GEOLOGY AND GEOPHYSICS

The Surtsey Research Drilling Project of 1979

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INTRODUCTION

The scientific value of a Surtsey drilling program was first conceived shortly after the eruption ceased (Proceed. Surtsey Res. Conf., Reykjavík, June 1967, p. 73), because of the exceptional opportunity to study the development of a historic, well-studied, oceanic volcano from its inception on the seafloor, through the formation of a volcanic island, to the modification of the volcanic edifice by hydrothermal processes.

However, mainly because of problems concerning funding, the project was not realized before 1979. In January 1979, a drilling proposal was approved as a cooperative scientific effort by the Geothermal Research Program of the U.S. Geological Survey and the Icelandic Museum of Natural History.

The purpose of the drilling was mainly to provide constraints on 1) the nature of basaltic submarine volcanic activity from vents in the depth range from about 130 m to sealevel, and the composition of rocks erupted during the course of the submarine eruption; and 2) hydrothermal processes, including the nature of palagonitization of the basaltic hyaloclastites and formation of secondary minerals, and, 3) the thermal history both above and below sea level as indicated by thermal logging and character of alteration.

The drilling was performed by the Icelandic State Drilling Contractors from June 29 to August 22, 1979, during 34 days of active drilling. Frequent storms made the drilling conditions arduous with high winds, producing sand storms, and heavy seas causing frequent disruption of the seawater intake pipe and difficulties in landing men and equipment on the beach in a rubber dinghy. However, on the whole the drilling operation was successful and core recovery was excellent. The scientific party, consisting of Sveinn P. Jakobsson, James G. Moore, Ólafur Ingólfsson and Bjarni Kristinsson, monitored drilling progress, logged core, and made detailed studies of surface geology. The drilling costs, excluding post-drilling science, amounted to $119,000, of which 24 percent were transport costs. This was about 8 percent above the projected expenditure.

THE GEOLOGY OF SURTSEY

Eruption history

The eruption history of Surtsey and the two adjacent temporary islands is well known through the work of Thorarinsson et al. (1964) and Thorarinsson (1965, 1968), and has been outlined previously along with preliminary drilling results (Jakobsson & Moore 1980). However, since the history of the Surtsey eruption is of vital importance in understanding the drilling results, the main events are listed below, and further summarized in Table I.

The visible eruption started with phreatic explosions from a 300-400 m long fissure trending 035° on November 14, 1963. Presumably the eruption broke through the sea floor a few days before it became visible. The most recent pre-eruption soundings in the Surtsey area were made in 1901 by the Royal Danish Hydrographic Office (Copenhagen 1931), and the closest measure-

TABLE I
History of the Surtsey eruptions.

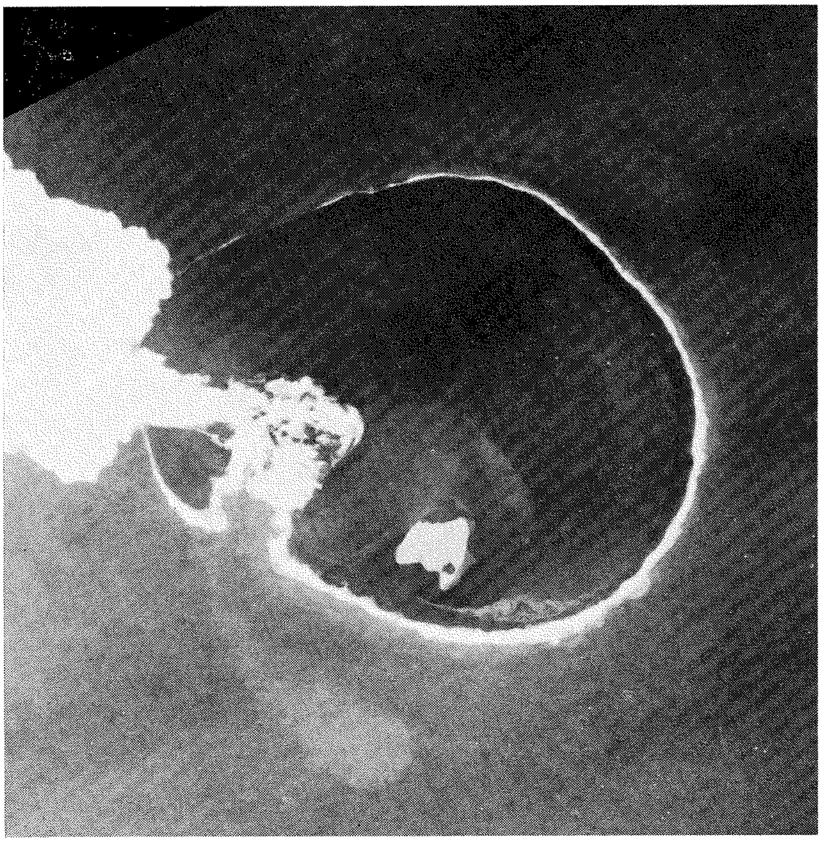
Year	Mo	Date	
1963	Nov.	8—12	Approximate beginning of eruption on sea floor?
	Nov.	14	First visible explosive activity broke sea surface in vicinity of eastern vent.
	Nov.	15	First appearance of island of Surtsey.
	Dec.	28	Submarine activity (Surtla) became visible 2.5 km eastnortheast of Surtsey.
1964	Jan.	6	Submarine activity (Surtla) ceased 2.5 km eastnortheast of Surtsey after building a submarine ridge more than 100 m high.
	Jan.	31	Activity ceased at eastern Surtsey vent.
	Feb.	1	Explosive (phreatic) activity began at site of western Surtsey vent.
	Mar.	19- Apr. 1	Surtsey northern lagoon formed.
	Apr.	4	Surtsey western vent ceased explosive activity and began effusive phase.
	Apr.	29	Effusion of lava ceases from western Surtsey vent.
	May-July		Probably some lava extruded (submarine) on the seafloor southwest of Surtsey.
	July	9	Effusion (visible) of lava resumes from western Surtsey vent.
1965	May	11?	Submarine activity at site of Syrtlingur may have begun.
	May	17	Effusion of lava ceases from western Surtsey vent.
	May	22	Explosive activity begins visibly at site of Syrtlingur 0.6 km eastnortheast of Surtsey.
	Oct.	17	Explosive activity of Syrtlingur has ceased.
	Oct.	24	Syrtlingur completly washed away.
	Oct.	end?	Submarine eruptive activity probably began on ridge 1 km southwest of Surtsey (site of later-appearing Jólnir).
	Dec.	26	Visible explosive activity southwest of Surtsey.
	Dec.	28	First appearance of the island of Jólnir.
1966	May	late	Fault-bounded lagoon appears on north side of Jólnir.
	Aug.	10	Phreatic activity of Jólnir ceases.
	Aug.	19	Effusive activity started from Surtsey eastern vent.
	Oct.	31	Jólnir completely washed away.
	Dec.	12-17	Vent on inner northwest wall of eastern tephra cone erupted small lava flow.
1967	Jan.	1-4	Vent on outer north slope of eastern tephra cone erupted lava which flowed into north lagoon.
	Jan.	1-8	Vent on inner north wall on eastern tephra cone erupted lava which flowed south past drillhole site.
	Jan.	2	Vent on outer northeast slope of eastern tephra cone erupted tiny lava flow.
	Jan.	2-7	Two curved faults formed on inner east wall of eastern tephra cone and the lower one erupted small lava flow.
	June	5	Effusive activity ceased at Surtsey eastern vent.

