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The thermophilic bryoflora of Deception Island: unique plant communities as a criterion for designating an Antarctic Specially Protected Area

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Abstract: Deception Island in the South Shetland Islands is one of the most volcanically active sites south of 60°S. Between 1967 and 1970 three major eruptions devastated large expanses of the landscape and its vegetation. Since 1970 extensive recolonization has occurred on the more stable surfaces. Unheated ground supports several bryophyte and lichen communities typical of much of the Maritime Antarctic, but geothermal habitats possess remarkable associations of bryophytes, many of which are unknown or very rare elsewhere in the Antarctic. Nine geothermal sites and their vegetation are described. Communities associated with more transient sites have disappeared when the geothermal activity ceased. Mosses and liverworts occur to within a few centimetres of the vents where temperatures reach 90–95°C, while temperatures within adjacent moss turf can reach 35–50°C or more and remain consistently between 25 and 45°C. Most of the bryoflora has a Patagonian–Fuegian provenance.It is presumed that, unlike most species, the thermophiles are not pre-adapted to the Antarctic environment, being able to colonize only where the warm and humid conditions prevail. The floristic and ecological importance of these thermophilic communities, and their sensitivity to perturbation by the rapidly increasing annual summer influx of tourists, as well as scientists, has resulted in these unique sites being proposed as components of a new Antarctic Specially Protected Area under the Antarctic Treaty.

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Introduction

The Antarctic is defined geopolitically as all that part of the world south of 60°S. Almost all activities within the region are regulated through the Antarctic Treaty System. The Antarctic terrestrial biome comprises all land within that area, *c*. 14.5 million km^2, although less than 1% is ice-free. Biogeographically, there are two distinct zones. Biologically, Continental Antarctica includes all of the continental land mass except the western side of the Antarctic Peninsula north of *c.* 70°S; mean monthly summer air temperatures in coastal areas reach 0–1°C for only 1–2 months. The Maritime Antarctic is a much smaller region, and includes the western Antarctic Peninsula northwards from about 70°S and the island archipelagos of the South Shetland, South Orkney and South Sandwich islands, and Bouvetøya. Although the South Sandwich Islands and Bouvetøya lie between 54° and 59°S, their climate and biota are very similar to those of the more southerly island groups, and are therefore considered as being within the Maritime Antarctic. This zone has proportionately a much greater area of ice-free terrain than Continental Antarctica due to the milder and wetter climate with mean monthly summer air temperatures between 0 and 3°C extending over 3–5 months. Consequently, the flora of the maritime zone is much more diverse (*c*. 112 mosses, 27 liverworts) than the continental zone (*c.* 20 mosses, one liverwort) (Bednarek-Ochyra *et al*. 2000, Ochyra *et al.* in press).

In a global context geothermal areas provide an unique type of habitat for plants. The combination of heat, steam, substrate instability and often negligible nutrient concentrations or toxic levels of sulphurous gas and mineral deposits, impose severe constraints on colonising plants, few of which are adapted to survive such conditions. There are only six known active volcanic sites in the Antarctic (Fig. 1): three are high mountains in Victoria Land, continental Antarctica (Mount Erebus, Mount Melbourne, Mount Rittmann), each with fumaroles near their summits, and three are at low altitude in the northern Maritime Antarctic (Bouvetøya, most of the South Sandwich Islands, Deception Island) with fumaroles from sea level to their summits (Smith 2000). Each volcano has its own distinctive bryoflora and, in the case of the Maritime Antarctic sites, some lichens are also present. However, most of the bryophytes associated with fumaroles on Bouvetøya are typical of the unheated communities on the island, but grow much more luxuriantly (Bell & Blom 1986, Engelskjøn 1987).

Deception Island has had several eruptive episodes in the past two centuries (Roobol 1973, Baker *et al.* 1975, Smellie

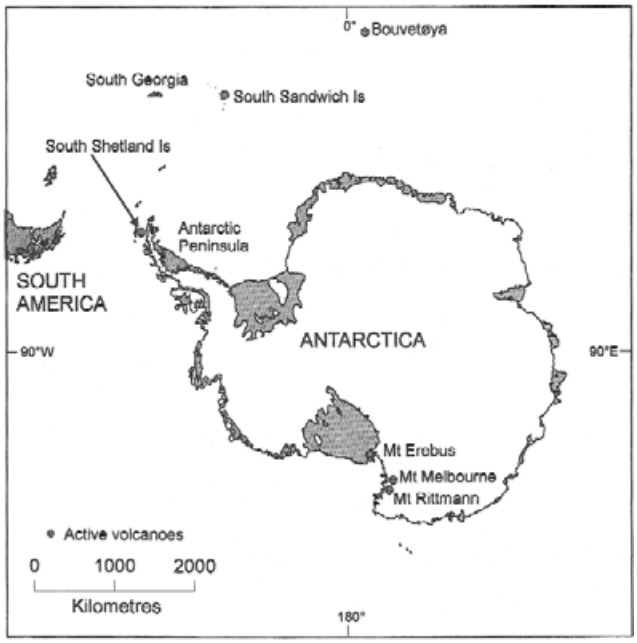

Fig. 1. Location of Deception Island (South Shetland Islands) and of all active volcanic sites in the Antarctic biome.

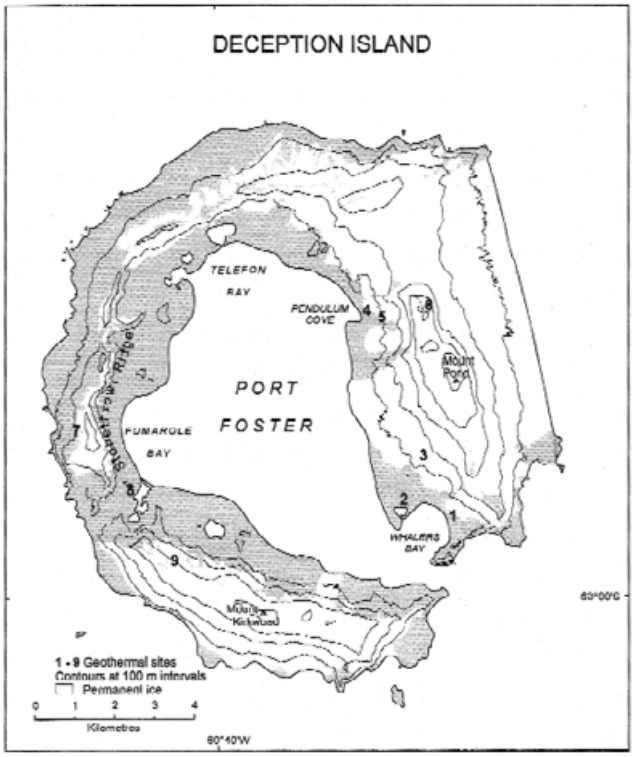

Fig. 2. Deception Island, showing location of the geothermal sites. Site 1 Whalers Bay, Site 2 Kroner Lake to Ronald Hill, Site 3 "Perchuć Cone", Site 4 Pendulum Cove beach terraces, Site 5 Pendulum Cove ridge, Site 6 Mount Pond summit ridge, Site 7 Western Stonethrow Ridge, Site 8 Summit above Fumarole Bay, Site 9 Between Mount Kirkwood and Mount Irizar.

