern Victoria Land, and at Cape Barne, Ross Island, reflect ice-shelf thicknesses during glacial periods. In Antarctica, mirabilite deposits occur in the McMurdo Sound area, the Kronprins Olav Kyst, and in the Vestfold Hills, Princess Elizabeth Land (Dort and Dort, 1972).

SITE DESCRIPTION—THE CAPE SPIRIT MIRABILITE BEDS

A fascinating topography of melt pools, ablated ice pinnacles, pressure ridges, and morainal belts covers the western Ross Ice Shelf near Black and White Islands, and Brown Peninsula. In many places, siliceous sponges, Bryzoa, and shells cover the surface. These are added to the base of the ice shelf by anchor ice which traps sea-floor sediments and floats upwards against the ice shelf. Wind ablation steadily brings these organisms and sediments to the surface. Bryzoan tubes attached to rocks indicate that some of the erratics reach the surface in the same manner (Debenham, 1920; Dayton and others, 1969). In the summer months of January and February streams flow on the ice-shelf surface. Debenham, in Scott's final expedition, traced some of these for 36 km. Individual streams are narrow (2–20 m wide) and where pressure

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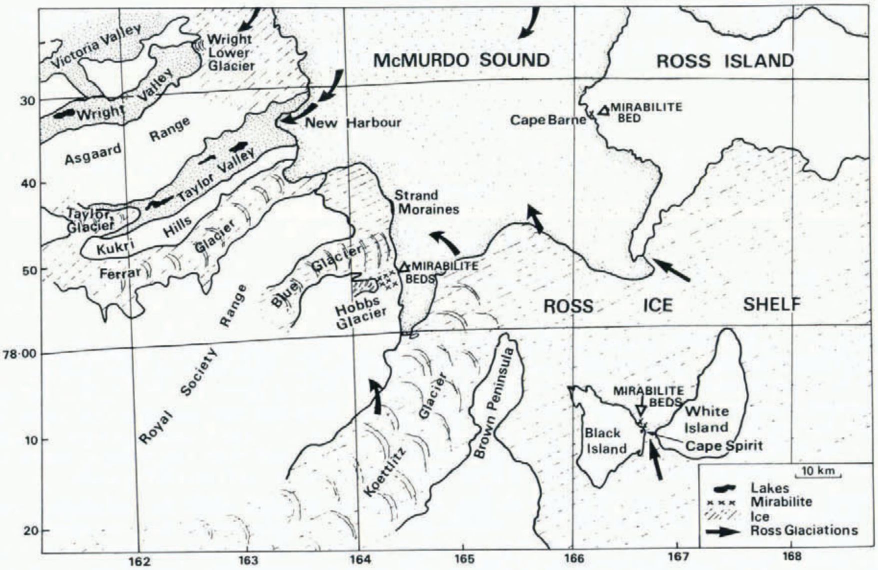

Fig. 1. McMurdo Sound and principal mirabilite deposits.

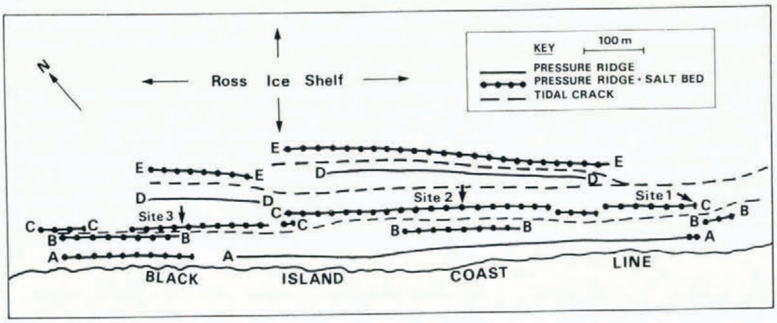

Fig. 2. The distribution of mirabilite beds near Cape Spirit, Black Island.

ridges are developed near land they flow parallel to the coast. Fresh-water algae abound in these pools and streams (West and West, 1911; Fritsch, 1917).