ments to the drill site show a water depth of 128 m 1.5 km east. From the general bathymetric configuration we estimate preeruption water depth at the drill hole site to be 130 ± 5 m. The island was born on Nov. 15, and grew rapidly in size. On January 31, 1964, the eruption ceased in the eastern vent (Surtur I) which had been active until then, but broke out the following day in a northeast trending fissure on the northwest side of the crater (Fig. 1A). On April 4, 1964, the eruption in the western crater (Surtur II) changed over to an effusive phase, as the island was then obviously large enough to isolate the vent from the inflow of seawater. Between December 28, 1963, and January 6, 1964, submarine activity was visible about 2.0 km eastnortheast of Surtsey. A submarine ridge, called Surtla, was built up to more than 100 m in height but did not reach the sea surface.

Effusive Hawaiian-type activity continued in the western crater (Fig. 1B and Fig. 2) until May 17, 1965 and gradually built up a flat lava plain towards the south, while foreset-bedded (flow-foot) breccia formed at the front below sea level at the same time.

Explosive activity appeared on May 22, 1965, at a site about 600 m eastnortheast of Surtsey. A small island, Syrtlingur, was formed and reached a height of 70 m. This island was washed away by wave action a few days after the eruption ceased about October 17, 1965. Another island, Jólnir, was created by submarine activity some 800 m southwest of Surtsey on December 26, 1965. Eruptions continued until August 10, 1966, and the island disappeared in late October of that year.

On Surtsey, new eruptions started on August 19, 1966, when a ca. 220 m long fissure opened up on the floor of the eastern crater (Surtur I), which had been inactive since the end of January 1964. From this fissure (Fig. 1C), lava flowed incessantly during late 1966 and early 1967, and was last seen to flow on June 5, 1967. Between December 12-17, 1966, another fissure



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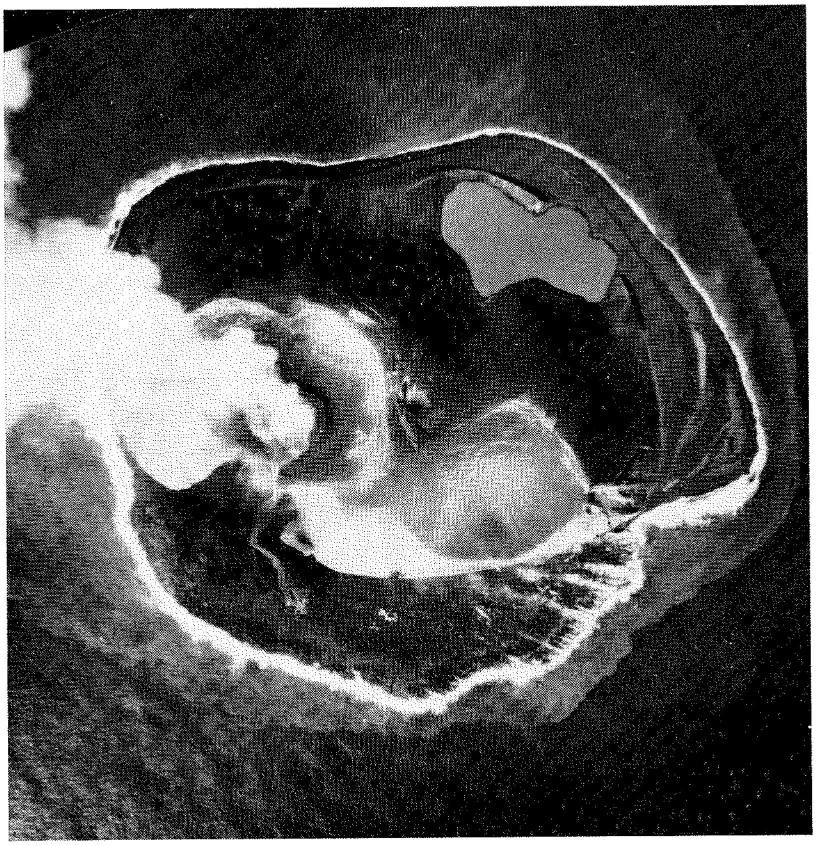
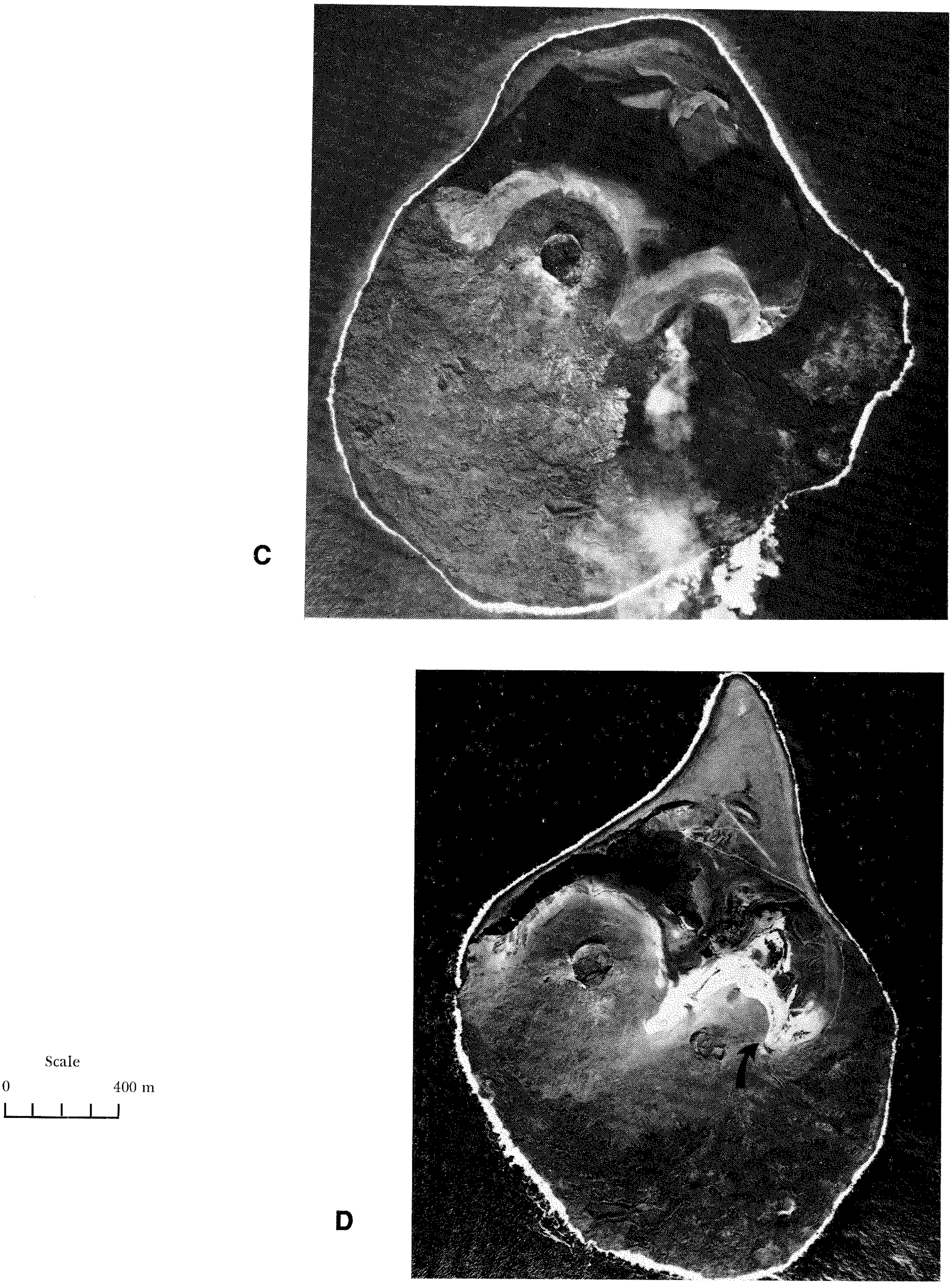