2001, 2002). The most recent, between 1967 and 1970, altered many of the topographical features and created new and often transient surfaces for colonization by plants and other terrestrial biota (Collins 1969, Cameron & Benoit 1970, Young & Kläy 1971, Smith 1984a, 1984b, 1988). Of particular botanical interest is a number of sites of geothermal activity, some with fumaroles (Smellie *et al.* 2003), and it is the bryoflora of these, and the thermal regime of some of their communities, that are reported here.

Study area

Deception Island (62°57'S, 60°38'W) lies in Bransfield Strait, south-west South Shetland Islands, 100 km north of the Antarctic Peninsula (Fig. 1). It is an active volcano with recent eruptions in 1967, 1969 and 1970 (Baker *et al.* 1975). The horseshoe-shaped flooded caldera encloses a large bay (Port Foster). The island is 15 km in maximum diameter, rising to 539 m at Mount Pond, and 452 m at Mount Kirkwood, both summits being covered by permanent ice. About 57% of the island is covered by ice caps, glaciers and ice-cored moraines and pyroclasts. Its climate is typical of the northern Maritime Antarctic with a long cold summer with mean monthly air temperatures of 0–2.5°C from November–March and 0 to -10°C from April–October. Precipitation throughout the year (*c.* 900 mm) is mainly as snow, but summer rainfall, fog and low cloud are frequent. The island experiences little sunshine and frequent strong winds.

The island has been of considerable commercial and scientific interest since its discovery in 1820 (Headland 2002). On the south-eastern shore of Port Foster a Norwegian whaling station operated from 1912–31 (Hacquebord 1992). Post-Second World War research stations were established on the shore of Port Foster by United Kingdom (1944), Argentina (1947) and Chile (1955), although the UK and Chilean stations were destroyed by the eruptions of 1967 and 1969; in 1989 a Spanish research station was erected near the Argentine station. Some degree of legal protection was given to ecologically and floristically important sites that were potentially vulnerable to human impact when, in 1985, five small Sites of Special Scientific Interest (SSSI 21A-E, Anon 2003) were designated by the Antarctic Treaty.

Besides its scientific and historical values, Deception Island has, in recent years, become a major tourist attraction, being the most visited site in the Antarctic, with almost 15 000 person-landings made at four sites (in 2003; www.iaato.org.). Because of the sensitivity to perturbation of terrestrial habitats and vegetation, as well as potential for damage to historic features, it was recognized that an integrated strategy was required for the management of all activities on the island. In 2002 an international expedition (Argentina, Chile, Norway, Spain, United Kingdom, and United States) visited the island to undertake baseline

Table I. Bryophyte species recorded at nine geothermal sites on Deception Island. Species in bold are rare or unknown elsewhere in the Antarctic biome. *Species that are common and often abundant in unheated habitats but rare or absent in geothermal habitats. (x) Species not seen in 2002 survey, but recorded previously.