The Cape Spirit mirabilite beds are exposed on the surface of pressure ridges 20–250 m from the Black Island coast 800 m north-west of Cape Spirit. The pressure ridges, up to 7 m high, lie parallel to the coast. The pools between the pressure ridges are linked in channel systems during warm melt periods. The salt beds, varying in thickness from 60 to 102 cm, can be traced along three large pressure ridges (Fig. 2). In one place, site 3, it is clear that pressure ridges B and C are being formed along a tidal crack system which is dividing the salt bed. At site 3, the two ridges are 4 m apart and the salt bed has the appearance of a folded and faulted anticline. In the widening gap between the ridges, a new channel system is being formed and marine organisms are being carried to the surface.

Site stratigraphy

The Cape Spirit salt beds occur in an area 1 250 m by 200 m. The longest continuous bed is 750 m long, 2–30 m wide, and 60–102 cm thick, but it was once a continuous bed 1 250 m

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long prior to lateral displacement within ridge system B. It would be wrong to presume the salt bed is continuous over the 1 250 m by 200 m area but the salt bed is not simply confined to the three main ridge systems; a few salt-bed exposures lie elsewhere just above stream channel height. There could be ridge remnants isolated after faulting and lateral drift or they could indicate further separate salt beds still hidden underneath pool systems.

The Cape Spirit salt beds are often underlain by a thin bed of mud (0–8 cm) which itself directly overlies the ice-shelf surface. The salt beds are overlain by a boulder lag (0–30 cm) and a non-marine algal mat (0–26 cm). Figure 3 summarizes stratigraphical sections at sites 1–3.

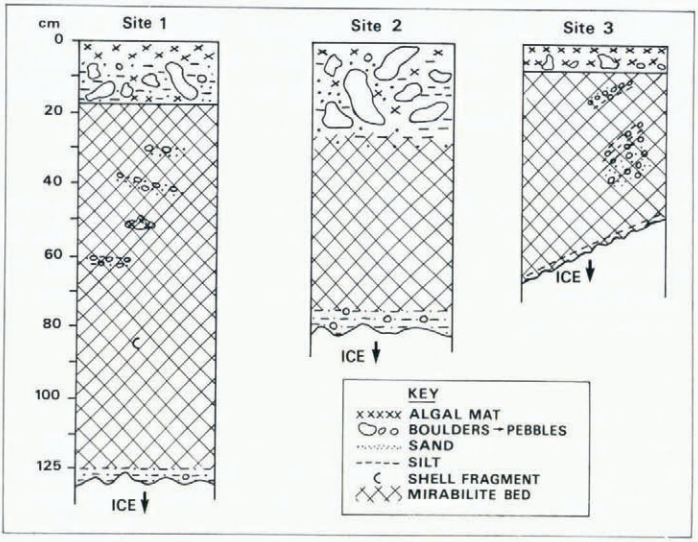

Fig. 3. Stratigraphic sections in the Cape Spirit mirabilite beds at the sites listed in Figure 2.

Basal ice

The surface of the underlying ice is not conformable with the salt beds for there are often small irregularities in its surface from 2 to 6 cm high. These control the thickness of the overlying sediment layer.

Sediment layer (0–8 cm)

The upper surface of the sediment layer forms a sharp conformable contact with the overlying salt bed, while the lower surface contours slight irregularities of the underlying ice surface. The sediment layer, devoid of internal bedding, consists of 80% glacial flour mixed with sand and small pebbles. The sand comprises volcanic rock fragments, angular grains of quartz and plagioclase, and shards of volcanic glass. One bryzoan fragment (<1 cm long) was recovered. The rare pebbles are basaltic; the largest measures 1.4 cm along its longest axis.

The sediment contains many fragments of marine diatoms and sponge spicules, $<10\ \mu$m. No species are identifiable, although most fragments come from large centric planktonic marine diatoms and some fragments belong to the *Thalassiothrix*/*Thalassionema* genera. The sponge spicules are badly preserved, often with iron-stained and weathered central canals. Some fragments are similar to those produced by one of the authors in the laboratory by repeated ice fracturing (paper in preparation by H. T. Brady). Non-marine diatom frustules and algal spores are absent from the four sediment samples inspected.

Salt layer

The salt bed is massive, consisting of coarse crystals of mirabilite; sometimes these crystals form large granules up to 95 mm across which are coated with anhydrous sodium sulphate powder when exposed to the air. Although there is no obvious bedding in the salt bed, small pods and stringers of pebbly sand occur. These are usually parallel or sub-parallel to the salt bed itself and vary in thickness from 0 to 12 cm. Broken shell fragments occur as rare isolated individual fragments.

