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THE GEOLOGY OF THE SOUTH SHETLAND ISLANDS

II. THE GEOLOGY AND PETROLOGY OF DECEPTION ISLAND

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ABSTRACT

DECEPTION ISLAND is a caldera formed by the subsidence of a group of overlapping volcanoes along arcuate and radial faults. Three volcanic episodes occurred after the formation of the caldera and the location of these post-caldera volcanoes is controlled by the fault pattern which limits the caldera.

Although it is possible to establish the relative ages of the four volcanic episodes, there is little information as to their absolute ages. It is probable that the latest eruptions occurred in historic times.

Petrographically the Deception Island suite is a local alkaline deviation from the normal andesite-rhyolite association of the South Shetland Islands. Its lavas are characterized by an unusually high soda content. The sequence of crystallization is analogous to that of melts of certain composition in the system MgO–FeO–SiO_2 crystallizing under conditions of strong fractionation.

The geochemistry of the Deception Island volcanic rocks is reviewed and four new chemical analyses are presented.

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I. INTRODUCTION

THIS report is based on a field investigation, and subsequent laboratory examination of specimens collected, during the Antarctic summer of 1957–58. All station and serial numbers given in the text refer to these specimens which are housed in the Department of Geology, University of Birmingham.

Deception Island (lat. 62°57′S., long. 60°38′W.) is an almost circular volcanic island lying in the Bransfield Strait at the southern end of the South Shetland Islands. From a distance it appears to be a low dome-shaped island bounded on all sides by vertical cliffs of rock and ice, but in the south-east a narrow channel gives access to the interior deep-water basin of Port Foster. In the stormy Southern Ocean this basin affords an excellent harbour and almost every expedition ship in these waters has used Port Foster at one time or another as an anchorage.

1. HISTORICAL

The earliest detailed description is that of Kendall (1831) who visited the island in 1829 and recorded:

> "The depth of the lake [*Port Foster*] was ninety-seven fathoms, with a bottom of cinders; and the beaches, which were composed of the same material, abounded with springs of hot water, which afforded the extra-ordinary spectacle of water, at the temperature of 140°, issuing from beneath the snow-clad surface of the soil, . . ." and ". . . at least one hundred and fifty holes, from which steam was issuing with a loud hissing noise, . . ."

In 1839 Johnson (Wilkes, 1844, p. 148) observed:

> ". . . several small craters, of three to four feet in diameter. From these a heated vapour is constantly issuing, accompanied by much noise."

Three years later Smiley (Wilkes, 1844, p. 149) stated that:

> ". . . the whole south side of Deception Island appeared as if on fire" and he ". . . counted thirteen volcanoes in action."

Andersson (1906) and Adie (1957) have regarded this report as exaggerated but, assuming that Smiley did not fabricate his entire account, two facts are worthy of consideration. First, no fumaroles or signs of volcanic activity are present today on the southern side of the island. Secondly, there is evidence that the youngest lava flows on the island are the Mount Kirkwood lavas (p. 28), which occur along the whole of the southern flank of Deception Island. The coincidence between Smiley's report and the location of these very young lavas is remarkable and the possibility that the latest eruptions occurred in 1842 must at least be considered.

Only two papers published this century discuss the stratigraphy and structure of the island. Holtedahl (1929) has observed that the basin of Port Foster is far too large to be an explosion crater and has postulated that the island is a caldera formed by the subsidence of an original volcano along circular faults. He has subdivided the lavas and agglomerates into an *Older Volcanic Series* and a *Younger Volcanic Series*, the former including all the agglomerates on the island and the latter represented by the post-caldera lavas of the Kroner Lake area.

The most recent account of the geology is that of Olsacher (1956), who has published a geological map on a scale of 1:68,370 which is unfortunately completely devoid of any structural detail and omits many important volcanic centres. Olsacher mainly restates Holtedahl's interpretation and presents little new evidence on the structure or stratigraphy of the island, subdividing the volcanics into a *Serie Volcanica Antigua* and a *Serie Volcanica Moderna*. His paper contains a description of the fumarolic activity.

Both Holtedahl and Olsacher have assumed that the caldera resulted from the collapse of a *single* original cone, the flanks of which form the outer coastline of the island today. Evidence will be presented to show that the caldera is the result of collapse along arcuate and radial faults of four major overlapping cones, and that subsequent to engulfment there were three further distinct episodes of vulcanicity.

The petrography of Deception Island has received more attention but all accounts have been handicapped by the paucity of available specimens. Gourdon (1914) has given only a brief description of the petrography but he has contributed the first five chemical analyses. Barth and Holmsen (1939) have described the rocks collected by Holtedahl and have published three further analyses together with some optical data on the mineralogy of the lavas. They drew attention to the abnormal sodic composition of this lava suite and indicated the existence of closely analogous lavas in the Santorin volcano.

Tyrrell (1945) has given a useful summary of the petrography and chemistry of the specimens available up to that date but he has incorrectly concluded that andesites are the commonest lavas of the Deception Island suite.

This report includes four new chemical analyses and a detailed description of the petrology. A geological map on a scale of 1:25,000 is enclosed in the end pocket, and diagrammatic cross-sections of the caldera are shown in Fig. 9.

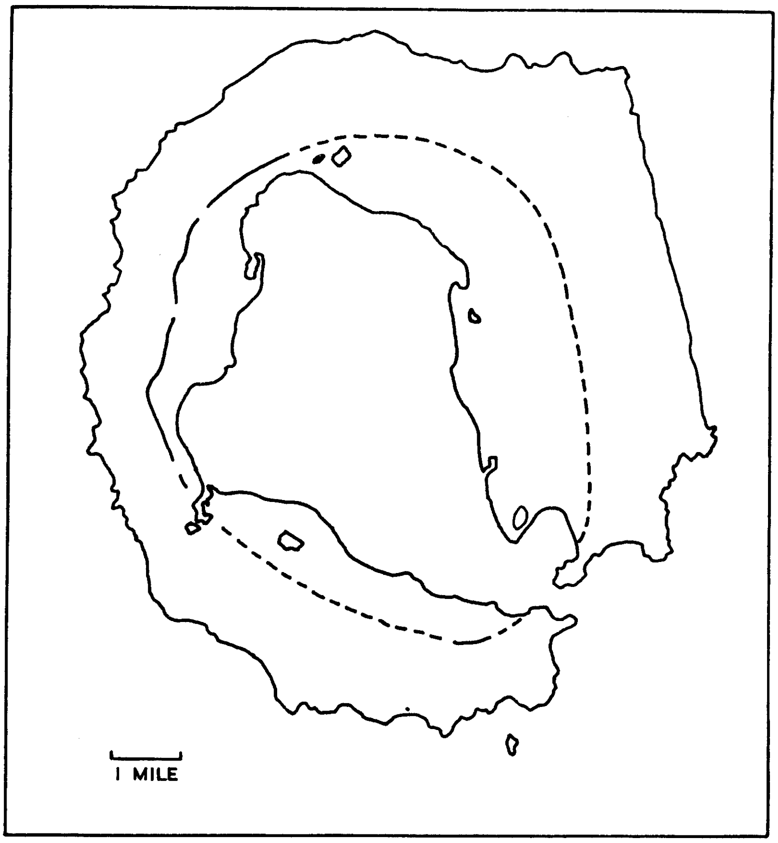

FIGURE 1

The Deception Island caldera. Solid lines indicate the caldera wall, and broken lines the inferred position of the rim.

2. PHYSIOGRAPHY

Subaerial erosion and deposition have only locally modified the fundamental physiography of Deception Island which was controlled by endogenetic processes. Its peculiar annular shape is the result of the collapse and subsidence of the pre-caldera volcanoes along circular faults, which have also strictly controlled the location of the post-caldera volcanic activity. The caldera, which is roughly circular in outline (Fig. 1), has a diameter of approximately 6–7 miles and is surrounded by mountains of low relief attaining a maximum height of 1,809 ft. at Mount Pond.

Four physiographic regions, which are of some geological significance, may be recognized:

a. The outer slopes
b. The caldera wall
c. The inner volcanic zone
d. The basin.

These regions are well illustrated near Telefon Bay (Fig. 2) but are not readily apparent in the south-east of the island, where the mountain ring is breached to form Neptunes Bellows.

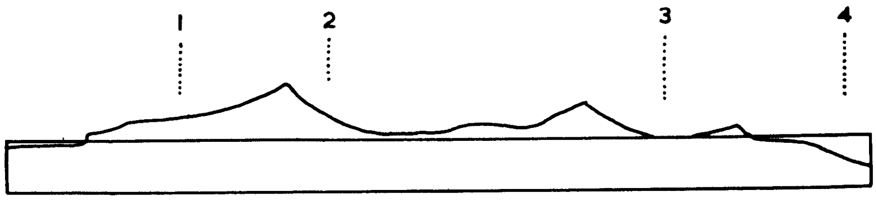

FIGURE 2

Topographical cross-section through Telefon Ridge and Cross Hill. 1. Outer slope; 2. Caldera wall; 3. Inner volcanic zone; 4. Basin.

a. *The outer slopes*

The outer slopes are gentle but almost everywhere they are terminated by sea cliffs more than 150 ft. in height. The northern and western slopes of the island constitute Kendall Terrace, a probable 200 ft. marine platform truncating the Outer Coast Tuff. Gentle concave slopes, the remanent flanks of two pre-caldera volcanoes, rise to the rim of the caldera.

From Macaroni Point to Baily Head the outer eastern slope of Mount Pond is heavily glacierized and the eastern coast of the island is formed by a continuous, remarkably straight ice cliff attaining a height of 200 ft.

The outer slope in the south is also mainly covered by snow and ice but at South Point the Outer Coast Tuff forms spectacular vertical cliffs, to the west and east of which are low promontories formed of lava flows of the Neptunes Bellows Group.

The submarine contours around Deception Island indicate that the original extent of the island was greater than at present. Holtedahl (1929) has discussed the submarine platform which exists off the eastern side of the island and has attributed it to marine abrasion. West of the island there are numerous shallow reefs of Outer Coast Tuff and the depth is under 25 fathoms for more than a mile offshore.

b. *The caldera wall*

The caldera wall is well defined along the entire western side of the island, where steep cliffs of bedded lavas and agglomerates rise to over 800 ft. There is considerable evidence that here the caldera wall is a fault scarp. In the south the caldera wall is only intermittently represented and it is partly obscured by later lava flows. The continuity of the caldera rim is broken in a number of places by transverse depressions controlled by radial faults, while in the south-east it is completely breached by Neptunes Bellows. Glaciers cover the eastern part of the island.

c. *The inner volcanic zone*

This is a discontinuous zone occurring between the basin and the caldera wall. It is well represented in the south of the island, where the topography consists of low hills and the deep volcanic craters of the Pendulum Cove Group. The original cones, which were built up after the formation of the caldera, have been deeply eroded and are now mantled by glacial and scree deposits. This zone is absent on the shores of Fumarole and Telefon Bays, where the caldera wall rises abruptly from Port Foster.

d. *The basin*

The greater part of the caldera floor is submerged beneath Port Foster. Submarine contours indicate a steep drop away from the coast and then an irregular but fairly constant depth of between 500 and 575 ft. The deeper water occurs in the centre of Port Foster while in the south-east it is less than 100 ft. in Neptunes Bellows. The scalloped margin of the basin is reminiscent of the Santorin caldera (Williams, 1941), where the coastal outline is related to concentric fracturing and collapse of volcanic cones.

II. GENERAL STRATIGRAPHY

THE stratigraphical divisions established during the present investigation are given in Table I, and in Table II this succession is compared with those of previous workers. Holtedahl's sub-divisions are based on the examination of only a few localities and will not be further discussed. Many of the lavas and pyroclastic rocks included by Olsacher (1956) in the Serie Volcanica Antigua were not derived from an original volcano but from a number of smaller cones which are in fact post-caldera in age. Three distinct volcanic episodes after the formation of the caldera have now been recognized and are described for the first time.

TABLE I

STRATIGRAPHICAL SUCCESSION OF DECEPTION ISLAND

Post-caldera Series	*Whalers Bay Group*	Telefon Ridge and Stonethrow Ridge lavas, Kroner Lake and Kendall Terrace lavas, and Mount Kirkwood lavas.
	Pendulum Cove Group	Small cones at Cross Hill, Wensleydale Beacon, north of Mount Kirkwood, Ronald Hill and Pendulum Cove.
	Neptunes Bellows Group	Vent agglomerates and associated volcanics of Vapour Col, Entrance Point and South East Point.
Pre-caldera Series	*Port Foster Group*	*Outer Coast Tuff*, *Fumarole Bay Volcanics*, *Telefon Bay Volcanics*, lavas and agglomerates of Macaroni Point, vent agglomerate of Cathedral Crags.

TABLE II

COMPARISON OF STRATIGRAPHICAL SUCCESSIONS OF PREVIOUS AUTHORS WITH THE PRESENT INTERPRETATION

Holtedahl (1929)	Olsacher (1956)	Present Interpretation	
Younger Volcanic Series		**Post-caldera Series**	Whalers Bay Group
Caldera subsidence	**Serie Volcanica Moderna**		Pendulum Cove Group
	Caldera subsidence		
Older Volcanic Series			Neptunes Bellows Group
	Serie Volcanica Antigua	*Caldera subsidence*	
		Pre-caldera Series	Port Foster Group

The nature of the basement. The basement, which is assumed to underlie Deception Island, is not exposed but xenoliths in the lavas and fragments in the agglomerates include older andesites together with dioritic rocks of undoubted Andean affinity. The depth of this basement is unknown but in the diagrammatic sections in Fig. 9 it is tentatively assumed to be at 250 m., at which depth a submarine platform unites all the islands of the South Shetland Islands group (Herdman, 1932).

1. THE PRE-CALDERA SERIES

The Port Foster Group. The oldest lavas and agglomerates are exposed at Cathedral Crags, near Macaroni Point and in the caldera wall on the west of the island. These volcanic rocks were not derived from a single original volcano but from a complex group of four overlapping cones. The evidence for the existence of two of these volcanoes is well documented but for the others it is somewhat uncertain. The maximum observed thickness of the Port Foster Group is the 475 ft. of lavas and agglomerates which constitute the *Fumarole Bay Volcanics*. These are well exposed in the section on Stonethrow Ridge. Basaltic and andesitic lavas were the main products of these early volcanoes.

The closing phase of the first volcanic episode was marked by the eruption of thick deposits of andesitic pumice-tuff which locally exceed 700 ft. in thickness. These pumice deposits are called the *Outer Coast Tuff*.

2. The Formation of the Caldera

The volcanoes which constitute the Port Foster Group collapsed along a series of arcuate and radial faults. The main engulfment of the caldera by the sea occurred after the formation of the Outer Coast Tuff, but there is evidence of faulting soon after the formation of the Telefon Bay volcano and prior to the deposition of the Outer Coast Tuff.

3. The Post-caldera Series

The Neptunes Bellows Group. The pattern of faulting which delimits the caldera had a profound control on the location of the post-caldera activity. The volcanoes of the Neptunes Bellows Group are located along the outer caldera fault zone (p. 31), close to the intersection of the major arcuate and radial faults. They are now represented by vent agglomerates (previously unrecorded), and the associated lavas are olivine-basalts.

The Pendulum Cove Group. The lavas and pyroclastics of this group were derived from eight small cones situated on arcuate lines which are inside and concentric to the outer caldera fault zone. The soda-rich andesitic lavas, which have received so much attention in the literature, are now known to be restricted to the Pendulum Cove Group.

The Whalers Bay Group. These lavas represent the latest volcanic phase in the history of the island, and they rest with pronounced unconformity upon glacial deposits or the volcanics of the earlier groups. They were extruded from fissures and scoria mounds which lie on arcuate lines essentially parallel to the ring faults of the caldera. Tuffs and agglomerates are not represented in the Whalers Bay Group and the lavas are red scoriaceous or black coarsely vesicular basalts, the former containing many fine examples of volcanic bombs.

Although it is possible to establish the relative ages of the four volcanic episodes, there is as yet, except for the Whalers Bay Group, no data on their absolute ages.

The 200 ft. marine platform of Kendall Terrace was cut after the vulcanicity of the Port Foster Group and prior to that of the Neptunes Bellows Group. If further investigation enables the age of this platform to be established it will provide an approximate dating for the formation of the caldera.

Tertiary vulcanicity in the South Shetland Islands commenced during the early Miocene (Hawkes, 1960) and it is possible that the eruptions of the Port Foster Group may be contemporaneous.

Molluscan fragments with present day affinities have been found in agglomerates on the screes near Whalers Bay, and it is likely that the source of these fragments will eventually be found.

III. THE PORT FOSTER GROUP

The strike section in the caldera wall west of Port Foster exposes some of the oldest lavas on Deception Island. These lavas together with associated tuffs and agglomerates were erupted from two separate volcanoes, the original areas of which can be determined with some accuracy. Much of the eastern part of the island is covered by snow and ice, but a further eruptive centre is undoubtedly represented by the vent agglomerate of Cathedral Crags, while the lavas exposed near Macaroni Point are tentatively assumed to have been derived from a centre south-east of Goddard Hill.

The lavas and pyroclastic rocks of these four volcanoes, which are referred to the *Port Foster Group*, are pre-caldera in age and represent the earliest known volcanic episode in the history of Deception Island. This episode closed with the eruption, probably from all four centres, of thick deposits of pumice-tuff which are referred to as the *Outer Coast Tuff*.

A. The Western Area

In the western part of the island, from north of Telefon Bay to Vapour Col, the caldera wall forms a prominent feature. North-west of Wensleydale Beacon its continuity is interrupted by a deep col which separates two distinct volcanic successions, the *Telefon Bay Volcanics* to the north and the *Fumarole Bay Volcanics* to the south. These two successions are compared in Fig. 4. There is no correlation between the two successions and it is concluded from evidence given below that they were derived from two separate eruptive centres.

Although two distinct volcanic successions separated by a col have been recorded in the caldera wall, the sea cliffs to the west are composed of Outer Coast Tuff for over 14 miles, and this tuff rests unconformably upon the Telefon Bay and Fumarole Bay Volcanics.

1. *The Telefon Bay Volcanics*

The morphology of the outer slope in the north-west of the island indicates a denuded remnant or somma ring of a volcano with a gentle concave dip slope and a steep scarp facing the east (Fig. 2). The simple outline and undissected form of the inner face suggest it is a fault scarp, and north of Telefon Bay there is evidence of arcuate step-faulting with a downthrow towards the basin. In Fig. 3 the present distribution of the Telefon Bay Volcanics and a reconstruction of the original volcano are shown. The vent corresponds closely with a deep-water basin in Port Foster, and has been located by drawing radii from the existing somma ring.

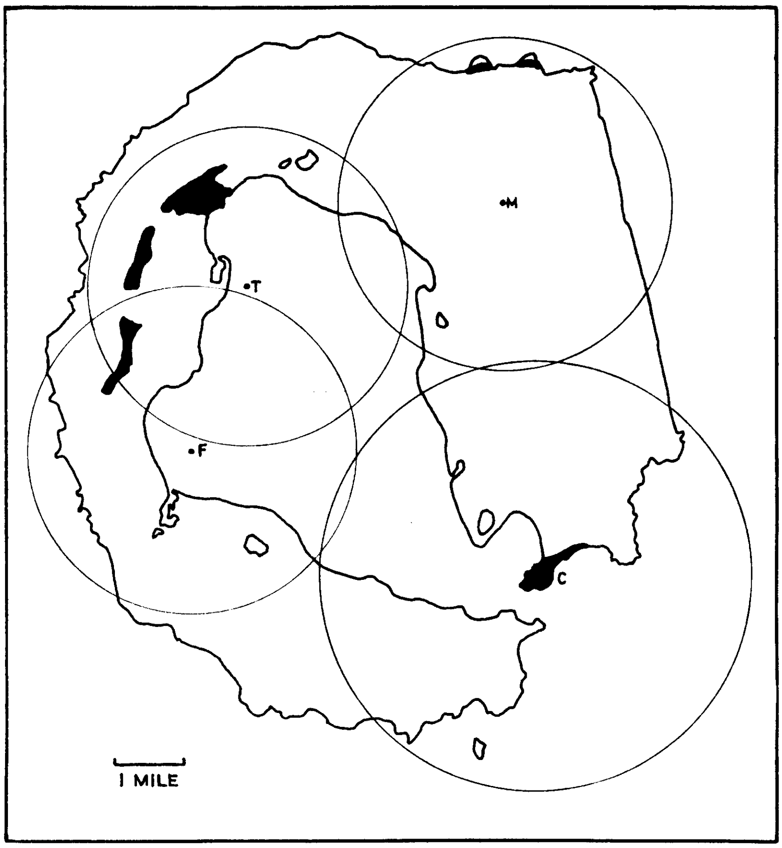

FIGURE 3

The present distribution of the lavas and agglomerates of the Port Foster Group (black) and the probable positions of the four volcanoes. T. Telefon Bay volcano; F. Fumarole Bay volcano; C. Cathedral Crags volcano; M. Macaroni Point volcano.

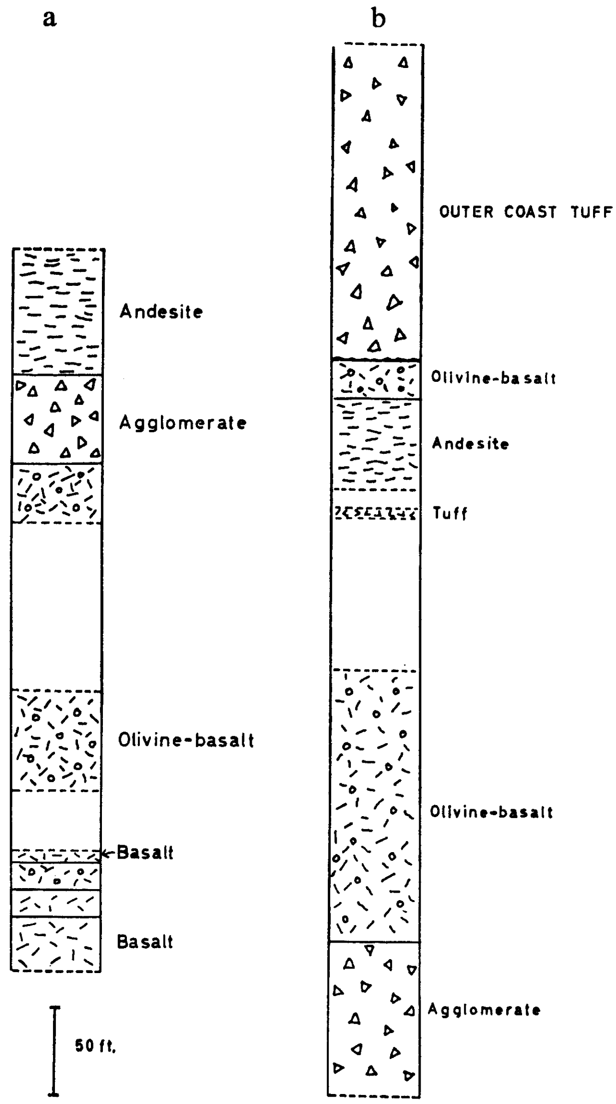

FIGURE 4
Comparative successions in the Telefon Bay Volcanics (a) and the Fumarole Bay Volcanics (b).