Species	Site No. (see text) 1	2	3	4	5	6	7	8	9
Mosses									
Andreaea regularis Müll. Hal.	-	x	-	-	-	-	-	-	-
Bartramia patens Brid.*	-	x	-	-	-	-	x	-	-
Brachythecium austrosalebrosum (Müll. Hal.) Kindb.*	x	-	-	-	x	-	-	-	-
Bryum amblyodon Müll. Hal.	-	-	-	x	x	-	-	x	-
B. dichotomum Hedw.	**x**	**-**	**x**	**x**	**x**	**x**	**x**	**x**	**-**
B. orbiculatifolium Cardot & Broth.	**-**	**x**	**-**	**-**	**x**	**x**	**-**	**-**	**-**
B. pseudotriquetrum(Hedw.) P. Gaertn., B. Mey & Scherb.*	x	x	-	x	-	x	-	-	-
B. subrotundifolium A. Jaeger	-	(x)	x	-	**-**	x	**-**	**-**	**-**
Bucklandiella didyma (Mont.) Bednarek-Ochyra & Ochrya	**-**	**-**	**-**	**-**	**x**	**-**	**-**	**-**	**-**
B. pachydictyon(Cardot) Bednarek-Ochyra & Ochyra	-	**-**	**-**	**-**	**x**	**-**	**-**	**-**	**x**
B. subsecunda(Hook. & Grev.) Bednarek-Ochyra & Ochyra	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**x**	**-**
B. sudetica (Funck) Bednarek-Ochyra & Ochyra	**-**	**(x)**	**-**	**-**	**-**	**-**	**-**	**-**	**-**
Ceratodon purpureus (Hedw.) Brid.*	x	x	-	x	x	-	-	x	-
Dicranella hookeri (Müll. Hal.) Cardot	**-**	**-**	**x**	**-**	**-**	**x**	**x**	**x**	**-**
Didymodon brachyphyllus (Sull.) R.H. Zander	-	-	-	x	x	x	-	-	-
Ditrichum conicum (Mont.) Mitt.	**-**	**-**	**-**	**x**	**(x)**	**-**	**x**	**x**	**-**
D. ditrichoideum (Cardot) Ochyra	**-**	**-**	**x**	**x**	**x**	**-**	**-**	**x**	**-**
D. heteromallum (Hedw.) E. Britton	**-**	**-**	**-**	**-**	**-**	**x**	**-**	**x**	**-**
D. hyalinocuspidatum Cardot	**-**	**-**	**-**	**x**	**x**	**-**	**x**	**-**	**-**
D. hyalinum (Mitt.) Kuntze	-	x	-	-	x	-	x	-	x
Funaria hygrometrica Hedw.	**-**	**-**	**-**	**-**	**(x)**	**-**	**-**	**-**	**-**
Hennediella antarctica (Engstr.) Ochyra & Matteri	-	x	-	-	x	-	-	x	-
H. heimii (Hedw.) R.H. Zander*	-	x	-	-	x	-	-	-	-
Holodontium sp.	**-**	**-**	**-**	**-**	**x**	**-**	**-**	**-**	**-**
Hymenoloma antarcticum (Müll. Hal.) Ochyra	**-**	**x**	**-**	**-**	**-**	**-**	**x**	**x**	**-**
H. crispulum (Hedw.) Ochyra	**-**	**-**	**-**	**-**	**x**	**-**	**-**	**-**	**-**
Leptobryum pyriforme (Hedw.) Wilson	**-**	**-**	**-**	**-**	**(x)**	**-**	**-**	**-**	**-**
Notoligotrichum trichodon (Hook. f. & Wilson) G.L. Sm.	**-**	**x**	**-**	**-**	**-**	**-**	**-**	**-**	**-**
Philonotis polymorpha (Müll. Hal.) Broth.	**x**	**-**	**-**	**-**	**x**	**x**	**x**	**-**	**-**
Pohlia cruda (Hedw.) Lindb.*	-	-	-	-	-	x	x	-	-
P. nutans (Hedw.) Lindb.*	x	x	-	x	x	x	-	-	-
P. wahlenbergii (F. Weber & D. Mohr) A.L. Andrews	**-**	**-**	**-**	**-**	**-**	**x**	**x**	**x**	**-**
Polytrichastrum alpinum (Hedw.) G.L. Sm.*	-	x	-	x	x	-	-	x	-
P. longisetum (Brid.) G.L. Sm.	**-**	**x**	**-**	**-**	**-**	**-**	**-**	**-**	**-**
Polytrichum juniperinum Hedw.*	-	x	-	x	x	-	-	-	-
P. piliferum Hedw.	-	x	-	-	x	-	-	-	-
P. strictum Brid.	-	-	-	-	x	-	-	-	-
Racomitrium lanuginosum (Hedw.) Brid.	**-**	**-**	**-**	**-**	**x**	**-**	**-**	**-**	**-**
Sanionia georgicouncinata (Müll. Hal.) Ochyra & Hedenas*	x	-	-	-	-	-	-	-	-
S. uncinata (Hedw.) Loeske*	x	x	-	-	x	-	-	x	-
Schistidium amblyophyllum (Müll. Hal.) Ochyra & Hertel	**-**	**-**	**-**	**-**	**x**	**x**	**-**	**x**	**x**
S. andinum (Mitt.) Herzog	**-**	**-**	**-**	**-**	**-**	**x**	**-**	**x**	**-**
S. antarctici (Cardot) L.I. Savicz & Smirnova*	x	x	-	x	x	x	-	-	-
S. praemorsum (Müll. Hal.) Herzog	**-**	**-**	**-**	**-**	**-**	**x**	**-**	**-**	**-**
Sciuro-hypnum fuegianum (Broth.) Ochyra & Żarnowiec	**-**	**-**	**-**	**-**	**x**	**-**	**-**	**x**	**x**
Syntrichia filaris (Müll. Hal.) R.H. Zander*	-	-	-	-	(x)	-	-	-	-
S. princeps (De Not.) Mitt.	-	x	-	-	x	x	x	-	-
S. saxicola (Cardot) R.H. Zander*	-	x	-	-	-	-	x	-	-
Liverworts									
Barbilophozia hatcheri (A. Evans) Loeske	x	-	-	-	-	-	-	-	-
Cephalozia badia (Gottsche) Steph.	-	-	-	-	-	-	-	-	x
Cephaloziella hispidissima R.M. Schust.	**x**	-	-	-	-	-	-	-	-
C. varians (Gottsche) Steph.*	-	x	-	-	-	x	x	x	-
Cryptochila grandiflora (Lindenb. & Gottsche) Grolle	-	-	-	-	-	-	x	-	-
Lophozia excisa (Dicks.) Dumort.	-	x	-	-	-	-	-	-	-
Marchantia berteroana Lehm. & Lindenb.	-	-	-	-	(x)	x	-	-	-
M. polymorpha L. emend. Raddi	-	-	-	-	**(x)**	-	-	-	-
Pachyglossa spegazziniana (C. Massal.) Herzog & Grolle	-	-	-	-	-	-	-	-	**x**

survey fieldwork to assist with the preparation of an Antarctic Specially Managed Area (ASMA) Management Plan. This included a floristic and ecological review of SSSI 21 and other areas of botanical importance. These were then assessed for possible inclusion as sub-sites of an Antarctic Specially Protected Area (ASPA) within the ASMA, thus replacing the former SSSI.

Botanical survey

Between 28 January and 12 February 2002 the author undertook a detailed survey of the existing SSSI sub-sites and other sites of botanical importance. Plant specimens collected during the survey for identification, together with collections made on several previous occasions between 1963 and 1995 (total *c*. 2500), are housed in the herbarium of the British Antarctic Survey (AAS) with specimen details held in the Antarctic Plant Database (website http://www.antarctica.ac.uk/Resources/BSD/PlantDatabase/aas_form.html). The identification of all specimens was confirmed by R. Ochyra during the preparation of a comprehensive Antarctic Moss Flora (Ochyra *et al*. in press), during which all Antarctic taxa have been revised. Virtually all the island has been comprehensively surveyed between 1981 and 2002. Most of the island's ice-free terrain is covered by a mantle of fine ash and lapilli, scoria, shattered lava bombs, and tuff cones and craters, some containing lakes. The ash-covered substratum is very dry and unstable and subject to rapid erosion by rain, snow melt and wind. Extensive tracts of these areas are largely devoid of vegetation, although many are being colonized by very sparse bryophytes and lichens. Colonization, especially by some mosses (notably species of Polytrichaceae), greatly aids soil stabilization, but is often only temporary before a new erosion event occurs. There is little diversity of habitats, so the flora and communities tend to be rather uniform with certain species dominating where a particular environmental feature prevails (see Longton 1967, Collins 1969). The island's extant bryoflora comprises *c*. 56 mosses and eight liverworts. However, three additional mosses (*Funaria hygrometrica*, *Leptobryum pyriforme* and *Bucklandiella* (*=Racomitrium) sudetica*) and a liverwort (*Marchantia polymorpha*), previously recorded at geothermal sites, now appear to be extinct. Very few species achieve dominance within large closed communities (i.e. >10 m^2), although *Polytrichastrum alpinum* and *Sanionia uncinata* have locally developed stands up to about 1 ha in areas unaffected by the recent eruptions.

During the course of the survey eight areas of geothermal activity supporting bryophyte vegetation were located, ranging in area from *c*. 100 m^2 to 2 ha (Fig. 2); a ninth geothermal site had been investigated in 1987 and is included here. Several species found in crevices in a cliff west of Telefon Bay indicate the possibility of fumarolic activity, but this site is not included as the evidence is uncertain.

Species were recorded semi-quantitatively at each site and spot temperatures measured at various positions within the vegetation or soil associated with these, using a Checktemp rigid thermometer probe with digital readout (Hanna Instruments, Woonsocket, RI). During a previous survey of the island in 1987 a 12-channel Squirrel Data Logger (Grant Instruments, Cambridge) was used to record temperatures at 15 min intervals over several days at two fumarole sites.

