A MODEL FOR THE ERUPTIVE MECHANISM OF DECEPTION ISLAND FROM 1820 TO 1970

By M. J. ROOBOL*

ABSTRACT. Historical records show that the localities of obvious heat escape on Deception Island are restricted to the 3 km. wide ring-fault zone around the central caldera, whereas at different times the obvious heat escape has been from very different sectors. The more complete records of the twentieth century reveal a build-up in these areas from 1908 to a maximum development at the time of the 1967, 1969 and 1970 eruptions. The areas of obvious heat escape appear to mark the sites of future eruptive vents for up to six decades prior to eruption. They are interpreted as marking the positions of bodies of magma at a high level in the ring-fault zone. Although the historical records are incomplete, at least five intrusive episodes culminating in eruptions are indicated since 1820. The sectors of the ring-fault zone which showed obvious heat escape are: 1. Mount Pond, 1829 (? Pendulum Cove eruption); 2. Mount Kirkwood, 1839–42 (Mount Kirkwood fissure eruptions); 3. Pendulum Cove–Mount Pond–Whalers Bay sector, 1908–70 (1969 fissure eruption); 4. Telefon Bay, ~1956–70 (1967 and 1970 eruptions); 5. Wensleydale Beacon, post-1962 to 1970 (1970 eruption). The (?) 1839–1970 record of heat escape in the Fumarole Bay sector has not resulted in an eruption and may represent a pre-1829 residue of magma or hot rock after the formation of the prehistoric Fumarole Bay crater.

The above magma-pod hypothesis adequately accounts for the chemical variation of material erupted in 1967, 1969 and 1970 from around half of the ring-fault zone, when about five uniform but distinct magma bodies were tapped. This finer division based on chemistry indicates that events 4 and 5 (above), deduced from field observations, can be further subdivided due to three intrusive episodes which occurred between the last two occasions when the areas of heat escape were mapped in 1962 and 1968.

THE 1967, 1969 and 1970 pyroclastic eruptions from the ring-fault zone of the large volcanic caldera of Deception Island (Baker and others, 1975) clearly demonstrated for the first time the active state of one of the volcanoes of Bransfield Strait (Deception, Bridgeman and Penguin Islands). Prior to these events, opinions as to their state of activity varied to all extremes. Weddell (1825, p. 133) passed within 200 yards of Bridgeman Island in 1821 and observed "smoke" issuing through fissures in the rock, apparently with much force. He regarded the island as an active volcano. On the other hand, this opinion was dismissed by Charcot (1910), who landed a party there on 24 December 1909 and considered previous accounts as referring to dust clouds, clouds clinging to the island and even drifting snow. A similar broad range of opinion existed for Deception Island and the possibility that it was extinct (e.g. Christie, 1951, p. 85) probably had some influence on the building of three stations inside the caldera, first identified by Holtedahl (1929).

Deception Island is now regarded (Baker and others, 1975) as having undergone a cone or cone-complex building episode of lava flows and yellow palagonitized tuffs (airfall and reworked) followed by cauldron subsidence which probably produced the pyroclastic flow tuffs of Cathedral Crags and Fumarole Bay (Fig. 1). At present the volcano is in a late or post-caldera stage in which eruptions are largely restricted to the 3 km. wide ring-fault zone inside the caldera rim. There are a few young lava flows outside the caldera rim on Kendall Terrace. The products of this latest stage of activity (which ring the shores of Port Foster) are either lava flows where the vents opened on dry ground, or ash cones of pyroclastic fall deposits where the vents opened below sea-level, in the waterlogged shores of Port Foster or beneath the ice caps. Morphological comparison of the accurate 1829 topographic map of Kendal (1831; correctly spelt Kendall throughout Webster (1834)) with the 1956 Hunting Aerosurveys photographs and 1959 topographic map by Roobol (1973) suggests many local changes due to maars being infilled by sediments and younger pyroclastic deposits as well as the formation of new craters.

The historical accounts of Deception Island span 150 years and provide data which can be used for the construction of a model of the volcanic mechanism of the caldera in its present

*Present address: Institute of Applied Geology, Jeddah, Saudi Arabia.

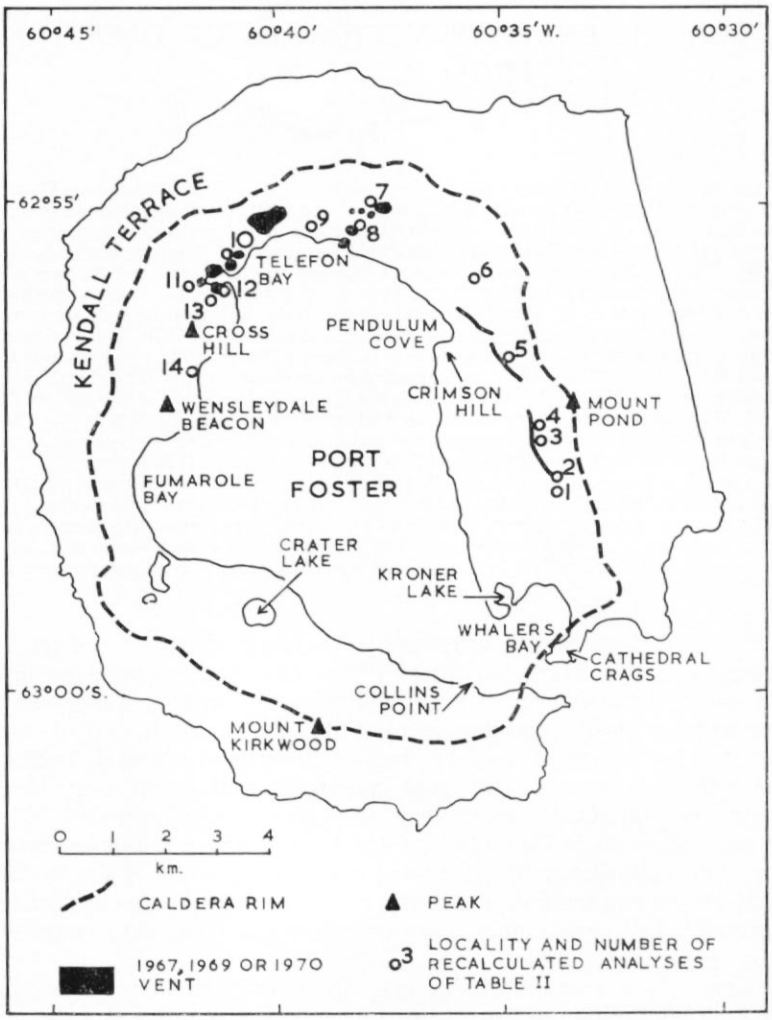

Fig. 1. Map of Deception Island showing vents of the latest eruptive episode and positions of analysed samples in Table II. The outline of the coast is that after the 1970 eruption.

stage of evolution. This is attempted here and the historical observations are considered first in chronological sequence.

1820–28

The flooded caldera was probably discovered in the Antarctic summer of 1820–21 by a party of fur sealers from Stonington, Connecticut, led by Benjamin Pendleton, who made it a base (Christie, 1951). Charcot (1910) thought it might have been discovered by members of this party during the previous Antarctic summer. Nathanial Palmer was present on both of these visits to the South Shetland Islands and in the Antarctic summer of 1820–21 he encountered the Russian expedition of Bellingshausen. Unfortunately, this well-documented expedition did not stop at Deception Island (Debenham, 1945, Vol. 2, p. 426). By 1825, the fur seals of the South Shetland Islands had been virtually exterminated and the industry died out.

The earliest accounts with volcanological detail are those of the first scientific expedition to

the island in 1829. Captain Henry Foster commanded H.M. Sloop *Chanticleer* and he visited the island for 2 months. Some of Captain Foster's remarks on the then-abandoned fur sealers' harbour have a bearing on a possible volcanic event in the period 1825–28. His writings are reproduced here at some length for later consideration. Captain Foster moored *Chanticleer* in Pendulum Cove (Fig. 1) and wrote (*in* Webster, 1834, Vol. 2, p. 278–79) of the flooded caldera:

> "In the centre of the basin there are ninety-seven fathoms of water, and the shores are everywhere too bold for anchoring, at a suitable distance from the beach; besides which the bottom, being composed of either loose mud or cinders, affords no hold for the anchors. On the eastern side, however, and at the foot of the highest hill on the island, which is crested with ice in a very remarkable manner, there is a cove, lying in a north and south direction, in which three or four vessels might be secured by placing, as was done in the Chanticleer, a bower anchor on each side of its opposite shores, and having another under foot in fourteen fathoms water, at the distance of about half a cable from either side. This mode of securing a ship will be found absolutely necessary for her safety at this place, and even then the topmasts should be struck and the anchors well backed, as the gales of wind from the north-east are not only of frequent occurrence in the summer months (January and February), but are of the most severe character, from the lowness of the temperature, 33° to 29°, and the sleet with which they are usually attended. Off the entrance into this cove there is anchorage in twenty-two fathoms, but from the badness of the holding ground it will be necessary to have both bowers down with the wind from the eastward, to prevent being blown off into deep water; and with westerly winds the situation of the vessel would then be extremely hazardous, being upon a dead lee-shore, and exposed to the fetch of the sea over the widest part of the basin. Water may be procured from a variety of places in the cove; but it will be found necessary, from its muddy condition, to sink wells in the beds of the different streams that discharge themselves into the sea, in which a sufficiency may be collected clear enough for use. From the Report of Lieutenant Kendall, who surveyed the island, it appears that the only secure place now afforded for shipping is this small cove; and there is reason to believe that this cove is not the one spoken of by the sealers, as neither its situation, form, or character of the soundings in it, accord with their descriptions; but that the place which once afforded anchorage for ships is now rendered inaccessible, except for boats, by the observable changes which the face of nature on this island daily undergoes. At all events, there is a snug-looking place a little to the northward of this anchorage, and where several articles useful to sealers were found, and the dilapidated remains of places built for the purpose of boiling the blubber of seals for oils. There was also the shank of a large merchant-vessel's anchor, which, together with other articles, gave us reason to suppose that they must have been landed directly from the vessel to which they might have belonged when inside of the cove, as the distance they were from the outer shores would have made the labour of transporting them to the places where they were found excessive. Near the same spot, too, there were the remains of a seaman, who had ended his days on this inhospitable island; and from all these circumstances, I am induced to believe that the cove in question is the one which is stated as capable of affording anchorage for five or six vessels in four or five fathoms water over a bottom of good clay, the entrance into which is now nearly blocked up by a split that has extended itself right across the entrance, and in some places is dry at low water. In the event of this island being hereafter visited by persons furnished with proper instruments for surveying, it would be highly interesting to ascertain to what extent the present form of this island may have changed by the active agency of rivulets, or the more powerful action of volcanic eruptions, for which purpose the careful survey made by Lieutenant Kendall will prove very valuable."

Thus, in 1829 the only good harbour inside Port Foster was Pendulum Cove because that of the fur sealers had silted up. This change of harbours by 1829 is surprising and four lines of evidence suggest that the flooded Pendulum Cove crater was at that time extremely youthful, perhaps having formed by an explosion between 1825 and 1829. First, in 1829 there were no signs of the fur sealers having used Pendulum Cove, yet such ships of several nationalities had used Port Foster. William Smith (the discoverer of the South Shetland Islands) estimated that in 1820–21 there were at least 52 fur-sealing ships in the South Shetland Islands (Christie, 1951). Secondly, although Captain Foster had records of anchorages inside Port Foster from the sealers, Pendulum Cove was unknown to him. Thirdly, in 1829 subterranean sounds were frequently heard inside Pendulum Cove which on one occasion resulted in some of the instruments being taken back on board ship (see next extract here from Captain Foster). Fourthly, the 1829 deep-water cove rapidly silted up to form land by the present century. Fig. 2 is from

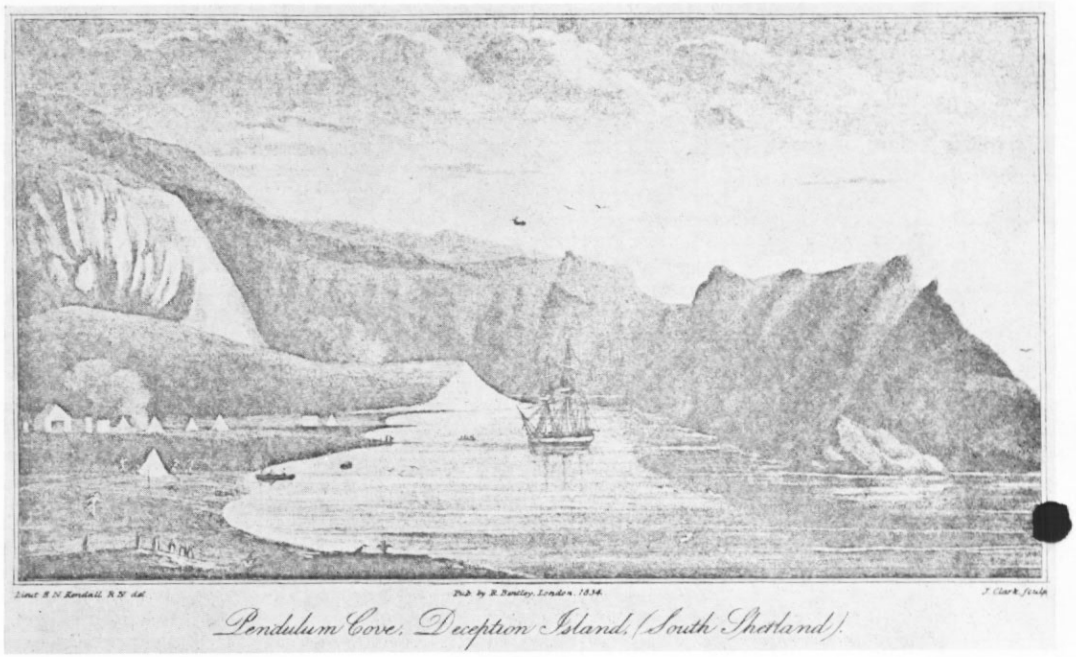

Fig. 2. H.M. Sloop *Chanticleer* moored in Pendulum Cove while pendulum experiments were being conducted on shore in the vicinity of the steam vents. (From Webster, 1834.)

Fig. 3. Pendulum Cove in December 1968. This area was largely unaffected by the 1967 eruption except for a thin ash-scoria layer. The original Pendulum Cove is infilled and the beach connects direct with Crimson Hill. The glacier on the site of the original cove can be seen with the former Chilean station just visible at its foot.

Webster (1834, Vol. 1, facing p. 146) showing *Chanticleer* moored inside Crimson Hill, while Fig. 3 is a photograph of the same area taken in December 1968. An indication of the rate of silting up has been given by Mossman (Hydrographic Department, 1974, p. 171):

> "From a comparison of Foster's soundings with those made by the *Uruguay* in 1905, it was found that in the 76 years that had elapsed since his visit there is a difference of 12·8 m (42 ft), because where he got 45·7 m (25 fm) of water there are now only 33 m (18 fm). Whether this is due to general elevation of the land or to a filling up of the basin by volcanic emanations is a matter of conjecture."

Gourdon (1910), geologist to the Deuxième Expédition Antarctique Française, recorded that in December 1908 the original Pendulum Cove was almost entirely filled up with cinders, while a photograph from the same period (Charcot, 1910, p. 331) shows the original cove as infilled and blocked by a beach bar. In 1957, Hawkes (1961, p. 24) found only dry land inland from Crimson Hill, except for a small relict lake in the deepest recess. The present-day Pendulum Cove is the bay nearest the original crater. In view of the rapid silting up process, the deep-water crater of 1829 could not have then been very old.

9 January–8 March 1829

This was the period when *Chanticleer* remained at the island and pendulum measurements were made in the cove. Lieut. Kendall made an accurate topographic map of the island which was reproduced by Roobol (1973). Captain Foster described the Pendulum Cove area in his remarks on the harbour (*in* Webster, 1834, Vol. 2, p. 276–77) as:

> "At the base of the highest hill on the island the pendulum experiments were performed; and there also hot-water streams were found discharging themselves into the sea. The summit of the hill, or rather the earthy parts of it, were perforated with numberless small holes, through which steam issued with a loud hissing noise; and the surrounding ground was too hot to be touched by the naked hand with impunity. There was a vast quantity of ice on the summit, so much so that the hill appeared from the observatory to be an entire iceberg, covered here and there with loose cinders and ashes. Subterranean sounds, as of mountain torrents, were frequently heard; and on one occasion were so loud as to create some apprehensions for the safety of the instruments, and accordingly the pendulums that had been experimented with were immediately taken on board."

One of the unfortunate consequences of the death of Captain Foster in Panama before the expedition returned to England was that further description of the island by the ship's surgeon, Webster, contained far less detail of localities. Webster (1834, Vol. 1, p. 151–53) gave a similar picture but less information on the position of the "fumaroles":

> "During our stay at Deception Island we observed no appearance of any active crater, although, as I have before remarked, the peaks of some of the mountains sent forth smoke; but the numerous hot springs with which the shore of the basin abounds, would indicate that the subterranean fire is merely abated and not extinguished. In our rambles about the hills, subterranean noises were frequently heard, and seemed much like the violent rushing of water under ground. The hot springs to which I have before alluded, present a remarkable phenomenon in Deception Island. In many places on the shores of the basin, particularly between high and low water-mark of the tide, vast volumes of steam are seen rising from the ground for several hundred yards in extent. As the tide ebbs, the beach begins to send forth steam; and, in walking along the shore, a person is fairly enveloped in hot steam; while on one side he is hemmed in with towering icebergs, and on the other by the sea-water of a temperature not far from the freezing point. The hot water bubbles up through the beach, which in some places is of a stiff and compact nature; and on digging into it a strong sulphureous odour is sent forth, the water at the same time becoming hotter, and, at a trifling depth from the surface, being within a few degrees of the boiling point. We found the temperature of the water issuing from these hot springs to be 185° Fahrenheit; and considerably higher near some beds of alum rock in some parts of the beach. There is also another very remarkable feature attending these springs in point of locality; they are not only confined to particular places, but also extend in narrow bands along the beach, nor does the heat from them extend to any distance around. The water belonging to them has a slight styptic flavour where it is near the alum rocks, and in other places it does not differ from common hot water, more particularly when it comes up through a bed of ashes.
>
> "There can be little doubt that these thermal springs are the effects of some latent fire produced by the chemical agency of sulphureous earth and pyrites. Some of the lofty hills, especially Iceberg Hill

> over the observatory, was always sending forth steam. On examining the summit of it, a bed of hot sulphureous clay and some aluminous efflorescences were found to compose it, from which the same sort of steam arose as from the beach. The vapour generally forms a dense cloud over the hill, and encircles it like a wreath of mist."

