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GEOTHERMAL ACTIVITY IN VICTORIA LAND, ANTARCTICA

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Abstract

Fumarolic ice towers and areas of steaming ground are the only surface manifestations of geothermal activity near the summits of Mounts Melbourne and Erebus, Victoria Land, Antarctica. The distribution, nature, and limited range of the geothermal features reflect the lack of liquid water in the normal environment of these volcanoes, where modes of heat transport are confined to conduction and convection of air and water vapour. Under such conditions, only localised occurrence of liquid water is considered possible.

Introduction

Victoria Land, Antarctica (Fig. 1, inset), includes considerable areas of Quaternary and late Tertiary volcanism (Warren 1969; Gair *et al.* 1969). However, only two volcanoes, Mounts Melbourne and Erebus, show signs of present day activity. Mt Erebus, on Ross Island, has long been known for its steam plume (Ross 1847), and present volcanism there has recently been documented (Giggenbach *et al.* 1973). The fumarolic ice towers are a conspicuous feature of thermal activity near its summit (David & Priestley 1914; Holdsworth & Ugolini 1965). Mt Melbourne, 350 km north of Ross Island, is also geothermally active and volcanic activity is likely to have occurred in the last few hundred years (Nathan & Schulte 1967; Adamson & Cavaney 1967).

An aerial infra-red survey in 1967 (Burge & Parker 1969) recorded very high temperatures within the crater of Mt Erebus, as would be expected if molten lava was present (Giggenbach *et al.* 1973). Anomalously high temperatures were also considered possible at Mt Morning, 130 km southwest of Mt Erebus, but this has not been confirmed by ground survey. Elsewhere in Antarctica, fumarolic activity has been observed in mountains of Marie Byrd Land (LeMasurier & Wade 1968), and an eruption has recently occurred at Deception Island, off the coast of the Antarctic Peninsula (Shultz 1972).

In the summer of 1972–73, both Mt Erebus and Mt Melbourne were visited, and most geothermal features examined.