Results

The bryophyte species recorded at the nine geothermal sites are listed in Table I. Numerous species were noted to occur either exclusively at these sites, or only rarely elsewhere on the island. Furthermore, several of the mosses and three liverworts are known nowhere else in the Antarctic biome or, in some cases, at only one or two other localities. Attention is drawn to these biogeographically interesting species in the site accounts below. Species which are common and often abundant in unheated habitats, but rare or absent in geothermal habitats are indicated (by an asterisk) in Table I.

Site 1. Whalers Bay (2–5 m altitude)

This small (*c*. 20 x 20 m) scoria outcrop is about 100 m from the shore. The intertidal beach area adjacent to this site produces large volumes of steam, and the sea here is often exceedingly hot. The site was largely unaffected by the 1969 eruption which devastated the entire area immediately to the north. Although the site is largely unheated, several crevices in the vertical face are fumarole vents with dense growths of bryophytes. A short fissure with vents also occurs on the uphill side of the knoll, and supports a few scattered colonies of moss. The crevices were strongly shaded and moist with condensed water droplets. The temperature within the moss turf was 25 to 35°C. Of the species recorded, *Bryum dichotomum*, *Philonotis polymorpha* and *Cephaloziella hispidissima* are of particular interest.

Site 2. Kroner Lake to Ronald Hill (0–5 m altitude)

This site, covering an area of *c*. 2 ha, underwent catastrophic change during the 1969 eruption when the sparse but diverse vegetation in the shallow Ronald Hill crater and dry shallow gully leading to the thermal Kroner Lake were buried beneath several metres of mudflow (lahar). Much of this ashy mud was quickly washed away by snow melt and rain and the site resumed a similar topography to its original state. Kroner Lake has intermittently been a discrete lake and an intertidal lagoon; since the mid-1980s it has been the latter. Throughout the

site there are areas of warm ground (20–28°C), while water issuing from a system of bubbling vents in Kroner Lake reached 53°C (with associated marine algae growing to within 10 cm of the vents). Colonization has proceeded rapidly, with many more species recorded than before the eruption. Of particular importance here, and indeed everywhere on the island, are species of Polytrichaceae which stabilize the dry loose substratum with their subterranean rhizome system. Several other taxa with dense rhizoids, notably *Bryum pseudotriquetrum*, are also important in stabilizing the substratum. This permits colonization by other species, leading to the development of distinct communities. The microfoliose lichen *Psoroma cinnamomeum* Malme is also abundant and plays an important role as a soil stabilizer. Species of particular importance include *Bryum orbiculatifolium*, *Ditrichum hyalinum, Hymenoloma antarcticum*, *Notoligotrichum trichodon*, *Polytrichastrum longisetum* and *Lophozia excisa*. In addition, tiny thalli of the foliose lichen *Peltigera didactyla* (With.) J.R. Laundon are colonizing the former crater basin in greater abundance than is known anywhere in the Antarctic. The centre of Ronald Hill crater was formerly the only known site on the island where *Notoligotrichum trichodon* occurred (its only other known Antarctic locations being two sites in the South Orkney Islands, and Candlemas and Bellingshausen islands in the South Sandwich Islands, Smith 1972, as *Psilopilum antarcticum*, Convey *et al.* 2000). Following the 1969 eruption it was not seen again until the present survey; a single sparse colony of *c*. 30 cm diameter was found about 300 m from its original site. Unless it arose from a new immigrant propagule from beyond Deception Island, it could be construed as having recolonized from a viable vegetative fragment, possibly buried for several years or decades by fine mud, which had been transported from the original site in the mudflow. The few colonies of *P. longisetum* are the only ones known on the island. It is also a recent colonist on exposed ground below a receding ice field on Signy Island, South Orkney Islands (Smith 1993).

Site 3. "Perchuć Cone" (c. 185 m altitude)

This site comprises a narrow line of fumaroles and adjacent heated ground covering about 25 x 10 m, and about 25 m from an ice cliff in the Mount Pond glacier. It was created by the 1969 eruption, and by 1987 it was colonized by large patches of moss although, by 1993, the extent of these had diminished. By 2002 the moss cover was very localized and sparse, and the shoots very short. All four species recorded were typical of the island's fumarole vegetation: *Bryum dichotomum*, *B. subrotundifolium*, *Dicranella hookeri* and *Ditrichum ditrichoideum*. Temperatures at the vents were 80–95°C, and 1 cm beneath the moss only 5 cm from vents it was 34–48°C.

Site 4. Pendulum Cove beach terraces (2–5 m altitude)

Like Site 2 this is a geothermal area without fumaroles. It has been the centre of intense volcanic activity probably in the mid to late 1800s and again in 1969. As around the shore of Whalers Bay, the shoreline of Pendulum Cove is almost always steaming vigorously and the sea immediately offshore can reach boiling point. The present substratum was deposited by the 1969 eruption, but was also affected by deposits from the 1970 eruption. When examined in 1981 and 1987 the beach area supported a cryptic moss community amongst the warm moist lapilli. It was dominated by *Bryum dichotomum* producing large masses of deciduous bulbils which were clearly responsible for the species' widespread distribution here. Temperatures then were 20–45°C at 5 cm depth, but by 1987 they were 15–20°C and by 2002 only 8–12°C and the substratum was very dry and devoid of vegetation. Because this was recognized as an unique site in 1981, and because of its vulnerability to disturbance by trampling, in 1984 it was designated a subsite of SSSI 21 to protect it from the large numbers of tourists from cruise ships who visited this site to experience the thermal activity and view the ruined Chilean station. Unfortunately, this protection was uncontrolled and the disappearance of the cryptic vegetation was due, in part at least, to human impact, although the declining geothermal activity must also have been a contributory factor. However, a small area of slightly warmed ground about 10 x 30 m still exists at the back of the beach, and here there is a relatively diverse but scattered moss flora, with colonies of several species expanding radially, particularly species of *Ditrichum* and *Polytrichum juniperinum*. Of importance are *Bryum amblyodon*, *B. dichotomum*, *Ditrichum conicum*, *D. ditrichoideum* and *D. hyalinocuspidatum*.

Site 5. Pendulum Cove ridge (75–100 m altitude)

This undulating gently sloping ridge extends inland from near Pendulum Cove to the foot of the Mount Pond glacier ice cliffs. The upper part is a relatively level plateau, probably ice-cored, which was one of the centres of the 1969 eruption (Smellie 2002). The site covers an area of *c*. 100 x 100 m. The present mantle of black and red scoria is largely the product of the 1969 eruption, although much of the ridge had been created by eruptions in 1839 and 1842. Colonization by plants almost certainly dates from 1969. The vegetation is very sparse but surprisingly diverse considering the lack of soil, other than that formed by the decay of scoria, and the dryness of the substrata. In 1987 about 40 narrow shafts were found, often hidden beneath scoria boulders. The temperature at *c.* 50 cm within these "chimneys" ranged from 11 to 38°C, the air was humid and moss grew on the rock down to 20 cm depth where the temperature was 12–21°C, although it received almost no

light (L. Greenfield, *in litt.*).