By analogy with Captain Foster's comments, Webster was mainly describing the area around Pendulum Cove and "Iceberg Hill" (to which he referred using the popular name given by the *Chanticleer* party to Mount Pond), which is correctly named on Kendall's 1829 map.

The description of the "fumaroles" or tidal areas giving forth steam with and without sulphurous odours is identical to the situation existing in 1968–69 and similar to the descriptions of Charcot (1910), Holtedahl (1929) and later writers. As has been pointed out by other writers, these are not true fumaroles. Rather than becoming involved in dispute as to which are/were fumaroles with juvenile water and materials and which are/were simply heated sea- or ground water carrying material derived from the chemical break-down of the scoria, all are referred to here as areas of high heat escape. They are restricted to the ring-fault zone and are identified where the shoreline of Port Foster indents this zone and where the intertidal zone steams and the shallow water may boil.

Much of the hot water is probably heated sea-water with minor amounts of material ad[illegible] as found by Elderfield (1972) for the waters of the 1967 crater lakes. Aside from the shoreline areas of heat escape, the summit of Mount Pond in 1829 was probably nearer to having fumaroles.

Further description has been given by Webster (1834, Vol. 2, p. 300–01):

> "The whole island being of volcanic origin and yet almost entombed in snow, our knowledge of its geological products must necessarily be very imperfect. One of the chief features was the prevalence of lateritium, or brick-stone, the burnt earths and clay. Many of the hills had very extensive strata of it, and some of the more conspicuous peaks, especially where they were crowded together, obtained the name of the brick-kilns. The crimson hill, near the observatory, had large strata of it. It was dispersed upon the beaches, and lay in large fragments upon the hills; it prevailed in every quarter of the island, and gave great relief to the dull scenery. It was both cellular and compact, and some contained crystals.
>
> "The principal rock was blue volcanic whinstone, more or less compact and crystalline. Basalt was found only in one part; it was dark, compact, of a fine lustre, imbedding numerous crystals of felspar; and in many parts fine veined with white felspar. Perlite, or pearl-stone, was found in dark basalt. Pumice was found on the beach and where the streams of water ran. Large masses of red sandstone, with radiated crystals of gypsum, crystals of sulphate of lime, in a variety of forms, were prevalent; and masses of fine milk-white semi-translucent gypsum were obtained near the hot springs. Many of the stones about the springs were completely bronzed by being coated with pyrites.
>
> "Streams of sulphuretted hydrogen were emitted from the caverns, evidenced by the peculiar smell and fœtor; and when this was mixed with steam, the arches against which it issued became covered with efflorescence of sulphur, and occasionally with fine crystals thereof. Where the sulphuretted hydrogen and steam came in contact with a body of clay, sulphur was deposited and alum formed. The alum of the volcanic districts appears to be formed from the sulphuretted hydrogen, and not from sulphurous acid gas, the sulphuretted hydrogen becoming acidified, or the sulphur deposited therefr[illegible] and the gradual deposit of sulphur from its gaseous state, may account for the heat observed in s[illegible] circumscribed spots, the immediate vicinity of which was frost and snow. Every one was struck with the partial and limited heat, which appeared in many instances in spots and patches, which it was difficult to reconcile to the idea of some great internal heat, but was referable to a local chemical action —the heat arising from the condensation of the sulphuretted hydrogen and its passing from a gaseous to a solid state, by which a large volume of heat is extricated. At any rate, whatever the cause may be, it is totally inexplicable upon the supposition of any general subterranean heat; for wherever you attempted to dig a few feet into the earth, even in the immediate vicinity of the hot springs, all was frozen and congealed as hard as adamant, and which the pick-axe could with difficulty penetrate, although merely ashes and cinders; and in no part of the island was the temperature of the hottest springs above 190°, however deep you penetrated into them."

Recent visitors to Deception Island will have noticed that the red scoria described by Webster as being so abundant (a description still repeated in *The Antarctic pilot* (Hydrographic Department, 1974)) have largely disappeared. The island now has a darker appearance due to the widespread but thin cover of ash and lapilli from the post-1829 eruptions. The red horizons are

still visible between the truncated and near flat-lying lava–scoria strata of Crimson Hill. This truncated structure, plus Webster's mention of red clasts on the beaches and hills, suggests that the Pendulum Cove crater may well have originated by a gas blast or phreatic explosion in which no new magma was ejected but only clasts of the older strata including the many red horizons.

10–17 March 1839

During this period the island was visited by the U.S. Schooner *Sea Gull* commanded by Lieut. Johnson as part of the U.S. Exploring Expedition of 1838–42. Two accounts of this brief visit (when much time was lost to snow storms) have been published. The expedition commander, Captain Charles Wilkes, based his account on Lieut. Johnson's journal, while the expedition geologist, the well-known mineralogist J. D. Dana, extracted his account from the journal of *Sea Gull*'s surgeon, Dr. J. S. Whittle. Neither Wilkes nor Dana visited Deception Island. The main contribution of this expedition was to show that by 1839 the main area of heat escape for Deception Island was on the northern slopes of Mount Kirkwood. *Sea Gull* was moored in Pendulum Cove. The following section is taken from Dana (1849, p. 547–48):

> "On the southern side of the harbour, about two miles from the anchorage, several streams of salt water were observed running from the lower part of the hills and emptying into the bay, which were hot enough to have boiled an egg. Three miles farther towards the mouth of the harbour we saw vapour rising in immense quantity; and on approaching the place, found that it was the crater of an extinct volcano. It was situated about six hundred yards from the beach, from which it was separated by a strip of low land; on the other sides it was bounded by high hills. The crater had fallen in, and was filled with salt water. It was probably three-fourths of a mile in circumference, and the banks of the pond or crater were from fifteen to forty feet high. Around this crater there were many smaller ones, varying from a foot to a yard square; and on the side farthest from the bay there were numerous hot springs, some in ebullition, and every crack in the earth emitted steam.
>
> "About the mouth of one of the small craters there was a lining of lichen, which appeared to be the only kind of vegetation on the island. Crystallized salt was found attached to stones, where it had been deposited by the evaporation of sea-water. Other steaming hills were observed in the distance, but were not visited for want of time.
>
> "Proceeding in a boat from the volcano just mentioned, we sailed along that side of the harbour. We found a beautiful gravel beach, and passed many singular peaks, cones, arches, and columns of rock, and one which was an inverted pyramid sixty feet high. Some scoria was here collected that was light enough to float.
>
> "The appearances of volcanic action were as conspicuous in all parts of the island as in that above described, the only difference being that the eruptions there may have been the most recent."

A somewhat more generalized account was given by Wilkes (1845, Vol. 1, p. 144):

> "Lieutenant Johnson, in company with Assistant-Surgeon Whittle, visited an old crater at the head of the bay, where a gentle ascent of about four hundred feet, brought them to the edge of an abrupt bank, some twenty feet high, surrounding the crater on the bay side. The crater was about fifteen hundred feet in diameter, from east to west, bounded on the west or farther side by lofty hills, with many ravines, which had apparently been much washed by heavy rains. This led to the belief that the water found within the crater would be fresh, but its taste, and the incrustation of salt found on its borders, showed that it was not so. Near the east end of the crater, the water boils in many places, sometimes bubbling out of the side of a bank, at others near the water's edge, with a hissing noise. The surface water was found to be on a level with the waters of the bay, and to be milk-warm. A few inches below, it was perceptibly colder. No thermometric observations were obtained. The ground near the Boiling Springs was quite hot. In the vicinity were lying quantities of cellular and scoriaceous lava. The only sign of vegetation was a lichen, growing in small tufts, around the mouth of several small craters, of three or four feet in diameter. From these a heated vapour is constantly issuing, accompanied by much noise."

A striking feature of these accounts is the absence of comment on subterranean sounds and hot springs in Pendulum Cove and the fumaroles of Mount Pond, despite the fact that *Sea Gull* was moored in Pendulum Cove. That the only comments described the opposite shores of Port Foster suggest that the Pendulum Cove event, which was probably still in progress in 1829, had largely ceased by 1839.