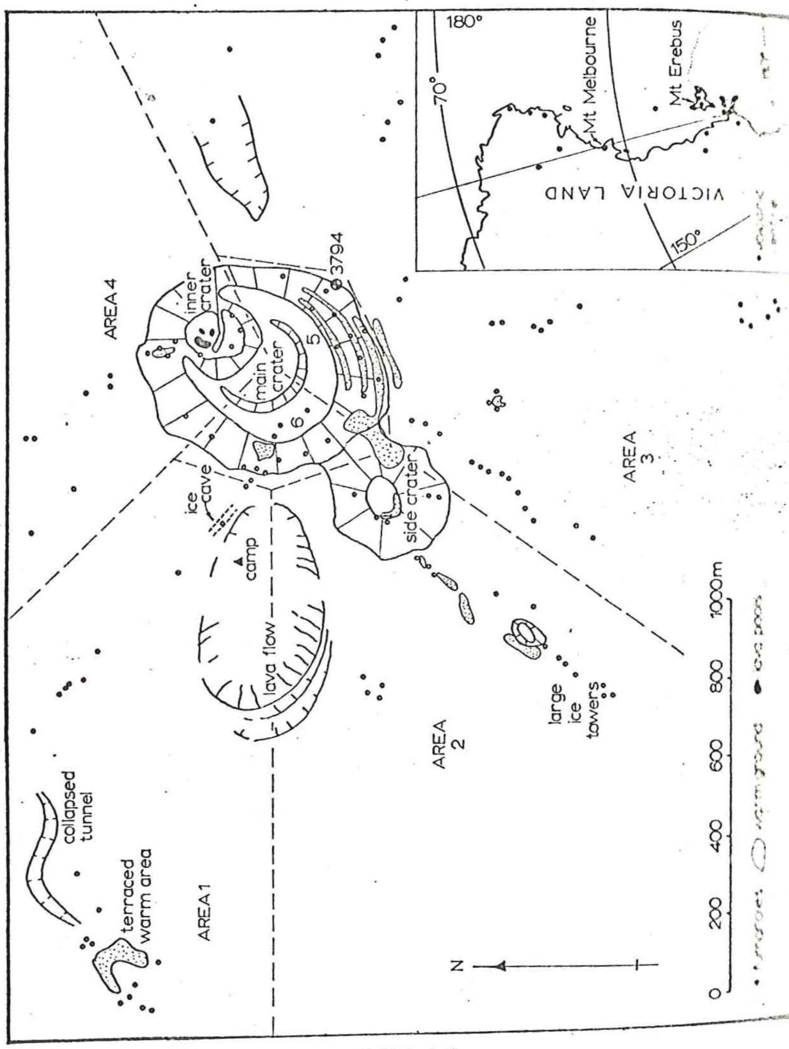
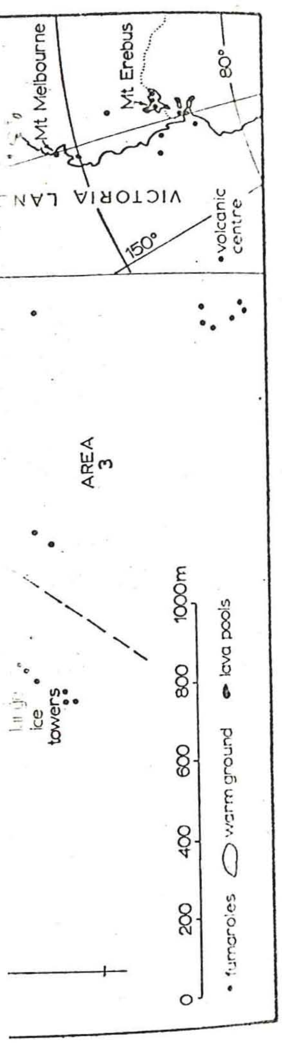


FIG. 1—The summit region of Mt Erebus, and the locations of Mt Erebus and Mt Melbourne (inset map). Ice towers are marked as fumaroles.



MOUNT EREBUS

Mt Erebus, latitude 77° 32′ S, longitude 167° 8′ E, rises to an altitude of 3794 m and is the dominant cone of Ross Island. The predominant rock type, and the only one which crops out near the summit, is anorthoclase phonolite. It is characterised by large (up to 10 cm) anorthoclase phenocrysts in a generally glassy matrix containing microphenocrysts of olivine, augite, and occasional incipient nepheline (P. R. Kyle pers. comm.).

The summit crater (Fig. 1) has a flat floor about 150 m below the lowest part of the crater rim, with the floor of an inner crater about 100 m further below at the north-east end of the main crater. Only the inner crater exhibits high temperature activity (Giggenbach *et al.* 1973). The initial relatively steep outer slopes of the main crater flatten to an extensive plateau at an altitude of about 3200–3500 m except on the south-east where the outer slope continues to drop steeply. Geothermal activity has been recorded on the plateau and the northern and western slopes of the summit crater (David & Priestley 1909; 1914; Holdsworth & Ugolini 1965; Ugolini 1967). Early visitors observed the conspicuous ice towers and recognised they were due to condensation of thermal vapours. (The term "ice pinnacle" as used by Nathan & Schulte (1967) is here restricted to ice features which are too small to be described as towers.)

Figure 1 shows all areas of warm ground and ice towers observed during this visit. Most of the ice towers irregularly scattered over the flatter parts of the plateau are not obviously associated with warm ground, but some, especially to the east of the crater, were not visited, and are only mapped from aerial photographs. Those aligned in groups on the slopes, however, are generally associated with warm ground. The flatter parts of the plateau have an irregular lava surface that, in many places, shows signs of collapse subsequent to surface solidification. For convenience of description, six main areas of thermal activity can be distinguished (Fig. 1).