B

Fig. 1. Air photographs of Surtsey, taken by the Icelandic Geodetic Survey. In all photographs north is toward the top. A) February 17, 1964; phreatic eruptions issue from the western tephra crater; the eastern crater which ceased activity on January 31, is partly filled with lake. B) April 11, 1964; activity in the western crater became effusive on April 4, and lava flows



enlarged the island southward; the eastern crater has been covered with a blanket of tephra from the western crater. C) October 2, 1966; effusive activity from vents within the eastern tephra crater. D) July 20, 1979, 12 years after eruptions ceased. The location of the drill site is indicated with a black arrow. Published with the permission of the Icelandic Geodetic Survey.

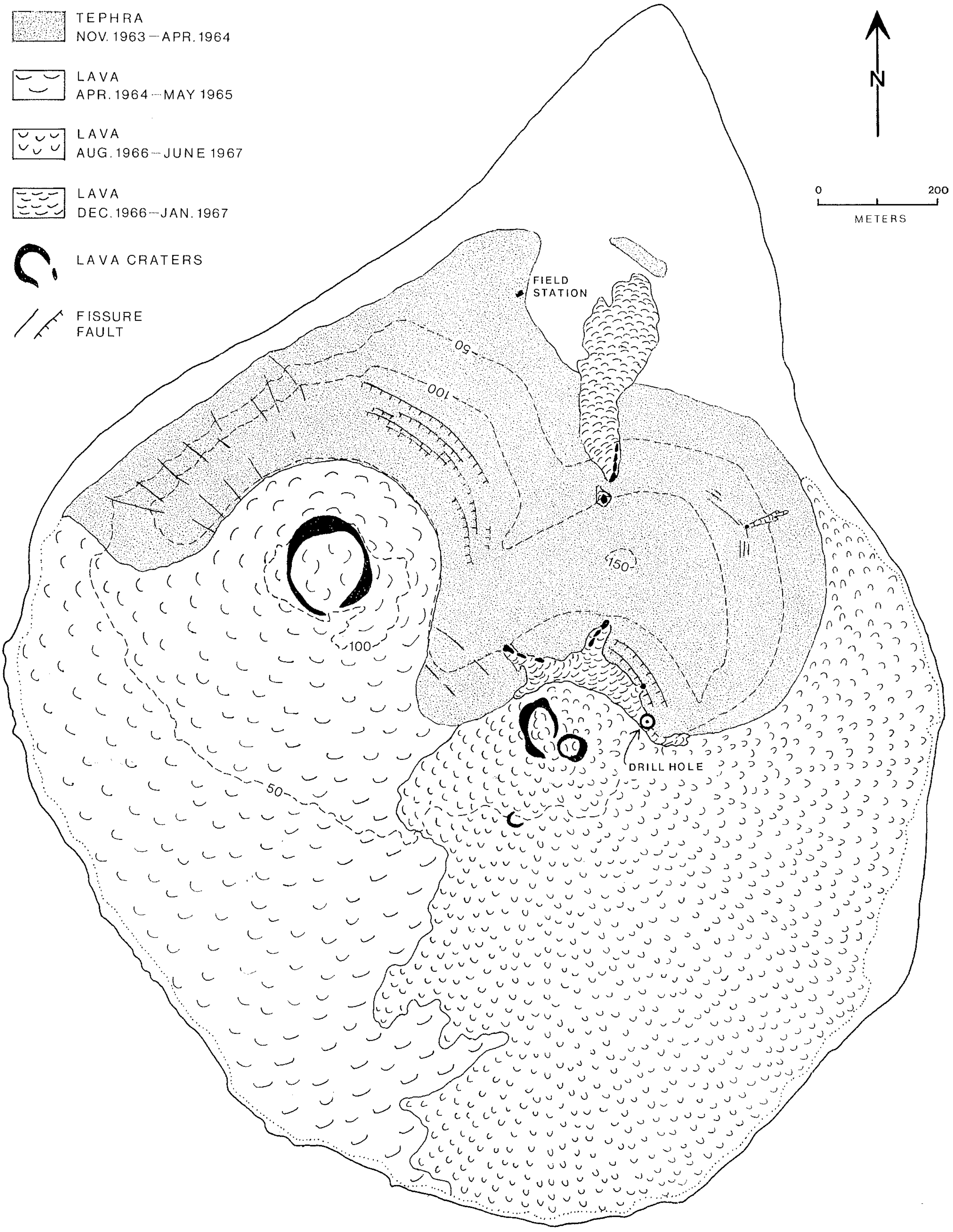


Fig. 2. Geologic map of Surtsey, based on topography of 1975 by Norrman (1978). The extensive western vent lava flows of April 1964 — May 1965 and east vent lava flows of August 1966 — June 1967 are shown by pattern. The small flows of December 1966 — January 1967 within and on the flanks of the east vent are shown separately. Known fissures and faults (teeth on downthrown side) are indicated. Elevation contours in meters are shown by dashed lines.