As reported by Smith (1988) this site is of especial interest as it is the only known locality within the Antarctic biome where *Racomitrium lanuginosum* occurs, while *Bucklandiella pachydictyon* (originally given as *R. heterostichum* in error for *R. heterostichoides*) also occurs here and, even more scarcely, at Site 9. Both grow as very small plants within an area of *c*. 30 x 30 m and both are very rare. *R. lanuginosum* does not typically colonize rock surfaces, although it is the usual habitat for *B. pachydictyon*. Within this small area, another member of this family, *B. didyma*, was collected, also its only known Antarctic location. For three species of *Bucklandiella/Racomitrium*, all unknown elsewhere in the Antarctic biome, to be recent colonists of a very small area is remarkable and inexplicable. This is also one of very few known Antarctic stations for *Sciuro-hypnum fuegianum*. Also at this site a small colony of *Polytrichum strictum* was located. While this species is abundant and widespread throughout the northern Maritime Antarctic, it is largely unknown on volcanic substrata and this is its only known occurrence on Deception Island. Other species that are rare here include *Bryum dichotomum*, *B. orbiculatifolium*, *Ditrichum ditrichoideum, D. hyalinocuspidatum*, *D. hyalinum, Holodontium* sp., *Hymenoloma crispulum*, *Philonotis polymorpha* and *Schistidium amblyophyllum.*

A geothermal gully on the southern slope of this site was discovered in 1983. The moist stable substratum was extensively colonized by mosses (Smith 1984a), including *Bryum dichotomum*, *Ceratodon purpureus*, *Ditrichum conicum* (given erroneously as *Campylopus introflexus*), *Leptobryum pyriforme*, *Marchantia berteroana*, *Polytrichum juniperinum*, and *Syntrichia filaris.* This was the first record of the cosmopolitan *L. pyriforme* in Antarctica, although it has been recorded in recently deglaciated soil below a receding ice field on Signy Island, South Orkney Islands when cultured under laboratory conditions (Smith 1987). It was also the first record of *M. berteroana* on the island, although it has colonised several new sites since then. However, nine months after the 1969 eruption, Young & Kläy (1971) descended to the floor of a 60 m deep chasm in the Mount Pond glacier above Pendulum Cove and found patches of colonizing moss (*Funaria* sp. and *Syntrichia* sp.) and tiny thalli of the liverwort *Marchantia polymorpha*, developed from gemmae, growing on warm steaming ash. This may have been the original site from where *M. berteroana* was later found after the retreat of the glacier cliff. However, there is doubt about the identity of *M. polymorpha* (Smith 1984a), which Young & Kläy (1971) considered to be an example of long-distance dispersal from South America.

Site 6. Mount Pond summit ridge (485–500 m altitude)

Situated about 1.5 km north of Mount Pond summit, this is the most important geothermal botanical site on the island, and comprises two distinct areas. The lower part extends about 250 x 50 m along the wind-exposed broad crest of a gently sloping ridge where there is a series of *c.* 40 small steaming vents arranged along parallel rock fissures. These fumaroles have created low mounds or strips of heat-cemented sulphurous clay. These are surrounded by inconspicuous open stands of very short moss shoots only 1–3 mm high and often partially buried in the fine baked soil. Colonization commences about 10 cm from the vents and extends outwards for up to *c.* 50 cm. The seven mosses recorded here were *Bryum dichotomum*, *B. orbiculatifolium*, *Dicranella hookeri*, *Ditrichum heteromallum*, *Philonotis polymorpha*, *Pohlia nutans* and *P. wahlenbergii*. Vent temperatures were 75–90°C and in the soil crust below moss at 10 and 35 cm from a vent they were 34°C and 27°C, respectively.

The second area comprises four principal groups of vigorously steaming fumaroles. These occur within an area of *c*. 50 x 25 m in a sheltered steep-sided basin on the east side and lee of a long 10 m high rime dome or chimney formed over another system of fumaroles which are not visible. The exposed fumaroles support luxuriant closed stands of moss forming both mixed and pure turves up to 6 cm tall. This unique community includes *Bryum dichotomum*, *B. orbiculatifolium*, *B. subrotundifolium*, *Dicranella hookeri*, *Ditrichum heteromallum*, *Philonotis polymorpha*, *Pohlia cruda* and *P. wahlenbergii*. Small sporing bodies of an unknown basidiomycete occurred amongst one stand of *D. hookeri*, the highest altitude for such a fungus in the Antarctic. This is the only site on the island where there is evidence of zonation of species centred on specific fumaroles. In the central areas a tall turf of *D. hookeri* predominates, but in the more peripheral zone the turf comprises mainly *P. polymorpha* and *P. wahlenbergii*. The latter two species are common associates at the margins of streams and pools on sub-Antarctic South Georgia, but unknown elsewhere in the Antarctic. On the fine moist compacted clay at the margin of the main moss turves there is a peripheral zone of *Marchantia berteroana*, mainly as small bilobed thalli developing from the copiously produced and widely dispersed gemmae. Here also, several of the mosses are colonizing as scattered very short shoots from masses of fragments detached from the main populations. The liverwort was not seen here in 1987 and must be considered as a very recent immigrant and colonist at this site. These colonizing stands on the steep slope are extremely vulnerable to trampling damage and natural disturbance, and dispersal of vegetative propagules from the established stands must owe much to precipitation and wind.