Stratigraphy and structure. Exposures in the caldera wall west of Telefon Bay (Fig. 5) are largely obscured by thick scree deposits. However, the following general succession can be distinguished:

3.	Scoriaceous andesites	80 ft.
2.	Massive agglomerate	60 ft.
1.	Basaltic lavas	200 ft.

A probable detailed succession compiled from outcrops at different localities is given in Fig. 4a. The lowest exposure in this section occurs at an altitude of 200 ft. above sea-level.

The Telefon Bay Volcanics dip away in all directions from the position of the assumed vent in Port Foster. Radial faulting has been observed at several localities in the caldera wall with a maximum down-

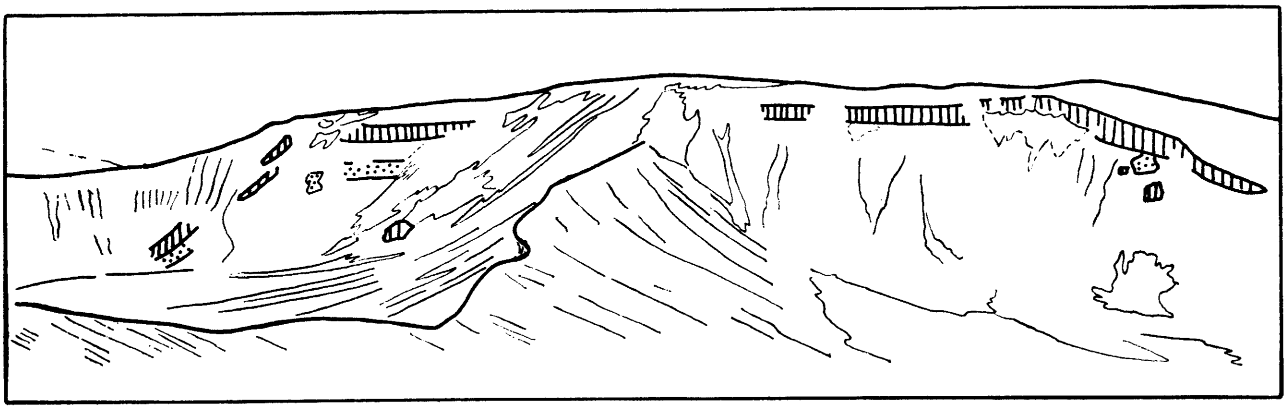

FIGURE 5

Sketch of Telefon Ridge from the east, showing the distribution of the lavas (vertical shading) and agglomerates (stippled) of the Telefon Bay Volcanics.

throw of 330 ft. to the south near the deep col mentioned previously. North of Telefon Bay only the highest members of the succession are exposed. The succession here consists of:

6. Andesitic lavas
5. ? Agglomerate
4. Andesitic lavas
3. Agglomerate
2. Andesitic lavas
1. Agglomerate.

The lavas at the top of the succession occur at an altitude of 450 ft. while the lowest agglomerate is only exposed as a submarine reef during low tide. The andesites at all three altitudes are identical in composition and texture and resemble the uppermost scoriaceous andesite in the succession west of the bay. The above succession is tentatively interpreted as a repetition of outcrops resulting from two arcuate strike faults roughly parallel to the shore of the bay.

Petrography. The oldest exposed lava flows of the Telefon Bay Volcanics occur immediately west of Cross Hill. All the lavas are basaltic and the detailed succession comprises:

4. Black cindery basalt	6 ft.
3. Grey vesicular olivine-basalt	15 ft. (B.138.4)
2. Red scoriaceous basalt	15 ft.
1. Grey flow-banded basalt	30 ft. (B.138.1–3)

The basal flow forms massive crags with well-developed vertical jointing trending north—south and east—west. Specimen B.138.1 contains microphenocrysts of zoned labradorite ($Ab_{11}An_{89}-Ab_{71}An_{29}$), diopsidic augite and minor olivine set in a dense groundmass of labradorite, pyroxene and magnetite. Measurements on four crystals show the following compositional variation between normal discontinuous zones in the plagioclase:

$$An_{89} - An_{72} - An_{62} - An_{29}$$
$$An_{72} - An_{62} - An_{54}$$
$$An_{72} - An_{64}$$
$$An_{72} - An_{48}$$

The diopsidic augite microphenocrysts also show zoning. The pyroxene of the groundmass includes granules of subcalcic augite ($2V\gamma \simeq 45°$) and irregular areas of pale green (?) hypersthene. The labradorite of the groundmass tends to occur as large allotriomorphic crystals rather than as microlites. Slender prismatic needles of a deep straw-brown amphibole are scattered throughout the matrix.

Another specimen (B.138.2), collected a few feet higher in the succession, has well-developed flow-banding in the hand specimen with an alternation of dense (dark) and fine-grained (grey) bands. Mineralogically it is identical to B.138.1 except that the brown prismatic needles are absent from the groundmass, and the olivine microphenocrysts are pseudomorphed by black iron oxides. Near the upper surface of the flow the pyroxene of the fine-grained bands is partially altered to a reddish brown iron mineral.

The overlying scoriaceous basalt may represent the upper surface of the basal flow, although the contact between the two is well defined.

Xenoliths of scoriaceous basalt occur in the succeeding olivine-basalt (B.138.4), which is intergranular and composed of labradorite, augite, olivine and magnetite. There are two generations of labradorite, the earlier intergrown with olivine which forms subhedral crystals showing incipient alteration to a mineral pleochroic in red and yellow-brown. Augite occurs as small granules between the felspar laths. The basalt xenoliths are rimmed with magnetite, and in the host rock straw-brown prismatic needles of amphibole occur near the contacts (cf. B.138.1). Some of the vesicles in the xenoliths are filled with an aggregate of yellow-green augite, labradorite and iron ore.

The succeeding outcrop occurs at an altitude of 300 ft. and at station B.140 a dark finely vesicular olivine-basalt forms crags about 50 ft. high. The flow is fine-grained and contains numerous small xenoliths of basic composition. Microphenocrysts of labradorite are sparsely distributed in an intergranular matrix of labradorite microlites, pyroxene granules, olivine and magnetite.

At the northern end of the caldera wall, west of Telefon Bay, the highest members of the Telefon Bay Volcanics are accessible. The following succession was recorded:

3. Scoriaceous andesite	80 ft.	(B.121.3)
2. Massive agglomerate	60 ft.	(B.121.2)
1. Vesicular olivine-basalt	30 ft.	(B.121.1, 4)

The olivine-basalt is dark grey in colour with a purplish blocky top. Microphenocrysts of zoned labradorite, olivine and clino-pyroxene are set in a rather coarse intergranular matrix of labradorite, subhedral olivine crystals, pyroxene and magnetite. The olivine microphenocrysts are fresh and colourless but those in the ground mass are greenish and partially pseudomorphed by iron oxide. Near the vesicles the pale green pyroxene in the matrix becomes yellow-brown in colour, probably as the result of oxidation. Haematite, secondary after magnetite, is abundant in this lava.

The massive agglomerate is ill-sorted, has closely spaced irregular jointing, and contains fragments up to 2 ft. in diameter but the majority are under 6 in. A variety of basaltic and andesitic lavas and agglomerate fragments are present. These are scattered in a matrix composed predominantly of fragments of pumiceous basic glass with occasional broken crystals of olivine, augite and plagioclase.

The highest lava flows in the Telefon Bay Volcanics are the most persistent and are exposed throughout the greater part of the ridge west of the bay. North of the bay the same lavas are believed to be represented but they occur at three successive altitudes due to step-faulting. West of Telefon Bay the lavas are red scoriaceous andesites with a matrix almost entirely replaced by haematite. The northern exposures include less altered andesites which are either fine-grained or dense intergranular lavas composed of basic andesine microlites, pyroxene granules and magnetite. Sparse microphenocrysts of labradorite and diopsidic augite are sometimes accompanied by a small amount of olivine. Tridymite commonly lines the vesicles but this was probably formed during the eruptions of the Pendulum Cove Group. Some of these lavas are more correctly termed andesine-basalts.

2. *The Fumarole Bay Volcanics*

The caldera wall along the northern part of Stonethrow Ridge is formed by a thick succession of lavas and pyroclastic rocks. The rocks comprising the lower 475 ft. of this section are referred to the *Fumarole Bay Volcanics*. They are unconformably overlain by the Outer Coast Tuff, the total exposed sequence exceeding 600 ft. in thickness (Plate Ia).

The entire succession is not exposed in any one locality but it is possible to deduce the fairly complete succession shown in Fig. 4b. Two main sub-divisions are represented:

2. Basaltic lava flows	325 ft.
1. Massive agglomerates	150 ft.

and the lowest outcrops in this sequence occur at 200 ft. above sea-level. The regional dip of the Fumarole Bay Volcanics is approximately 10° towards the outer coastline. The outward dips of the flows on Stonethrow Ridge suggest a common source from a centre located in Fumarole Bay (Fig. 3).

At some localities red basaltic lavas of the Whalers Bay Group rest unconformably upon the Fumarole Bay Volcanics, and to the south and west the latter are completely overstepped by the Stonethrow Ridge lavas (p. 26).

The caldera wall west of Wensleydale Beacon trends approximately north—south but near Fumarole Bay it curves sharply to the south-west. Here the wall rises steeply from sea-level to 900 ft. and it is significant that the scarp is parallel to the curved outline of Fumarole Bay. It is probable that an arcuate fault defines the scarp face and that this fault was a line of fracture along which the original cone collapsed. The rounded outlines of Fumarole and Telefon Bays are very similar to the scalloped bays of the Santorin caldera, where they are related to concentric fracturing and collapse of separate cones (Williams, 1941).

Farther south, below the summit of Stonethrow Ridge, vertical cliffs of yellow agglomerate rise to 600 ft. from the shore of the bay. These crags represent a composite volcanic neck (p.17). The age of the older vent agglomerate is unknown but it is tentatively suggested that it represents the neck of a parasitic cone on the flank of the main Fumarole Bay volcano.

At the extreme southern end of the ridge a major radial fault or fault zone of unknown magnitude terminates the Outer Coast Tuff and the underlying Fumarole Bay Volcanics.

Petrography. A thick andesine-basalt flow in the succession on Stonethrow Ridge gives rise to prominent vertical crags at a height of 550 ft. (Plate Ia). It extends for nearly a mile and is only accessible at the extreme northern and southern ends of the outcrop. The bulk of this flow is a dense blue-grey rock and, except near the margins, vesicles are absent. At the northern end of the ridge it consists of 42 ft. of dense lava with a 6 ft. red scoriaceous top and a 3 ft. scoriaceous base. Small xenoliths of dioritic and basaltic composition are very common.

Throughout its length and breadth the flow is remarkably uniform in composition and texture. Sparsely porphyritic, it consists of microphenocrysts of labradorite ($Ab_{48}An_{52}$), olivine and yellowish green augite set in a very fine-grained matrix of andesine microlites, pyroxene and olivine granules with anhedral iron ore. The texture of the matrix is pilotaxitic. A minor amount of feebly pleochroic hypersthene also occurs as microphenocrysts.

A short distance above this lava is a 15 ft. flow of purplish grey olivine-basalt (B.163.1; Plate IVe), which has well-developed prismatic jointing and, except for large vesicles near its upper surface, is fine-grained and compact. It is composed of intergranular labradorite laths ($Ab_{30}An_{70}$), olivine, augite and iron ore. Olivine occurs mainly as pale greenish anhedral crystals ($2V\alpha \leqq 90°$) in the interstices between the plagioclase laths but some early olivine is intergrown with the felspar. The lava is very fresh although there are traces of incipient alteration of the olivine to a reddish mineral. A few microphenocrysts of zoned plagioclase are present and one crystal shows a compositional variation of $Ab_{16}An_{84}$ to $Ab_{36}An_{64}$ from core to rim. The chemical analysis of this lava is given in Table VII.

A thin black agglomerate composed entirely of cindery basalt fragments crops out 12 ft. below the main lava flow but this horizon has not been traced for more than 50 yd.

The lowest outcrop in the succession on the north-east spur of Stonethrow Ridge consists of 100 ft. of black coarsely vesicular olivine-basalt (B.160.1). This lava has a rubbly appearance and on the north side contains numerous lenses of grey agglomerate. It is not certain whether these lenticular structures are xenoliths or whether they are fault breccias. The texture of the lava is hyalo-ophitic. Olivine, diopsidic augite and laths of labradorite are set in a matrix of dark iron-rich glass.

The habit of the olivine is of interest, because the crystals are frequently hollow and elongated along the *a*-axis. They are a combination of the (100) and (0*kl*) faces; at each end a funnel-shaped hollow extends from the (100) faces towards the centre of the crystal. Kuno (1950) has described identical crystals from the lavas of the Hakone volcano and Barth (1956) from the Pribilof Islands lavas. It is probable that the deposition of impurities on the (100) faces has retarded the growth of those faces (Hawkes, 1959).

A short distance to the south at station B.144 a similar flow of olivine-basalt crops out at an altitude of 250 ft., and this lava is the lowest exposed flow of the Fumarole Bay Volcanics. It is fine-grained and composed of labradorite ($Ab_{38}An_{62}$), augite, olivine and anhedral iron ore. The augite, which is commonly zoned, is diopsidic ($2V\gamma \simeq 60°$) and bears a subophitic relationship to the felspar. A second generation pyroxene occurs as small granules between the plagioclase laths and has a $2V\gamma \simeq$ 40–50°. The olivine (chrysolite) is pale green in colour, shows evidence of resorption and is frequently surrounded by a corona of pyroxene granules. A few crystals are altered to a mineral pleochroic in red.

The basal member of the Fumarole Bay Volcanics is a massive yellow agglomerate which in some localities exceeds 150 ft. in thickness. It is composed of fragments of light yellow pumiceous glass, dark brown nearly opaque glass with ragged vesicles, and large crystal fragments of olivine, augite and felspar. Lithic fragments appear to comprise only a minor proportion of this agglomerate.

B. The Eastern Area

1. *The vent agglomerate of Cathedral Crags*

Cathedral Crags, which rise sheer out of the sea (Plate Ib) at the entrance to Port Foster, are formed of some 460 ft. of agglomerates. The lower 350 ft. are massive yellow agglomerates, completely devoid of bedding but with conspicuous vertical jointing trending east—west and north—south. Cognate fragments of black vesicular lava predominate, but are accompanied by occasional accidental fragments of dioritic and andesitic rocks. It is assumed that this agglomerate represents the vent agglomerate of a pre-caldera volcano. Occasional basaltic dykes intrude the agglomerate and tend to follow the joint directions. The vent agglomerate is overlain by thin-bedded lapilli-tuffs possibly belonging to the Neptunes Bellows Group.

Little remains of the flank of this ancient volcano, but to the north-east and south-west are two fault blocks of massive-bedded yellow tuff and agglomerate, exposed at Baily Head and South Point. There is no direct evidence but it is likely that these pyroclastic rocks (see below) are contemporaneous with the Outer Coast Tuff, and it is suggested that they were deposited on the flanks of the Cathedral Crags volcano. The original radial structure of this volcano has been drastically modified by faulting and prolonged erosion. Because this cone is so severely denuded it is possible that it was the first volcano in the history of Deception Island. A hypothetical reconstruction of its original extent is shown in Fig. 3.

2. *The lavas and agglomerates of Macaroni Point*

In the extreme north-east of the island are three prominent headlands with cliffs rising to over 250 ft. These were not visited in the field but an examination of aerial photographs indicates the following succession:

2. Lava flows
1. Massive agglomerate.

The dip appears to be slightly seaward. Olsacher (1956) has mapped lava flows only on the western and eastern headlands and has included them in his Serie Volcanica Antigua, the equivalent of the Pre-caldera Series (Table II). Unfortunately there is no mention of these lavas in the text of Olsacher's paper.

Until further information is obtained these lavas and agglomerates are included in the Port Foster Group, and it is tentatively assumed that they were derived from a vent somewhere to the south-west (Fig. 3).

C. The Outer Coast Tuff

From Macaroni Point, in the extreme north-east, to the pronounced depression of Vapour Col, the outer coastline is composed of vertical cliffs of tuff exceeding 150 ft. in height. This continuous section comprises nearly half the outer circumference of Deception Island. These cliffs are inaccessible but when viewed from above they appear very constant in character throughout their length, and are formed of massive-bedded yellow tuffs with a slight seaward dip (Plate Ic). These pyroclastics constitute the Outer Coast Tuff, which from its constant character and continuous outcrop is assumed to be the product of a single major eruptive phase.

Following the uplift of the Kendall Terrace marine platform (p. 4) considerable subaerial erosion must have taken place, as the Outer Coast Tuff varies in thickness from 90 to 225 ft. Fluvio-glacial deposits and the Kendall Terrace lavas (p. 27) now mantle the underlying irregular tuff surface.

Inland exposures of the Outer Coast Tuff are rare but this unit is believed to be exposed at the extreme southern end of Stonethrow Ridge, in the cliffs south-west of Collins Point and at Baily Head. At all these localities the tuff occurs as massive, poorly graded beds. The included fragments may be up to 1 ft. in diameter but rarely exceed 1 in. The fragments are mainly pumiceous glass accompanied by occasional broken crystals of olivine, augite and plagioclase (Plate IVa). There is a significant scarcity of accidental or accessory lithic fragments.

The Outer Coast Tuff is essentially a pumice-tuff and it probably represents the final paroxysmal eruptions which emptied the magma chamber prior to the engulfment of the pre-caldera volcanoes. Some indication of its former widespread extent is seen in the submerged reefs off the western outer coastline, its probable presence on New Rock and Låvebrua Island and the submarine platform on the eastern side of the island (Holtedahl, 1929).

IV. THE NEPTUNES BELLOWS GROUP

FOLLOWING the collapse and subsidence of the volcanoes of the Port Foster Group, igneous activity was renewed in the south of the island along the rim of the caldera. Many of the cones are located near the intersection of the major radial arcuate faults which determine the boundary of the caldera. The lavas and pyroclastic rocks associated with these cones comprise the *Neptunes Bellows Group* and they represent the second volcanic episode in the history of Deception Island.

Vent agglomerates marking the eruptive centres occur half a mile west of Entrance Point, at Vapour Col and north-west of South East Point. For convenience the vent agglomerate west of Fumarole Bay is included in this section but it is believed to represent a parasitic cone which broke out on the flank of the Fumarole Bay volcano (p. 11). The positions of these volcanoes and their probable original extent is shown in Fig. 6. From the interpretation of aerial photographs there is some evidence to suggest the presence of one or two further cones concealed beneath the ice of Mount Kirkwood.

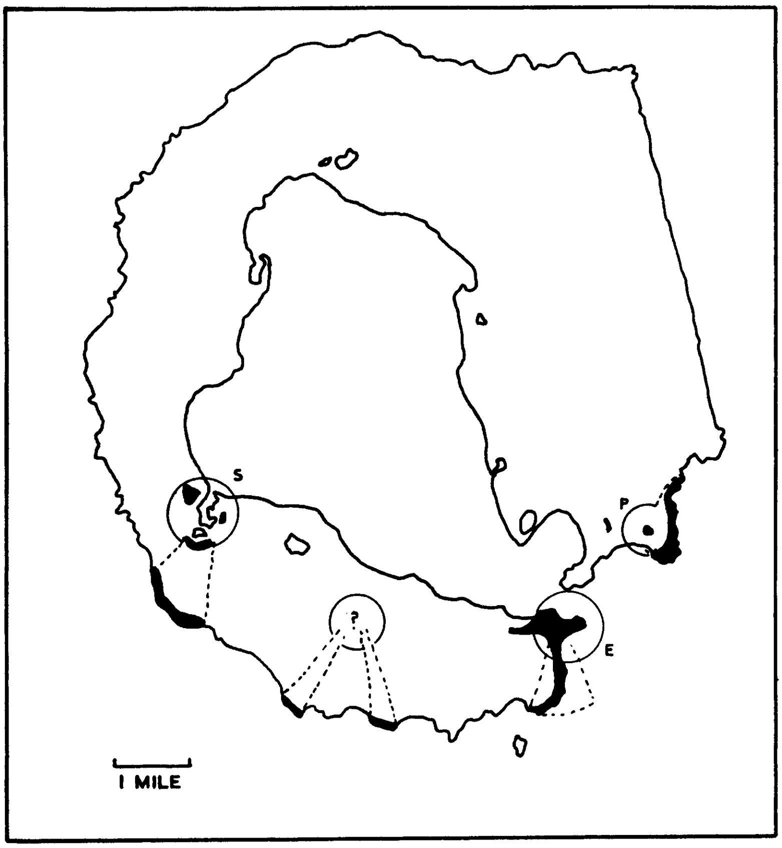

FIGURE 6

The present distribution of the lavas and agglomerates of the Neptunes Bellows Group (black) and the probable positions of the original volcanoes. S. Vapour Col vent; E. Entrance Point vent; P. South East Point vent.

Eruptive activity was dominantly explosive but at least once in the history of each cone, flows of olivine-basalt lava breached the crater wall. These now form the low rocky promontories along the southern and south-eastern outer coastline of the island. At all localities these lavas are overlain by thick moraine deposits.