Area 1

The ice towers to the north and north-west of the camp form a discontinuous line from the crater rim down about 300 m altitude to the most extensive warm area, which is probably the same as sample site E_3 of Ugolini (1967). This area is more than 100 m long, sloping to the south-west. Parts form terraces with a tread about 2–3 m and riser 1 m high (Fig. 2). On the riser of several terraces, green and red algal growth was found, at ground temperatures (close to the surface) of 42–43°C (red algae) and 34–36°C (green algae) and an air temperature of −21°C. At 0·15 m depth in the soft soil, below the algae, 65°C was recorded. When the area was visited, vapour was continually rising from the ground in the calm weather, and several large boulders scattered across the area were covered in frost. Nearby, a snow field terminating in an enclosed basin, with its lowest point beside the warm ground, forms a depression with subcircular crevasses, about 30 m diameter.

The ice tower nearest to the camp marks the highest point of an ice cavern about 10 m high and wide. The cave walls consist of downhill

FIG. 2—Terraces with algae at the warm area north-west of the camp on Mt Erebus.

sloping parallel bands of ash, lava, and ice from 0·05 to 1 m thick; volcanic debris fallen from the ceiling forms the floor. The cave slopes downwards from the point of entry both away from and towards the main crater. In the latter direction, the cave intersects the lava and ice bands at an angle of about 20°, penetrating successively deeper layers. The cave was investigated to about 100 m east of the entrance, to a point where the walls are made up of clean ice, without lava bands. The end of the cave was still out of sight; no smell of sulphur gases was noticed, and the air temperature was +1°C.

Area 2

Numerous small ice towers and areas of bare ground occur both inside and on the western slopes of the side crater. The southern-western alignment of these areas continues from the main crater past the side crater towards the sharp rim at the edge of the plateau (Fig. 3). Temperatures up to 36°C at 0·15 m depth were measured in open parts of the warm areas. A nearby depression shows signs of collapse as indicated by crevasses on its margins and is surfaced by smooth bubbly ice, while surrounding areas are hard snow sastrugi.

Further south-west, the rim of a nearly circular crater about 15 m wide and about 5 m high is partly covered by warm ground and low ice formations. Frost heave with ice crystals up to 0·3 m long, were found within 0.2 m of

FIG. 3—View south-west fro... in the foreground, depre... the background.

FIG. 3—View south-west from outside the side crater of Mt Erebus. Ice pinnacles in the foreground, depression on the right, the small crater and ice towers in the background.

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a measured temperature of 23°C at 0·15 m depth. The snow which fills this crater appears to be collapsing inward, presumably from melting or evaporation at its base.

A further twenty metres to the south-west of the small crater, the largest ice towers observed on Mt Erebus form part of a line of towers continuing to the plateau edge. The first three towers rise to about 5 m and are built up on top of 2-m-high mounds of rocks. No steam orifices were observed, though some towers were later seen from a distance to be steaming in calm weather. This line of towers is visible, in suitable lighting, from sea level near McMurdo Station more than 40 km away.

Area 3

To the south of the main crater an extensive area of warm ground has built up an almost continuous ice sheet cover, up to 0·3 m above the ground, with occasional vents forming ice pinnacles.

In two other areas to the east and south-east some ice towers are associated with snow-filled depressions. A large snow-filled valley, about 150 m wide, to the east of the main crater shows wide cracks in the ground suggesting collapse downslope into a hollow.

Area 4

Inside the main crater steam is emitted from warm ground, fumarolic ice towers, and the inner crater, often in amounts sufficient to obscure vision. The inner crater and its eruptive activity have been described elsewhere (Giggenbach *et al.* 1973). Several small (1 m high) cones of ice also occur outside the crater and these appear to be extinct ice towers, now eroding, as no warm temperatures were found related to them.