When the salt is dissolved in distilled water, some fine mud and rare sand grains can be recovered. This mud, in three salt samples inspected, contains a perfectly preserved flora of non-marine diatoms. The five recovered species are: *Navicula cymatopleura* West and West, *Navicula shackletoni* West and West, *Nitzschia antarctica* (West and West) Baker, *Navicula seminulum* Grun, and *Tropidoneis laevissima* West and West. Some small marine diatom fragments also occur but these are poorly preserved; the only identifiable fragment was from *Nitzschia kerguelensis* (O'Meara) Hasle.

Boulder lag (0–30 cm)

The salt bed is covered by a lag of sediment, pebbles, cobbles, and boulders. The majority of these erratics, some of which are striated, come from the McMurdo alkaline volcanic province but there are some erratics of gneiss, granite, and sandstone from continental suites. This lag is mostly overlain by a non-marine algal mat but, in some places, the mat underlies or is mixed with the boulder lag.

Algal mat (0–26 cm)

The algal mat, which overlies the deposit, forms a compact and often continuous layer. One sample 4 m above the level of the pool-and-channel systems on pressure ridge C, site 1, yielded a radiocarbon age of 870 ± 70 years B.P. (Sydney University Radiocarbon Laboratory, sample SUA 842). The one radiocarbon age so far obtained cannot be used to date the whole algal mat, since algae are still growing in pools which lie on the salt deposit in small depressions. The algal mat contains non-marine diatoms but these are not as numerous as in nearby pools on the present-day ice shelf. A high pH which re-cycles the silica of diatom frustules is consistent with massive non-marine algal production and may explain the scarcity of non-marine diatom fossils; pH values as high as 10.2 have been recorded in non-marine pools in the McMurdo Sound area (Armitage and House, 1962; Spurr, 1975).

Interpretation

Debenham (1920) suggested that the mirabilite he had observed on the Ross Ice Shelf was formed under the ice shelf by precipitation from brines. Anchor ice incorporated the salt into the ice shelf and it rose to the surface gradually as the surface ablated. Some small irregular pockets of mirabilite on the ice-shelf surface in this area could well be explained by Debenham's hypothesis but not the large beds near Black Island. It does not seem possible that such large linear beds of friable salt could be brought directly to the surface by anchor ice; furthermore, the salt beds contain non-marine diatoms which indicate surface precipitation. If mirabilite reaching the surface from basal anchor ice was re-worked and recrystallized in large beds on the ice-shelf surface, then one would expect the basal sediment layer which has fallen through the settling brines to contain non-marine diatoms from ice-shelf pools. One would also expect more re-worked surface sediment to be bedded with the salt. But the basal sediment contains only marine diatom and sponge-spicule fragments ($<10\ \mu m$), which could be carried in suspension in a sub-ice-shelf brine. Since non-marine diatoms have only settled in the salt itself, it would seem that the basal sediment layer was formed immediately after the injection of a sub-ice-shelf brine and prior to non-marine algal production in the brine pools.

Black and Bowser (1968) described 132 continental mirabilite deposits near Hobbs Glacier on the western coast of southern McMurdo Sound (Fig. 1). Radiocarbon dates of non-marine algae associated with these deposits range from 12 200±100 years B.P. These authors concluded that the mirabilite evaporated in surface non-marine pools but they regarded the ultimate source of the brines as unknown. Because the mirabilite is associated with volcanic erratics deposited by continental incursions of Koettlitz Glacier from McMurdo Sound (Péwé, 1960), they suggested a volcanic source for the mirabilite. However, no such salt beds have been discovered on Ross Island or near volcanic cones in southern Victoria Land which can be directly associated with volcanic activity. Since all deposits in the McMurdo Sound area can be associated with ice-shelf advances, it is logical to find the key to mirabilite deposition in ice-shelf processes themselves. The mirabilite deposits near Hobbs Glacier up to 200 m above sea-level and those near Cape Barne 24 m above sea-level are at altitudes consistent with former Ross Ice Shelf levels in McMurdo Sound (Denton and Borns, 1974).