The original volcanoes have been deeply dissected and only the basal parts remain, the simple radial structure of which is often complicated by minor faulting. In each case the presence of an original centre of eruption is indicated by the occurrence of a vent agglomerate and by the fact that the surrounding lavas and pyroclastic rocks dip away in all directions from this agglomerate.

The vent agglomerates. At several localities in the mountain ring of Deception Island there are impressive cliffs of massive agglomerate showing considerable vertical thickness but limited lateral extent. These agglomerates are devoid of bedding but they have conspicuous vertical prismatic jointing. Their texture is "porphyritic" and among the included fragments are boulders up to 6 ft. in diameter. Accidental and accessory lithic material is present but cognate fragments are the most abundant. The latter are irregularly shaped, highly vesicular lava fragments which often have a thin glassy selvage; they appear to have been plastic when erupted and some resemble volcanic bombs. They are embedded in a matrix of fine material composed mainly of pumiceous basic glass with occasional broken crystals of augite, olivine and felspar.

Intrusive rocks are rare on Deception Island but the few basaltic dykes that have been recorded are disposed radially around these vent agglomerates. Fumaroles are active today near two of the vents.

1. THE ENTRANCE POINT VENT

This vent agglomerate forms vertical cliffs on the outer coastline a quarter of a mile west of Entrance Point (Plate IIb). The surrounding lavas and tuffs dip away from the vent in all directions. The cliffs consist of 500 ft. of agglomerate overlain by 100 ft. of red scoriaceous basalt. Although the cliffs are inaccessible here, 150 ft. of the same massive yellow vent agglomerate are well exposed in the prominent buttress overlooking Neptunes Bellows. The agglomerate is completely devoid of bedding but it has vertical prismatic jointing trending east-north-east/west-south-west and north-north-west/south-south-east. The irregularly-shaped included fragments are predominantly of a grey pumiceous glassy basalt and they are set in a matrix of pumiceous basic glass with some fractured crystals of augite, olivine and felspar.

There is a close similarity in composition and texture between the associated olivine-basalt lavas to the north and south of the vent. Radial faulting occurs on the east of the vent agglomerate, while in the south-east the original flank of the cone has been deeply embayed by marine erosion. A broad syncline, pitching steeply to the north, occurs in the tuff beds west of the vent and this may represent an original stream valley filled with tuff.

Immediately south of the vent the lava flows dip steeply southward, but this gradually becomes horizontal and the flows form a broad rocky promontory with sea cliffs 20 ft. high. Inland this plain is overlain by thick ice and morainic deposits, the latter in places probably exceeding 250 ft. in thickness. Three specimens from the sea cliffs are olivine-basalts.

Specimen B.183.1 is fine-grained and intergranular, being composed of labradorite ($Ab_{32}An_{68}$), olivine, augite and magnetite. A preferred orientation is shown by the felspar microlites. There are sparse microphenocrysts of all the constituent minerals, the olivine as subhedral crystals ($2V\alpha \leqq 90°$) showing incipient alteration to a red mineral and the diopsidic augite as pale green anhedral zoned crystals.

Specimen B.173.1 is a dark vesicular lava with sparse microphenocrysts of zoned labradorite, olivine and diopsidic augite set in a fine-grained intergranular matrix of labradorite microlites, pyroxene granules, olivine and magnetite. The pyroxene in the groundmass includes a subcalcic augite ($2V\gamma \simeq 45°$), and near the vesicles the augite and olivine are partially replaced by green chloritic material.

The third specimen (B.173.2) contains interstitial brown glass, so heavily charged with iron ores as to be almost opaque.

In the northern exposures red vesicular olivine-basalts dip steeply to the north and north-west, becoming nearly horizontal three-quarters of a mile west-north-west of the vent. These lavas are similar to those above the vent and on the southern flank. South-east of Collins Point the following succession has been recorded:

3.	Massive, dark grey olivine-basalt	(B.103.4)
2.	Thinly jointed, light grey olivine-basalt	(B.103.3)
1.	Massive, dark grey olivine-basalt	(B.103.1, 2)

The total thickness is 40 ft. and the dip is gentle towards the north-west. All the lavas have essentially the same composition and texture, being composed of intergranular labradorite, augite, olivine and magnetite (Plate IVf). A chemical analysis of B.103.3 is given in Table VII. The lower and upper flows are finely vesicular and in specimen B.103.4, near the vesicles, the magnetite is replaced by haematite, while the augite shows alteration to a bright yellow-green mineral. This distinctive alteration product also occurs in the lavas north of the vent and in those forming the broad promontory south of the vent.

Immediately north of the vent are 100 ft. sea cliffs of red highly vesicular lava showing vertical prismatic jointing and dipping steeply towards Neptunes Bellows. This olivine-basalt (B.110) contains microphenocrysts of labradorite, olivine and diopsidic augite, the former showing both normal and reverse discontinuous zoning. The matrix is intergranular and fine-grained, being composed of labradorite microlites ($Ab_{42}An_{58}$), subcalcic and pigeonitic augite ($2V\gamma < 30°$), olivine and magnetite.

A short distance to the east this lava is faulted against tuff beds, the fault having a downthrow to the east of at least 500 ft. Associated with the Entrance Point volcano are well-bedded lithic tuffs, containing boulders up to 3 ft. in diameter near the base but becoming finer towards the top of the succession.

2. The South East Point Vent

The prominent headland of South East Point is composed of 80 ft. of basaltic lavas resting with marked unconformity upon the eroded surface of the Cathedral Crags agglomerate (Plate IIc). These lavas, which have an easterly dip, extend on the outer coast for 1½ miles north of the point. Identical lavas are exposed on the Whalers Bay side of the ridge running from Mount Pond to South East Point, and here the succession comprises 25 ft. of lava overlain by 20 ft. of bedded tuff, dipping in a westerly direction.

These lavas and tuffs are associated with a partly exposed volcanic neck a short distance north-west of the point, where crags of massive yellow agglomerate contain large boulders and volcanic bombs of black and red highly vesicular lava.

All the lavas are olivine-basalts, which are fine-grained intergranular rocks composed of labradorite microlites, olivine, clino-pyroxene and magnetite. Any of the constituent minerals, except the magnetite, may occur as microphenocrysts. The pyroxene microphenocrysts are diopsidic, while the pyroxene of the matrix is probably a subcalcic variety. The olivine occurs as subhedral prisms commonly with a "hollow shell" or skeletal habit (p. 11). A little interstitial dark brown glass is present in some of the lavas.

3. The Vapour Col Vent

The pronounced depression of Vapour Col breaks the continuity of the mountain ring and is the site of a volcano which has been breached and deeply embayed on the northern side by a shallow-water lagoon. A considerable part of the original crater rim remains intact (Plate IId), although the slopes are now mantled by thick scree deposits. There is fumarolic activity on the shores of the lagoon.

West of this lagoon is a low arcuate ridge (Plate IIIb), which is the continuation of the semi-circular ridge to the east and south of the lagoon. The western ridge is composed of stratified tuffs and agglomerates which have the form of an asymmetric anticline, the southern limb dipping at 32° to the south-south-west and the northern limb at 25° to the north-north-west. Tectonic folding is completely absent on Deception Island, and the lavas and pyroclastic rocks show original dips only locally modified by faulting. It is suggested that this anticlinal structure is an original feature, the steeper limb representing the inner slope of the crater and the more gently dipping limb the outer flank of the cone. The value of 32° on the inner side of the crater would appear to be a reasonable angle of repose for these illsorted pyroclastics containing boulders up to 3 ft. in diameter. Fragments of a dark, very highly vesicular olivine-basalt are the most abundant.

Most of the western flank of the cone, which is bounded by the fault scarp terminating the Outer Coast Tuff (p. 32), has been removed by erosion, while in the south the crater rim has been breached by melt streams and covered by scree and moraine.

On the eastern side of the col the crater rim is well preserved and spectacular vertical cliffs of agglomerate tower above the small lake south of the lagoon. The succession comprises:

2. Stratified tuffs	Stratified tuffs and agglomerates with lava flows near the top	150 ft.
	Whitened agglomerate	3 ft.
	Sill of olivine-basalt	1 ft.
1. Massive agglomerate		200 ft.

Both the lithology and structure indicate that this is a massive vent agglomerate. Bedding is poorly developed but vertical jointing trending north-north-west and east-south-east is conspicuous; several narrow dykes follow the directions of these joint planes. Near the base there are boulders up to 5 ft. in diameter, and the included fragments are mainly of highly vesicular olivine-basalt.

The massive agglomerate is abruptly terminated in the north-east and south-west, and is overlain and flanked by the stratified tuffs, which are horizontal on top of the vent agglomerate but along the southern side (Fig. 7) dip at 35° to the west-north-west. Measurements in the surrounding stratified tuff exposures show a dip away from the massive agglomerate. A short distance north of the main cliffs stratified tuffs and lava flows dip at 20° to the north-east. Olsacher (1956) places his hypothetical ring fault along the col separating this northern exposure from the main agglomerate cliffs. If the concept of a volcanic neck is accepted then no fault need be postulated, since the northern tuffs show a normal outward dip from the eruption centre (p. 30).

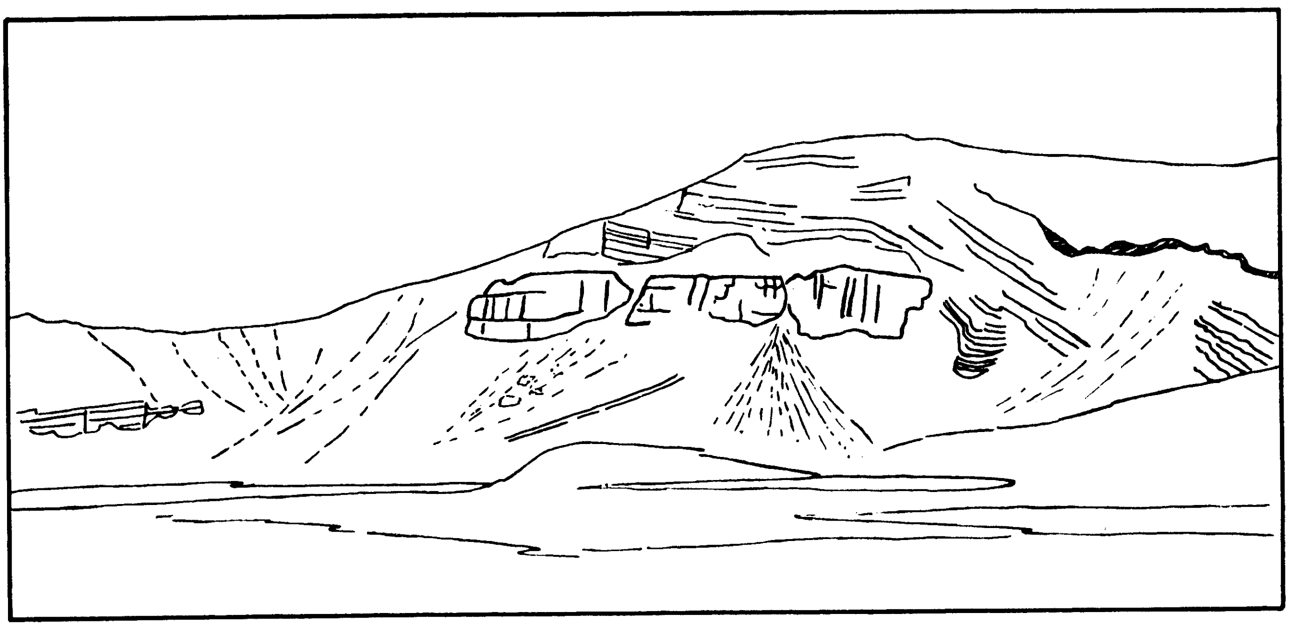

FIGURE 7

Sketch of the Vapour Col vent, showing the massive cliffs of vent agglomerate (heavy outline) overlain and flanked by stratified tuffs and lava flows.

The activity of the Vapour Col volcano was mainly explosive and pyroclastic rocks dominate over lava flows. However, south of the vent a low rocky promontory composed of lava flows forms the outer coastline. The maximum thickness of lava does not exceed 25 ft. and inland the flows are overlain by a thick deposit of moraine and scree. Along the coast these flows are nearly horizontal but the dip gradually steepens towards the north and the vent.

All the lavas associated with this volcano are fine-grained intergranular olivine-basalts, which are identical in composition and texture to those of the contemporaneous vent at Entrance Point. They are finely vesicular and composed of orientated labradorite or basic andesine microlites, small prisms of olivine, augite and magnetite. The olivine frequently occurs as hollow crystals and shows incipient alteration to a cryptocrystalline mineral pleochroic in red and pale yellow-red. Typically these lavas are aphanitic but sparse microphenocrysts of diopsidic augite and labradorite ($Ab_{48}An_{52} - Ab_{62}An_{38}$) may be present. There is dark brown interstitial glass in some specimens.

4. The Fumarole Bay Vent

The spectacular cliffs of massive agglomerate rising to 600 ft. from the shore of Fumarole Bay represent a composite volcanic neck. Two types of agglomerate comprise this vent:

Type A. Massive yellow agglomerate with conspicuous vertical prismatic jointing. The contained fragments, which are irregular in shape and sparse in distribution, are mainly a highly vesicular grey olivine-basalt.

Type B. Darker in colour than Type A, because of a very high proportion of dark olivine-basalt fragments. The proportion of fragments to matrix may be so high that locally the rock resembles a lava with xenoliths of tuff.

At the northern end of the cliffs the yellow agglomerates of Type A are grey in patches as a result of solfataric alteration. From field relationships it has been established that the Type B agglomerate is older than Type A. In thin section the matrix of the two types is similar, being composed essentially of fragments of pumiceous basic glass. However, the included fragments of the older vent agglomerate are of olivine-basalt similar in composition and texture to the lavas of the Fumarole Bay Volcanics, and it is tentatively assumed (p. 11) that this vent agglomerate marks the site of a parasitic cone on the flank of the Fumarole Bay volcano. The younger vent agglomerate may represent a volcano of the Neptunes Bellows Group, and the lapilli-tuffs on the outer coast west of this vent may have been derived from it. The terrain in the vicinity of this composite vent is heavily glacierized and field relationships are somewhat obscure.

V. THE PENDULUM COVE GROUP

THE volcanoes of the Pendulum Cove Group are post-caldera in age, and in the south of the island they are unconformably overlain by red scoriaceous basalts of the Whalers Bay Group.

During this volcanic episode lavas and pyroclastic rocks were erupted from a number of small independent volcanoes, which form the volcanic zone within the caldera rim. The overall pattern of vulcanicity is strongly indicative of structural control; the centres are located along arcuate lines, which are concentric with the ring faults defining the caldera boundary (Fig. 12).

The activity was mainly explosive in character with the formation of cinder cones and the deposition of pumice sheets. The soda-rich andesites and oligoclase-andesites, which have previously attracted so much attention, are restricted to the Pendulum Cove Group. Erosion and minor faulting have destroyed much of the original volcanic structure and the eruptive centres are now represented by deep craters mantled by scree. The pumice sheets have been reworked by melt streams but an indication of their former extent may be gained from the numerous pumice fragments in the stream terraces and scree.

Eruptive centres occur at Cross Hill, Collins Point, the promontory 1¼ miles west-north-west of Collins Point, Ronald Hill, Wensleydale Beacon, Crater Lake, the crater ½ mile east of Crater Lake and Pendulum Cove (Fig. 8).

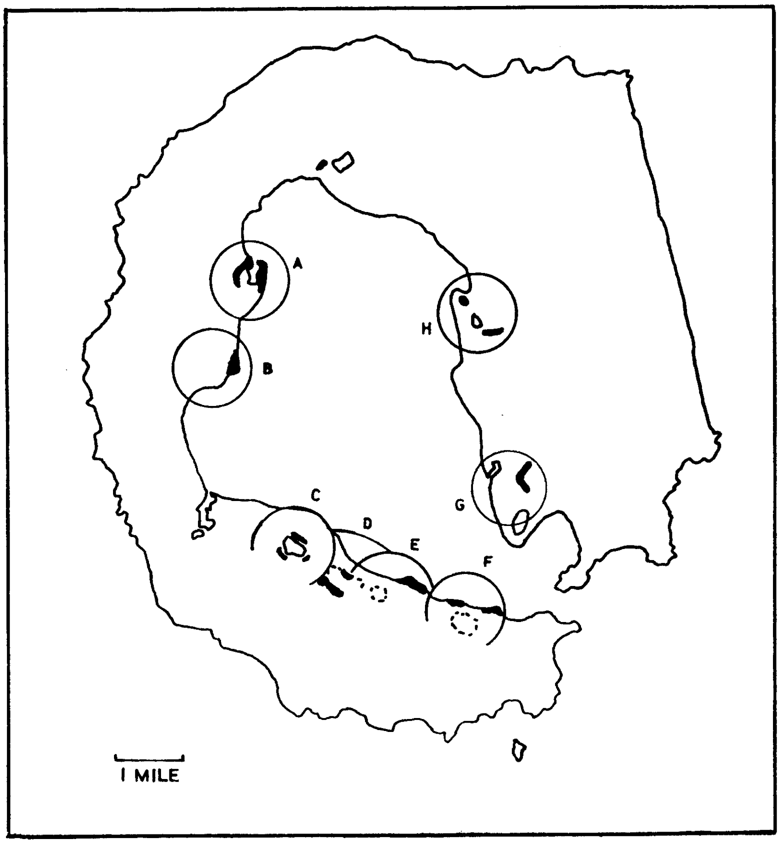

FIGURE 8

The present distribution of the lavas and agglomerates of the Pendulum Cove Group (black) and the positions of the original volcanoes. A. Cross Hill; B. Wensleydale Beacon; C. Crater Lake; D. The crater ½ mile east of Crater Lake; E. The promontory 1¼ miles west-north-west of Collins Point; F. Collins Point; G. Ronald Hill; H. Pendulum Cove.

The lavas associated with these centres are either andesitic or basaltic and accordingly the Pendulum Cove volcanoes may be subdivided into:

a. *Andesitic lavas*	b. *Basaltic lavas*
Cross Hill	Crater Lake
Collins Point	Crater ½ mile east of Crater Lake
Promontory 1¼ miles west-north-west of Collins Point	Pendulum Cove
Ronald Hill	

The activity of the Wensleydale Beacon volcano was apparently explosive, unaccompanied by the eruption of lava flows.

1. CROSS HILL

South of Telefon Bay is a well-preserved crater partly breached by the sea to form a shallow lagoon. The western crater slope rises to 529 ft. forming the summit of Cross Hill; the eastern rim is narrow and terminated on the Port Foster side by cliffs of pyroclastic deposits* attaining 150 ft. in height. On the outer western flank of the crater there is a large amount of white andesitic pumice in the scree. The topography of the hill and lagoon has a typical volcanic profile (Fig. 9).

* Holtedahl (1929) regards these deposits as tuff but Olsacher (1956) maps them as moraine. They appear to be identical with the deposits at Wensleydale Beacon (Plate IIIa), which Olsacher maps as tuff.

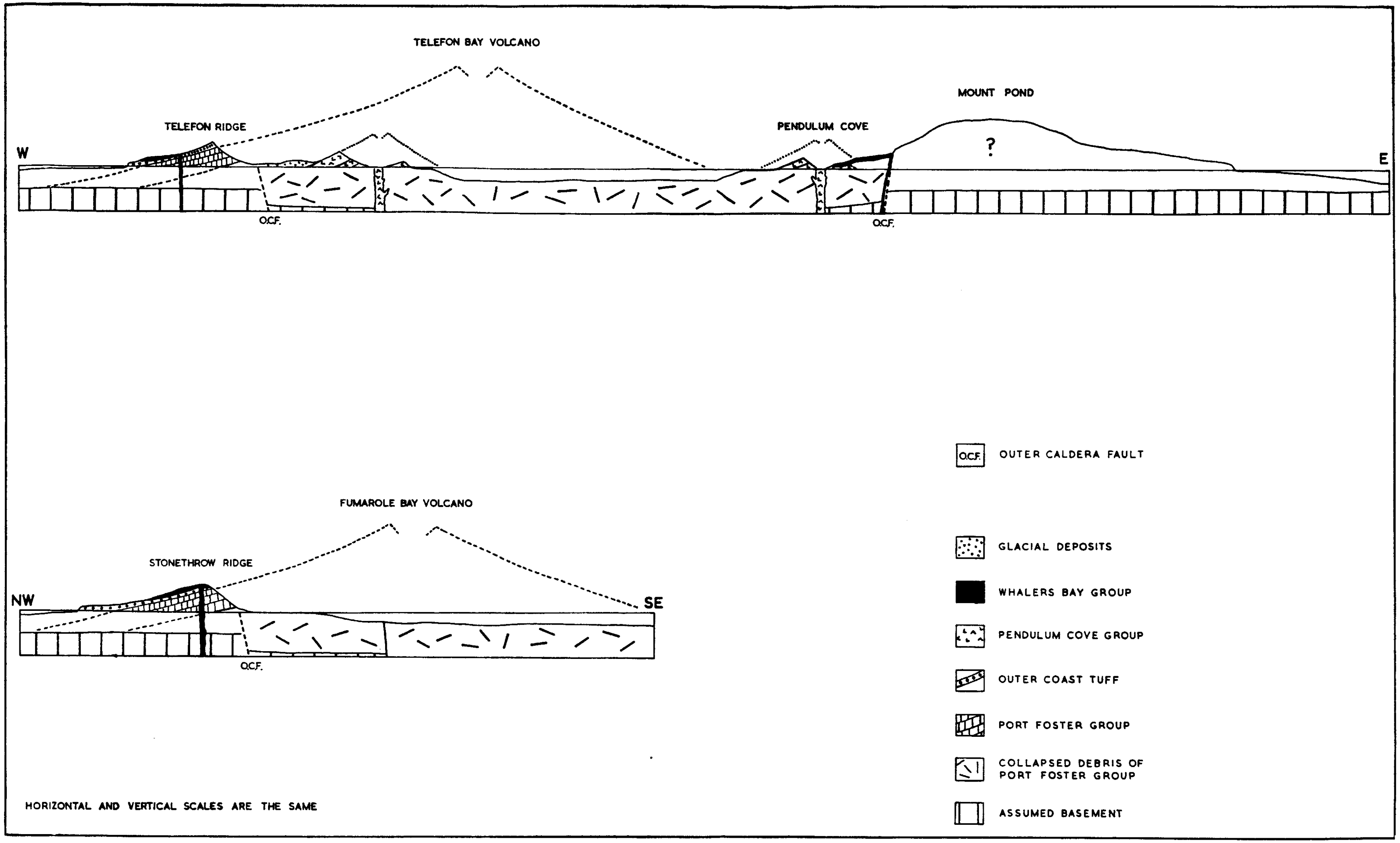

FIGURE 9
Geological cross-sections through Deception Island.