Area 5

On the south and south-east wall, three main horizontal bands of steaming ground consisting of loose, brown soil extend more than 200 m across the wall. They are separated by more solid lava layers covered with ice. On some of the cliffs, ice formations up to 3 m high have built up, and these are likely to collapse periodically, avalanching debris into the crater.

Area 6

The largest patch of warm ground within the main crater, below the cliffs of the western wall and at the top of an otherwise ice and snow-covered talus slope, links ice towers near the small escarpment on the floor of the main crater with the line of fumaroles and ice towers outside the crater. One of the authors (WFG) was lowered by means of a hand-operated winch to this area about 80 m below the crater rim. A steady flow of steam emanating from a small vent at 80·5°C was sampled. Later analysis showed that the discharge was mostly air and water vapour but with 2·5% carbon dioxide (by volume). No hydrogen, methane, or sulphur gases were detected. Near the steam vent were patches of emerald green moss, and part of the area appeared to be underlain by a crust of salt 50 mm below the soil surface.

FIG. 4—The summit region of Mt Melbourne.

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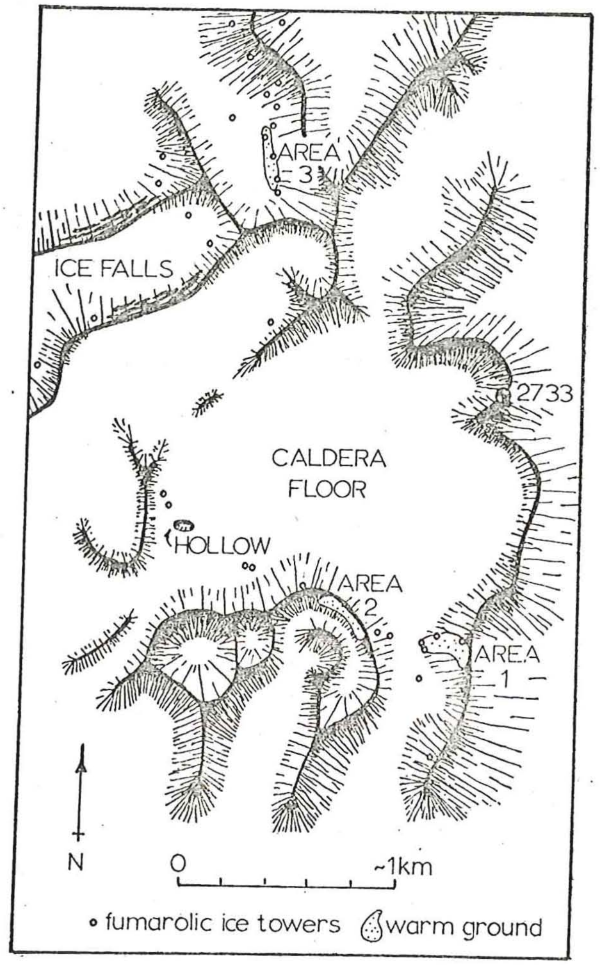

Fig. 4—The summit region of Mt Melbourne.

Mount Melbourne

The volcanic origin of Mt Melbourne (2733 m; latitude 74° 21′ S; longitude 164° 43′ E) was recognised by Ross (1847) when he recorded an "immense crater" in January 1841. Ice cliffs at its base and in nearby glaciers contain possible volcanic debris layers (Adamson & Cavaney 1967), indicating recent volcanic activity. The petrology of the volcanic rocks has been detailed by Nathan & Schulte (1968) as trachyte to trachyandesite on the mountain itself, with basalt at its base.

The thermal activity, as shown earlier by Nathan & Schulte (1967), is restricted to three main areas of warm or steaming ground with ice towers or pinnacles. At the summit, the caldera (Fig. 4) is about 1 km in diameter and forms the névé for a glacier flowing westward; it contains the two main areas of warm ground on the edge of the caldera, with a third area about 250 m lower on the northern slopes. Numerous isolated ice towers or pinnacles were also observed and most of these are marked in Fig. 4.