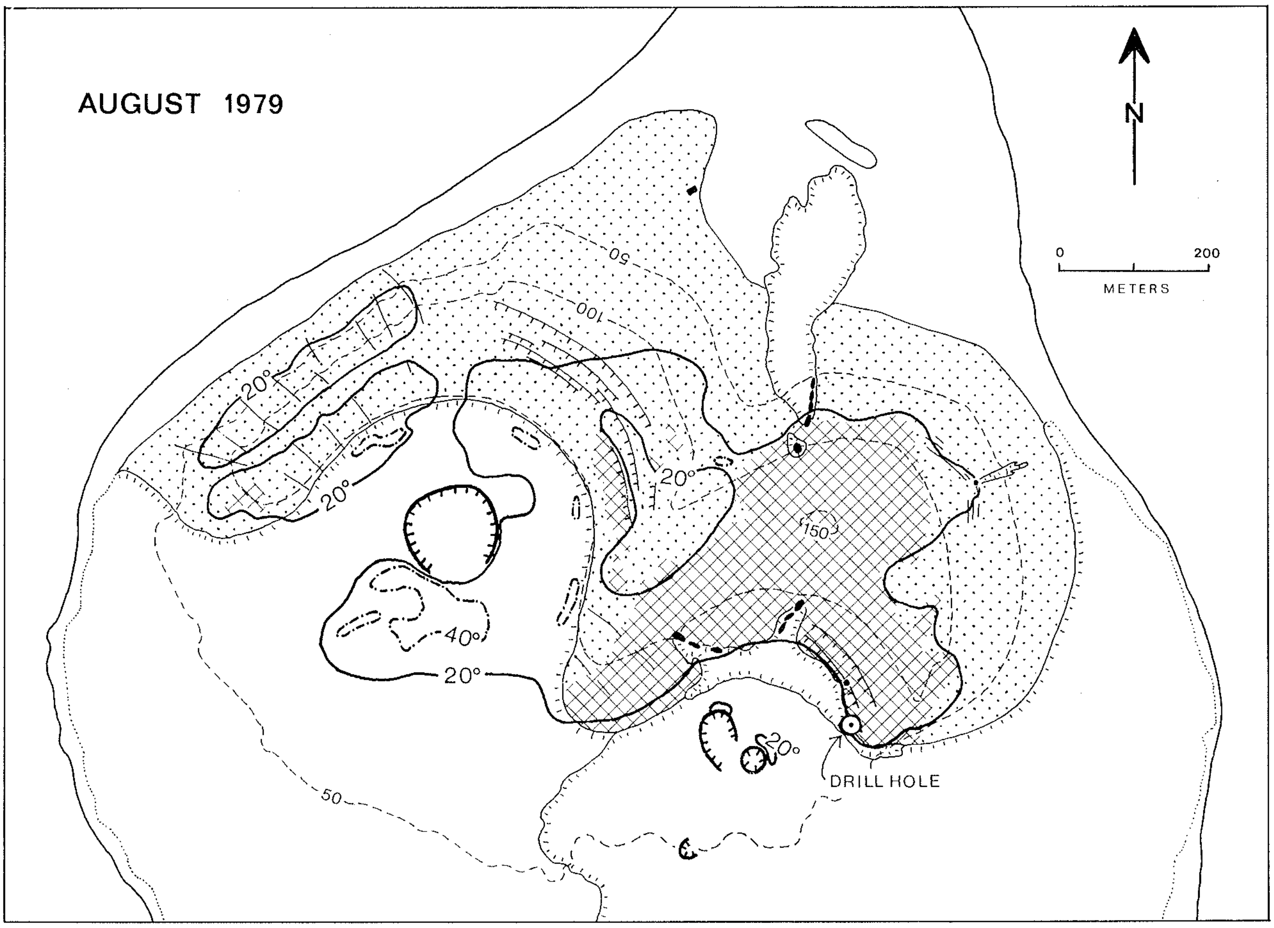


Fig. 3. Map of the central part of Surtsey; compare with Figs. 2 and 1D. The area of primary tephra is dotted. The hydrothermal area is indicated by the 20°C and 40°C isotherms (as measured at a depth of 20 cm), of August, 1979. Surface exposures of palagonitized tephra are cross-hatched.

was active in the western inside wall of the eastern tephra crater producing a small lava flow, and between January 1-8 1967 lava broke through the eastern tephra ring at four additional sites (Fig. 2 and Table I). The southernmost eruption site (now covered by sand drift) is situated only 60 m from the drill site.

At the end of the eruptions in 1967 Surtsey had reached a size of 2.8 km^2, and the total amount of material erupted was estimated to be 1.1-1.2 km^3, about 60-70 percent of which was tephra.

Drill site events.

Probably by November 16, 1963 and definitely by November 22 (Thorarinsson et. al. 1964, Fig. 6), the area of the drill site location was above sea level. As far as the record goes, the drill site area has been above sea level since that time.

Examination of unpublished photographs, mainly those of Sigurdur Thorarinsson, reveal that the part of the eastern tephra ring where the drill site is located, was largely built up during November 1963, and was fully developed late in December 1963. However, during the phreatic activity in the western tephra crater between February 1 — April 3, 1964, a blanket of tephra (about 10-15 m thick) was desposited on the eastern crater. Eolian erosion (Ingólfsson 1982) later removed a substantial part of this blanket from the drill site area.

Eyewitness and photographic evidence indicates that no major disturbances of the tephra layers occurred at the drill hole site. However, the drill site may have subsided about 4 m from 1964 to the time of drilling in 1979 (Moore 1982).