Outcrops of pyroxene-andesites, which are restricted to the inner western slope of the crater, are intermittently exposed through the scree. Individual flows are commonly grey compact lavas with a vesicular zone near the upper surface, but the thick red scoriaceous tops typical of the Whalers Bay Group lavas are not present in these flows. The thicker flows have a massive appearance with well-developed vertical (north-north-west and west-north-west at station B.124) or curved joints, while the thinner flows, usually of acid andesite, have close horizontal joints giving a "flaggy" appearance. Irregular jointing aided by frost-shattering gives a superficial contorted appearance and it is difficult to determine the dip, but at the northern end of the main outcrop (B.124) it appears to be 25° to the west-north-west, dipping away from the lagoon.

Petrography. A total thickness of 66 ft. of hypersthene-augite-andesites and minor augite-andesites is exposed inside the crater.

The hypersthene-augite-andesites are usually porphyritic with prominent phenocrysts of zoned andesine ($Ab_{35}An_{65} - Ab_{70}An_{30}$). Glassy varieties, which are common among the hypersthene-bearing andesites, are black, vitreous and frequently flow-banded in the hand specimen.

The hypersthene occurs as euhedral or subhedral phenocrysts, very fresh although often having a narrow reaction rim of clino-pyroxene. Typically, it is feebly pleochroic with α = pale brownish pink, β = pale yellowish brown, and γ = pale clear green. A pale green diopsidic augite accompanies the hypersthene and occurs as subhedral crystals commonly twinned on (100). Some optical properties of the pyroxenes are given in Table VI. A minor amount of anhedral magnetite is associated with the ferromagnesian phenocrysts.

The groundmass, which commonly has a trachytic texture, is composed of andesine microlites, pyroxene and magnetite grains with or without interstitial light brown glass.

Late stage deuteric minerals are uncommon in the hypersthene-augite-andesites but specimen B.124.5 is amygdaloidal. These minerals include:

Tridymite occurring as anhedral plates with a distinct negative refringence, and showing wedge-shaped twinning; anhedral crystals of *quartz* radiating from the walls of the vesicles and surrounding the tridymite; short prismatic needles of a strongly coloured *amphibole*, provisionally identified as riebeckite, which is pleochroic in dark bluish green and brown and has well-developed prismatic cleavages and a good basal parting. (It is not only restricted to the vesicles but also occurs in the surrounding matrix.)

With the disappearance of the orthopyroxene, the hypersthene-augite-andesites grade into the augite-andesites. Every gradation between the two varieties is represented. The latter are porphyritic with andesine or oligoclase phenocrysts accompanied by a brownish or yellowish green augite ($2V\gamma \simeq 40$–$50°$) set in a trachytic groundmass of oligoclase or albite-oligoclase microlites, pyroxene and iron ore granules with some interstitial alkali-felspar. Glassy varieties are subordinate to holocrystalline varieties.

2. Collins Point

Collins Point is a low rocky headland formed of 20 ft. of andesitic lavas. These lavas and those a short distance westwards were erupted from the deep crater immediately to the south-west. Olsacher (1956) has described contorted lava flows, which were intruded into moraine, but an examination of the critical locality showed no evidence for this.

The crater is bounded on the south by a fault scarp and here cliffs of the Outer Coast Tuff rise to over 900 ft. The lavas of the coastal section present a confused appearance but the general dip is towards Port Foster, away from the crater. The cliff section at Collins Point is:

3. Dark scoriaceous andesite	10 ft. (B.107.8)
2. Thinly jointed oligoclase-andesite	3 ft. (B.107.2)
1. Massive andesite	7 ft. (B.107.1)

The middle flow, which has closely-spaced, roughly horizontal, irregular joints, succeeds and passes laterally into the underlying massive andesite. Some 50 yd. west of Collins Point another coastal section comprises:

3. Massive andesite	6 ft. (B.184.3)
2. Thinly jointed andesite	3 ft. (B.184.2)
1. Scoriaceous hyalo-andesite (top of flow)	6 ft. (B.184.1)

Petrography. The lavas in the vicinity of Collins Point are andesitic in character but are peculiar in that iron-rich olivine is a common minor constituent. These types correspond to the hyalo-andesites and oligoclase-andesites described by Tyrrell (1945). They are similar in composition and texture to the lavas of the promontory 1¼ miles west-north-west of Collins Point and Ronald Hill.

The more basic varieties (andesine-andesites) are composed of phenocrysts of plagioclase, augite, olivine and magnetite set in a glassy or felspathic matrix. When holocrystalline the matrix consists of orientated acid andesine microlites, pyroxene and magnetite. The composition of plagioclase phenocrysts varies from labradorite to oligoclase, and often two generations are present.

In the acid varieties (oligoclase-andesites) oligoclase or albite-oligoclase microlites, often accompanied by interstitial patches of alkali-felspar, form the groundmass.

At Collins Point the lowest lava exposed is a massive grey andesite. Phenocrysts of andesine, diopsidic augite ($2V\gamma \simeq 50°$), olivine and magnetite are set in a fine-grained matrix of the same minerals. The phenocrysts tend to occur in glomeroporphyritic clusters set in a matrix with a pilotaxitic texture.

The succeeding oligoclase-andesite (B.107.2) is more felspathic with a trachytic groundmass composed mainly of albite-oligoclase microlites and interstitial alkali-felspar. Microphenocrysts of zoned andesine, diopsidic augite ($2V\gamma \simeq 60°$), olivine and magnetite commonly form mixed glomeroporphyritic clusters. The olivine occurs as rounded crystals, faintly yellow-green in colour and with a composition $Fo_{53}Fa_{47}$. Pleochroic brown apatite is a minor accessory mineral.

On the inner slope of the crater a small outcrop of dark highly vesicular andesite (B.182.2) is exposed. This is a hemicrystalline rock composed of andesine microlites, pyroxene, olivine and magnetite in a base of dark brown glass. All the minerals are present as two generations, forming sparse microphenocrysts.

An identical vesicular hyalo-andesite (B.184.1) occurs on the outside of the crater 50 yd. west of Collins Point. Overlying this are two flows of andesine-andesite, which have sparse microphenocrysts of labradorite, diopsidic augite ($2V\gamma = 50$–$60°$) and fayalitic olivine set in a fluidal groundmass of acid andesine and pyroxene microlites, magnetite and a small amount of interstitial brown glass ($n < 1{\cdot}54$).

3. Promontory 1¼ Miles West-north-west of Collins Point

Much of the cliff section here is inaccessible but some 60 ft. of lava flows are exposed and at the extreme western end the succession is:

3. Black hypersthene-augite-hyalo-andesite 15 ft. (B.111.3)
2. Grey, thinly jointed oligoclase-andesite 10 ft. (B.111.2)
1. Grey massive oligoclase-andesite 4 ft. (B.111.1)

The whole exposure presents a contorted appearance because of irregular jointing. From the interpretation of vertical aerial photographs it seems certain that these lavas were derived from the deep circular crater to the south-west of this promontory.

Petrography. The lowest flow of oligoclase-andesite is fine-grained with microphenocrysts (often as mixed glomeroporphyritic clusters) of andesine, hypersthene, augite, magnetite and olivine in a felspathic groundmass. The olivine is a distinctly iron-rich variety ($Fo_{45}Fa_{55}$) and it occurs as resorbed crystals occasionally rimmed by pyroxene granules. The augite is present as pale yellow-green subhedral crystals with a $2V\gamma = 60°$. The trachytic groundmass is composed of albite-oligoclase microlites and pyroxene granules with interstitial alkali-felspar.

A flow (B.111.4) from a nearby locality is similar in composition but contains interstitial glass in the matrix. It contains phenocrysts of fayalitic olivine (faintly pleochroic in yellow-green) and andesine associated with occasional microphenocrysts of diopsidic augite and hypersthene (Plate IVd). The felspathic groundmass is composed of oligoclase microlites set in a base of pale brown glass ($n < 1{\cdot}54$). A chemical analysis of this oligoclase-andesite is given in Table VII.

The succeeding oligoclase-andesite (B.111.2) is almost identical to the basal flow except for the absence of olivine. Hypersthene occurs as prismatic sections, showing only feeble pleochroism and sometimes surrounded by a reaction rim of augite (Plate IVb). The groundmass is again felspathic with a trachytic texture, and consists of albite-oligoclase microlites, some pyroxene microlites and interstitial patches of alkali-felspar. The exact composition of the alkali-felspar is difficult to determine but chemical analyses of comparable lavas (Table VII) indicate that it is soda-rich.

The highest lava flow is scoriaceous and vitreous in appearance. Phenocrysts of andesine, diopsidic augite and hypersthene are present in a glassy matrix with abundant oligoclase microlites. The clino-pyroxene is pale green in colour and heavily rimmed with magnetite. Some thin sections suggest that the clino-pyroxene is replacing hypersthene with the formation of iron ore. The glass ($n < 1.54$) is pale brown in colour, mainly fresh, but in patches it is altered to a bright red anisotropic substance.

4. Ronald Hill

Ronald Hill (340 ft.) has steep western and north-western faces overlooking the lava plain formed of the Kroner Lake lavas (p. 27). There is a two-fold succession:

2. Lava flows 100 ft.
1. Tuffs 120 ft.

and the baked contact between the two sub-divisions is exposed on the north-western side of the hill. Olsacher (1956) shows an incorrect inverted succession at Ronald Hill and omits all structural information on his published map.

On the north-western face the lavas and agglomerates dip at 24° to the north-north-east which is regarded as close to the original dip of the volcanics. A major dip fault, which trends approximately north—south and displaces the beds 100 ft. to the west, forms a gully on both the north-western and south-western faces of the hill. West of the main dislocation is a minor branch fault with a downthrow of 20 ft. to the west.

The summit of Ronald Hill is a flat surface, which truncates the lavas and is overlain by coarse unconsolidated gravels unaffected by the faults. Holtedahl (1929) regarded these gravels as equivalent to the fluvio-glacial gravels underlying the Kroner Lake lavas, inferring that the faulting is later than the gravels in age. There is, however, no real evidence to support the correlation of these two gravel deposits.

There is no definite indication as to the source of these lavas and agglomerates, but south of Ronald Hill there is an arcuate scree-covered ridge underlain by volcanic rocks, which has a steep inner concave slope and a gentle outer slope. The composition of the lavas is very similar to that of the lava cones north of Mount Kirkwood and it is very probable that Ronald Hill is the remnant of a small volcano belonging to the Pendulum Cove Group.

Petrography. The lavas are all andesitic and include oligoclase-andesites and subordinate hypersthene-augite-andesites. In the hand specimen they are compact and grey in colour with only microscopic vesicles but often traversed by thin veins of tridymite.

The oligoclase-andesites are porphyritic with numerous phenocrysts of andesine or oligoclase, fayalitic olivine ($Fo_{40}Fa_{60} - Fo_{26}Fa_{74}$), clino-pyroxene and minor hypersthene (Plate IVc). The fayalitic olivine is pale yellow in colour and it occurs as large (1·5 mm.) subhedral phenocrysts often sub-ophitically enclosing andesine or oligoclase crystals. In some lavas fayalitic olivine is also associated with tridymite in veins and vesicles. Both augite and diopsidic augite are present among the phenocrysts, the former as subhedral and the latter as anhedral crystals.

Oligoclase and albite-oligoclase microlites predominate in the trachytic matrix. In many of the lavas the groundmass contains a felspar with refractive indices appreciably below 1·54, suggesting a potash-soda variety. A glassy selvage occurs at the base of individual flows, where the matrix consists mainly of acid andesine microlites in a pale brown glass ($n < 1{\cdot}54$).

5. Wensleydale Beacon

The 100 ft. cliffs bounding the small promontory east of Wensleydale Beacon are composed of well-bedded grey lapilli-tuffs (Plate IIIa). Although there are occasional boulders up to 1 ft. the majority of the fragments are below 1 in. in size. Lapilli of dark, vesicular olivine-basalt and light grey andesite are the commonest fragments. Because of marine erosion the beds have a superficial slumped appearance; the true dip is gentle towards the east. Vertical jointing is conspicuous. It is assumed that these tuff deposits represent the eroded eastern flank of a small volcano (Fig. 8) which is now obscured by thick scree deposits.

6. Crater Lake

Crater Lake is a deep water-filled crater approximately ¼ mile in diameter and lying to the north-north-west of Mount Kirkwood (Plate IIIb). Along the inner walls lavas and tuffs are intermittently exposed through thick scree and fluvio-glacial deposits. The dip of these volcanic rocks is away from the centre of the lake and it is assumed that the lake occupies the vent of an eroded volcanic cone.

The section in the south is especially interesting and merits detailed description (Fig. 10). A deep overflow channel cuts through the fluvio-glacial deposits and the underlying lavas and pyroclastic rocks. Occupying this channel is a thick black lava flow belonging to the Mount Kirkwood lavas (Whalers Bay Group) and this effectively dams the water in the lake.

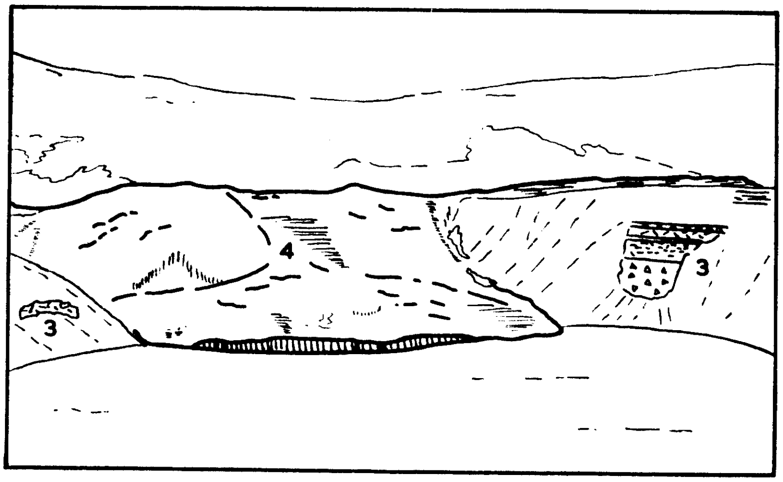

Figure 10

Sketch of the southern side of Crater Lake. Lavas of the Whalers Bay Group (4) occupy a deep stream valley and rest unconformably upon fluvio-glacial deposits and the volcanics of the Pendulum Cove Group (3).

The detailed section through the volcanic rocks of the Pendulum Cove Group on the south side of Crater Lake is given in Table III. There are further exposures on the northern and south-eastern sides of the lake. Minor radial faulting has also been recorded.

Table III

STRATIGRAPHICAL SUCCESSION SOUTH OF CRATER LAKE

7. Red block lava	25–80 ft.	**Whalers Bay Group**
～～～～～ *unconformity*		
6. Glacial and fluvio-glacial deposits	0–55 ft.	
～～～～～ *unconformity*		
5. Lapilli-tuff (B.213.4)	10 ft.	**Pendulum Cove Group**
～～～～～ *unconformity*		
4. Olivine-basalt (B.213.3)	12 ft.	
3. Tuff	3 ft.	
2. Olivine-basalt (B.213.2)	25 ft.	
1. Agglomerate	60 ft.	

Petrography. Lava flows are subordinate to pyroclastic rocks in the volcanics associated with this vent and from their interstratification it appears that mild explosive phases alternated with the quiet extrusion of fluid basaltic lava.

The lowest member on the south side of the lake is a massive yellow agglomerate with strong vertical east-north-east and north-north-west jointing, containing coarse (3 ft. in diameter) angular boulders of andesite, red vesicular lava and agglomerate. Graded and false-bedding on a large scale are present.

The succeeding 25 ft. massive flow is a banded olivine-basalt lava. In the hand specimen (B.213.2) it is a hard, compact, grey aphanitic rock possessing a marked fluidal texture. It is mainly composed of labradorite ($Ab_{48}An_{52}$) microlites with intergranular subcalcic and pigeonitic augite ($2V\gamma < 15°$), olivine and anhedral iron ore. The lava is very fresh, although the olivine shows incipient alteration to a reddish brown mineral.

A thin bed of yellow tuff separates this flow from B.213.3, which is a grey finely vesicular olivine-basalt containing sparse microphenocrysts of labradorite and augite in a matrix of labradorite microlites, augite granules and iron ore. Olivine is only a minor constituent of this rock, while the fluidal texture is not so pronounced as that in the underlying olivine-basalt flow. A chemical analysis of this lava is given in Table VII.

The highest member of the succession is a grey thinly-bedded lapilli-tuff, which rests unconformably upon the olivine-basalt. The tuff is well graded and composed of sub-rounded lapilli (0·2 in. in diameter) of black vesicular basalt. A similar tuff, exposed east of the lake, may have been derived from the vent ½ mile east of Crater Lake.

On the north side of the lake at crater level is a 10 ft. dark, porphyritic olivine-basalt flow (B.189.1). It is composed of sparse, heavily zoned phenocrysts of labradorite ($Ab_{22}An_{78} - Ab_{42}An_{58}$) and microphenocrysts of olivine in a groundmass of labradorite microlites, pyroxene granules, olivine, iron ore and interstitial dark brown glass. Because of the excessive amount of the glassy phase more olivine is preserved than in B.213.3; it occurs as small euhedral crystals often containing cores of brown glass.

An olivine-basalt (B.214.1), identical to and possibly the same flow as B.213.3, occurs in the south-east. Measurements on the labradorite phenocrysts showed normal discontinuous zoning ranging from $Ab_{20}An_{80}$ to $Ab_{43}An_{57}$.

7. Crater ½ Mile East of Crater Lake

This deep crater has a roughly oblong shape and both lava flows and pyroclastic rocks are intermittently exposed on its inner slopes. On the north side the following succession occurs at an altitude of 100 ft.:

3. Thin-bedded yellow agglomerate	8 ft.
2. Dark grey andesine-basalt	15 ft.
1. Thin-bedded agglomerate	20 ft.

To the south some 200 ft. of coarse yellow agglomerate are faulted against a similar thickness of flow lavas. Both the lavas and agglomerates are unconformably overlain by scoriaceous basalts of the Whalers Bay Group, which are unaffected by the fault.

Petrography. The lavas of this eruptive centre are andesine-basalts which are similar in composition and texture to those of Crater Lake. Typically dense or very fine-grained intergranular lavas, they are composed of andesine microlites, pyroxene granules, iron ore and small olivine prisms. Microphenocrysts of labradorite and diopsidic augite occur but these are rare.

The agglomerates on the southern side of the crater contain coarse boulders up to 5 ft. in diameter and show false-bedding on a large scale. The agglomerate fragments include boulders of diorite which are also abundant in the scree surrounding the crater. Olsacher (1956) has given a detailed description of a diorite block from this locality and has suggested that it is a glacial erratic probably from Graham Land, but an abundance of these dioritic blocks in the agglomerates renders this suggestion most unlikely. Several thin flows of a black highly vesicular basalt are interbedded with the agglomerates.

8. Pendulum Cove

Relict Lake, which is at the southern end of a deep crater south of Pendulum Cove, was part of a shallow lagoon connected to Port Foster little over a century ago (Kendall, 1831). The western slope of the crater is formed by Crimson Hill and near sea-level there are outcrops of grey lapilli-tuffs, identical to the tuffs associated with the other Pendulum Cove Group cones. To the south a prominent spur trends westwards from the ice slopes of Mount Pond and here a two-fold succession comprises:

2. Lava flows
1. Massive agglomerates.

The andesine-basalt lavas are similar in composition and texture to those of the crater ½ mile east of Crater Lake (see above), and they are regarded as being derived from a small cone which occupied the depression near Relict Lake (Fig. 8).

In addition to the lavas and pyroclastic rocks in the vicinity of the eight craters described above, there are scattered exposures of thin-bedded lapilli-tuffs at various localities. It is difficult to relate these outcrops to individual centres but it is reasonable to assign them to the Pendulum Cove Group. They probably represent the remnants of a tuff deposit which blanketed the island at the end of the third explosive volcanic phase.

VI. THE WHALERS BAY GROUP

THE lavas of the Whalers Bay Group constitute the latest volcanic phase in the history of Deception Island. They have a widespread distribution and at various localities rest unconformably upon moraine and each of the earlier volcanic groups. The age of these lavas is uncertain but they all appear to be very recent and it is probable that the closing eruptions occurred in historic times. The Mount Kirkwood lavas are fresh scoriaceous block lavas which occupy pre-existing stream valleys in the moraine. They are for the most part devoid of any morainic or scree cover and appear to represent the latest flows on the island. These observations coincide with Smiley's report (Wilkes, 1844, p. 149) that in 1842 "the whole south side of Deception Island appeared as if on fire." A tentative stratigraphical succession based on the relationship of the Whalers Bay Group to glacial deposits is given in Table IV. The earliest lava flows are intercalated with glacial deposits, while later flows rest on top of moraines and fluvio-glacial deposits.

The eruptive centres, many of which can be seen today, are located along arcuate lines of weakness parallel to the caldera rim (Fig. 12). The lavas of the Whalers Bay Group occur in the following well-defined areas:

1. Stonethrow Ridge
2. Telefon Ridge
3. Kroner Lake
4. Kendall Terrace
5. Mount Kirkwood.

All the lavas are basaltic and can be genetically subdivided according to the type of vent:

a. *Fissure eruptions*
Kroner Lake lavas
Kendall Terrace lavas

b. *Scoria eruptions*
Stonethrow Ridge lavas
Telefon Ridge lavas
Mount Kirkwood lavas.