Area 1

Two patches, in the centre of this area (about 30 m^2) and near the south-east corner (10 m^2), are bare ground, and a temperature of 21°C was measured at a depth of about 0·15 m near several thin patches of yellow-green moss 0·1–0·3 m diameter. The remainder of the warm area is covered by low ice mounds and an irregular ice "roof" about 0·3 m above the ground, with numerous holes opening to the air; in calm weather steam was seen issuing from some vents.

The largest of three ice towers between areas 1 and 2 was found, when the wall was broken with an ice axe, to arise from a crevasse-like hole in the snow, at least 5 m deep.

Area 2

The warmest area on Mt Melbourne forms a low rim on the north to north-east sides of a young breached crater. It is about 100 m long and 10–20 m wide and is covered in part with low ice pinnacles and an ice "roof". Near some moss a temperature of 59°C was recorded about 0·25 m into a crack in the ground. Frost heave is common.

On the eastern wall of this crater some hydrothermally altered rock was observed, as were some brightly coloured hydrothermal alteration products on the southern wall of the western-most young crater.

An irregular line of ice pinnacles extends along the southern side of the main caldera to a hollow in the snow (5 m deep, 30 m wide), with the most vigorous fumarole further south, beyond an ice fall, about 100 m below the caldera.

Area 3

The largest ice tower on Mt Melbourne, about 7 m high, occupies the north end of a line of towers alongside the warm ground. This tower was only 2 m high in January 1967 (Nathan & Schulte 1967, fig. 5). A hole was broken into its wall and inside, where there was room for three or four people, a steady flow of steamy air of 38·5°C was issuing from the base of a 1-m-high bank of blocky lava. Behind this bank a low tunnel led to other ice-covered ground and small pinnacles up the slope. The strong localised heat flow caused water to drip from the inside walls, although at openings ice crystals condensed rapidly. Thirty metres to the north-west of the large tower a 5-m-diameter patch was covered with old hydrothermal sinter. It was near an ice tower about 100 m west of here that boiling or running water was heard beneath the surface in 1967 (Nathan & Schulte 1967; S. Nathan pers. comm.).

DISCUSSION

Surface manifestations of thermal activity at Mt Melbourne and Mt Erebus are restricted to areas of steaming ground and fumarolic ice towers. Geothermal features requiring the presence of liquid water are absent, indicating that convection of hot water as a means to transfer volcanic heat to the surface is not now available. Of the remaining possibilites for the maintenance of high temperature gradients (as indicated by a measured temperature difference of 85°C between air and 0·15 m depth), conduction can be of importance only in a few areas because of the low thermal conductivity of volcanic rocks. This is illustrated by the fact that rocks embedded in the soil of warm areas are often covered with frost.

The most probable heat transfer mechanism involves the movement of water vapour derived from snow or buried ice. A snow-field near the terraced warm area appears to flow into an enclosed basin. Snow from the lowest part of the field may be removed by partial melting and evaporation, with subsequent movement of water vapour to the surface, through sub-surface channels, where it is expelled through ice towers or pore spaces giving rise to warm and steaming ground.

Kiver & Mumma (1971) reported that the summit crater snow of Mt Rainier, Washington, U.S.A. is slowly collapsing due to removal of water carried as vapour through firn caves to the surface. Subsequently, Kiver & Lokey (1973) found a lake below the snow in the crater, formed by geothermal heat. It is possible that a similar lake exists on Mt Erebus; the ice cave to the north of the camp (Fig. 1) resembles the caves on Mt Rainier leading to the sub-surface crater lake.