Temperatures in the fumarole vents ranged from *c*. 70–90°C, while within the moss turf 30 cm from vents it reached 34°C and at the base of the turf it was 47°C. The temperatures at several positions in and close to a fumarole

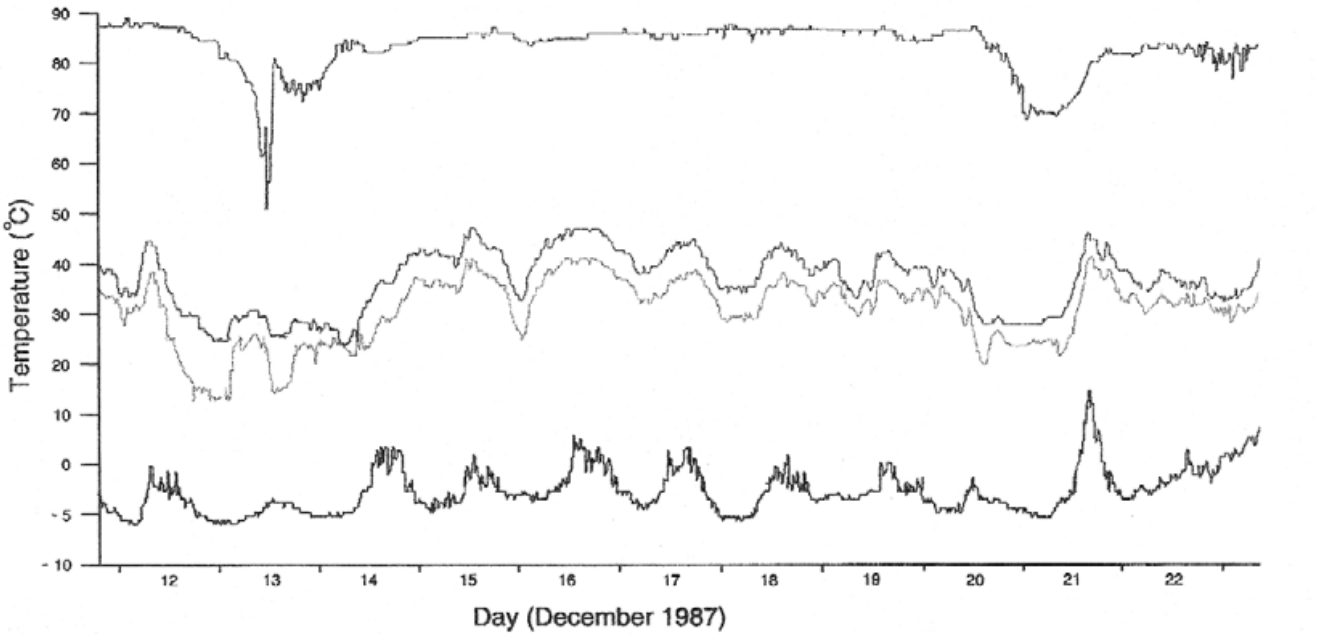

Fig. 3. Temperatures recorded continuously over 11 days at Site 6 at near the summit of Mount Pond. Top curve = fumarole vent, second top curve = base of moss turf 30 cm from vent, second bottom curve = amongst shoot apices of moss turf 30 cm from vent, bottom curve = air temperature at *c*. 1 m above unheated ground (the peak on 21 December occurred during the only day of sunshine).

vent, recorded continuously over 11 days, are given in Fig. 3. These reveal that, in general, the mosses experience continuously high temperatures, but which fluctuate between day and night. Sudden decreases in vent temperatures may indicate geothermal pulsing every few days, but the daily peaks reflect the cycle of solar radiation, even though the site was shrouded in thick cloud on all but the final day.

Within this latter area outcrops of yellow tephra support an unique community of lithophytic mosses, notably *Didymodon brachyphyllus*, *Syntrichia princeps* and several species of *Schistidium* (*S. amblyophyllum*, *S. andinum*, *S. antarctici*, *S. praemorsum*). Several lichens are also present (e.g. *Caloplaca*, *Leptogium*, *Placopsis*). The rock surface was warm (10–15°C), but this was due to steam drifting from the fumaroles and to solar irradiance penetrating the thick cloud cover.

It was probably the former area that provided the first evidence of a plant associated with a geothermal habitat in the Antarctic. E. Gourdon, geologist on the Second French Antarctic Expedition, collected *Philonotis gourdonii* Cardot in 1909 growing as very short small mats on calcareous and sulphurous deposits of warm springs at 450 m on the summit of Mount Pond (Cardot 1911, 1913). The occurrence of this site was not confirmed until 1987 when the moss was rediscovered and redetermined as *P. acicularis* (C. Müll.) Kindb. (Smith 1988) and subsequently as *P. polymorpha*, a species common on South Georgia (previously known as *P. acicularis*). This site was relatively unaffected by the recent eruptions, although it was almost certainly covered by varying depths of fine ash, possibly by up to 30 cm during the 1967 eruption (Baker *et al.* 1975, Smith 1984a).

Site 7. Western Stonethrow Ridge (c. 260–275 m altitude)

This is the only site on the outer slopes of the caldera. It comprises a decayed cone of red scoria with two small areas of geothermal activity, but no obvious fumaroles. Both areas are densely vegetated with luxuriant stands of bryophytes and some lichens, covering *c*. 10 x 5 m and 5 x 3 m, respectively, but with sparser vegetation occurring well beyond the direct influence of geothermal activity. The temperature within the moss turf ranged from 28 to 42°C when the weather conditions were thick fog, heavy rain, gale force wind and an air temperature of 2°C. The important species are *Bryum dichotomum*, *Dicranella hookeri, Ditrichum conicum*, *D. hyalinocuspidatum*, *D. hyalinum, Hymenoloma antarcticum, Philonotis polymorpha*, *Pohlia wahlenbergii*, *Syntrichia saxicola* and *Cryptochila grandiflora*. This last species, a liverwort, is of particular interest as it grows here in abundance, forming a loose turf up to 5 cm high, but it is known nowhere else on the island. Its only other Antarctic location is in similar geothermal habitats in the South Sandwich Islands (Longton & Holdgate 1979, Convey *et al.* 2000). There were several disused Antarctic skua (*Catharacta lönnbergii*) nest scoops amongst the moss, each probably representing a nest from a different year. This may be a clue as to how *Cryptochila* colonized this site, as these birds migrate to southern South America each winter and may have been responsible for transporting propagules of the

Table II. Mean temperatures at Site 8 (10 days, January 1988, $n = 960$).

Position	Mean (°C)	Range (°C)
Mouth of vent 1	77	48 to 95
Moss 10 cm from vent 1,		
surface	16	4 to 35
1 cm depth	40	14 to 64
Mouth of vent 2	90	62 to 95
Moss 25 cm from vent 2,		
surface	11	4 to 29
1 cm depth	23	13 to 34
Soil 1 m from vent 2,		
surface	3	-1 to 15
5 cm depth	4	0 to 14
Rock 1 m from vent 2,		
surface	2	-1 to 14
moss cushion surface	3	0 to 14
Air 1 m above rock	2	-2 to 8

liverwort and, indeed, one or more of the mosses to this favourable growing environment. Skuas are the only Antarctic birds which regularly venture inland in Tierra del Fuego. The lichen *Stereocaulon condensatum* Hoffm. also occurs frequently here, its only known Antarctic station Øvstedal & Lewis Smith (2004).