The fissure lavas are black, coarsely vesicular, often glassy olivine-basalts. The flows are thin but of comparatively wide extent. Those associated with scoria mounds are finely vesicular block lavas which contain volcanic bombs and are characterized by a red strongly oxidized upper surface.

TABLE IV

TENTATIVE STRATIGRAPHICAL SUCCESSION OF THE WHALERS BAY GROUP

	Relation to Glacial Deposits
Mount Kirkwood lavas	Rest upon moraines and fluvio-glacial deposits. Occupy pre-existing melt stream valleys in the moraine. No moraine or extensive scree deposits overlie the lavas.
Kroner Lake and Kendall Terrace lavas	Early flows alternate with fluvio-glacial deposits; later flows rest upon fluvio-glacial deposits. No moraine or extensive scree deposits overlie the later lavas.
Stonethrow Ridge and Telefon Ridge lavas	Overlain by appreciable amounts of moraine or ice. Rest upon moraine or unconformably upon earlier volcanic groups.

1. Stonethrow Ridge

Lavas of the Whalers Bay Group are widely distributed on the slopes of Stonethrow Ridge. The eruptive centres are concealed by the ice but it is probable that the flows were extruded from small cones or scoria mounds aligned along the mountain ridge. Basic lavas, including olivine-basalts, basalts and basic andesites constitute the series, and individual flows are usually highly scoriaceous, red block lavas. The dip of the lavas closely follows the original topography; in the west they dip gently down the outer slope towards the sea, while in the east they dip steeply down the scarp face of the caldera wall. At all localities the basal members rest with pronounced unconformity upon the underlying rocks. It is difficult to estimate the thickness of this lava succession but in the extreme south of the ridge it probably exceeds 250 ft.

a. *The western slopes*

On the northern half of Stonethrow Ridge andesitic lavas extend from the summit of the ridge westward to the sea cliffs. The flows are a jumbled mass of vesicular lava blocks, with twisted and corded forms, and volcanic bombs. In the cliff section on the outer coastline some 40 ft. of flow lavas rest unconformably upon the Outer Coast Tuff. A typical specimen (B.132.1) taken from a block lava at a height of 740 ft. is a highly vesicular basic andesite. Microphenocrysts of labradorite ($Ab_{38}An_{62}$) and diopsidic augite (pleochroic in pale green and yellow-green, and showing hour-glass structure) are set in a dense matrix of andesine microlites ($Ab_{52}An_{48}$), intergranular pyroxene and iron ore, with some interstitial glass.

At the north-western end of Stonethrow Ridge lava flows form 30 ft. crags of red autobrecciated basalt with well-developed north—south joint planes. In thin section the lava (B.130.1) is highly vesicular with microphenocrysts of labradorite set in a very dense matrix of labradorite microlites, pyroxene, iron ore and interstitial dark brown glass. A minor amount of clino-pyroxene, now largely pseudomorphed by a red iron-rich mineral, accompanies the felspar microphenocrysts. Red iron-rich minerals are abundantly scattered throughout the matrix.

A lava flow some 150 ft. higher than B.130 is very similar but shows no autobrecciation and much less oxidization. In this lava plagioclase phenocrysts show zoning with a compositional variation from $Ab_{34}An_{66}$ to $An_{49}An_{51}$.

b. *The eastern slopes*

The flows on the eastern side of Stonethrow Ridge obscure the caldera wall and overstep both the Fumarole Bay Volcanics and the Outer Coast Tuff. They dip steeply towards Port Foster and individual flows overlap one another, giving a "roof tile" effect, almost to sea-level. Two specimens from a hard grey flow at 150 ft. are olivine-basalts containing phenocrysts of labradorite and microphenocrysts of olivine ($2V\alpha \leq 90°$) set in a fine-grained matrix of labradorite microlites ($Ab_{40}An_{60}$), olivine and pyroxene granules with anhedral iron ore. The plagioclase phenocrysts are strongly zoned showing both normal discontinuous and oscillatory zoning. Three crystals gave the following compositional ranges:

Core	*Rim*
An_{60}	An_{46}
An_{70}	An_{53}
An_{76}—An_{57}—An_{76}—An_{57} (oscillatory zoning)	

c. *The southern exposures*

At the extreme southern end of Stonethrow Ridge red scoriaceous basalts and andesites rest with pronounced unconformity upon the Outer Coast Tuff. Specimen B.202.1 is a highly vesicular basic andesite composed of microphenocrysts of labradorite and diopsidic augite in a dense matrix of basic andesine, iron ore and pyroxene granules. The clino-pyroxene microphenocrysts are pale yellowish green and show "hour-glass" structure. In the matrix some microlites with straight extinction and high birefringence probably represent olivine. Mixed glomeroporphyritic clusters of pyroxene and plagioclase are common.

2. Telefon Ridge

The Telefon Ridge lavas were extruded from a small scoria mound north of Telefon Bay. The flows dip steeply down the fault scarp and overlap the higher members of the Telefon Bay Volcanics. To the west of the cone at 300 ft. is an arcuate line of small scoria mounds which erupted a highly vesicular red cindery basalt.

The lavas associated with this cone are olivine-basalts, grey and fine-grained but highly vesicular and oxidized near the upper surfaces. They are composed of occasional phenocrysts of zoned labradorite and microphenocrysts of olivine set in a matrix of orientated labradorite microlites with intergranular olivine, pyroxene and magnetite. The olivine is partially pseudomorphed by a red anisotropic mineral, which is strongly pleochroic in clear cherry red and opaque cherry red. Parts of the matrix are often cryptocrystalline while in the upper parts of a flow haematite is abundant.

3. Kroner Lake

Immediately north-west of Whalers Bay is a low even plain formed by a thin lava flow resting on fluvio-glacial deposits. The low sea cliff 400 yd. west of the Falkland Islands Dependencies Survey station shows the following succession:

3. Dark highly vesicular olivine-basalt	5 in.
2. Stratified fluvio-glacial deposits	5 ft. 4 in.
1. "Cinder bed"	10 in.

The "cinder bed" is only intermittently exposed and consists of black, highly vesicular lava cinders, which may represent a frost-shattered flow or even a fluvio-glacial deposit. Holtedahl (1929) considers that the upper flow is a pillow lava, the individual pillows having a concentric structure with a fine-grained or glassy skin surrounding a highly vesicular core. It should be noted, however, that this is not a typical pillow lava, because the pillows are isolated and are rarely seen in contact with one another. It seems possible that these are lava blisters formed by the escape of gasses.

The lava is an olivine-basalt composed of labradorite microlites, small zoned crystals of diopsidic augite and cored olivine prisms (p. 11) in a matrix of abundant dark brown glass so densely charged with iron ore as to be almost opaque.

In the east the lava plain ends abruptly at the foot of Ronald Hill which is a fault scarp (p. 22). No source for the lava is visible but it is reasonable to assume that it erupted from along the fault plane.

Several more or less circular depressions occur on the plain, the largest being Kroner Lake with a diameter of about ¼ mile. A rough sounding traverse of this lake showed a maximum recorded depth of 36 ft. and indicated a steeply shelving northern shore. The most southerly depression is a very small circular dry hole apparently formed during this century (Holtedahl, 1929).

4. Kendall Terrace

The remarkable platform of Kendall Terrace is mantled in many places by fluvio-glacial deposits, which are intercalated with and overlain by thin olivine-basalt flows west of Telefon Bay (Plate IIIc). They dip gently towards the west and were erupted from low mounds aligned along an arcuate fissure. The mounds occur at 400 ft. and are of small dimension, never exceeding 30 ft. in height (Plate IIId).

Olsacher (1956) has recorded lava flows alternating with fluvio-glacial deposits and gives the following succession:

5. Basalt	2 m.
4. Fluvio-glacial deposits	1 m.
3. Basalt	4 m.
2. Fluvio-glacial deposits	5 m.
1. Massive agglomerate	20 m.

The maximum thickness of lava observed during the present investigation was 40 ft., resting unconformably upon the Outer Coast Tuff and exposed in the outer sea cliffs north-west of Telefon Bay.

These black, coarsely vesicular flow lavas are composed of labradorite laths ($Ab_{35}An_{65}$), olivine and diopsidic augite prisms in a dark brown glass matrix densely charged with iron ores. Cored crystals of olivine are common, while the clino-pyroxene is often zoned. The Kendall Terrace lavas are petrographically similar to those of Kroner Lake and both were probably characterized by the quiet extrusion of fluid lava.

5. Mount Kirkwood

These lavas were erupted from scoria mounds aligned along the northern flank of Mount Kirkwood, and individual flows rest upon fluvio-glacial deposits and follow very closely the topography of the country immediately prior to eruption. Many of the eruptive centres are still intact and the lowest scoria mound occurs at a height of 600 ft. The flows dip steeply to the north but at the foot of the mountain scarp they rest nearly horizontally upon a 300 ft. terrace of fluvio-glacial deposits; at Crater Lake a thick flow dams the water of the lake (Fig. 10). Both here and at the crater ½ mile east of Crater Lake they rest with pronounced unconformity upon the volcanics of the Pendulum Cove Group.

The flows have a fresh appearance, are unaffected by frost-shattering and have no covering of moraine or scree. There is little doubt that they represent some of the latest eruptions on the island. Typically block lavas, they have a rough scoriaceous and oxidized surface upon which rest many fine specimens of volcanic bombs.

Petrographically they are highly vesicular olivine-basalts composed of sparse labradorite and diopsidic augite microphenocrysts in a dense intergranular matrix of labradorite microlites, augite, olivine and iron ore. Cryptocrystalline and vitreous varieties are also represented.

VII. THE FUMAROLES

The fumaroles of Deception Island have been repeatedly mentioned in the literature, and from the early accounts (Kendall, 1831; Wilkes, 1844) it is apparent that fumarolic activity was far greater during the last century than it is today. During the present investigation steam was seen rising on the beaches, especially during low tides, at four main localities:

1. Whalers Bay
2. Fumarole Bay
3. Telefon Bay
4. Pendulum Cove.

There are no localized vents at any of these localities but large areas of the shore are warm; Holtedahl (1929, p. 40), has doubted whether true fumaroles are present, suggesting that the steam "... is the sea water [present in the sand] which heated from below gives off some of its vapours." Much of the steam is undoubtedly cognate water heated from below, but the sulphurous odour and the precipitation of aragonite in Fumarole Bay indicate that at least part of the steam is juvenile in origin. Olsacher (1956) has proposed a broad classification of the fumaroles into sulphurous and non-sulphurous groups, but this appears unsatisfactory because at some localities the steam may be sulphurous on some days and odourless on others.

Tidal observations, and measurements of the temperature and height of the water table in an artificial well on the shore of Whalers Bay show a very close relationship between tide and temperature (Fig. 11).* Although the steam from the fumaroles is more apparent at low tide, the highest temperatures rather unexpectedly occur during the highest tides or after periods of heavy precipitation. This suggests that the sudden incursion of cold water causes circulation in the ground water, resulting in hot water rising from below. The mean temperature recorded over a period of 30 days at Whalers Bay was 113.5°F, the temperature fluctuating from 100°F to 151°F. At Fumarole Bay water bubbling through cracks in an agglomerate reef exposed during low tides was at boiling point when visited on several occasions.

All the fumaroles are located near the rim of the caldera, those of Telefon and Fumarole Bays occurring where the inner volcanic zone is absent and where the caldera wall rises sharply from the basin. 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.

* Mr. K. V. Gibson kindly recorded the data given in Fig. 11 over a period of 30 days.

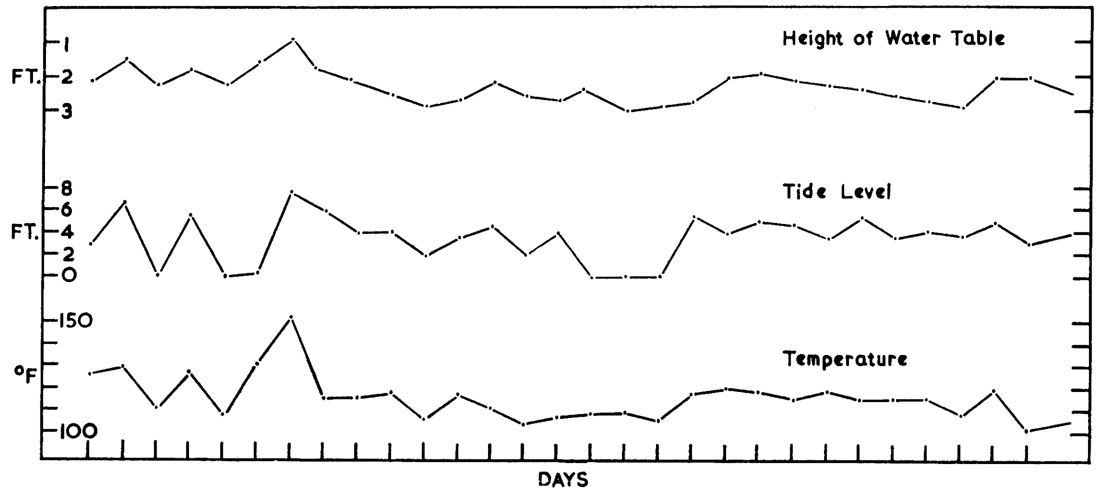

FIGURE 11

Graphs showing the relationship of the temperature of the Whalers Bay fumaroles to tide level and height of water table.

VIII. STRUCTURAL GEOLOGY

1. Regional Setting

Herdman (1932) has shown that all the islands of the South Shetland Islands are united by a submarine platform at a depth of 250 m. On the north-western side this platform is broad but in the south-east it descends abruptly to the depression of the Bransfield Strait. Deception Island lies to the south of the main group and separates a small depression of 1,371 m. south of Snow Island from the main strait, which has a maximum depth of over 2,000 m. south of King George Island.

The main structural trends of King George Island (Hawkes, 1960), and by analogy those of the other islands, are roughly north-east to south-west parallel to the geographic trend of the South Shetland Islands. Each island is separated from its neighbour by shallow straits which trend north-west to south-east, and which are probably controlled by faults.

During the Tertiary the South Shetland Islands formed a volcanic island arc convex towards the Pacific Ocean. At the present time there is evidence of a 5 km. trench north of the arc, which is associated with minor seismicity. The caldera of Deception Island lies on the concave side of this arc.

2. Structure according to Holtedahl (1929)

Early theories regarded the basin of Port Foster as a single crater which had been breached in the south-east and flooded by the sea (Andersson, 1906).

Holtedahl (1929) has observed quite correctly that this basin is too large to be a normal explosion crater, and he has reasoned that Deception Island is a caldera resulting from the subsidence of an original volcano along a circular fault or series of faults. In support of a main caldera fault along the inner foot of the mountain ring he has stated (p. 35) that:

> ". . . outcrops of lava belonging to the older series are seen both on the north and south side of the basin at or near sea-level, while the tuff mass rises several hundreds of meters in the ring mountain and from what has been observed the original place of this lava is on top of the tuff. The coast section on the south side of the entrance directly indicates the existence of a dislocation between the lava to the north and the tuff to the south. Unfortunately I had no opportunity of studying this critical section in detail."

It is apparent from Holtedahl's paper that his Older Volcanic Series is pre-caldera in age and is assumed to be derived from the original volcano of Deception Island. It has been shown that many of the lavas of the Older Volcanic Series (e.g., Ronald Hill and Entrance Point) were not extruded from an original cone but from a number of smaller vents of post-caldera age. The presence of these lavas at sea-level is the result of primary deposition and not of faulting.

The coast section south of Neptunes Bellows has been re-examined in detail (p. 14) and it is now clear that the agglomerate (tuff of Holtedahl) is a volcanic neck with the lavas to the north dipping away from it. No tangential fault is necessary to explain the relative distribution of the lava and agglomerate.

3. Structure according to Olsacher (1956)

Olsacher has presented little additional information and has mainly repeated the evidence of Holtedahl. However, in support of a ring fault he cites the cliff section at the extreme western end of Mount Kirkwood (Vapour Col). This critical section is one of the finest exposures on the island. It is described on p. 16 but the relevant structural details are repeated here.

At the north-eastern end of the main cliffs the succession comprises:

2. Stratified tuffs
1. Massive agglomerates.

To the south-west the massive agglomerates are terminated abruptly (Fig. 7) and are overlain and flanked by the stratified tuffs which dip at 35° to the west-north-west. Olsacher has placed a fault at the western end of the massive agglomerate. The exposure is difficult of access but by careful examination it has been possible to trace the south-westward continuity of certain horizons in the stratified tuffs above the massive agglomerates, thus demonstrating that no fault exists.

The massive agglomerates represent another volcanic vent and measurements in the surrounding exposures indicate a dip away from this vent. A short distance to the north are further exposures of stratified tuffs which are separated from the main cliffs by a col. Olsacher has placed the hypothetical ring fault along this col with a downthrow to the north. If the concept of a volcanic vent is to be accepted, and all the available evidence indicates that it should be, then no fault need be postulated, because the northern stratified tuffs show a normal angle of repose away from the eruption centre.

4. Present Interpretation

Deception Island is a caldera formed by the subsidence of a group of overlapping cones along arcuate and radial faults. The greater part of the original cones subsided beneath the sea, but the characteristic shape of the island was preserved by the formation of a post-caldera volcanic ring mountain. The arcuate faults delimiting the original caldera were obscured by this post-caldera vulcanicity.

The evidence cited both by Holtedahl and Olsacher in support of a circular fault or series of faults is incorrect (pp. 29–30). However, evidence of a different nature unmistakably indicates the existence of major arcuate and radial faults, which form the boundary of the caldera.

a. *Arcuate faulting*

The location of the four vents of the Port Foster Group is not haphazard; they lie close to the circumference of a circle. It is difficult to avoid the conclusion that these early volcanoes were related to a fundamental ring fracture in the underlying basement.

Wherever the caldera wall is preserved it forms a slope which rises steeply from the basin or inner volcanic zone. The simple outline and undissected form of the inner face strongly suggests it is a fault scarp and north-west of Telefon Bay there is indeed some evidence of arcuate step-faulting (p. 9).

Along most of the southern and eastern inner slopes of Deception Island the caldera wall is absent or obscured by snow and ice, but the presence of underlying arcuate faulting is clearly expressed by the curvilinear arrangement of the post-caldera volcanoes (Fig. 12). The vents of the Neptunes Bellows Group lie on an arcuate line which is essentially the eastern continuation of the caldera wall, and this (which may be called the outer caldera fault zone) forms the caldera boundary.

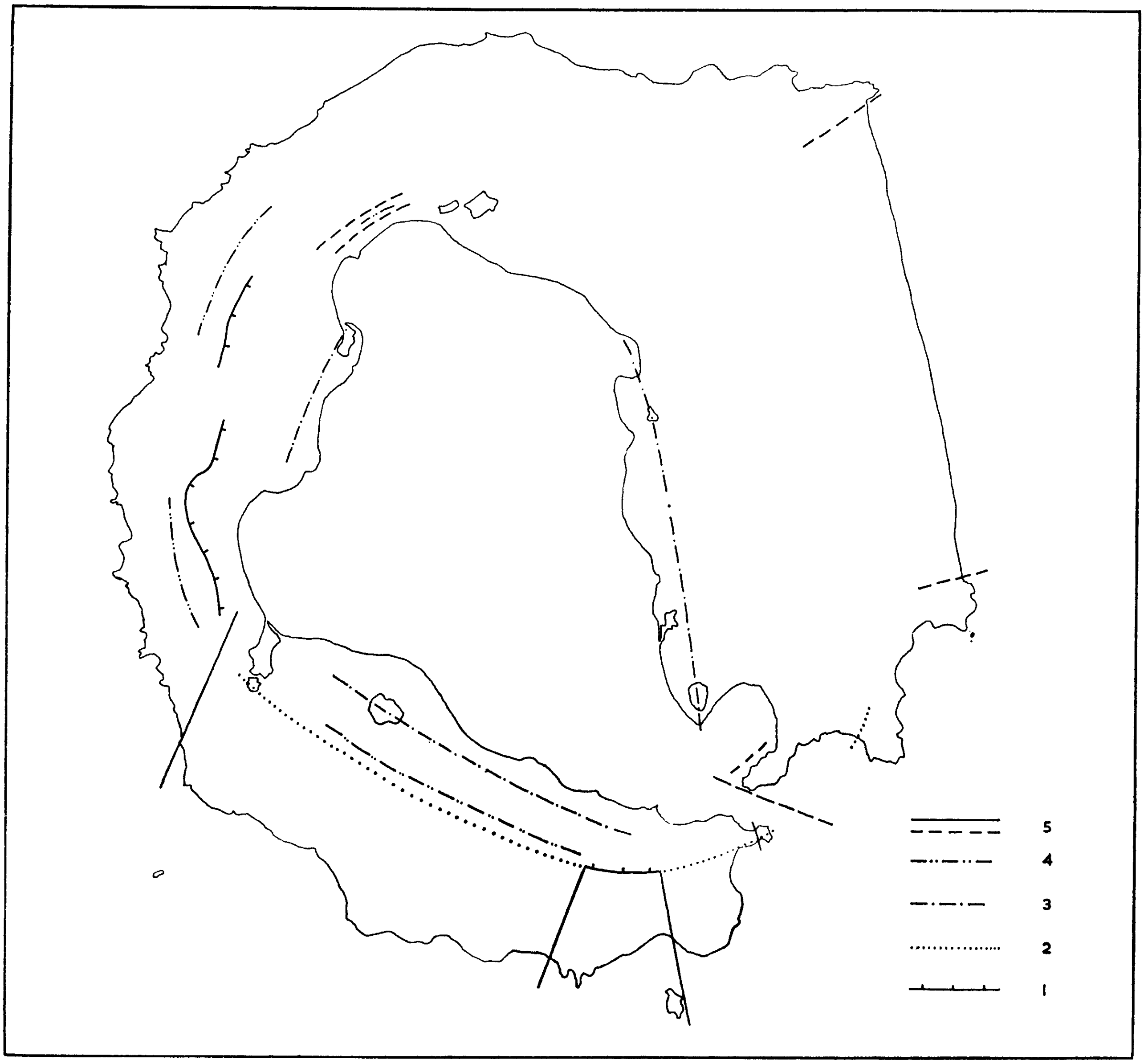

FIGURE 12

The structural geology of Deception Island. 1. Caldera wall; 2. Line joining the vents of the Neptunes Bellows Group; 3. Line joining the vents of the Pendulum Cove Group; 4. Line joining the vents of the Whalers Bay Group; 5. Faults.