The same conditions for the formation of a sub-surface reservoir of liquid water, by underground snow melt, exist at a depression and the small crater (area 2) on Mt Erebus, and at the hollow near the ice-fall outlet from the Mt Melbourne summit caldera. At each of these places, obvious slumping of snow has occurred giving rise to sub-circular crevasses as snow is removed from below and expelled through the ice tower orifices as water vapour. Many other ice towers occur over crevasses where warm vapours from melting or evaporating snow are being channelled to the surface. The ice towers on the plateau area of Mt Erebus are likely to be due to residual heat supplied by extensive lava flows. Lineaments similar in form and appearance to collapsed lava tubes, are common on Mt Erebus, especially on the western slope below the plateau, and may have formed by collapse after sub-surface removal of snow rather than lava.

Many of the ice towers have been considered extinct (Holdsworth & Parolini 1965) and indeed some appear to be eroded remnants, with no sign of orifices. However, observations of steam flow can only be made in calm, relatively humid weather as the steamy air being expelled is rapidly dispersed in the dry Antarctic air. Ice tower vents which were accessible released air without any smell of sulphur gases. This fact and the alignment of many vents, suggesting sub-surface connections, indicate that fresh air is probably entering in some vents and, after being warmed and taking up water vapour below the surface, it may be released through other vents. Convection would maintain circulation in calm weather. Formation of an ice tower will only occur at exits where warm saturated air comes in contact with cold surfaces and ice is precipitated. By contrast, little erosion will occur at inlets until the air is warmed. During windy periods however, the flow direction could be reversed leading to the build up of an ice tower at each end. This would account for the stream of warm vapour issuing from some ice towers and the absence of visible emission from others.

Where there is an absence of fissures allowing air to flow underground and to transfer heat, warm ground may develop on the suface. Such a surface will be steaming if water is available. The area inside the side crater of Mt Erebus has only a limited supply of water, and during our visit was not steaming. However, a photograph taken in 1965 shows that when fresh snow is lying nearby, this ground steams. Ice-free bare ground will occur if all the ground is at a temperature greater than 0°C, but if it is localised sufficiently for the 0°C isotherm to be nearby, water vapour will condense as ice crystals, and a pinnacle, tower, or low roof of ice can form over the warm ground. Large towers will only form where a base can be sustained and sufficient heat and air can flow to transfer the necessary amounts of water vapour. Isotopic analysis of snow, frost-heave crystals, and "roof ice" from warm ground near the small crater on Mt Erebus shows that all have similar deuterium contents (δD_{SMOW} values -260 to $-330‰$), confirming that the water vapour emitted from warm ground is local snow melt. During our visit, the inside walls of ice towers were often melting, but freezing and melting will vary on a diurnal and annual pattern as the ambient air temperature varies.

Warm ground in many places can be assumed to have been at relatively stable temperatures and moisture contents for considerable times as evidenced by the growth of moss. However, at Mt Melbourne, the largest tower was 7 m high in December 1972, as compared to 2 m in January 1967 (Nathan & Schulte 1967). Either the rate of steam flow changes, or a tower may periodically become too large and unstable and collapse, to re-build itself again later. Large local variation in the rate of heat flow is indicated by the presence of moss inside the crater of Mt Erebus only about 1 m from a steam jet. This flow consisted of air and water vapour with only a small amount of carbon dioxide. Its temperature, 80·5°C, was about 10°C below the boiling point for that altitude. The carbon dioxide content is about 100 times that of air and indicates a direct contribution from outgassing lava.

The bands of ice and steaming ground on the south wall of the crater of Mt Erebus also indicate that some layers are able to conduct heat, or transfer water or vapour, much better than other layers. The less efficiently conducting layers remain cold at the surface, allowing vapour emitted by other layers to condense and giving the appearance of bands of ice. This led David & Priestley (1914) to suggest that snow and lava were interbedded in the walls of the crater.

As stated above, we observed no liquid water on these volcanoes, although the possibility of its occurrence beneath the snow exists in some areas. Nathan & Schulte (1967) had reported hearing boiling water below the surface, but this is not present now. However, hydrothermal sinter was collected at Mt Melbourne at several places, indicating that hot aqueous thermal fluids have been present at some time in the past.

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