The tephra: Mode of emplacement and composition

The tephra above sea level was deposited as bedded air fall tephra and base surge flows, cf. Thorarinsson et al. 1964, Figs. 5,7 and 11, and Moore 1967. Two types of phreatic explosive activity dominated, intermittent „cocks-tail“ explosions and continuous uprush of tephra (Thorarinsson 1965). Information from the recent drill hole (Fig. 7) indicates that subaerially deposited tephra extends at least to a depth of 14 m below

A

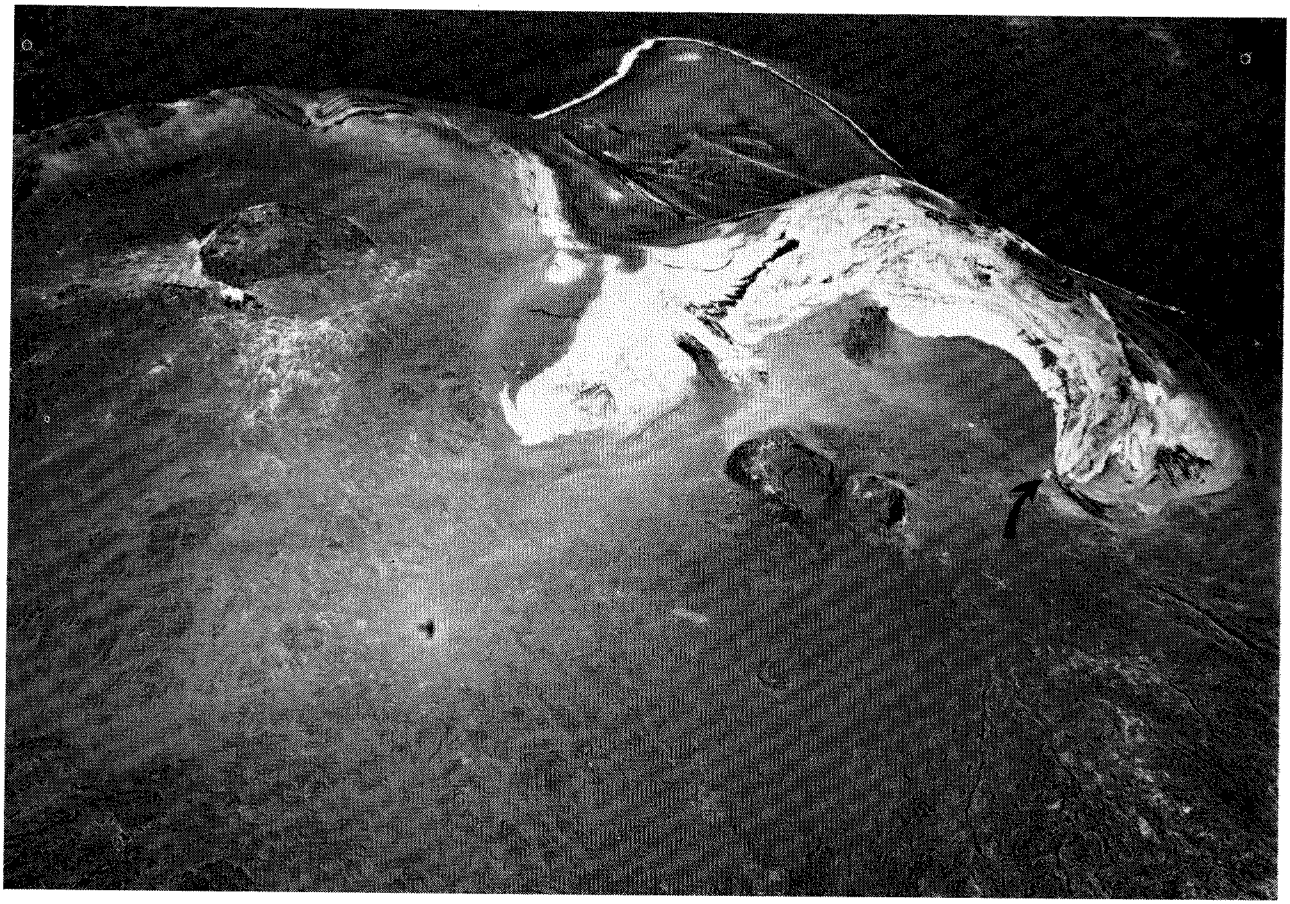


Fig. 4. Oblique air photographs of Surtsey, taken on July 20, 1979, by the Icelandic Geodetic Survey. A) Central part of Surtsey, looking NNE; The drill site is indicated with a black arrow at the SE rim of the eastern tuff ring. Light areas are consolidated palagonitized tuff.

sea level and possibly deeper, indicating a considerable subsidence. Whether deeper layers are formed by submarine or subaerial activity is difficult to determine.

The original unaltered tephra is generally poorly sorted with some 60-70 percent in the coarse ash (0.06-2 mm) fraction. Exceptions are the reworked sedimentary layers (p. 92), and the sand/tephra below ~176.5 m depth (Fig. 7). Surtsey is *locus typicus* of „surtseyan" tephra and the reader is referred to Walker & Croasdale (1972) for descriptions of pyroclast shape and size sorting.

About 80-90 percent of the alkali olivine basalt tephra is made up of fracture-bounded clasts of basaltic glass (sideromelane n: 1.605± 0.002). The remainder is composed of phenocrysts and glassy basalt fragments of varying crystallinity. The phenocrysts are Cr-spinel (picotite), olivine (Fo 84-86) and plagioclase of two generations, a large (An 63-65), and a small (An 70-75). Melting experiments at one atmosphere pressure (dry conditions), made on the first Surtsey lava of April 1964 (Tilley et al. 1967), showed that olivine crystallized at 1220°C, plagioclase at 1180°C and clinopyroxene at 1155°C. Since clinopyroxene is not observed in the Surtsey tephra, the magma was apparently quenched during contact with seawater at 1155°-1180° C. This temperature range is in harmony with measurements in March 1965, when temperatures of 1151° and 1162° C were obtained from molten lava in the lava crater (Sigurgeirsson 1966). About 15-20 percent of the glass is tachylite, i.e. opaque black glass, with chemical composition and density similar to that of the sideromelane. The chief difference is that the tachylite is strongly magnetic.

Hydrothermal and palagonitized areas.