The volcanoes of the Pendulum Cove Group forming the inner volcanic zone also lie on arcuate lines which are concentric to the outer caldera fault.

Furthermore, all the scoria mounds of the Whalers Bay Group are located on arcuate lines. There can be no doubt that the Deception Island caldera is the result of subsidence about a series of circular or arcuate faults.

b. *Radial faulting*

Radial faulting is closely related to the collapse and engulfment of the four volcanoes of the Port Foster Group. The earliest movements apparently occurred after the formation of the Telefon Bay volcano, the cone of which had probably partially collapsed before the growth of the Fumarole Bay volcano. The main period of radial and arcuate faulting took place after the deposition of the Outer Coast Tuff. The lavas and tuffs of the Post-caldera Series are unaffected by these radial faults, although the pattern of faulting which determined the caldera had a profound effect on the location of all the post-caldera volcanoes.

Vapour Col fault. A deep col breaks the continuity of the mountain ring in the south-west of the island. To the west of this col the outer coastline is formed by vertical cliffs of Outer Coast Tuff, whereas to the east there is a low rocky promontory of the Neptunes Bellows Group lavas. A fault with a downthrow to the east terminates the tuff here. This fault is of unknown magnitude but at present the downthrow side is below sea-level. The lavas and tuffs of the Vapour Col vent (Neptunes Bellows Group) are unaffected by this fault and presumably rest unconformably upon the downfaulted Outer Coast Tuff.

Collins Point faults. South-south-west of Collins Point cliffs of Outer Coast Tuff rise to 900 ft., while the same tuff is exposed in the cliffs of South Point. A short distance to the west and east of this fault block the tuff is terminated abruptly and on either side are low lava promontories (Neptunes Bellows Group).

Neptunes Bellows fault. The Cathedral Crags vent agglomerate forms the vertical cliffs at the entrance to Port Foster. The Port Foster Group is absent south of Neptunes Bellows and Cathedral Crags are bounded by an east–west fault, which probably also forms the submarine channel on their southern side.

Macaroni Point and Baily Head faults. A low col separating Goddard Hill from Mount Pond is probably the site of a major north-east/south-west fault or fault zone, which terminates the Outer Coast Tuff at Macaroni Point. There is probably another fault north of Baily Head.

c. *Mechanics of the caldera collapse*

The subsidence and subsequent engulfment of the major strato-volcanoes of the Port Foster Group implies the removal of support from below. It appears that there are two possible processes:

i. An "explosion-collapse" mechanism with the rapid emptying of the magma chamber by the eruption of the pumice-tuffs of the Outer Coast Tuff.
ii. The subterranean withdrawal of magma from the chamber.

The Outer Coast Tuff undoubtedly represents some degree of emptying of the magma chamber, but no quantitative data are yet available as to whether the volume of pumice-tuff alone represents a sufficient discharge of magma to provide the requisite volume for engulfment. The second process is hypothetical but Williams (1954) has considered that it is an important factor in the evolution of some calderas. Possibly, the answer is that both processes contributed to the formation of the Deception Island caldera.

IX. PETROGENESIS

THE Tertiary lavas of the South Shetland Islands form a calc-alkaline suite with an andesite-rhyolite association. The intermediate and acid lavas of Deception Island contain an unusually high soda content and represent a local alkaline deviation from the normal andesite-rhyolite association of the circum-Pacific areas.

Olivine-basalts, which occur in each of the four volcanic groups, are now known to be the commonest lavas on Deception Island. The lava associations and serial trends in each group are shown below:

4. Whalers Bay Group	Olivine-basalt → basalt → andesine-basalt
3. Pendulum Cove Group	Olivine-basalt → basalt → andesine-basalt → hypersthene-augite-andesite → oligoclase-andesite
2. Neptunes Bellows Group	Olivine-basalt → basalt → andesine-basalt
1. Port Foster Group	Olivine-basalt → basalt → andesine-basalt → andesite.

The essential minerals and textures of each lava type are summarized in Table V. Basaltic lavas are common to each of the four volcanic groups and, considering the Deception Island suite as a whole, two main trends are apparent:

hypersthene-augite-andesite → oligoclase-andesite (*Pendulum Cove Group*)
↗
Olivine-basalt → basalt → andesine-basalt
↘
andesite (*Port Foster Group*)

The andesites of the Port Foster Group contain only a monoclinic pyroxene, whereas the andesites of the Pendulum Cove Group contain both monoclinic and orthorhombic pyroxenes.

TABLE V

THE MINERALOGICAL COMPOSITIONS AND TEXTURES OF THE LAVAS OF DECEPTION ISLAND

	Occurrence	*Texture*	*Mineralogical Composition*
Olivine-basalt	All groups	Intergranular and fine-grained	Labradorite, olivine (Fa_{18-23}), pigeonitic and subcalcic augite, iron ores. Occasional microphenocrysts of labradorite and olivine.
Basalt	All groups	Intergranular and fine-grained	Labradorite, pigeonitic and subcalcic augite, iron ores; minor olivine. Occasional microphenocrysts of diopsidic augite.
Andesine-basalt	All groups	Intergranular and fine-grained	Andesine, pigeonitic and subcalcic augite, iron ores; minor olivine. Occasional microphenocrysts of labradorite and diopsidic augite.
Andesite	Port Foster Group	Porphyritic with fine-grained intergranular matrix	*Phenocrysts:* labradorite and diopsidic augite. *Matrix:* andesine, augite and iron ores.
Hypersthene-augite-andesite	Pendulum Cove Group	Porphyritic with fine-grained intergranular or glassy matrix	*Phenocrysts:* labradorite or andesine, diopsidic augite and hypersthene (Fs_{38-41}). *Matrix:* andesine, augite and iron ores. Often glassy.
Oligoclase-andesite	Pendulum Cove Group	Porphyritic with fine-grained intergranular matrix. Often flow-banded	*Phenocrysts:* andesine or oligoclase, fayalitic olivine (Fa_{47-84}) and hypersthene (Fs_{41-48}). *Matrix:* oligoclase or albite-oligoclase, alkali-felspar and tridymite.

a. *Sequence of crystallization*

The sequence of crystallization of the principal mineral phases is shown in Fig. 13. Of particular significance is the occurrence of olivine as a primary phase in the olivine-basalts, its total absence in the hypersthene-augite-andesites and its reappearance as a distinctly iron-rich phase in the oligoclase-andesites. Its absence in the hypersthene-augite-andesites does not imply a break in the olivine solid solution series; the crystallization behaviour is strictly analogous to that of certain melts in the system $MgO–FeO–SiO_2$ (Bowen and Schairer, 1935), which have crystallized under conditions of strong fractionation.

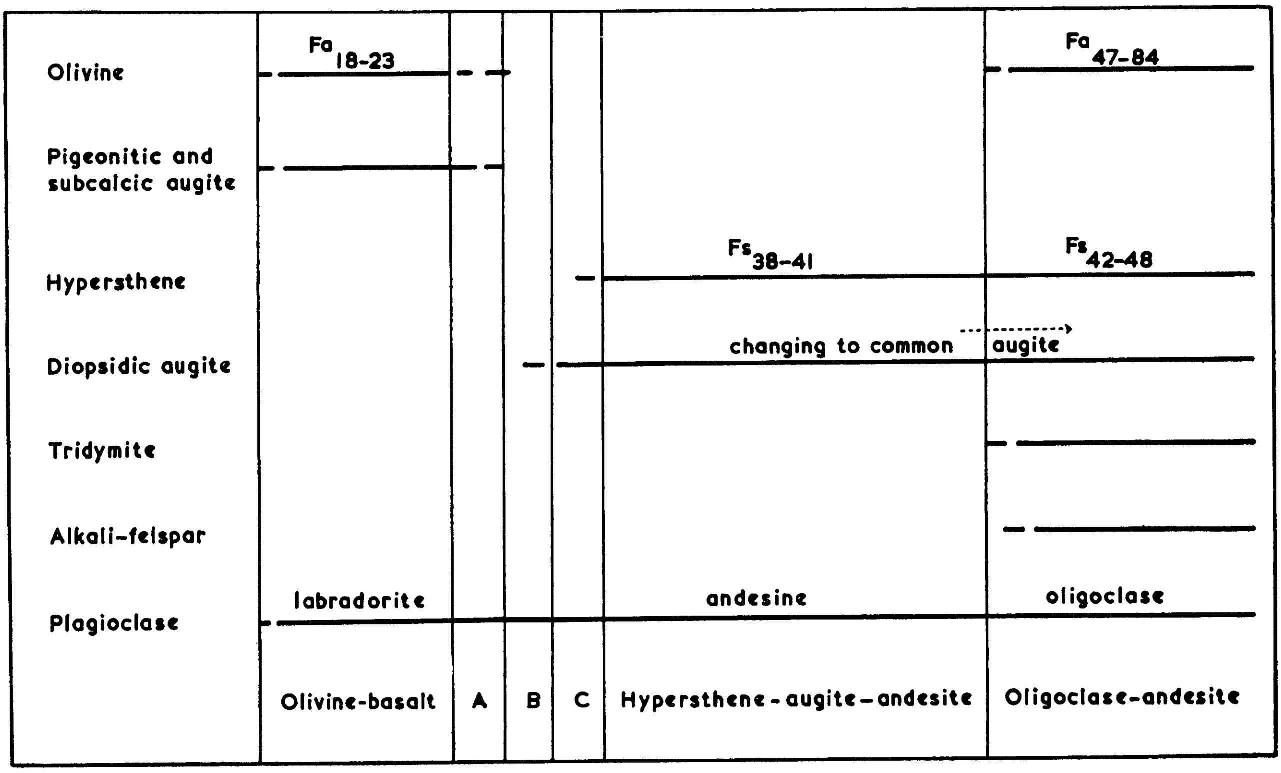

FIGURE 13

Diagram illustrating the sequence of crystallization in the Deception Island lavas. A. Basalt; B. Andesine-basalt; C. Andesite.

Barth and Holmsen (1939) have noted this analogy but their description is incomplete and confined only to the later stages of the trend in the Deception Island suite. It is of interest to note that there is some similarity between the crystallization sequence of the Deception Island lavas and that observed in the Skaergaard intrusion (Wager and Deer, 1939), although in Deception Island the magmatic trend is towards absolute alkali enrichment.

In the artificial system MgO–FeO–SiO_2 some liquids (Bowen and Schairer, 1935, pp. 209–10) crystallize under conditions of strong fractionation (very limited reaction between crystals and liquid) to give the following mineral phases:

1. Magnesia-rich olivine
2. Clino-pyroxene
3. Clino-pyroxene and tridymite
4. Iron-rich olivine and tridymite.

The complete sequence of fractionation is shown by the lavas of Deception Island.

Olivine. In the olivine-basalts the olivine is chrysolite with a composition ranging from $Fo_{82}Fa_{18}$ to $Fo_{77}Fa_{23}$. Olivine is absent in the hypersthene-augite-andesites but reappears in the oligoclase-andesites as a distinctly iron-rich variety with a composition between $Fo_{53}Fa_{47}$ and $Fo_{40}Fa_{60}$. In the later differentiates it is even richer in iron and in the acid oligoclase-andesites it has a composition ranging from $Fo_{40}Fa_{60}$ to $Fo_{16}Fa_{84}$* (Table VI).

The early-formed magnesian olivine usually occurs as small subhedral crystals and only rarely as phenocrysts. In the acid lavas, fayalitic olivine commonly forms large subhedral or euhedral phenocrysts, but there is textural evidence to suggest that these crystals were not formed in the intratelluric stage. Small prisms of fayalitic olivine also occur in veins associated with tridymite.

* The extreme value measured by Dr. R. J. Adie (personal communication).

TABLE VI

OPTICAL DATA FOR OLIVINES AND HYPERSTHENES

	Olivine	*Hypersthene*
Olivine-basalt (B.219.1)	$\beta = 1{\cdot}689$ ($Fo_{82}Fa_{18}$)	*not present*
Olivine-basalt (B.144.1)	$\beta = 1{\cdot}696$ ($Fo_{79}Fa_{21}$)	*not present*
Olivine-basalt (B.119.2)	$\beta = 1{\cdot}699$ ($Fo_{67}Fa_{33}$)	*not present*
Hypersthene-augite-andesite (B.125.4)	*not present*	$\alpha = 1{\cdot}702$ $\gamma = 1{\cdot}715$ $\gamma\text{-}\alpha = 0{\cdot}013$ ($En_{62}Fs_{38}$)
Hypersthene-augite-andesite (B.124.4)	*not present*	$\alpha = 1{\cdot}702$ $\gamma = 1{\cdot}717$ $\gamma\text{-}\alpha = 0{\cdot}015$ ($En_{59}Fs_{41}$)
Oligoclase-andesite (B.107.2)	$\beta = 1{\cdot}750$ ($Fo_{53}Fa_{47}$)	*not present*
Oligoclase-andesite (B.111.1)	$\beta = 1{\cdot}767$ ($Fo_{45}Fa_{55}$)	$\alpha = 1{\cdot}705$ $\gamma = 1{\cdot}718$ $\gamma\text{-}\alpha = 0{\cdot}013$ ($En_{59}Fs_{41}$)
Oligoclase-andesite (B.114.2)	$\beta = 1{\cdot}777$ ($Fo_{40}Fa_{60}$)	$\alpha = 1{\cdot}710$ $\gamma = 1{\cdot}725$ $\gamma\text{-}\alpha = 0{\cdot}015$ ($En_{52}Fs_{48}$)

Pyroxene. The early pyroxene crystallizing from an artificial melt is a member of the clino-enstatite – clino-hypersthene series (Bowen and Schairer, 1935), but pigeonite and subcalcic augite ($2V\gamma \simeq 45°$) are precipitated from the natural magma and occur in the olivine-basalts. There is no evidence as to which of these minerals crystallized first, but the pigeonite may represent the complete miscibility of the pyroxene constituents under effusive conditions.

In the andesites of the Pendulum Cove Group two pyroxene phases occur as phenocrysts of diopsidic augite and hypersthene. The presence of orthorhombic pyroxene ($En_{62}Fs_{38}$) indicates that the inversion temperature between orthorhombic and clino-pyroxene had been reached, and these two pyroxenes are probably the result of crystallization in the intratelluric stage. The groundmass pyroxene of the andesites appears to be augite.

As yet there are few data on the clino-pyroxenes in these lavas but preliminary refractive index measurements suggest some increase of iron in the diopsidic augite as fractionation proceeded. Some of the clino-pyroxene phenocrysts have a $2V\gamma = 60\text{–}66°$; these high values may in fact indicate the presence of soda in the mineral.

In many of the hypersthene-augite-andesites the early orthorhombic pyroxene reacted with magma and is enclosed by clino-pyroxene (Plate IVb) but for some reason this reaction was arrested and hypersthene continued to crystallize as an iron-rich variety. With continued fractionation the hypersthene became progressively enriched in iron with compositions ranging from $En_{62}Fs_{38}$ to $En_{52}Fs_{48}$ (Table VI).

Tridymite. Tridymite has crystallized alongside fayalitic olivine only in the oligoclase-andesites, where it occurs both interstitially and in veins and vesicles. Barth and Kvalheim (1944) have described christensenite, a tridymite with anomalously high refractive indices and have suggested that it may be regarded as "a mixed crystal of tridymite with 5 per cent nepheline in solid solution." Three samples of tridymite examined during the present investigation had the refractive indices of normal tridymite.

TABLE VII

NEW AND PREVIOUS CHEMICAL ANALYSES OF THE DECEPTION ISLAND SUITE

	8	B.163.1	B.103.3	6	B.213.3	7	5	4	B.111.4	3	2	1	
SiO_2	49·84	50·65	51·81	52·93	52·96	53·50	56·89	60·62	67·40	67·71	68·28	69·01	SiO_2
TiO_2	1·32	1·78	1·63	2·29	1·78	1·65	1·79	1·54	0·60	1·00	0·70	0·58	TiO_2
Al_2O_3	19·37	17·67	17·04	15·86	14·89	17·62	16·07	16·22	15·41	14·65	15·95	14·21	Al_2O_3
Fe_2O_3	3·42	2·50	2·16	2·01	6·33	2·58	1·81	1·76	1·16	1·59	2·00	2·23	Fe_2O_3
FeO	3·69	6·14	6·58	8·90	4·69	6·07	7·08	5·67	3·81	3·29	1·82	2·89	FeO
MnO	—	0·16	0·11	0·11	0·15	—	0·08	—	0·13	—	—	—	MnO
MgO	4·71	5·82	5·22	3·63	4·68	4·39	2·79	1·62	0·36	0·85	0·09	0·62	MgO
CaO	12·35	10·14	9·91	7·60	8·65	9·22	5·89	4·18	1·88	2·34	1·78	2·11	CaO
Na_2O	2·50	4·10	4·23	5·03	4·38	4·15	5·89	6·25	7·27	6·09	7·03	6·30	Na_2O
K_2O	0·87	0·52	0·55	0·64	0·60	0·75	0·94	1·20	1·99	1·99	1·75	2·07	K_2O
H_2O+	} 1·79	0·11	0·25	0·42	0·26	} 0·00	0·56	} 0·56	0·07	} 0·16	0·24	0·09 {	H_2O+
H_2O-		0·04	0·04	0·04	0·04		0·08		0·04				H_2O-
P_2O_5	0·11	0·30	0·29	0·35	0·34	0·36	0·21	0·24	0·21	0·16	0·07	0·12	P_2O_5
S	—	—	—	0·06	—	—	0·06	—	—	—	—	—	S
TOTAL	99·97	99·93	99·82	99·87	99·75	100·29	100·14	99·86	100·33	99·83	99·71	100·23	TOTAL
	ANALYSES LESS TOTAL WATER (Recalculated to 100)												
SiO_2	50·76	50·77	52·06	53·25	53·25	53·34	57·18	61·05	67·25	67·94	68·65	68·90	SiO_2
TiO_2	1·34	1·78	1·64	2·30	1·79	1·65	1·80	1·56	0·60	1·00	0·70	0·58	TiO_2
Al_2O_3	19·73	17·71	17·12	15·96	14·97	17·57	16·15	16·33	15·38	14·69	16·03	14·19	Al_2O_3
Fe_2O_3	3·48	2·51	2·17	2·02	6·37	2·57	1·82	1·77	1·16	1·60	2·01	2·23	Fe_2O_3
FeO	3·76	6·15	6·61	8·95	4·72	6·05	7·12	5·71	3·79	3·30	1·83	2·89	FeO
MnO	—	0·16	0·11	0·11	0·15	—	0·08	—	0·13	—	—	—	MnO
MgO	4·80	5·83	5·24	3·65	4·71	4·38	2·80	1·63	0·36	0·85	0·09	0·62	MgO
CaO	12·58	10·16	9·96	7·65	8·70	9·19	5·92	4·21	1·88	2·35	1·79	2·11	CaO
Na_2O	2·55	4·11	4·25	5·06	4·40	4·14	5·92	6·29	7·25	6·11	7·07	6·29	Na_2O
K_2O	0·89	0·52	0·55	0·64	0·60	0·75	0·94	1·21	1·99	2·00	1·76	2·07	K_2O
P_2O_5	0·11	0·30	0·29	0·35	0·34	0·36	0·21	0·24	0·21	0·16	0·07	0·12	P_2O_5
S	—	—	—	0·06	—	—	0·06	—	—	—	—	—	S

8. Doleritic basalt, Deception Island (Gourdon, 1914).

B.163.1. Olivine-basalt, Stonethrow Ridge, Deception Island. *Port Foster Group* (anal. D. D. Hawkes).

B.103.3. Olivine-basalt, near Collins Point, Deception Island. *Neptunes Bellows Group* (anal. D. D. Hawkes).

6. Andesine-basalt, Deception Island (Barth and Holmsen, 1939).

B.213.3. Olivine-basalt, Crater Lake, Deception Island. *Pendulum Cove Group* (anal. D. D. Hawkes).

7. Basalt ("labradorite"; Gourdon, 1914), Deception Island (Gourdon, 1914).

5. Hypersthene-augite-andesite ("bandaite"; Barth and Holmsen, 1939), Deception Island (Barth and Holmsen, 1939).

4. Andesite, Deception Island (Gourdon, 1914).

B.111.4. Oligoclase-andesite, promontory 1¼ miles west-north-west of Collins Point, Deception Island. *Pendulum Cove Group* (anal. D. D. Hawkes).

3. Oligoclase-andesite ("trachyandesite"; Gourdon, 1914), Deception Island (Gourdon, 1914).

2. Oligoclase-andesite ("tridymite-santorinite"; Barth and Holmsen, 1939), Deception Island (Barth and Holmsen, 1939).

1. Oligoclase-andesite ("trachyandesite"; Gourdon, 1914), Deception Island (Gourdon, 1914).

Analyses 1–8 are quoted from Tyrrell (1945)

b. *Variation diagrams*

Many of the characteristics of the Deception Island suite are fully displayed when the available chemical analyses (Table VII) are plotted on variation diagrams (Figs. 14 and 15). On the Harker diagram (Fig. 14) the smooth curves for each oxide demonstrate that all the lavas are genetically related. Referring to analysis No. 8, described by Gourdon (1914) as a doleritic basalt not found *in situ*, Tyrrell (1945, p. 60) has stated:

> "As its analysis agrees fairly closely with those of the Recent basalts of King George Island and Bridgeman Island, it is possible that the rock represents a fragment torn from a foundation of Recent basalts through which the Deception Island volcano, of quite different constitution, has burst. It will be so regarded in the present investigation."

Since it has been shown in this report that the commonest lavas on Deception Island are basaltic, it is now reasonable to assume that this doleritic basalt is in fact a basic member of the suite. The olivine-basalts of Deception Island are indeed comparable to those of Penguin Island (Hawkes, 1960) and Bridgeman Island, which points to a common parental magma for all the Recent volcanoes in the South Shetland Islands.