Dort and Dort (1972) reviewed the literature on the McMurdo Sound and other continental mirabilites, and concluded that the salts were precipitated from sea-water stranded during the fall of high sea-levels. These authors simply applied the work of Nelson and Thompson (1954) on the crystallization of salts from freezing sea-water to the McMurdo Sound mirabilites. It is possible to precipitate mirabilite from brines after 88% of the sea-water has frozen between the temperatures of −8.9°C and −22.9°C. These authors agree that mirabilite is formed in this manner but disagree with Dort and Dort's suggestions about high sea-levels and stranded sea-water. Since mirabilite can form in large quantities on an ice-shelf surface, it is not necessary to invoke high sea-levels at all.

These authors suggest that massive mirabilite beds near Black Island are formed after the direct injection of sub-ice-shelf brines to the surface. The beds are deposited on a pre-existing ice-shelf surface as the basal sediment layer contours the basal ice. This sediment layer only contains small marine diatom and sponge-spicule fragments with a size consistent with suspended particles. The salt bed contains non-marine diatoms that have settled in the crystallizing brines from subsequent non-marine algal production from large productive surface pools. Mirabilite brines (density *c.* 1.4 g cm^{-3}) could be displaced from underneath a less dense but extensive ice body. This requirement can be met by a grounded and moving ice shelf forcing pockets of basal brines through crevasses or tidal cracks to its surface. The Ross Ice Shelf has moved eastward from McMurdo Sound through continental areas that were not directly glaciated by the ice sheet further to the west. Such glaciations have been well documented by Péwé (1960), Bull and others (1962), Nichols (1964, 1971), Denton and others (1968, 1970), and Denton and Borns (1974). During the collapse of such a glaciation, discrete blocks of mirabilite carried by the intruding ice shelf would be stranded at heights consistent with ice-shelf thickness. Stagnant remnants of previous glaciations such as the Strand Moraines in western McMurdo Sound or Lower Wright Glacier would release mirabilite spasmodically in melt waters whenever it is exposed either on their surfaces or at their termini but salt would normally be absent in these streams. It is not surprising that sulphur-isotope ratios from mirabilite and gypsum associated with Lake Vanda in Wright Valley indicate a marine origin of sulphate (Nakai and others, 1975). Such salts do not prove high sea-levels or isostatic rebound, because they could originate in melt waters from Ross glaciations mapped in easternmost Wright Valley (Bull and others, 1962; Nichols, 1964, 1971).

Because isotope fractionation occurs during sea-ice formation, deuterium values were obtained from ice samples taken directly below the mirabilite beds and from the water of hydration trapped in the mirabilite crystal ($10H_2O$). The presence of marine fossils on the ice-shelf surface suggests that the ice shelf at this location now consists of frozen sea-water. Using the fractionation factor of Craig and Horn (1968) for the concentration of deuterium in ice from frozen sea-water ($\alpha_D = 1.002\,65$), we obtained a theoretical value, assuming perfect fractionation in equilibrium conditions, of +20. Our values for ice samples under the mirabilite deposits at 128 and 141 cm, site 1 (cf. Fig. 3), are +10, +19, and +21, +14, +27.4, respectively. These values are consistent with a sea-water origin for such ice. Furthermore, deuterium values of lake ice in the southern Victoria Land area are much lower, e.g. −210 for Lake Fryxell, −150 for Don Juan Pond (Matsubaya and others, 1979). If mirabilite crystallized from the saline terrestrial lakes of southern Victoria Land (even if it had originally come from sea-water) or if it was simply dissolved and crystallized from glacial melt waters, we would expect the water of hydration trapped in the salt crystal to show these very negative values. Such is not the case. Our readings of −27.8 and −32.0 δ_D (w.r.t. SMOW) indicate a direct sea-water origin after a substantial amount of sea-water is frozen.

In our hypothesis, the Cape Spirit mirabilite beds were formed after the brine beneath the ice shelf has been displaced to its surface. Because the basal growth of the ice shelf was due to sea-water, the sub-ice-shelf brine has a sea-water origin. When the ice shelf grounds over the irregular sea floor, the trapped brines are displaced to the ice-shelf surface due to the weight of a large area of the ice shelf. If these brines immediately precipitate mirabilite, prior to dilution from snow, the deuterium values of the water of hydration in mirabilite should reflect those in the original brine.