Since the formation of Surtsey the area of primary tephra has been inspected frequently (Jakobsson 1972, 1978). In 1969 the first signs of palagonitization of the basaltic glass were observed. The process was clearly related to the formation of a hydrothermal anomaly established after the period of effusive and intrusive activity in the eastern crater during August 1966 – June 1967, and probably mainly due to intrusive activity in December 1966 – January 1967

B

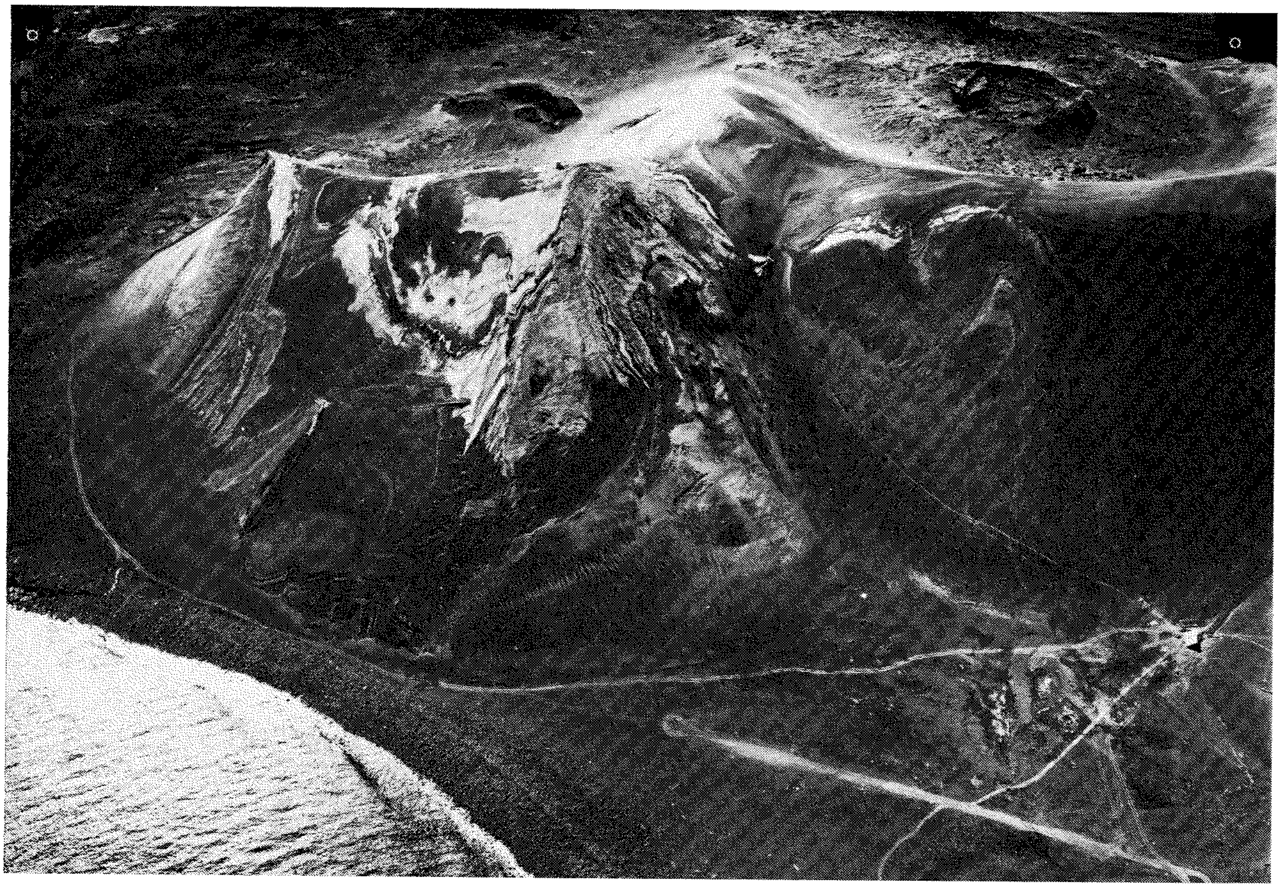


Fig. 4. B) Northern part of Surtsey, looking SW; trails radiate from Pálsbaer, the field station at lower right. The air strip at bottom is 280 m long. Published with the permission of the Icelandic Geodetic Survey.

(Table I, Fig. 2). Heat transfer in the tephra has been inferred to occur by upward convection of steam produced by vaporization of ground water of both marine and meteoric origin, the heat source being feeder dikes and shallow intrusions related to the 1966-67 effusive activity (Jakobsson 1978). This is confirmed by the recent study of Axelsson et al. (1982) who conclude that the heat content of the Surtsey tuff can originate from intrusions, and that the heat transfer in Surtsey is dominated by hydrothermal convection, both above and below sea level.

The extent of the hydrothermal area as measured at a depth of 20 cm in August 1979, is shown in Fig. 3. The size and near-surface temperature of the hydrothermal area in 1976 (Jakobsson 1978, Fig. 8) and 1979 (Fig. 3) is similar, and small changes, especially in the western crater, probably result largely from erosion. The highest temperature measured within the tephra pile in August 1979 was 100° C. The highest temperature measured in the lava at the surface was 153° C, just south of the western lava crater, where the lava pile is approximately 100 m thick.

In August 1979, the surface exposures of palagonitized tuff (Fig. 3), were somewhat larger than in 1976, due mainly to wind erosion, as the thin cover of unconsolidated tephra is continuously blown off the underlying palagonitized tuff. The volume of palagonitized tephra is much larger than would appear from surface exposures and is estimated to include 70-80 percent of the tephra pile above sea level.

THE DRILLING OPERATION

The drill hole is located at an elevation of 58.39 ± 0.15 m above sea level, just inside the eastern tephra crater, approximately 100 m southeast of the fissure vent active between November 1963 – February 1964 (Figs. 2-4). In order to achieve the main objectives of the project, the drilling was sited within the hydrothermal area, and outside the main lava field. Proximity to the lava craters of August 1966 – January 1967, was avoided because of the possibility of transecting extensive subvertical feeder dikes. Moreover the site had to be accessible by tractor, and reasonably close in elevation and distance to the sea, since seawater was the only feasible drilling fluid, and had to be pumped to the site through plastic pipe.

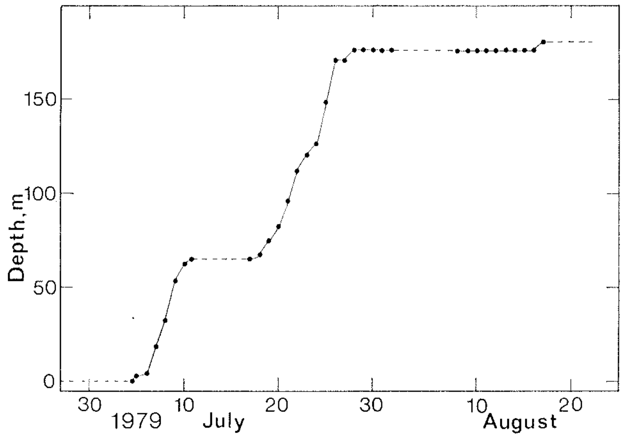


Fig. 5. The progress of drilling as indicated by daily hole depth in 1979. Unconsolidated tephra (sand?) at a depth of 171 m caused repeated drilling problems because of both loss of water circulation and hole collapse. Dashed lines indicate no drilling during preparation and completion periods, and drilling recesses.