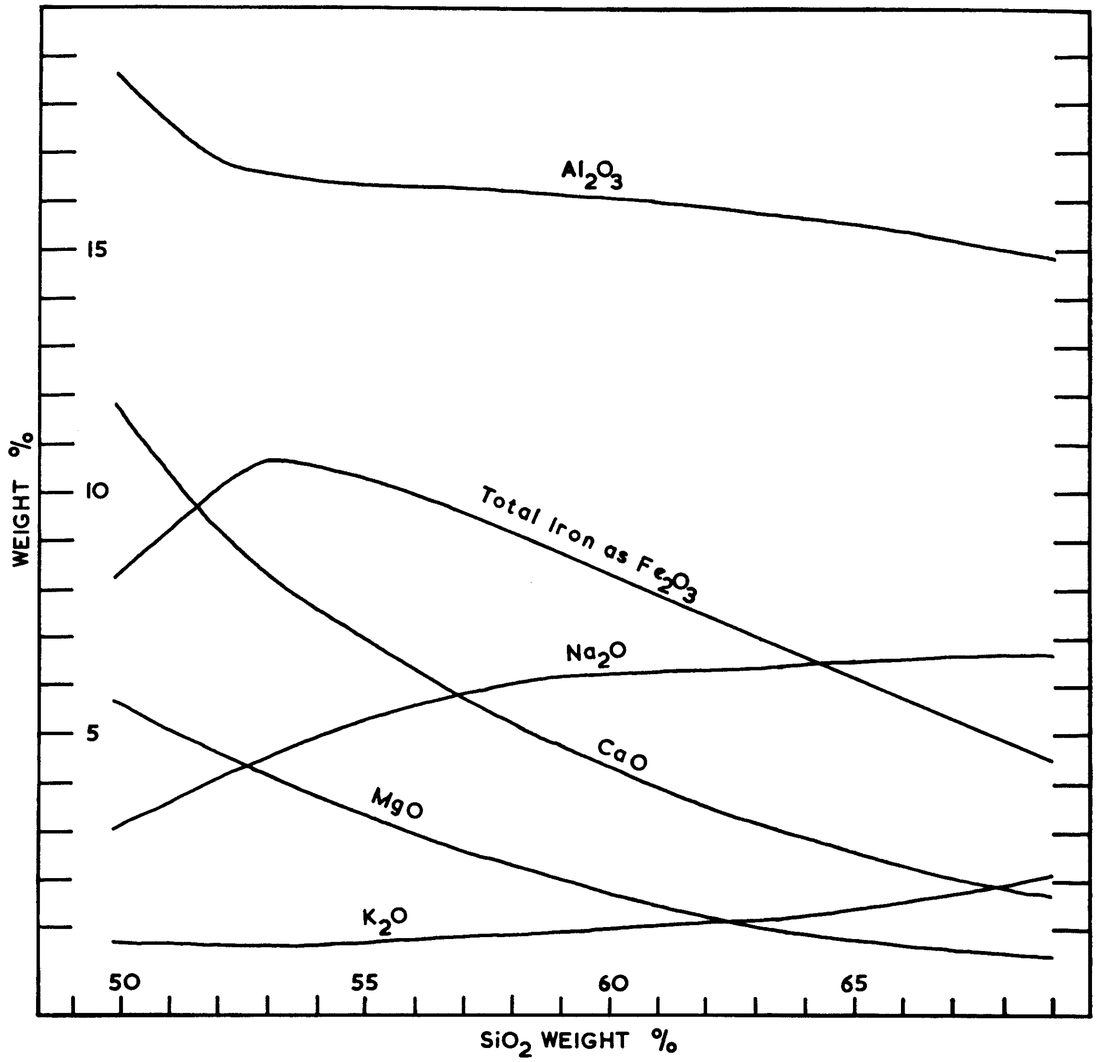

FIGURE 14

Harker variation diagram for the Deception Island lavas (see Table VII).

When plotted on a Harker variation diagram analysis No. 7 appears to be anomalous, but when the analysis is plotted on a diagram omitting silica (Fig. 15) it is clearly apparent that it is a true member of the suite. The discrepancy arises from the fact that the silica content is slightly too high, and it is very possible that the original lava contained secondary tridymite which is present in many lavas of the island.

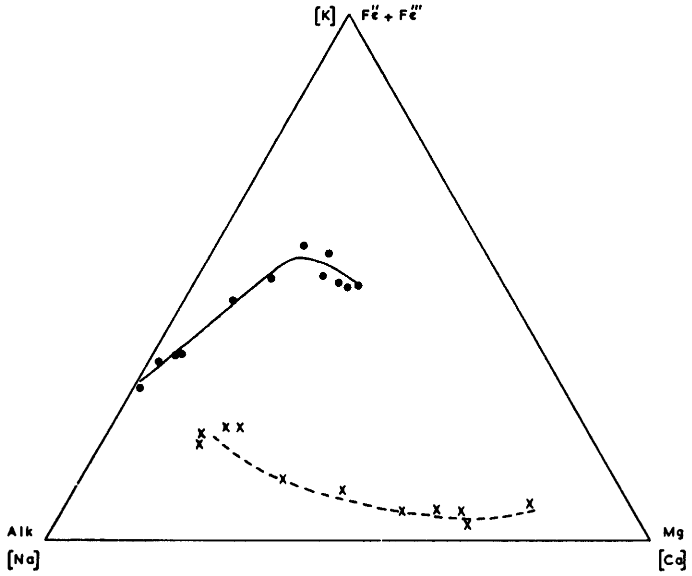

FIGURE 15

Triangular variation diagrams for the Deception Island lavas, plotted on the co-ordinates (Fe''+Fe''') – Alk – Mg and K – Na – Ca.

There is some correlation between the nature of the curves for the various oxides and the minerals actually observed in the lavas.

Lime and alumina. With increasing acidity lime decreases regularly throughout the series. The sharp drop in both lime and alumina at the basic end of the series corresponds to the early crystallization of basic plagioclase. The alumina content is unusually high and in this respect the basaltic lavas of Deception Island are similar to the basic rocks of the other islands in the South Shetland Islands group.

Magnesia and iron oxides. Magnesia decreases regularly with increasing acidity throughout the series, an early stage corresponding to the crystallization of magnesia-rich olivine. The curve for total iron shows a concentration of iron in the early period of crystallization then an abrupt decrease at about 52 per cent silica, correlated with the precipitation of hypersthene and later of fayalitic olivine in the andesitic lavas. Evidence for the early iron enrichment is afforded by the glass residuum densely charged with iron ores, which occurs in many of the basalts.

Soda and potash. The Na_2O:K_2O ratio increases rapidly at first but begins to fall at the acid end of the series. The unusually high soda content of all the lavas is the most striking feature of the Deception Island suite. The greater part of the soda is contained in the acid plagioclase, and the failure of sodic pyroxenes to crystallize is due to the high alumina content.

c. *Magmatic evolution*

Two trends are of interest: the enrichment in soda (and to a much lesser extent potash) resulting from the fractional crystallization of the plagioclase felspars, and the increase in the FeO:MgO ratio due to the fractional crystallization of the olivine and pyroxene series.

Bowen and Schairer (1938), who have investigated the system nepheline–albite–silica, have shown that in complex melts where both the above trends appear the net result would be an enrichment of the late differentiates in alkali-alumina silicates. The lavas of Deception Island support this conclusion but, although the net result is enrichment in alkalis, it is of interest to note that relative enrichment in iron occurs in the *early stages*. The two trends are clearly illustrated when the analyses are plotted on a triangular variation diagram with co-ordinates (Fe″ + Fe‴) – Alk(K + Na) – Mg and K – Na – Ca (Fig. 15).

d. *The parent magma*

Basalts are now known to be the commonest lavas on Deception Island and they occur in each of the four volcanic episodes. Because of their fine-grained or dense intergranular texture, they must closely approximate to the chemical composition of the parental magma. In Table VIII the parental magma composition, based on the mean of analyses Nos. 7, 8 and B.163.1, is given and compared with the compositions of other basaltic magma-types.

TABLE VIII

THE PARENT MAGMA OF DECEPTION ISLAND AND COMPARABLE ANALYSES

	A	B	C	D	E	F
SiO_2	50·9	50·73	49·4	50	50	45
TiO_2	1·7	1·30	0·9	1·3	—	—
Al_2O_3	18·2	18·06	18·3	18	13	15
Fe_2O_3	2·7	1·62	8·7 (Fe₂O₃ + FeO)	9 (Fe₂O₃ + FeO)	13 (Fe₂O₃ + FeO)	13 (Fe₂O₃ + FeO)
FeO	5·7	6·96				
MnO	0·1	0·40	—	—	—	—
MgO	5·3	7·61	8·2	5	5	8
CaO	10·9	9·71	10·4	10	10	9
Na_2O	3·6	2·70	2·7	2·5	2·8	2·5
K_2O	0·7	0·68	0·5	0·4	1·2	0·5
P_2O_5	0·2	0·23	—	—	—	—

A. Deception Island parent magma computed from the mean of analyses 7, 8 and B.163.1 (Table VII).
B. Basalt (recalculated water-free), Newberry volcano, Oregon (Williams, 1935).
C. Average of basalts from Modoc, California (Powers, 1932).
D. Porphyritic central type basalt, Mull (quoted from Powers, 1932).
E. Tholeiitic magma-type (Kennedy, 1933).
F. Olivine-basalt magma-type (Kennedy, 1933).

It is clearly impossible to compare the Deception Island magma closely with either the olivine-basalt or tholeiitic magma-types given by Kennedy (1933). High alumina, low titania and iron oxide, and very low potash contents are, however, features common to many basalts of the orogenic belts. With the exception of the soda percentage, the Deception Island parental magma is similar to some basalts of the Cascade volcanic province in the north-western United States of America. Its closest analogy is with the porphyritic central magma-type of Mull (Table VIII), and this may indicate derivation from an original tholeiitic magma.

X. VOLCANIC HISTORY

FROM the evidence that has been presented it is clear that the geological evolution of Deception Island is considerably more complicated than was previously thought. The geological history is summarized below, and in Fig. 16 the probable palaeogeographic evolution of the island during its various stages is shown in a series of diagrams.

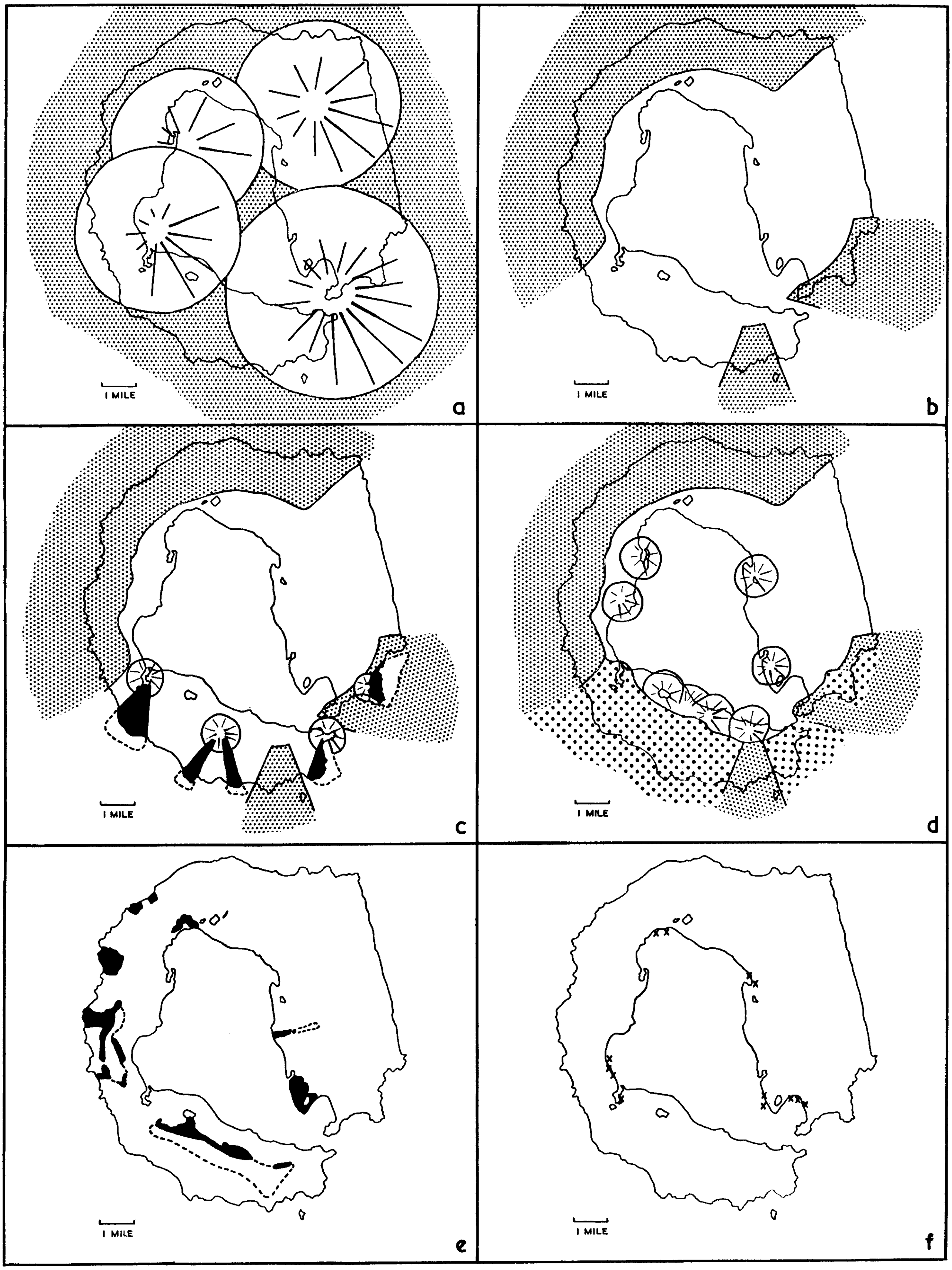

FIGURE 16

The palaeogeography of Deception Island. a. After the eruption of the Outer Coast Tuff (stippled); b. After the collapse and subsidence of the Port Foster Group volcanoes, leaving three islands (stippled) round the rim of the submarine caldera; c. After the eruption of the Neptunes Bellows Group volcanoes (black); d. After the eruption of the Pendulum Cove Group volcanoes. Land formed by Port Foster Group (light stipple) and Neptunes Bellows Group (heavy stipple) is also shown; e. After the eruption of the Whalers Bay Group (black). The probable extent of these volcanics is shown by the pecked line; f. The present day distribution of fumaroles.

The Port Foster Group (Fig. 16a). The earliest volcanic episode is represented by four strato-volcanoes of the Port Foster Group, which are probably the surface expression of a ring fracture in the underlying basement. Although they are broadly contemporaneous the relative ages of the four cones is unknown. It can be demonstrated, however, that the Telefon Bay volcano already existed when the formation of the Fumarole Bay volcano commenced. This episode was terminated by the violent eruption of the pumice-tuffs comprising the Outer Coast Tuff. Fig. 16a illustrates the palaeogeography of the island immediately after the eruption of the Outer Coast Tuff (shown as stipple). The previous extent of the outer coastline is uncertain but the existence of shallow water reefs off the western coast of the island (p. 4) indicates that the total area of Deception Island was considerably greater than at present.

The formation of the caldera (Fig. 16b). The collapse of the Port Foster Group volcanoes took place along arcuate and radial faults (p. 30). The probable palaeogeography after the engulfment of the island can be deduced from the present distribution (both outcrops and from extrapolation beneath later deposits) of the Outer Coast Tuff. It should be noted that the southern part of the island probably subsided beneath the sea leaving three islands around the rim of a submarine caldera.

The Neptunes Bellows Group (Fig. 16c). Post-caldera vulcanicity commenced with the "building up" of the vanished southern part of the island. Some of the cones of the Neptunes Bellows Group are located close to the intersections of arcuate and radial faults bounding the caldera. In Fig. 16c the stippled areas represent the three islands composed of the volcanics of the Port Foster Group. The areas between the individual cones were the accumulation sites of thick tuff and agglomerate deposits, and the entire southern part of the island appeared above sea-level once again. Eruptive activity during this period was predominantly explosive but at least once in the history of each volcano flows of olivine-basalt lava breached the crater wall. These flows now form the low rocky promontories along the southern and south-eastern coastline of the island.

The Pendulum Cove Group (Fig. 16d). The third volcanic episode consisted of the formation of the eight small cinder cones which are located on arcuate lines inside and concentric to the caldera rim. In Fig. 16d the dark stippled areas show the distribution of land formed of the Port Foster Group volcanics, and the light stippled areas land formed of the Neptunes Bellows Group volcanics. After the eruptions of the Pendulum Cove Group the island had reached a configuration very similar to that of today. Erosion of the outer coastline continued and glaciers were established (not necessarily for the first time) on the higher mountains surrounding the caldera.

The Whalers Bay Group (Fig. 16e). The last phase was the eruption of scoriaceous basaltic lavas from mounds and fissures. A considerable period of time had probably elapsed between the eruptions of the Pendulum Cove and Whalers Bay Groups, because the latter lavas rest upon thick moraine and fluvio-glacial deposits. The black areas in Fig. 16e show the present distribution of the lava flows, and the broken lines their probable extent beneath the glaciers.

Fumaroles. The only signs of volcanic activity today are the fumaroles (Fig. 16f) which occur mainly in Pendulum Cove, Telefon, Fumarole and Whalers Bays. These perhaps represent the closing chapter of the violent history of Deception Island.

XI. ACKNOWLEDGMENTS

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XII. REFERENCES

ADIE, R. J. 1957. Geological Investigations in the Falkland Islands Dependencies before 1940. *Polar Rec.*, **8**, No. 57, 502–13.

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

BARTH, T. F. W. 1956. Geology and Petrology of the Pribilof Islands, Alaska. *Bull. U.S. geol. Surv.*, No. 1028–F, 160 pp.

————. *and* P. HOLMSEN. 1939. Rocks from the Antarctandes and the Southern Antilles. Being a description of rock samples collected by Olaf Holtedahl 1927–28, and a discussion of their mode of origin. *Sci. Res. Norweg. antarct. Exped.*, No. 18, 64 pp.

————. *and* A. KVALHEIM. 1944. Christensenite, a Solid Solution of Nepheline in Tridymite. *Sci. Res. Norweg. antarct. Exped.*, No. 22, 9 pp.

BOWEN, N. L. *and* J. F. SCHAIRER. 1935. The System MgO – FeO – SiO_2. *Amer. J. Sci.*, Ser. 5, **29**, No. 170, 151–217.

————. 1938. Crystallization Equilibrium in Nepheline–Albite–Silica Mixtures with Fayalite. *J. Geol.*, **46**, No. 3, 397–411.

GOURDON, E. 1914. Sur la constitution míneralogique des Shetlands du Sud (île Déception). *C.R. Acad. Sci., Paris*, **158**, No. 8, 583–6.

HAWKES, D. D. 1959. *The Geology of the South Shetland Islands, West Antarctica.* M.Sc. thesis, University of Birmingham, 190 pp. [unpublished.]

————. 1961. The Geology of the South Shetland Islands: I. The Petrology of King George Island. *Falkland Islands Dependencies Survey Scientific Reports*, No. 26, 28 pp.

HERDMAN, H. F. P. 1932. Report on Soundings taken during the Discovery Investigations, 1926–1932. *'Discovery' Rep.*, **6**, 205–36.

HOLTEDAHL, O. 1929. On the Geology and Physiography of Some Antarctic and Sub-antarctic Islands. *Sci. Res. Norweg. antarct. Exped.*, No. 3, 172 pp.

KENDALL, E. N. 1831. An Account of the Island of Deception, One of the New Shetland Isles. *J. roy. Geogr. Soc. Lond.*, **1**, No. 4, 62–66.

KENNEDY, W. Q. 1933. Trends of Differentiation in Basaltic Magmas. *Amer. J. Sci.*, **25**, No. 147, 239–56.

KUNO, H. 1950. Petrology of the Hakone Volcano and the Adjacent Areas, Japan. *Bull. geol. Soc. Amer.*, **61**, No. 9, 957–1020.

OLSACHER, J. 1956. Contribución a la Geología de la Antártida Occidental: I. Contribución al Conocimiento Geologíco de la Isla Decepción. *Instituto Antârtico Argentino*, Publicación No. 2, 1–76.

POWERS, H. A. 1932. The Lavas of the Modoc Lava-bed Quadrangle, California. *Amer. Min.*, **17**, No. 7, 253–94.

TYRRELL, G. W. 1945. Report on Rocks from West Antarctica and the Scotia Arc. *'Discovery' Rep.*, **23**, 37–102.

WAGER, L. R. *and* W. A. DEER. 1939. Geological Investigations in East Greenland. Part III. The Petrology of the Skaergaard Intrusion, Kangerdlugssuaq, East Greenland. *Medd. Grønland*, **105**, No. 4, 352 pp.

WILKES, C. 1844. *Narrative of the United States Exploring Expedition, during the years* 1838, 1839, 1840, 1841, 1842. Vol. I. Philadelphia.

WILLIAMS, H. 1935. Newberry Volcano of Central Oregon. *Bull. geol. Soc. Amer.*, **46**, Pt. 2, 253–304.

————. 1941. Calderas and their Origin. *Bull. Dep. Geol. Univ. Calif.*, **25**, No. 6, 239–346.

————. 1954. Problems and Progress in Vulcanology. *Quart. J. geol. Soc. Lond.*, **109** (for 1953), Pt. 3, No. 435, 311–32.

APPENDIX

A LIST OF PLACE NAMES AND THEIR CO-ORDINATES

Except where otherwise indicated, all features in the following list can be located on the 1/25,000 map of Deception Island (D.O.S. 310, 1960). The approximate mid latitude and longitude of each feature is given.