The description given by Dana suggests that the party crossed Port Foster, perhaps to Fumarole Bay where they observed hot streams, then turned towards the harbour entrance and arrived at the crater with immense quantities of vapour. The latter is almost certainly Crater Lake at the foot of the northern slopes of Mount Kirkwood (Fig. 1). This is the only lake in a crater with a description fitting that given. It has a circumference of 1 mile (rather than $\frac{3}{4}$ mile) and an east–west diameter of 1,700 ft. (rather than 1,500 ft.). That the party found this lake, which is completely hidden from sight from Port Foster, is a measure of the steam column rising from it. It was missed by the Deuxième Expédition Antarctique Française of 1908–10. It must be concluded that the main area of heat escape in 1839 was in the Mount Kirkwood sector of the ring-fault zone rather than that of Mount Pond.

In the account by Dana the two references to other steaming hills observed in the distance, as well as many small craters from a foot to a yard square at Crater Lake, provide a hint that some eruptive activity might already have occurred on Mount Kirkwood so that the surrounding surfaces were pitted by impact craters caused by the ejection of large clasts or bombs. Such craters were found in December 1968 around the 1967 "land centre".

February 1842

Captain W. H. Smiley (later U.S. Ambassador to the Falkland Islands) visited Deception Island in February 1842. He wrote an account of his visit in a letter to Captain Wilkes which was referred to by Wilkes (1845, Vol. 1, p. 144) as:

> "Knowing that Captain Foster, in the Chanticleer, had left here a self-registering thermometer, in 1829, I directed Lieutenant Johnson to look for it, and note its standing. Immediately on securing the tender he proceeded to search for it, but notwithstanding the particular directions, he did not find it. Since my return home, I have received a letter from William H. Smiley, master of a sealing vessel that touched there in February, 1842, stating that he had found the thermometer, and carefully noted its minimum temperature, which was 5° below zero."

Wilkes (1845, Vol. 1, p. 144–45) further wrote with regard to the departure of *Sea Gull* from Deception Island:

> "On the 17th of March they sailed from Deception Island, having left a bottle enclosing reports, tied to a flag-staff. This was afterwards found by Captain Smiley, who mentions in his letter to me, that in February, 1842, the whole south side of Deception Island appeared as if on fire. He counted thirteen volcanoes in action. He is of opinion that the island is undergoing many changes. He likewise reports that Palmer's Land consists of a number of islands, between which he has entered, and that the passages are deep, narrow, and dangerous."

The observation of 13 volcanoes by Smiley has been discussed in several geological reports, and Hawkes (1961, p. 2) drew attention to the correlation of Smiley's report with the occurrences of the youngest lava flows on Deception Island. On 29 December 1968 the present author visited the Mount Kirkwood vents and lavas. Because of their relatively high elevation they are partly hidden in permanent ice as well as being blanketed by snow for most of the year, but they appear to extend over a 4 km. fissure along the upper slopes of the caldera side of the Mount Kirkwood ridge.

As far as can be seen on the 1956 air photographs, these young deposits occur in two separate groups but both were erupted from one continuous fissure. One section lies immediately above Crater Lake, from which two short lava flows extend down the inside wall of the caldera. One of these has entered Crater Lake. The other group lies between the summit of Mount Kirkwood and Collins Point (Fig. 1). Here, a line of seven snow-filled crater depressions marks the vents along the fissure; these are scoria cones. A short lava flow extends part of the way down the caldera wall but it arises higher up-slope than the line of vents. These features indicate that as many as three eruptive events may have contributed to the youngest lavas and scoria cones of Mount Kirkwood. All are remarkably well preserved and lack erosional features, as well as a debris cover from later eruptions, indicating their extreme youth. The geology indicates

both explosive ejection of coarse clasts (bombs) and lava-flow activity, but no extensive fine-grained pyroclastic cover was produced as in 1967, 1969 and 1970.

Captain Smiley's report of "an appearance as if on fire" is here interpreted as indicating neither Strombolian explosions nor lava flowing but 13 very active sites of heat escape marked by billowing white steam clouds. Indeed, what Smiley saw in 1842 may well have been somewhat similar to what the *Sea Gull* party observed in 1839—being mainly a high heat escape from the Mount Kirkwood sector. The relationships of the youngest lavas and scoria cones of Mount Kirkwood suggest that several eruptive events may have occurred, perhaps spanning several years as those in 1967, 1969 and 1970. A high heat escape (in the form of vapour rising in immense quantity), as probably observed in 1839–42, points to such an eruptive episode occurring during this period. At present it is uncertain as to how soon after an eruptive episode the areas of high heat escape die out. Such information could be gained relatively easily by annual temperature measurements being made at selected fumaroles.

1842–1908

The enthusiastic and detailed recorded observations of the earliest visitors to Deception Island were followed by a 66 year period which lacks volcanological detail and is a gap in the record. The review of Antarctic work by David (1895) did not add any further details on the physical state of Deception Island. It is unfortunate that the Swedish petrologist, J. G. Andersson, was prevented from entering Port Foster in November 1902 as the entrance was blocked by ice. The few samples which he collected from the outer coast were later lost with *Antarctic* (Andersson, 1906, p. 49).

The first whaling expedition to the Antarctic arrived in the southern summer of 1905–06 and comprised a Norwegian party under the command of Alexander Lange with the factory ship *Admiralen* and two whale catchers. They made use of the harbour of Deception Island as did others until 1910, when a permanent whaling station was built in Whalers Bay (Christie, 1951). This station was used each summer until 1931.

Intrusive/eruptive episodes probably occurred during the period 1842–1908. One of the most striking indications is the addition of the Kroner Lake peninsula to the shores of Whalers Bay (Roobol, 1973, fig. 4). This is not interpreted as a local error in Kendall's map, because the 1829 topography is distinct on the 1956 air photographs and as it was not completely buried by the Kroner Lake air-fall pyroclastic deposits. The presence of whale bones on the shores of this peninsula fix the upper age limit, while the lower limit can only be fixed by its absence from the 1829 map. The whale bones were buried and lost by the flood of melt water which accompanied the 1969 eruption. The Kroner Lake event considerably reduced the size of Whalers Bay and so contributed to it becoming another anchorage inside Port Foster.

Another eruptive event occurred sometime between 1829 and 1956, as the silted-up harbour of the fur sealers described by Captain Foster and mapped by Kendall in 1829 had been replaced by two youthful maars by 1956 (Roobol, 1973).

1908–09

The Deuxième Expédition Antarctique Française of 1908–10, led by J.-B. Charcot in *Pourquoi-Pas?*, visited Deception Island during 22–25 December 1908, 28 November–22 December 1909 and 31 December 1909–6 January 1910 (Charcot, 1910). This expedition produced topographic maps and soundings, and was the first to map the positions of the "fumaroles". Their topographic map of Deception Island (Bongrain, 1912, pl. X) at a scale of 1:50,000 marks fumaroles at the present Fumarole Bay (Fig. 1). The inset of Pendulum Cove, also at a scale of 1:10,000 marks the shoreline as "rivage borde de fumerolles". The inset of Whalers Bay, also at a scale of 1:10,000, marks fumaroles as occurring along 600 m. of the shoreline immediately

north of Cathedral Crags. A photograph in Charcot (1910, p. 43) shows *Pourquoi Pas?* coaling on 24 December 1908, while in the background the steaming shoreline of Pendulum Cove looks much as it did in 1968–69.

The expedition geologist, Gourdon (1910), recorded a water temperature of 68° C on the shoreline of Pendulum Cove, an area of hot ground situated 200 m. a.s.l. at Pendulum Cove (i.e. on the lower slopes of Mount Pond), a shoreline temperature of 50° C at Whalers Bay and a maximum "fumarole" temperature of 89° C at an unspecified locality.

The observations of this expedition are particularly valuable since they indicate that the heat escape from the Pendulum Cove–Mount Pond–Whalers Bay sector of the ring-fault zone was established by 1908.

Summer 1913–14

The next account is based on observations made in the southern summer of 1913–14 by Ferguson (1921, p. 45), who wrote:

> "At the north side of the inner rim of the island is a fine glaciated corrie with the hollow occupied by a tarn ([his] plate III, fig. 3). The water of this tarn is moderately warm, and is evidently fed from hot springs bringing up water from heated rocks below. This is the only existing volcanic action on Deception Island."

The photograph of an elongate body of water, as well as its caption implying that it lies on the north-west of the caldera rather than the north as stated above, suggests that this can only be the inside of the crater immediately north-east of Cross Hill (Fig. 1). That it is not a corrie but an explosion crater in a pyroclastic cone is evident, in the photograph, by the gullied black lapilli slopes. Many visitors (without volcanological training) to Deception Island had difficulty in recognizing the significance of the many pyroclastic cones around Port Foster which are formed of black, stratified air-fall lapilli of vesicular lava. Holtedahl (1929) had similar problems with the crater depression of Kroner Lake and he regarded the stratified air-fall deposits around it as a lava flow which had fragmented.

Ferguson's statement that the warm water in the crater lake was then the only evidence of volcanic action at first appears remarkable in the light of the maps of Charcot's expedition and those of subsequent visitors which refer to the heat escape at Fumarole Bay, Pendulum Cove and Whalers Bay. Is it possible that Ferguson missed the areas of heat escape of Whalers Bay near the then-operating whaling station, or the steaming shoreline of Pendulum Cove as photographed by Charcot's expedition? How could he miss these yet find the relatively obscure occurrence inside an explosion crater which is mainly hidden from view? Could these details have been forgotten in the 8 years' intervals before his observations were published?