Site 8. Fumarole Bay (103–107 m altitude)

This very exposed site extends about 30–40 x 3 m along the crest of the ridge above the north side of a large intertidal lagoon at the south end of Fumarole Bay. There are several long fissures, 1–2 cm wide, with weakly steaming fumarole vents. Small populations of very short mosses colonize the fine cemented clay crust close to the fissures. Ground surface temperatures decline rapidly away from these, and at 1 m from the vents they are unaffected by geothermal activity. In places, moss grows to within 2 cm of fissures in which temperatures of 90–93°C were recorded; temperatures 5 cm below the moss was 65°C, but only 22–25°C on the moss surface. Mean temperatures recorded continuously over eight days are summarized in Table II. These indicate fluctuating activity, but with temperatures remaining consistently higher than ambient. Mosses of special importance include *Bryum amblyodon*, *B. dichotomum*, *Bucklandiella subsecunda*, *Dicranella hookeri, Ditrichum conicum*, *D. ditrichoideum*, *D. heteromallum*, *Hymenoloma antarcticum*, *Pohlia wahlenbergii*, *Schistidium amblyophyllum*, *S. andinum* (on rock at a short distance from the site). This is the only Antarctic site where *B. subsecunda* is known.

Site 9. Between Mount Kirkwood and Mount Irizar (340 m altitude)

This site lies on the summit ridge between Mount Kirkwood and Mount Irizar, the latter being 3.5 km north-west of Mount Kirkwood. Although not visited by the author, the existence of geothermal activity at this site was reported in 1994 by J. Smellie (personal communication). Several bryophytes collected on a scoria outcrop protruding through the ice cap are typical of heated ground elsewhere on the island. These included the rare, *Ditrichum hyalinum*, *Bucklandiella pachydictyon*, *Schistidium amblyophyllum*, *Sciuro-hypnum fuegianum, Cephaloziella badia* and *Pachyglossa spegazziniana*. This is the only known Antarctic location for *P. spegazziniana* (Bednarek-Ochyra *et al*. 2000). While several other taxa may have been overlooked, the composition of this community is certainly unique.

A tenth site on the island may have geothermal activity, as deduced by the presence of *Philonotis polymorpha*, a species known only from fumarole habitats. This, and several other species including an abundance of *Bryum pallescens* Schleich. *ex* Schwdgr., *Didymodon brachyphyllus* and fruiting *Hennediella heimii*, occurred in moist shaded crevices and overhangs on a cliff of red tuff and scoria above a small lake north of the southern Telefon Bay lagoon. However, no temperatures were recorded. This is at the margin of the 1967 eruption centre and, in 1987, J. Smellie (personal communication) recorded geothermal activity in the adjacent flooded crater which forms a lagoon in south-west Telefon Bay.

Discussion

The 2002 botanical survey confirmed earlier accounts of the uniqueness of Deception Island's bryoflora associated with geothermal habitats. With the exception of the South Sandwich Islands, lying 2400 km to the north-east of the South Shetland Islands, the geothermal sites on Deception Island possess a substantial number of species not known elsewhere, or which are rare, in the Antarctic biome. 47 (80%) of the island's 59 moss species and all nine (100%) of the island's liverworts (including three apparently extinct mosses and one extinct liverwort) occur or occurred in geothermal habitats, with 25 (42%) of the mosses and four (44%) of the liverworts being confined mainly to heated ground. Only 12 mosses have not been found in association with heated ground, although many others are of only casual occurrence. No additional liverworts are known from unheated sites.

All of the three geothermal sites in Victoria Land, continental Antarctica, are at high altitude near the summit of widely separated mountains, yet each possesses a unique simple cryptogamic and microbial community. The air temperature at these sites probably never exceeds *c*. -10°C. The heated ground on Mount Erebus at *c*. 3500 m altitude is colonized by small populations of moss protonemata, determined by DNA profiling as *Campylopus pyriformis* (Schulz) Brid. (Broady 1984, Skotnicki *et al*. 2001), that on Mount Melbourne at 2700 m by *Cephaloziella varians* and

Campylopus pyriformis (Broady *et al.* 1987), and that on Mount Rittmann at 2500 m by a rosette growth form of *Pohlia nutans* (Bargagli *et al.* 1996, Skotnicki *et al*. 2002). In 2003 *P. nutans* was also reported from geothermal ground on a subsidiary cone near the summit of Mount Melbourne (R. Bargagli, personal communication). The heated ground and fumarole sites in the South Sandwich Islands also possess unique communities with many rare bryophytes growing luxuriantly and in abundance (Convey *et al*. 2000). However, there are several species occurring only on Deception Island but not in the South Sandwich archipelago (notably species of *Schistidium*), and *vice versa* (notably liverworts).

The geothermal flora of Deception Island is very significant in terms of Antarctic phytogeography. Many of these species are restricted to the favourable conditions afforded by such habitats. Why they have not colonized unheated sites on the island is not clear although, in time, some may extend their range beyond the present areas of geothermal activity. Few of the dominant species elsewhere on the island and, indeed, throughout the Maritime Antarctic, appear to favour these heated sites, and several of the predominant "thermophiles" occur only rarely in unheated sites. An identical situation occurs in the South Sandwich Islands. It has been shown that recently deglaciated soil and rock in Antarctic regions can become colonized quite rapidly (Smith 1993) and that sites with favourable micro- and mesoclimates can support relatively diverse floras and probably serve as important centres of further local distribution (Smith 1997). Since ice-free areas in Antarctica are often remote and widely separated, many colonists probably rely on long-distance dispersal of propagules, particularly by wind (Smith 1991, Marshall & Convey 1997, Muňoz *et al*. 2004). Most bryophyte species in the Antarctic have a close affinity with the southern South American flora, and many also have a bipolar distribution (Bednarek-Ochyra *et al*. 2000, Ochyra *et al*. in press). Smith (1993) provided a model of Antarctic plant colonization, and stated "Clearly, there is a rain of [viable] spores over the Antarctic, a large proportion of which is trapped in ice. If they are successful in reaching a soil surface, either directly or in melt water from ice caps or glaciers, they may lie dormant indefinitely until conditions become favourable for germination." Geothermal habitats provide ideal conditions for species not pre-adapted to the typical Antarctic environment, although this does not explain the general absence of many other species.