Using Dansgaard's (1964) equation for deuterium fractionation in a two-phase system, presuming immediate removal of the second phase, we obtain δ_D (w.r.t. SMOW) values of −25, −34, −45, and −65 in the sea-water brine after 20, 50, 70, and 80% of the original sea-water has been frozen. Nelson and Thompson (1954) have shown that mirabilite precipitates from sea-water after 88% has been frozen. In this case, assuming maximum fractionation, the water of hydration of the mirabilite should reflect δ_D values near −65. But, if an ice–water equilibrium is first established, then the δ_D values of the sea-water will not be as low as −65. In nature the actual values lie between those formed in perfect equilibrium and those formed by the rapid removal of the second phase from the system (Dansgaard, 1964). Our δ_D values of −27.8 and −32 are therefore consistent with crystallization from a sub-ice-shelf brine in natural conditions.

The radiocarbon dates from the algal mats associated with mirabilite beds in the McMurdo Sound area range from 12 200±1 000 years B.P. near Hobbs Glacier (Black and Bowser, 1968) to 870±70 years B.P. near Black Island (this paper). Although the algal mats may often post-date the mirabilite beds, the existence of non-marine diatoms in the Black Island deposit indicates contemporaneous non-marine algal production. The spread of dates may indicate that mirabilite formation is episodic near ice shelves as their grounding line waxes and wanes.

The surface boulder lag covering the Cape Spirit salt beds could not have been present when the mirabilite was deposited as it is not found within the salt bed. Today the boulders, cobbles, pebbles, and sediment exposed on pressure ridges are continually collapsing into the adjacent pools and channel systems. In such a mobile system, boulders could be moved and deposited on the mirabilite or on overlying algal mats. The present model suggests that the precipitation of mirabilite is rapid due to the scarcity of algal mat within the salt, while the deposition of the overlying algal mats and boulders could occur over a long period of time (hundreds or even thousands of years). During this time the salt bed is divided laterally parallel to the coast as new tidal crack systems develop. While this lateral displacement is proceeding, boulders brought into the new channel system by anchor ice together with algae from overlying pools are gradually added to the surface.

Conclusions

1. Brines were formed underneath an ice shelf from freezing sea-water.

2. These brines were displaced to the ice-shelf surface by the weight of a large area of the ice shelf as it grounded.

3. Fine marine sediment carried in suspension by these brines settled to form an irregular thin discontinuous sediment layer containing marine diatoms.

4. Mirabilite salt crystallized from this brine and the δ_D (w.r.t. SMOW) of the water of hydration of this salt indicates a brine formed from freezing sea-water without significant dilution of the deuterium ratio by Antarctic snow or terrestrial glacial water.

5. During precipitation of these massive mirabilite beds, some non-marine diatoms which can tolerate the high salt content of Antarctic saline lakes were deposited with the salt.

6. After the deposition of the mirabilite, massive non-marine algal production occurred, forming a thick irregular mat up to 26 cm thick on the mirabilite surface.

7. Although only one algal sample has been dated (842 years B.P.), these algal mats have probably formed at different times depending on the local topography of surface pools which is changed continually by pressure-ridge formation.

8. Tidal cracks between pressure ridges have formed long faults in the original massive Cape Spirit mirabilite beds. These faults run parallel to the coast. The addition of new ice within these tidal cracks has caused irregular lateral displacement of the mirabilite beds.

9. Mirabilite beds lying on the Ross Island coast near Cape Barne and on the mainland near Hobbs Glacier were formed in the same manner as those at Cape Spirit. They were stranded on the coast as the ice shelf retreated to its present position in the south of McMurdo Sound during the post-Wisconsin interglacial period.

10. These processes of mirabilite formation may not only occur during ice ages but at any time if a section of an ice shelf undergoing basal freezing grounds and basal brines can be displaced to the surface through crevasses or tidal cracks.

11. Similar mirabilite beds may have been carried into the dry valleys of southern Victoria Land by the grounded ice shelves of the Ross glaciations.

ACKNOWLEDGEMENTS

This research was supported by the National Science Foundation of the United States of America, Grant OPP-74-22894 directed by P. N. Webb, Northern Illinois University. We thank M. Leckie and R. White of Northern Illinois University for assistance in mapping the salt beds and B. Roberts of Macquarie University, Sydney, for mass-spectrophotometer analyses.

MS. received 10 May 1979 and in revised form 22 November 1979

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