An alternative explanation is provided by the work of Orheim (1971). Annual wind-blown dust layers were exposed in the ice walls of the 1969 vents, which pointed to six pyroclastic eruptions during the period 1912±5 years to 1917±3 years. That these events were not recorded by the whalers is most probably because they occurred in the southern winters when the island was abandoned, or less likely when occupied but hidden by cloud cover or intervening topography. Ferguson's visit to Deception Island in the summer of 1913–14 corresponds with this period identified by Orheim. It is possible that Ferguson arrived after these eruptions at a time when the magma had withdrawn deeper into the ring-fault zone and there were almost no areas of obvious heat escape. The pinpointing of this crater by Ferguson is the only real clue to the possible vent area for the eruptions identified by Orheim as having occurred in 1912–17. In the summer of 1968–69 the summit of Cross Hill showed 3·5 m. of fresh black stratified air-fall lapilli overlying similar but older and yellowish partly altered deposits. Orheim (1971) has suggested a possible 1912–17 vent area on the south-west side of Port Foster below Mount Kirkwood and he argued that the glaciers of Mount Kirkwood should extend farther down-slope. However, this latter observation might be due to the 1829–42 vents of Mount Kirkwood rather than to others of the present century.

JANUARY 1923

Holtedahl (1929, p. 39) visited the island in the summer of 1927–28 and wrote:

> "As to very recent dislocations going on in the island I might mention that earthquakes have repeatedly taken place during the last few years. One occurred on January 4th, 1923. It was strongly felt at the land station [whaling station in Whalers Bay]. A man who was present told me that he nearly fell off his chair. In the harbour the sea was 'boiling' and considerable quantities of the gravel and sand on the shore just in front of the station slipped out into the harbour. Mr. ØHRE [whaling station manager] informed me that outside the station, where the floating factory "Ronald" was lying at anchor, the depth during the catastrophy was increased by several fathoms. In fact this harbour [i.e. Whalers Bay] probably represents a subsiding area, . . . "

This is probably the same event reported erroneously as occurring in 1921 in *The Antarctic pilot* (Hydrographic Department, 1974, p. 171) as:

> "In 1921, the shore in the vicinity of the whaling station suddenly subsided, imperilling the safety of the factory ship *Ronald*, while over half the bay the water boiled, taking all the paint off the ships."

1927–28

Two visits with recorded observations were made to Deception Island in 1927. In April, that of R.R.S. *Discovery* has been recorded in *The Antarctic pilot* (Hydrographic Department, 1974, p. 170):

> "In April, 1927, the RRS *Discovery* found much evidence of volcanic activity. Clouds of steam frequently arose at the water line in Whalers Bay and at low water mark. At 20 centimetres (8 inches) below the scoriae and ashes the temperature was found to be 56° C. A series of temperatures was also taken to the bottom at a depth of 168 m (92 fm), in the middle of Port Foster; nothing striking was apparent in the data obtained, there being a steady fall of temperature with depth to −1·5° at the bottom."

In the southern summer of 1927–28, Holtedahl (1929, p. 39–40) visited Deception Island for only 3 days but he described the "fumaroles" of Whalers Bay and Fumarole Bay. Although his short stay did not allow him time to visit all parts of Port Foster, his incomplete observations established that there were areas of heat escape in both Fumarole Bay and Whalers Bay.

JANUARY 1930

The Antarctic pilot (Hydrographic Department, 1974, p. 171) recorded another subsidence of the floor of Whalers Bay as:

> "In January, 1930, an earthquake shock was experienced in Deception Island; part of the bottom of the harbour dropped 4·6 m (15 ft), carrying with it the end of wharf, and a vessel in the harbour was rocked as if in a heavy sea."

JANUARY 1936

The Antarctic pilot (Hydrographic Department, 1974, p. 170) has reported:

> "In January, 1936, a member of the British Graham Land expedition measured the temperatures at the hot springs around Port Foster. The hottest water found in Whalers Bay was 53° C, in a brackish stream flowing down the beach N of the whaling station. At low tide the temperature of the sea along the shore was 35° C. At high tide the temperature of the surface of the sea at this point was 6·5° C, but 1 cable offshore it was 3·5° C. It is reported by the whalers that at times the water in this anchorage has been hot enough to blister the paint on the factory ships. In 1936 the only boiling water found was on the beach near the head of the large bay on the W side of Port Foster, where steam was issuing in powerful jets from fissures in the rocks."

The Antarctic pilot continues (p. 171):

> "In January, 1936, there were hot springs issuing along the beach at Pendulum Cove, and the whole area was characterised by patches of steaming hot sand."

These observations indicate a similar distribution of areas of obvious heat escape, i.e. 1. Pendulum Cove; 2. Whalers Bay; 3. Fumarole Bay, as mapped by Charcot's expedition in 1908–09 but they omit any mention of areas of hot ground on Mount Pond. The three coastal areas of heat escape were not found by Ferguson in 1913–14 but they had probably re-established by 1927, as suggested by the incomplete observations of R.R.S. *Discovery* and Holtedahl.

1949

The Antarctic pilot (Hydrographic Department, 1974, p. 170) reported:

> "In 1949, the only hot springs observed were those on the N shore of Kroner Lake, although the shores of Whalers Bay and Pendulum Cove gave off clouds of steam at low water. A small amount of steam was observed, in the same year, issuing from a fissure in the vicinity of a cairn, 1,185 ft (361 m) high, situated 3¼ miles WNW of Collins Point (*63° 00′ S, 60° 35′ W*)."

The bearing and distance position the steaming fissure at Fumarole Bay. The main areas of heat escape were in 1949 as established in 1908–09 and 1936, i.e. 1. Pendulum Cove; 2. Whalers Bay; 3. Fumarole Bay, but with an additional area of: 4. Kroner Lake. This is the first record of the Kroner Lake locality which continued to be reported up to 1968.

Southern Summers of 1952–53 and 1953–54

During this period Olsacher (1956) visited Deception Island. He described the "fumaroles" as occurring in: 1. Fumarole Bay; 2. Pendulum Cove; 3. Whalers Bay; 4. On the shore of Port Foster immediately west of the northern edge of Kroner Lake. The latter position is 300 m. west of the 1949 Kroner Lake position and is regarded as the same general area of heat escape. Olsacher (1956, p. 28) also produced a map of the positions of the "fumaroles". The distribution of the areas of heat escape at the time of Olsacher's visit was therefore virtually identical to that of 1949. Olsacher classified the "fumaroles" into two types:

i. Fumaroles sulfidricas (Fumarole Bay).
ii. Fumaroles no sulfidricas (Pendulum Cove and Whalers Bay).

Southern Summer of 1957–58

During this period Hawkes (1961) carried out field work and briefly recorded "fumaroles" at: 1. Fumarole Bay; 2. Telefon Bay; 3. Pendulum Cove; 4. Whalers Bay. He did not mention any to the west of Kroner Lake but, as these were later mapped in 1961–62 by Casertano (1964), it must be assumed that either they were missed by Hawkes or had temporarily disappeared. Hawkes' observations indicate that since the survey of Olsacher in 1952–54 another new area of heat escape had formed in Telefon Bay. Hawkes (1961, p. 28) further reported:

> "In addition to fumaroles there are local 'warm spots' or patches of snow-free ground, the highest of which is only 50 ft. below the summit of Mount Pond."

This is the first mention of warm ground on Mount Pond since the observation of Gourdon in 1909 when such an area was situated only 200 m. a.s.l. These two observations of warm ground are, however, valuable for the interpretation of the areas of heat escape.

Hawkes (1961, fig. 11) also recorded the height of the water table, tide level and water temperature for an artificial well on the shores of Whalers Bay for a 30 day period. He found a good correlation between the three, high-water level corresponding with high-tide level and high temperature. This suggests that the hot water is rafted on top of the cold sea-water as found by the R.R.S. *Discovery* investigations in 1927. Hawkes also questioned Olsacher's classification into sulphurous and non-sulphurous types, as some localities showed both characters at different times.

Southern Summer of 1961–62

Casertano (1964) participated in the 16th Chilean Antarctic Expedition and mapped the "fumaroles" of Deception Island. His report and map showed that around the shores of Port Foster the areas of obvious heat escape were in the same positions as reported by Hawkes (1961) in 1957–58. He positioned the fumaroles immediately west of Kroner Lake but made no reference to patches of warm ground on Mount Pond. His localities for heat escape are therefore: 1. Fumarole Bay; 2. Telefon Bay; 3. Pendulum Cove; 4. Whalers Bay; 5. Shore west of Kroner Lake.