New substrata on Deception Island created by the 1967–70 eruptions were colonized remarkably rapidly by bryophytes. Populations of several species were established on newly deposited ash around new fumaroles within 12 months of the 1967 eruption, including the moss *Funaria hygrometrica*, previously unknown in the Antarctic (Collins 1969). Probably the same species, and *Marchantia polymorpha,* were establishing on similar substrata on the floor of a 60 m deep chasm in a glacier only nine months after the 1969 eruption (Young & Kläy 1971). The moss *Leptobryum pyriforme*, also new to the Antarctic, was recorded at or near the latter site in 1983 (Smith 1984a), but it could not be relocated during the present survey, possibly because geothermal activity had ceased at that site. Elsewhere, new stable surfaces have been colonized to some extent by most of the terricolous species typical of unheated habitats. Colonization was well advanced by 1981 (Smith 1984a, 1984b) at the sites of the three most recent eruptions, and by 2002 many hectares of coastal ash plains had well-established but discontinuous communities, although locally forming closed stands of many square metres. A tongue of scoria at Crater Lake, 2.5 km east-south-east of Site 8, formed by an effusive eruption in 1838 or 1839 (Smellie *et al*. 2003), is similar in nature to that at Site 5 described above. In March 1839 immense quantities of steam were observed rising from what is now Crater Lake (Dana, cited in Roobol 1980), whilst in February 1842 13 eruptive sites on the south side of the island were observed (Wilkes 1845). However, while Site 5 is still in the very early stages of colonization, the Crater Lake site was extensively vegetated by a diverse flora a century after its creation. Also, it was not affected by ash deposits from the three recent eruptions. This north-facing site is very sheltered and now extensive thick (to 30 cm) turves of *Polytrichastrum alpinum* dominate much of the terrain, and the rock surfaces are densely covered by large lichens. It is also the only site known in the Antarctic where *P. alpinum* fruits abundantly. As with Site 5, this area was probably geothermal for some time after its formation, and may indeed still be mildly active.

Nothing is known of the physiological performance or thermal tolerance of any Antarctic fumarole bryophytes, although the upper temperature optimum for positive net photosynthesis of many other species is *c*. 20–25°C (e.g. Longton 1988). However, most species growing near fumaroles and on heated ground experience temperatures continuously between 25 and 45°C. While this may imply exceptional physiological requirements or tolerance, some of these same species occupy "normal" habitats elsewhere within their Antarctic range. Although the floristic composition of geothermal communities on Deception Island is very specific, it remains unclear what factors determine this selection and the apparent exclusion of many of the common and widespread species.

Conservation of Deception Island botanical sites

The 2002 botanical survey of Deception Island confirmed the exceptional importance of its bryophyte flora with regard to the Antarctic biome. In particular, the island's geothermal flora and communities at several sites are unique in the Antarctic, while some other sites are of special importance as they provide known-age substrata (created by

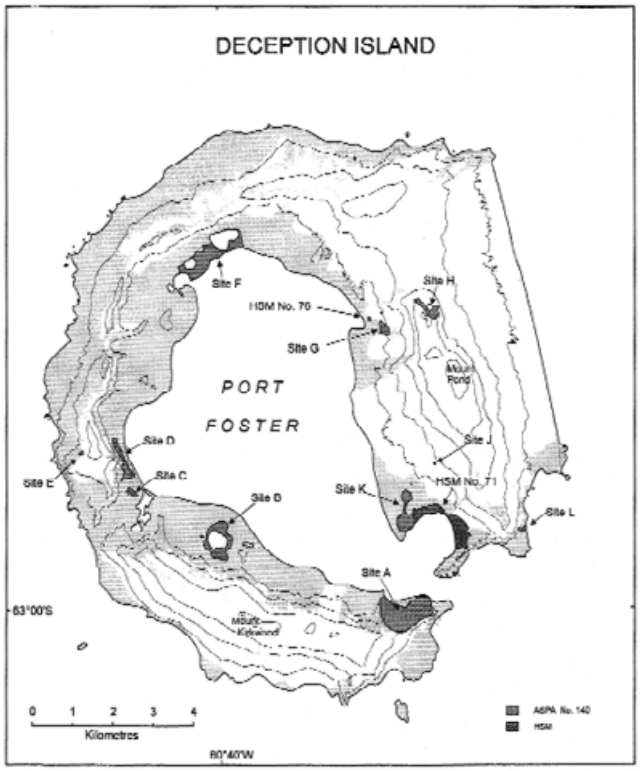

Fig. 4. Deception Island showing the location of the botanical sites (A–L) comprising Antarctic Specially Protected Area No. 140 (HSM = Historic Site or Monument).

dated eruptions between 1838 and 1970, see Roobol 1980), offering unique opportunities for studying colonization and community development dynamics. With the exception of the South Sandwich Islands, which lie outside the Antarctic Treaty Area, Deception Island has the greatest number of rare or extremely rare (in terms of known occurrences) plant species of any Antarctic locality (22 (39%) of the *c*. 56 extant mosses, three (38%) of the eight extant liverworts, 19% of the *c*. 75 lichens); this excludes three mosses and one liverwort which appear to have become extinct on the island. Because of the island's botanical and ecological importance, 11 sites (including geothermal sites 1–8 described here) were proposed at the XXVII Antarctic Treaty Consultative Meeting in 2004 as components of Antarctic Specially Protected Area No. 140, within the proposed Deception Island Antarctic Specially Managed Area (Fig. 4). Sites A, B and D are representative of large stands of bryophyte and lichen vegetation unaffected by the recent eruptions and by geothermal activity; D has the most diverse flora on the island. Site C is geothermal Site 8, Site E is geothermal Site 7, Site F was created by the 1967 eruption and provides known-age surfaces at which colonization is being monitored. Site G is geothermal Site 5, Site H is geothermal Site 6, Site J is geothermal Site 3 and Site K is geothermal Site 2. Site L is an unique site on the island supporting possibly the largest known stand of *Colobanthus quitensis* (Kunth) Bartl. in Antarctica; it was almost entirely destroyed by ash burial from the 1967 eruption (Collins 1969), but has recovered and during the past decade there has been a huge population increase over about 1 ha. Because of their very small size, geothermal Sites 4 and 9 are not afforded protection status, while geothermal Site 1 is incorporated in the Whalers Bay HSM (Historic Sites and Monuments No. 71).

A common management plan will apply to each of the botanical sites, and entry into each, and the activities allowed therein, will require a permit issued by the government or national agency of the person(s) proposing to visit the site, coordinated through the Deception Island Management Plan. This ASPA management plan, and that for the ASMA, will control human activity ashore and within Port Foster and afford maximum protection for the many features of the island, including two Historic Sites and Monuments (HSM No. 71 is the derelict whaling station and former British scientific base at Whalers Bay, and HSM No. 76 is the ruined Chilean base at Pendulum Cove), other areas of tourist interest, a facilities zone around the Argentine and Spanish research stations south of Fumarole Bay, and recommended boat and helicopter landing sites, and research camp sites. The management plan and boundary markings for the original five botanical sites designated SSSI No. 21 did not afford strict control over human activities within them. However, the new management plan, when it comes into force in 2005, will ensure maximum protection. Deception Island is one of several Antarctic Specially Protected Areas designated specifically to protect their important terrestrial flora and communities (Anon 2003, Ochyra *et al.* in press).

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