On June 29, 1979, the Icelandic Coast Guard ship *Ódinn* transported about 39 tons of drilling equipment, food and fresh water, besides the drilling crew and scientists, to Surtsey. An Icelandic Coast Guard helicopter ferried all equipment lighter than 0.4 ton from the ship to the island in about 80 round trips. A larger U.S. Air Force helicopter, from the U.S. military base at Keflavík, carried the heavier equipment including the drill rig, drill pumps, drilling shelter and tractor, in 6 round trips.

The 3-man drill crew from the Icelandic State Drilling Contractors was headed by Sigurdur Sveinsson; other members were Jón Stefánsson, Helgi Årsaelsson and Eiríkur Stígsson. Gudmundur Sigurdsson managed the drilling operation from Reykjavík. The crew and the scientists stayed in Pálsbaer, the field station which was built in 1966 (Fig. 4B). After five days of preparations, drilling started on June 5, 1979. The drill rig was of the type Craelius — 2 (P-1000), which allowed raising the core barrel by wire-line without pulling the drill rods. Core diameter is 4.7 cm.

Drilling was comparatively easy down to a depth of 138 m (Fig. 5), with a core recovery of 97.9 percent. Below 138 m core recovery was variable because of the occurrence of unconsolidated layers of tephra or sand (Fig. 7). On July 26, at a depth of 171 m, drilling became very difficult after drilling through 13 m of loose tephra where repeated grouting with cement proved unsuccessful. During this period the pumping of seawater used as the drilling fluid was frequently disrupted by damage to the seawater intake pipe and the seashore pump during heavy storms and high surf. On July 29 the NCQ drilling rod (outside diameter 6.99 cm) became stuck at a depth of 176.5 m. Drilling was continued with BQ rods inside the NCQ rod. At a depth of 180.6 m when the BQ rod (outside diameter 5.56 cm) became stuck (but was subsequently freed), the decision was made to stop drilling. Between July 28 and August 18 (when drilling was discontinued), only 10 additional meters had been acquired.

Core recovery below 138 m depth was 33 percent; only drill cuttings were obtained between 140.0 — 143.8, 148.5 — 150.6, 157.5 — 168.7 and 170.5 — 180.1 m depths; and no samples were obtained between 138.1 — 140.0, 171.0 — 171.4, 172.6 — 174.9 and 180.1 — 180.8 m depths (Fig. 7). Total core recovery from the drill hole was 148.4 m, or 82.0 percent of the hole depth.

Precise leveling and water-level measurements in a dug pit on the north side of Surtsey (Moore 1982) show that the elevation of the drill hole collar (top of the outer casing, Fig. 6) is at 58.3± 0.15 m above mean sea level. The drill hole collar was capped and sealed in September 1980, to protect it from corrosion. The present reference point is the top of the NCQ casing, at 58.9±0.2 m above mean sea level. An exact measurement of the height difference between the two reference points was lost with other data when the transport boat „Bravó" was lost in the surf of Surtsey, September 12, 1980.

DRILL HOLE LOG

The complete core log is compared in Fig. 7 with information on dip of primary layering and slumping planes, wet specific gravity and temperature profiles. Furthermore, Oddsson (1982, Table I) has measured the dry density, the specific density and the total porosity, of 22 samples from the core. The reference level is the top of the outer casing 1979 reference of Fig. 6, at 58.39 ±0.15 m above sea level.

Lithology.

0 — 1.0 m

Wind-blown (eolian) sand; with sand dunes at the surface, composed of grains in the coarse and very coarse sand range (cf. Ingólfsson 1982). The sand has been deposited and reworked since December 1966; its source is the unconsolidated tephra of the two tephra cones. Irregular layering resulting from size sorting is conspicuous in this layer: the sand grains are composed of the same constituents as the tephra/tuff as described below.

Slight palagonitization of sideromelane sand grains is evident and increases downwards.

1.0 – 2.7 m

Alkali olivine basalt lava; which flowed and solidified during January 1 – 8 1967 (Thorarinsson 1968, Fig. 8). The lava is vesicular and unaltered (except for some high-temperature oxidation), and contains phenocrysts of Cr-spinel, olivine and plagioclase. It is petrographically indistinguishable from the dikes at 71.9–84.8 m depth.

Below 2.7 m

Below 2.7 m depth the entire section is made of tuff/tephra, with the exception of the basaltic dikes at 71.9–84.8 m depth. The original material was unconsolidated tephra which was deposited in air or water, during November 1963 – April 3, 1964, and mainly during November-December 1963, as stated above. Generally, unless otherwise stated below, the tuff/tephra is of „ordinary" coarseness (i.e. mainly in the coarse ash fraction) and is poorly layered. Small basalt blocks and bombs about 8-12 cm in size are not uncommon, and xenoliths of sediment (some containing shell fragments) and crystalline basalt are present.

The material below 2.7 m depth was originally quite uniform, however, different degrees of alteration and compaction have produced variations in rock chemistry, mineralogy, density and porosity. No pillow lava is present in the drill core.

2.7 – 8.2 m

Tuff; finely layered, porous and altered, color mostly dusky yellow with dark grayish-green layers, (Fig. 8A).

8.2 – 17.3 m

Tuff; poorly layered, dense and altered, mostly dark grayish-brown.

17.3 – 19.1 m

Tuff; coarse to very coarse, porous to very porous (open-textured) and altered, many scoraceous fragments, a few bombs, – color mostly dark grayish brown.

19.1 – 32.4 m

Tuff; dense and altered, dark grayish brown, with scattered bombs, (Fig. 8B).