November 1968–January 1969

During this period, between the 1967 and 1969 eruptions, the areas of heat escape were again mapped (Baker and others, 1975, fig. 22). This distribution is shown here in Fig. 4 but it is

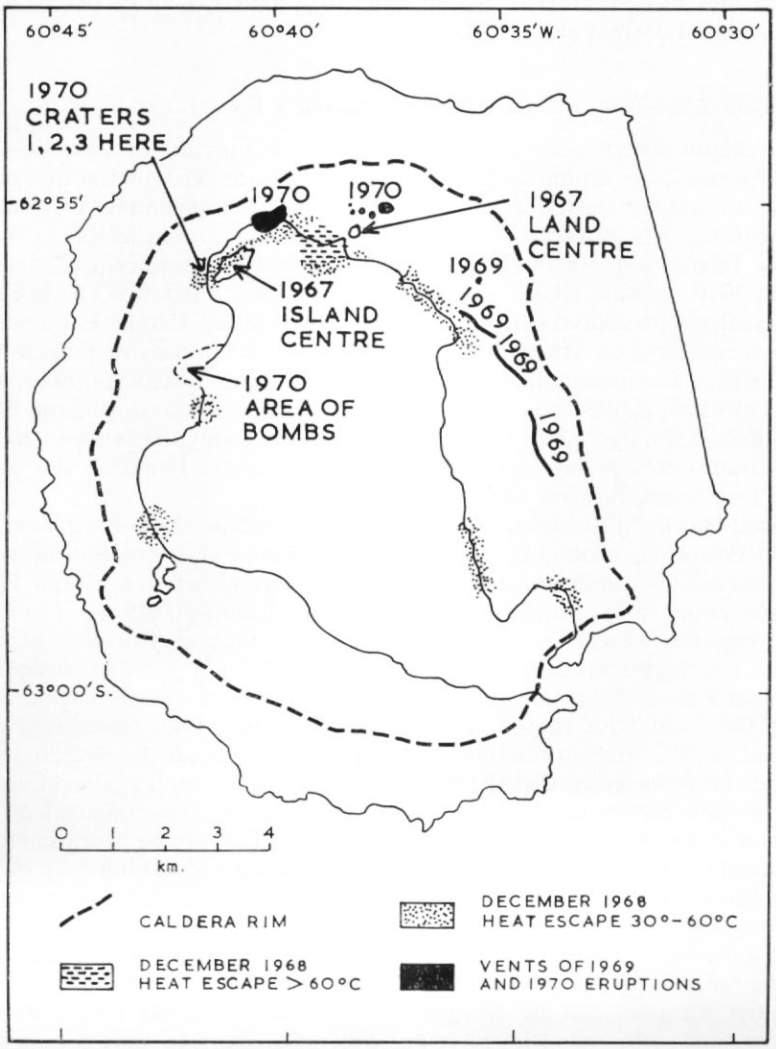

Fig. 4. Map of Deception Island showing the December 1968 shoreline and heat escape. The "island" and "land" centres of the 1967 eruption are shown. The positions of the 1969 and 1970 vents, which formed after the heat escape was mapped, are also shown. The areas of heat escape can be regarded as outlining those sectors of the ring-fault zone where eruptions subsequently occurred.

coded for maximum temperature. An omission from fig. 22 of Baker and others (1975) is corrected by inserting the area of heat escape to the west of Kroner Lake which was first located in 1949. On 19 December 1968, this area of heat escape extended along 1·5 km. of shore (Fig. 4). The maximum temperature on shore was in the water between the pebbles of the intertidal zone (40° C), while the maximum water temperature in the shallows of Port Foster was 25° C. By comparison with the map of Casertano (1964), this area had extended 1 km. farther to the north. In a similar manner, the area of heat escape on the shores of Telefon Bay was in 1968 considerably enlarged with extensions of 1·5 km. both to the east and west of the area mapped by Casertano. A new area of heat escape had appeared on the shore immediately east of Wensleydale Beacon. A visit to the top of Mount Pond showed that there were no areas of warm ground but some 2–3 m. high mounds with vertical sides of loose ice crystals may have been accumulations of hoar frost or frozen fumaroles similar to those described on Mount Erebus by Shackleton (1909, Vol. 1, p. 185).

Possible Significance of the Areas of Heat Escape and Fumaroles

The more frequent observations of this century provide a picture of a progressive build-up of the areas of heat escape, culminating in the latest eruptions. The distribution of these areas of heat escape around the shores of Port Foster in the southern summer of 1968–69 (Fig. 4) corresponds with the sites of the vents of the 1969 and 1970 eruptions as well as those of 1968. The belt across Telefon Bay, which extended almost to the 1968 "land centre", marked the line of vents of the 1970 eruption (Baker and others, 1975, figs. 29 and 30). The belt between the areas of heat escape in Pendulum Cove and those of Whalers Bay–Kroner Lake, which includes the areas of warm ground on Mount Pond, outlines the sector of the ring-fault zone where the 1969 fissure opened. The area immediately east of Wensleydale Beacon probably also marked the site of a vent which produced an anomalous area of large bombs during the 1970 eruption (Baker and others, 1975, figs. 32 and 33). Open fissures—possibly the vents—were reported in this area by Schultz (1971, p. 84). Only the area of heat escape in Fumarole Bay was unrelated to the site of a vent during the recent eruptions.

It is concluded that the distribution of the areas of heat escape and warm ground around the shores of Port Foster, i.e. around the ring-fault zone, show a close correlation with the vents of the later eruptions. A similar relationship probably existed between Mount Pond and the Pendulum Cove crater in 1829 and for Mount Kirkwood during 1839–42. The areas of heat escape can be regarded as marking the positions where small bodies or pods of magma have been emplaced at a high level into the ring-fault zone. It is not possible to say whether the Whalers Bay and Kroner Lake areas of heat escape represent two small magma pods close to the surface in the 3 km. wide ring-fault zone or whether they both represent a single larger body at greater depth. Such distinctions might perhaps be made by mapping the shadow areas of S-type shock waves around the ring-fault zone. However, the general idea suggested here may prove valuable for future observations of the volcano, as the areas of heat escape and the underlying magma pods mark the sites of the vents for varying periods before eruption of up to six decades. Had the historical record been searched and the build-up of the areas of heat escape noticed prior to the recent eruptions, then the latest activity might have been anticipated.

In terms of a model of magma pods in the ring-fault zone, the suggested intrusive-eruptive episodes of the volcano for the past 150 years are summarized in Table I. Only five possible intrusive-eruptive episodes can be recognized from the somewhat fragmentary historical record. Two or three other episodes have probably also occurred in this time (footnote to Table I). The model for the eruptive mechanism proposed here differs from that briefly outlined by Baker and others (1975, p. 76) when the historical record was not considered.

Both the 1845 and 1969 eruptions were from vents distant from the shores of Port Foster.

TABLE I. PARTIAL RECONSTRUCTION OF THE INTRUSIVE–ERUPTIVE HISTORY OF DECEPTION ISLAND BASED ON HISTORICAL RECORDS FROM 1820 TO 1970

Date	*Observations*	*Intrusive event*	*Eruptive event(s)*
1829	High heat escape from Mount Pond and Pendulum Cove. Possible extreme youth of Pendulum Cove crater	Magma pod at high level in Mount Pond sector of ring-fault zone, possibly withdrawing to depth	Possible phreatic explosion has already blasted Pendulum Cove crater through lava–red scoria succession seen in Crimson Hill
1839 to 1842	High heat escape from Mount Kirkwood sector of the ring-fault zone. Impact craters around Crater Lake. 13 possible fumaroles in 1842	Magma pod at high level in Mount Kirkwood sector of ring-fault zone	Fissure eruptions, perhaps three, from caldera slopes of Mount Kirkwood
1908 to 1970	Heat escape from Pendulum Cove and Whalers Bay. Between 1936 and 1949 new heat escape commenced near Kroner Lake, which considerably enlarged between 1962 and 1968. Warm ground reported on caldera slopes of Mount Pond in 1908–09 and 1957–58	Magma in Pendulum Cove–Mount Pond–Whalers Bay sector of ring-fault zone. Perhaps extended along ring-fault zone between 1936 and 1949 and again between 1962 and 1968	Erupted in 1969 from a 5 km. long fissure on the caldera slopes of Mount Pond
About 1956 to 1970	New area of heat escape established in Telefon Bay between 1954 and 1957 which extended considerably between 1962 and 1968	Magma pod emplaced into Telefon Bay sector of ring-fault zone. Other pods emplaced between 1962 and 1968	Telefon Bay eruptions of 1967 and 1970
Post-1962, Pre-1968	New area of heat escape established immediately west of Wensleydale Beacon	Small magma pod emplaced in ring-fault zone of Wensleydale Beacon sector	Small local eruption as part of the 1970 event to produce an anomalous area of large bombs
(?) 1839 to 1908 to 1970	Area of heat escape in Fumarole Bay	Magma in ring-fault zone at Fumarole Bay sector. Could be a residue from prehistoric Fumarole Bay eruption. Hot rock?	No historical eruption

For the lack of information, this table excludes the 1912–17 eruption (Ferguson, 1921; Orheim, 1971), that of the Kroner Lake peninsula between 1829 and 1908 (Roobol, 1973) and another on the site of the early fur sealers' harbour between 1829 and 1956 (Roobol, 1973).