Baily Head	62°58′S., 60°30′W.	
Bransfield Strait	—	1/500,000 Sheets A and B.
Bridgeman Island	62°04′S., 56°40′W.	1/500,000 Sheet B.
Cathedral Crags	63°00′S., 60°34′W.	
Collins Point	63°00′S., 60°35′W.	
Crater Lake	62°59′S., 60°40′W.	
Crimson Hill	62°57′S., 60°36′W.	
Cross Hill	62°56′S., 60°42′W.	
Deception Island	62°57′S., 60°38′W.	1/200,000 Sheet 62 60
Entrance Point	63°00′S., 60°34′W.	
Foster, Port	62°58′S., 60°39′W.	
Fumarole Bay	62°58′S., 60°42′W.	
Goddard Hill	62°55′S., 60°36′W.	
Kendall Terrace	62°55′S., 60°42′W.	
King George Island	62°00′S., 58°15′W.	1/200,000 Sheets 62 56, 62 58
Kirkwood, Mount	63°00′S., 60°39′W.	
Kroner Lake	62°59′S., 60°35′W.	
Låvebrua Island	63°02′S., 60°35′W.	
Macaroni Point	62°54′S., 60°32′W.	
Neptunes Bellows	63°00′S., 60°34′W.	
New Rock	63°01′S., 60°44′W.	
Pendulum Cove	62°56′S., 60°36′W.	
Penguin Island	62°05′S., 57°55′W.	1/200,000 Sheet 62 56
Pond, Mount	62°57′S., 60°34′W.	
Relict Lake	62°57′S., 60°36′W.	
Ronald Hill	62°59′S., 60°35′W.	
Snow Island	62°46′S., 61°23′W.	1/200,000 Sheet 62 60
South East Point	63°00′S., 60°31′W.	
South Point	63°01′S., 60°37′W.	
South Shetland Islands	—	1/500,000 Sheets A and B.
Stonethrow Ridge	62°58′S., 60°44′W.	
Telefon Bay	62°56′S., 60°41′W.	
Telefon Ridge	62°56′S., 60°43′W.	
Vapour Col	62°59′S., 60°44′W.	
Wensleydale Beacon	62°57′S., 60°42′W.	
Whalers Bay	62°59′S., 60°34′W.	

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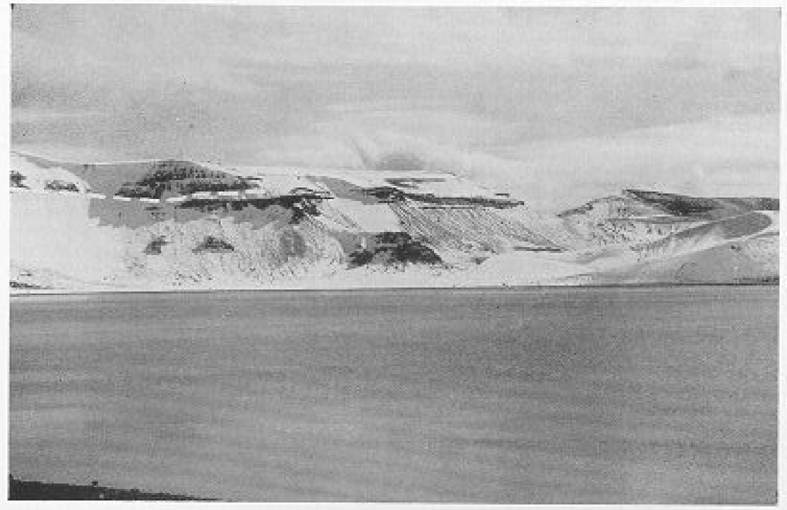
PLATE I

a. Stonethrow Ridge viewed from the south-east. The succession in the caldera wall consists of the Fumarole Bay Volcanics overlain unconformably by the Outer Coast Tuff.

b. Cathedral Crags, a vent agglomerate of the Port Foster Group, viewed from Whalers Bay. The agglomerate is about 350 ft. thick and completely devoid of bedding.

c. The outer coastline west of Stonethrow Ridge. The 200 ft. cliffs are composed of Outer Coast Tuff, which is overlain unconformably by scoriaceous basalts of the Whalers Bay Group in the foreground.

d. Baily Head on the eastern coastline. The headland and the offlying stacks are composed of the Outer Coast Tuff.



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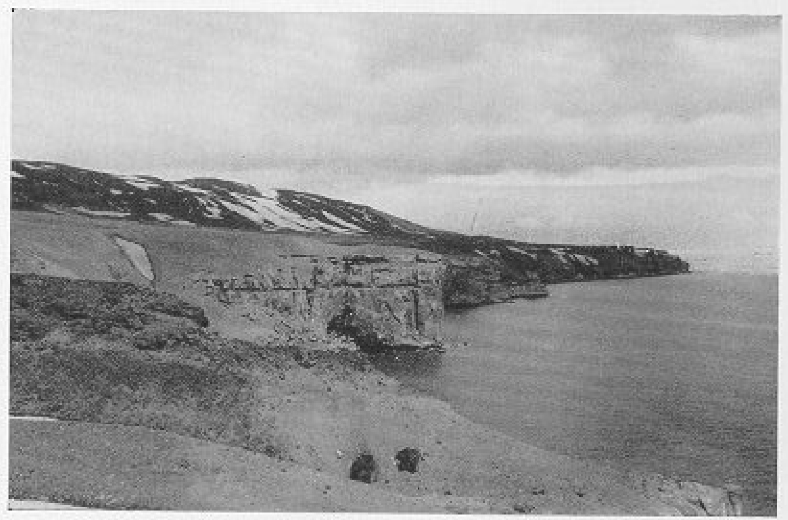

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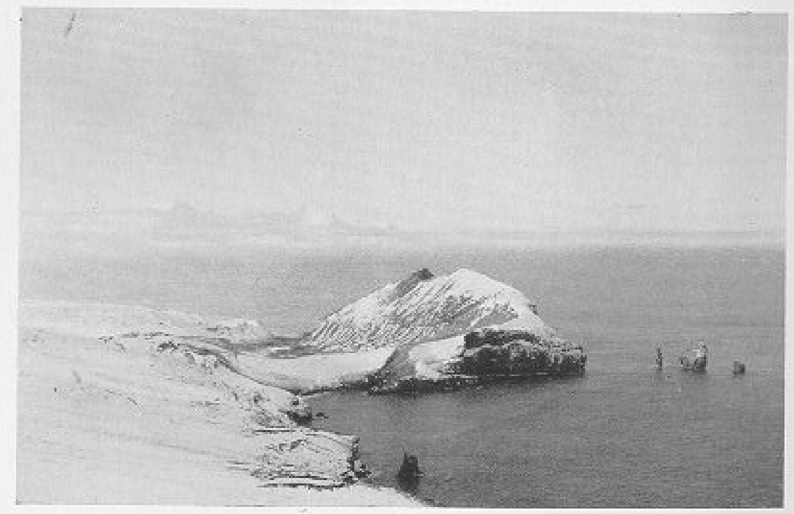

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PLATE I

PLATE II

a. The Fumarole Bay vent. Massive cliffs of yellow agglomerate rise to 600 ft. from the shore of Fumarole Bay.

b. The Entrance Point vent agglomerate exposed on the outer coastline west of the point. The photograph shows the associated lava flows dipping radially away from the vent agglomerate.

c. Cliffs west of South East Point, showing lavas of the Neptunes Bellows Group resting upon the eroded surface of the Outer Coast Tuff.

d. Vapour Col from Stonethrow Ridge, showing the remnants of a crater of the Neptunes Bellows Group.

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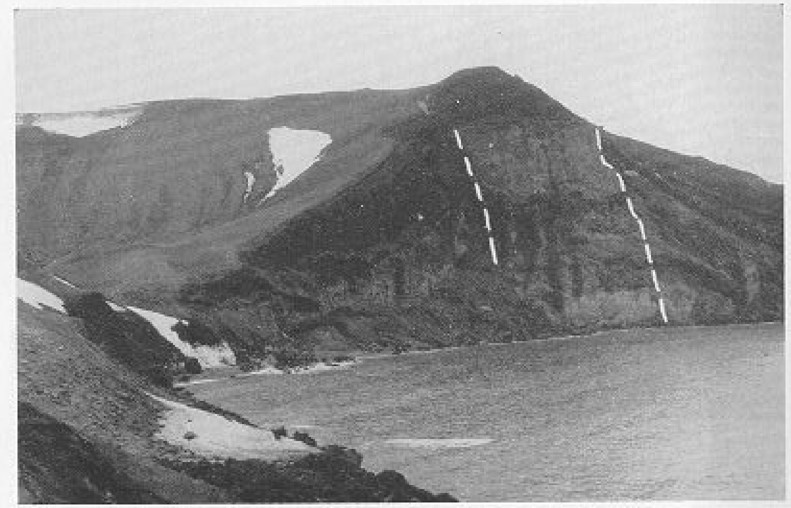

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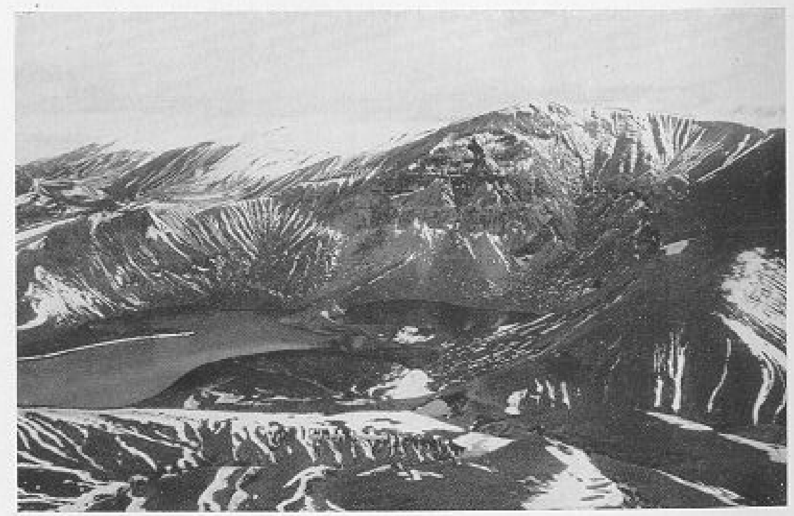

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PLATE II

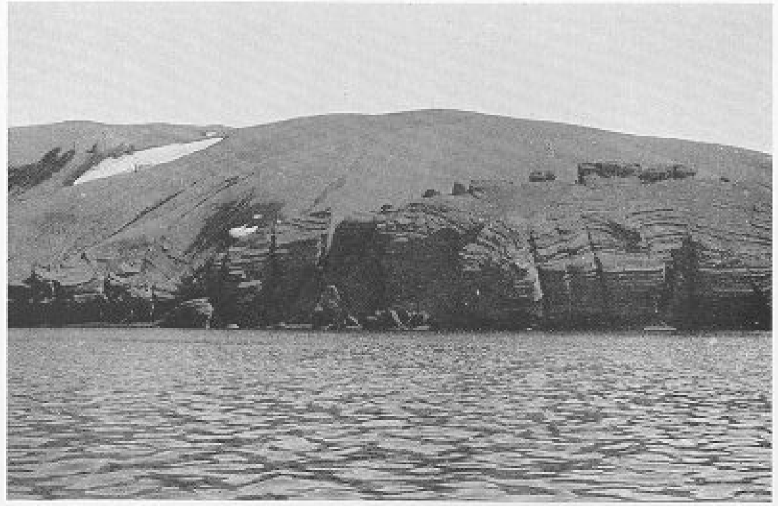
PLATE III

a. The cliffs east of Wensleydale Beacon which are composed of well-bedded grey lapilli-tuffs of the Pendulum Cove Group.

b. View due east from Vapour Col. Part of the crater rim of the Neptunes Bellows volcano is in the foreground, while the small cone of Crater Lake (a centre of the Pendulum Cove Group) is in the middle distance.

c. Kendall Terrace from the summit of Telefon Ridge. Lavas of the Whalers Bay Group rest unconformably upon fluvio-glacial gravels. The coastline is bounded by 200 ft. sea cliffs.

d. Low mounds (20 ft. high) aligned along an arcuate fissure, the source of the Kendall Terrace lavas of the Whalers Bay Group.



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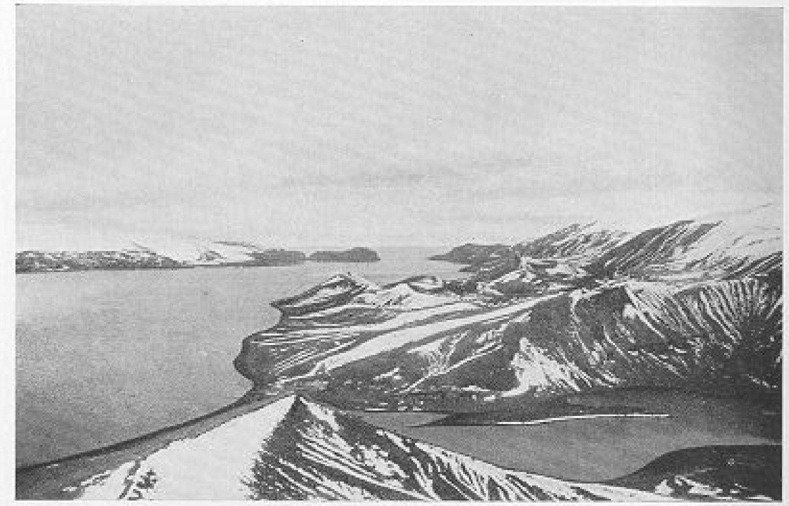

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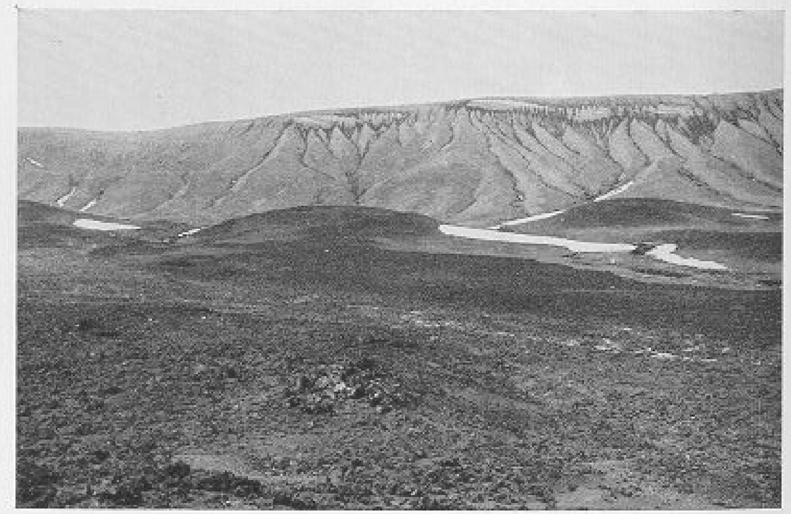

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PLATE III

PLATE IV

a. Pumice-tuff composed mainly of highly pumiceous glass fragments with occasional broken felspar, pyroxene and olivine crystals; Outer Coast Tuff, southern end of Stonethrow Ridge (B.200.1; ordinary light; × 32).

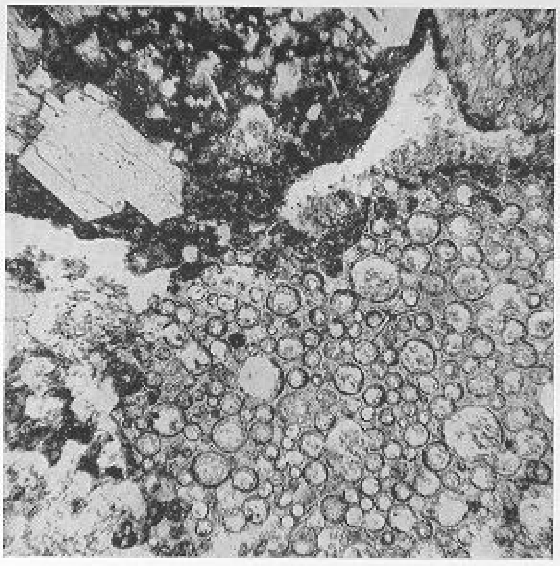
b. Oligoclase-andesite showing a microphenocryst of hypersthene surrounded by clino-pyroxene; Pendulum Cove Group, promontory 1¼ miles west-north-west of Collins Point (B.111.2; X-nicols; × 58).

c. Oligoclase-andesite showing a large subhedral phenocryst of fayalitic olivine; Pendulum Cove Group, Ronald Hill (B.114.2; ordinary light; × 32).

d. Oligoclase-andesite with phenocrysts of andesine and fayalitic olivine set in a matrix of oligoclase microlites and some interstitial glass; Pendulum Cove Group, promontory 1¼ miles west-north-west of Collins Point (B.111.4; ordinary light; × 32).

e. Olivine-basalt, a fresh lava composed of labradorite microlites with intergranular pyroxene, olivine and iron ore; Port Foster Group, Stonethrow Ridge (B.163.1; ordinary light; × 32).

f. Olivine-basalt with an intergranular texture and composed of labradorite, pyroxene, iron ore and a minor amount of olivine; Neptunes Bellows Group, near Collins Point (B.103.3; ordinary light; × 32).



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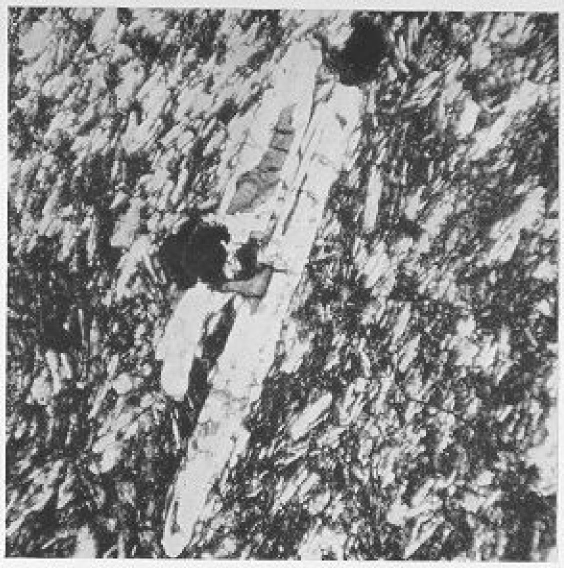

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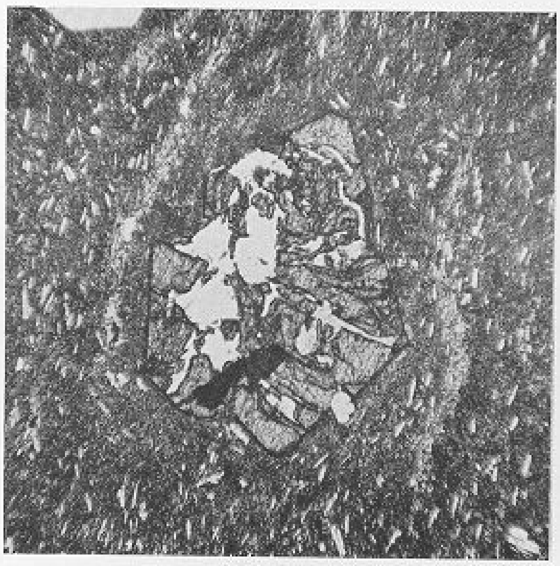

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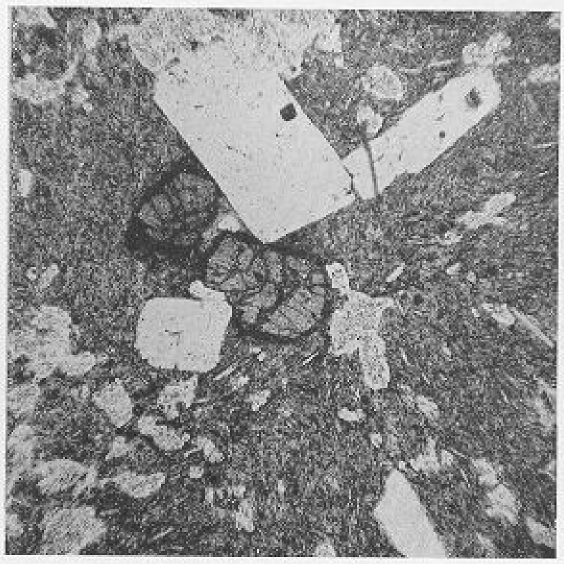

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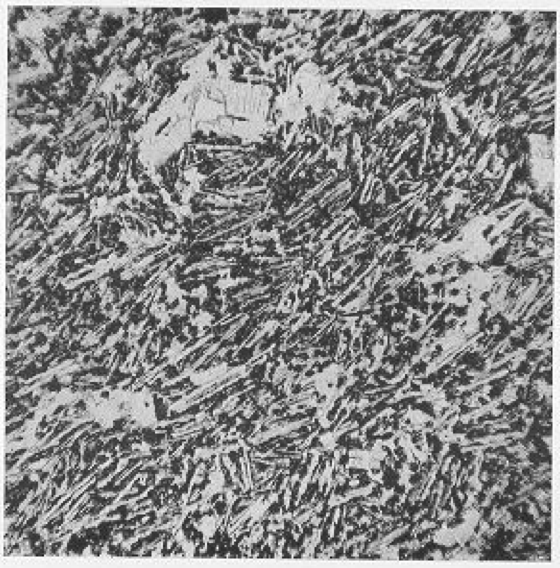

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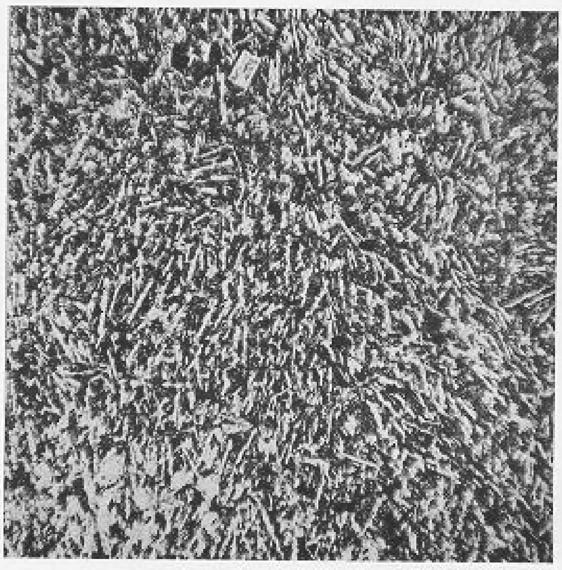

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