Evidence for the heating up of these two sectors of the ring-fault zone was nonetheless restricted largely to the shores of Port Foster and adjacent crater lakes. Warm patches of ground, such as those reported by Gourdon (1910) and Hawkes (1961), seem to have been more the exception or had been overlooked. Evidently the blanket of permanent ice or permafrost is sufficient to smother the heat escape in most areas except where there is sea-water (presumably permitting convection). The model proposed here suggests that in future some indication of the state of activity of the volcano can be obtained by observation of the distribution of areas of obvious heat escape with particular attention to:

i. Places where the shoreline of Port Foster deeply indents the ring-fault zone.
ii. Crater lakes situated inside the 3 km. wide ring-fault zone.
iii. Any "fumaroles" or areas of warm ground situated over the ring-fault zone but distant from the sea.

Chemical Variation of Magmas around the Ring-fault Zone

The eruption of magmas over almost one-half of the ring-fault zone in 1967, 1969 and 1970 can be regarded as an emptying of the upper levels of magma bodies within the ring-fault zone. An examination of the magma composition with regard to the position of the vents around the ring-fault zone provides an independent test of the magma-pod hypothesis proposed from the historical record. In Table II, samples of the 1967, 1969 and 1970 eruptions, which were analysed at the University of Leeds and thereby avoid problems of interlaboratory variation (data in Baker and others (1975)), are arranged according to position in the ring-fault zone and the dates of eruption are also noted. The analyses have been recalculated to 100 per cent volatile-free and with all iron as Fe_2O_3 (ΣFe_2O_3) to facilitate comparison. Distances around the ring-fault zone are measured anti-clockwise from the southern end of the 1969 fissure, following the method used for the 1969 event by Baker and others (1975). The analyses are re-numbered (1–14) and their positions are indicated on Fig. 1.

Table II indicates that around the ring-fault zone different sections have uniform but different compositions—a variation consistent with the hypothesis of several different magma bodies of fairly uniform composition. These have been grouped into five magma types as shown in Tables II and III. Perhaps most striking is the uniform material (analyses 1–5, type E) erupted in 1969 along the Pendulum Cove–Mount Pond–Whalers Bay sector of the ring-fault zone. These samples have lower SiO_2, Na_2O, K_2O, P_2O_5, Rb, Rb/Sr, Ba/Sr and higher TiO_2, ΣFe_2O_3, MgO, CaO, Ni, V than the other magma types. Another distinct but uniform body (analyses 11–14, type A) is represented by the 1970 products of the isolated area south of Cross Hill together with that of craters 1, 2 and 3 of south-west Telefon Bay. Again, the 1967 "island centre" material (analysis 10, type B) is also distinct.

The relationship between the two types of magma erupted in 1969 is of particular interest. The uniform magma type E (analyses 1–5) was erupted from a 5 km. long arcuate fissure on the slopes of Mount Pond. The dissimilar type C (analysis 6) was erupted from an isolated centre through the ice to the north-east of Pendulum Cove. This vent is considerably offset from the 5 km. arcuate fissure (Baker and others, 1975, fig. 29). This relationship also suggests that two magma pods were tapped during the 1969 eruption. Again, the spatial relationships of the 1970 magma types A, C and D suggest that three magma pods were tapped during this eruption, whereas in 1967 two magma pods (types B and D) were tapped.

The historical record suggests that the emplacement of the five magma pods identified on chemical grounds can be dated by the appearance of surface areas of obvious heat escape. The Pendulum Cove–Mount Pond–Whalers Bay sector (type E magma) was repeatedly recorded during 1908–58. The limited area of heat escape in Telefon Bay, first located by Hawkes in 1957–58 and mapped in 1961–62 by Casertano (1964, fig. 1), corresponds with crater 5 (type C magma) of the 1970 eruption (Baker and others, 1975, fig. 29). Thus, the sub-

TABLE II. RECALCULATED ANALYSES OF 1967, 1969 AND 1970 MATERIAL ARRANGED ACCORDING TO POSITION AROUND THE RING-FAULT ZONE

Number in Fig. 1	14	13	12	11	10	9	8	7	6	5	4	3	2	1
Eruption	1970	1970	1970	1970	1967	1970	1967	1970	1969	1969	1969	1969	1969	1969
Position	Cross Hill	Crater 1	Crater 2	Crater 3	Island centre	Crater 5	Land centre	Crater cluster	North Pendulum Cove	Pendulum Cove	West Mount Pond	West Mount Pond	West Mount Pond	South-west Mount Pond
Specimen number	B.710.1	B.701.2	B.702.1	B.704.1	B.276.1	B.711.1	B.428.1	B.707.1	B.560.1	B.571.1	B.568.3	B.567.1	B.561.1	B.556.1
Distance around ring-fault zone (km.)	12	11	11	11	10	8·5	6·5	6·5	4·4	3·0	1·3	1·0	0·5	0
SiO_2	59·2	59·3	59·1	59·1	61·5	58·8	57·4	57·8	59·1	54·4	54·8	54·9	55·8	56·1
TiO_2	1·61	1·61	1·61	1·64	1·27	1·74	1·90	1·90	1·73	2·05	2·03	2·01	1·98	1·97
Al_2O_3	15·9	15·8	15·9	16·0	15·84	15·78	15·87	15·85	16·0	15·96	15·92	15·6	15·8	15·9
ΣFe_2O_3	8·27	8·24	8·18	8·19	7·36	8·52	9·16	9·02	8·25	10·6	10·2	10·1	9·85	9·76
MnO	0·17	0·18	0·17	0·17	0·17	0·18	0·18	0·18	0·18	0·17	0·17	0·17	0·17	0·17
MgO	2·31	2·34	2·41	2·38	1·73	2·44	2·74	2·71	2·30	3·64	3·64	3·42	3·25	3·12
CaO	5·04	5·06	4·99	5·14	4·15	5·22	5·78	5·71	5·23	7·19	7·26	6·87	6·56	6·46
Na_2O	5·94	5·92	6·13	5·87	6·28	5·85	5·60	5·44	5·72	4·98	4·98	5·88	5·33	5·35
K_2O	1·10	1·08	1·08	1·07	1·24	1·02	0·96	0·98	1·04	0·72	0·75	0·76	0·85	0·85
P_2O_5	0·42	0·41	0·40	0·42	0·42	0·41	0·36	0·37	0·41	0·29	0·28	0·29	0·36	0·34
TOTAL	99·96	99·94	99·97	99·98	99·96	99·96	99·95	99·96	99·96	100·00	100·03	100·00	99·95	100·02
Li	—	—	—	—	30	30	—	—	—	16	—	—	—	20
Rb	—	—	—	—	17	14	15	13	—	9	—	—	—	12
Ba	—	—	—	—	250	195	—	—	—	185	—	—	—	180
Sr	—	—	—	—	270	305	340	320	—	320	—	—	—	335
Y	—	—	—	—	46	42	41	40	—	33	—	—	—	38
Co	—	—	—	—	30	29	—	—	—	26	—	—	—	26
Ni	—	—	—	—	10	10	11	tr.	—	15	—	—	—	13
Cr	—	—	—	—	25	25	—	—	—	30	—	—	—	25
V	—	—	—	—	55	57	—	—	—	275	—	—	—	195
Zr	—	—	—	—	370	305	305	305	—	210	—	—	—	310
K/Rb	—	—	—	—	605	628	531	626	—	664	—	—	—	588
Rb/Sr	—	—	—	—	0·063	0·046	0·044	0·041	—	0·028	—	—	—	0·036
Ba/Sr	—	—	—	—	0·93	0·64	—	—	—	0·58	—	—	—	0·54
Ti/Zr	—	—	—	—	20·6	35·4	37·3	37·3	—	58·5	—	—	—	38·1
Suggested magma type	A	A	A	A	B	C	D	D	C	E	E	E	E	E

[*face page 152*

TABLE III. SCHEME FOR INTERPRETATION OF THE 1967, 1969 AND 1970 MATERIAL IN TERMS OF MAGMA PODS AND THEIR DATE OF EMPLACEMENT BASED ON DEVELOPMENT OF AREAS OF OBVIOUS HEAT ESCAPE AROUND THE RING-FAULT ZONE

Number of analysis in Fig. 1	14	13	12	11	10	9	8	7	6	5	4	3	2	1
Distance around ring-fault zone in km.	12	11	11	11	10	8·5	6·5	6·5	4·4	3	1·3	1·0	0·5	0
Erupted 1970	—	—	—	—		—		—						
Erupted 1969									—	—	—	—	—	—
Erupted 1967					—		—							
Magma type	A	A	A	A	B	C	D	D	C	E	E	E	E	E
Heat escape recorded, 1908–68										○	○	○	○	○
Heat escape recorded, 1957–68						○	○	○	?					
Heat escape commenced post-1962 but pre-1968	○	○	○	○	○		○	○	○					

division of the 1970 material into magma types A and C, although chemically similar and differing only by type C having higher TiO_2, CaO and lower Na_2O, is justified in terms of the development of obvious surface-heat escape. Heat escape corresponding to the position of the 1970 magma type A along the south-west Telefon Bay sector did not appear until after 1962.

Comparison of the 1961–62 map of Casertano (1964, fig. 1) with that made in 1968–69 (incomplete in Baker and others, 1975; complete here as Fig. 4) suggests that magma types A, B and D were emplaced sometime between 1962 and 1968. Thus the post-1962, pre-1968 extension of the areas of heat escape around the ring-fault zone sector of Telefon Bay was due to the upward rise of new and different magma bodies (types A and B) rather than by the lateral extension of the pre-existing body (type C). This scheme for the 1967, 1969 and 1970 magmas is simply summarized in Table III.

Having developed the magma-pod hypothesis to this extent, it is possible to interpret the more complex sector between northern Pendulum Cove and middle Telefon Bay (analyses 6–9 of material erupted in 1967, 1969 and 1970). The 1967 material of analysis 8 (the "land centre") and the 1970 material of analysis 7 (the crater cluster) are virtually identical (type D). Similarly, the 1970 material of analysis 9 (crater 5) and the 1969 material of analysis 6 (northern Pendulum Cove) are also virtually identical (type C). These can be interpreted as two magma pods, th[illegible] of analyses 7 and 8 (type D) being intruded through an earlier pod of analyses 9 and 6 (type C) —a conclusion consistent with the development of surface areas of heat escape as shown in Table III.

Conclusions

The historical record suggests a model of magma pods emplaced into the ring-fault zone with the production of areas of obvious heat escape up to decades prior to eruption. This model adequately accounts for the chemical variation around the ring-fault zone of the materials erupted in 1967, 1969 and 1970. Future observations on areas of obvious heat escape (reflecting movement and build-up of magma pods) should be useful in anticipating future eruptions and positioning their vents. Observations about once every 5 years could provide the necessary data, which can readily be accomplished by one man in one calm day if equipped with a motor dinghy and thermometer (as was the 1968 heat-escape map).

The magma-pod model provides some explanations of other hitherto unexplained phenomena of Deception Island. One of these is the unusual style of eruption—several closely spaced small-volume eruptions (about $0{\cdot}2$ km.^{3} of magma for 1967, 1969 and 1970) followed by several decades of dormancy (since the similar events of 1912–17). If several magma pods of slightly different composition, volume, viscosity and depth exist in the ring-fault zone, eruption might then be triggered by further cauldron subsidence (alternatively they might trigger the subsidence by rafting or lubricating a central block). Either way, an abrupt change in stress mig[illegible] initiate the rise of the magma when the slightly different properties of the pods ensure that the magmas reach the surface at slightly different times.

Again, Baker and others (1975) noted that the sodic differentiates of Deception Island are restricted to the present late or post-caldera stage. This differentiation, in terms of a magma-pod model, appears not to have been the result of processes operating within the high-level magma pods, as the oldest emplaced magma (pre-1908) of the present century (type E) is the most basic, whereas the most felsic material (type B) appears to have been emplaced sometime between 1962 and 1968. The differentiation of the magmas therefore appears to occur at depths greater than those where obvious surface heat escape occurs.

The magma-pod model can account for events such as that of January 1923. Above a magma pod, a temperature gradient will exist from several hundreds of degrees to that of the warm surface water. Any disruption of the shores of Port Foster, e.g. by the production of a fault scarp or the submarine avalanching of unconsolidated material, will expose a hotter zone to

the cold waters of Port Foster. A short-term abnormal heating of the sea-water will occur until such time as a new stable gradient is established.

It is to be regretted that further study of Deception Island has so far not proved possible. During the past 7 years, data on the post-eruption events have been lost. The fragmented record suggests that the magmas may retreat to depth, producing subterranean sounds (as perhaps in 1829) to leave a ring-fault zone almost free of obvious heat escape (as perhaps in 1913–14) prior to a new build-up of magma pods at a high level. Many questions remain to be answered. Is cauldron subsidence still occurring? Would a study of the compositional zones of the plagioclases of the 1967, 1969 and 1970 material further support the magma-pod hypothesis? Would further chemical analyses of a stratigraphical section from one magma pod indicate to what extent differentiation occurs within a high-level magma body, because the sodic rhyodacite pumice with 70 per cent SiO_2 and 5·1 per cent Na_2O (Baker and others, 1975, table X, analysis 23) has not yet been accounted for? This was collected from the shores of Telefon Bay adjacent to the 1967 "island centre" and could well have been produced during that eruption.

ACKNOWLEDGEMENTS

I am grateful to the Royal Society, British Antarctic Survey and Dr. P. E. Baker for the opportunity to participate in the 1968 and 1969 field work, to Professor J. Sutton and Dr. R. J. Adie for continued interest, and to my wife Anne Roobol for financing this present work.

MS. received 20 December 1976

REFERENCES

ANDERSSON, J. G. 1906. On the geology of Graham Land. *Bull. geol. Instn Univ. Upsala*, **7**, 19–71.

BAKER, P. E., MCREATH, I., HARVEY, M. R., ROOBOL, M. J. *and* T. G. DAVIES. 1975. The geology of the South Shetland Islands: V. The volcanic evolution of Deception Island. *British Antarctic Survey Scientific Reports*, No. 78, 81 pp.

BONGRAIN, M. M. 1912. Ile Déception (Shetlands du Sud). (*In Cartes*. Paris, Masson et Cie, pl. X.) [Deuxième Expédition Antarctique Française (1908–1910), Sciences physiques: documents scientifiques.]

CASERTANO, L. 1964. Volcanic activity at Deception Island. (*In* ADIE, R. J., *ed. Antarctic geology*. Amsterdam, North-Holland Publishing Company, 33–47.)

CHARCOT, J. 1910. *Le Pourquoi-Pas? dans l'Antarctique. Journal de la deuxième expédition au pôle sud, 1908–1910*. Paris, Ernest Flammarion.

CHRISTIE, E. W. H. 1951. *The Antarctic problem*. London, George Allen & Unwin Ltd.

DANA, J. D. 1849. *United States exploring expedition during the years 1838–42 under command of Charles Wilkes, U.S.N. Vol. 10. Geology*. New York, P. Putnam.

DAVID, T. W. E. 1895. Notes on Antarctic rocks. *J. Proc. R. Soc. N.S.W.*, **29**, 461–92.

DEBENHAM, F., *ed.* 1945. *The voyage of Captain Bellingshausen to the Antarctic seas 1819–1821*. (Translated from the Russian.) London, Hakluyt Society. 2 vols.

ELDERFIELD, H. 1972. Effects of volcanism on water chemistry, Deception Island, Antarctica. *Mar. Geol.*, **13**, No. 1, M1–6.

FERGUSON, D. 1921. Geological observations in the South Shetlands, the Palmer Archipelago, and Graham Land, Antarctica. *Trans. R. Soc. Edinb.*, **53**, Pt. 1, No. 3, 29–55.

GOURDON, E. 1910. Rapport sur les travaux de geologie et de glaciologie. (*In* CHARCOT, J. *Le Pourquoi-Pas? dans l'Antarctique. Journal de la deuxième expédition au pôle sud, 1908–1910*. Paris, Ernest Flammarion, 388–93.)

HAWKES, D. D. 1961. The geology of the South Shetland Islands: II. The geology and petrology of Deception Island. *Falkland Islands Dependencies Survey Scientific Reports*, No. 27, 43 pp.

HOLTEDAHL, O. 1929. On the geology and physiography of some Antarctic and sub-Antarctic islands. *Scient. Results Norw. Antarct. Exped.*, No. 3, 172 pp.

HYDROGRAPHIC DEPARTMENT. 1974. *The Antarctic pilot. Comprising the coasts of Antarctica and all islands southward of the usual route of vessels*. 4th edition. London, Hydrographer of the Navy.

KENDAL, E. N. 1831. Account of the Island of Deception, one of the New Shetland Isles. *J. R. geogrl Soc.*, **1**, 62–66.

OLSACHER, J. 1956. Contribución al conocimiento geológico de la Isla Decepción. (*In* OLSACHER, J., DIAZ, H. *and* M. TERUGGI. Contribución a la geología de la Antártida occidental. *Publnes Inst. antárt. argent.*, No. 2, 19–76.)

ORHEIM, O. 1971. Volcanic activity on Deception Island, South Shetland Islands. (*In* ADIE, R. J., *ed. Antarctic geology and geophysics*. Oslo, Universitetsforlaget, 117–20.)

ROOBOL, M. J. 1973. Historic volcanic activity at Deception Island. *British Antarctic Survey Bulletin*, No. 32, 23–30.

SHACKLETON, E. H. 1909. *The heart of the Antarctic. Being the story of the British Antarctic Expedition 1907–1909.* London, William Heinemann. 2 vols.

SCHULTZ, C. H. 1971. Petrologic and volcanologic investigation of Deception Island. *Antarctic. Jnl U.S.*, **6**, No. 4, 83–84.

WEBSTER, W. H. B. 1834. *Narrative of a voyage to the South Atlantic Ocean, in 1828–30, in H.M. sloop "Chanticleer", under the command of Capt. Henry Foster.* London. 2 vols.

WEDDELL, J. 1825. *A voyage towards the South Pole performed in the years 1822–24.* London, Longman, Hurst, Rees, Orme, Brown and Green.

WILKES, C. 1845. *Narrative of the United States Exploring Expedition, during the years 1838, 1839, 1840, 1841, 1842.* Vols. I–V, Atlas. Philadelphia, Lea & Blanchard.