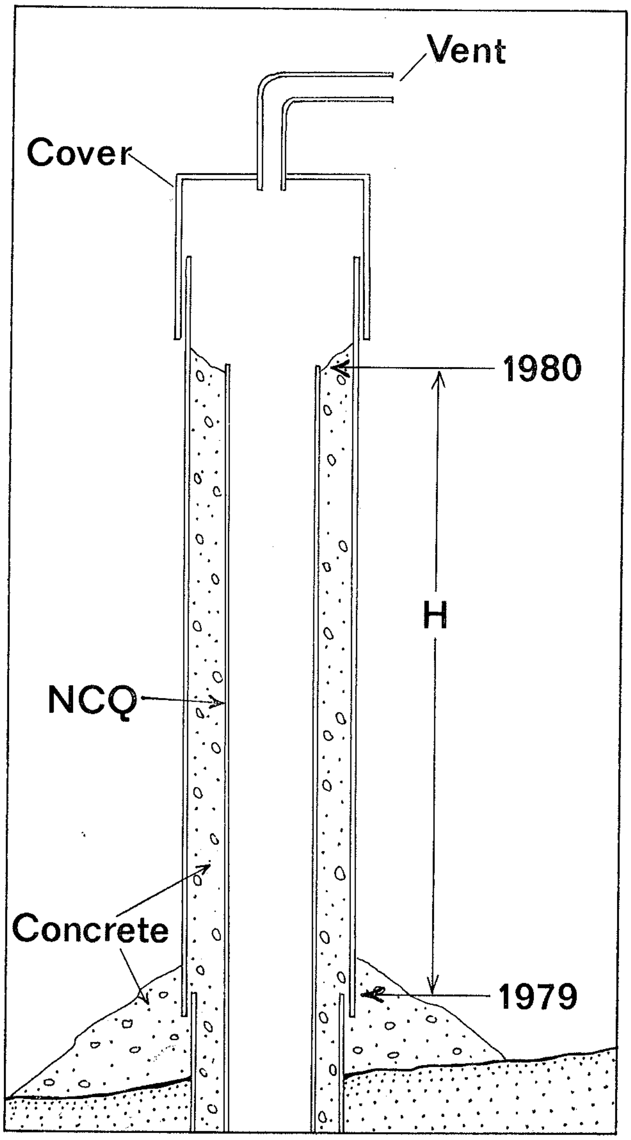


Fig. 6. Drillhead as completed in 1980. Reference level during 1979 drilling program was top of outer steel casing (58.39± 0.15 m above sea level which is now covered by cement). New reference level (1980) is 58.9±0.2 m above the 1979 level, but the exact measurement (H) was lost at sea.

32.4 – 35.7 m

Tuff; coarse to very coarse, porous to very porous, slightly altered, color dark grayish brown.

35.7 – 40.4 m

Tuff; slightly porous and slightly altered, dark grayish brown, (Fig. 8C).

40.0 – 52.5 m

Tuff; very coarse and porous, containing many pumiceous fragments and a few bombs, dark grayish brown.

52.5 – 71.9 m

Tuff; slightly porous to dense. Above 53.8 m depth the tuff is only slightly altered and is dark

SURTSEY 1979 DRILL HOLE

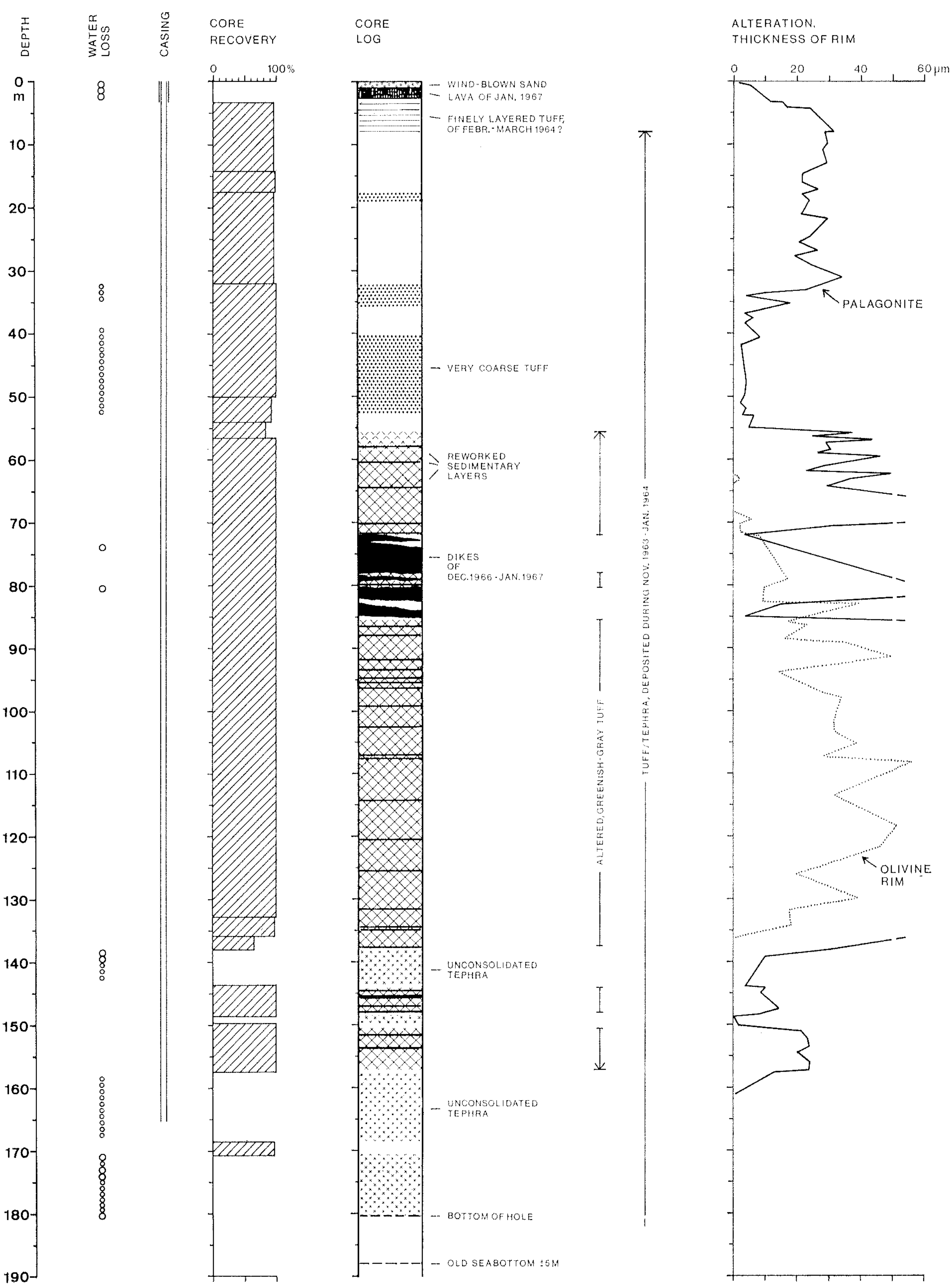
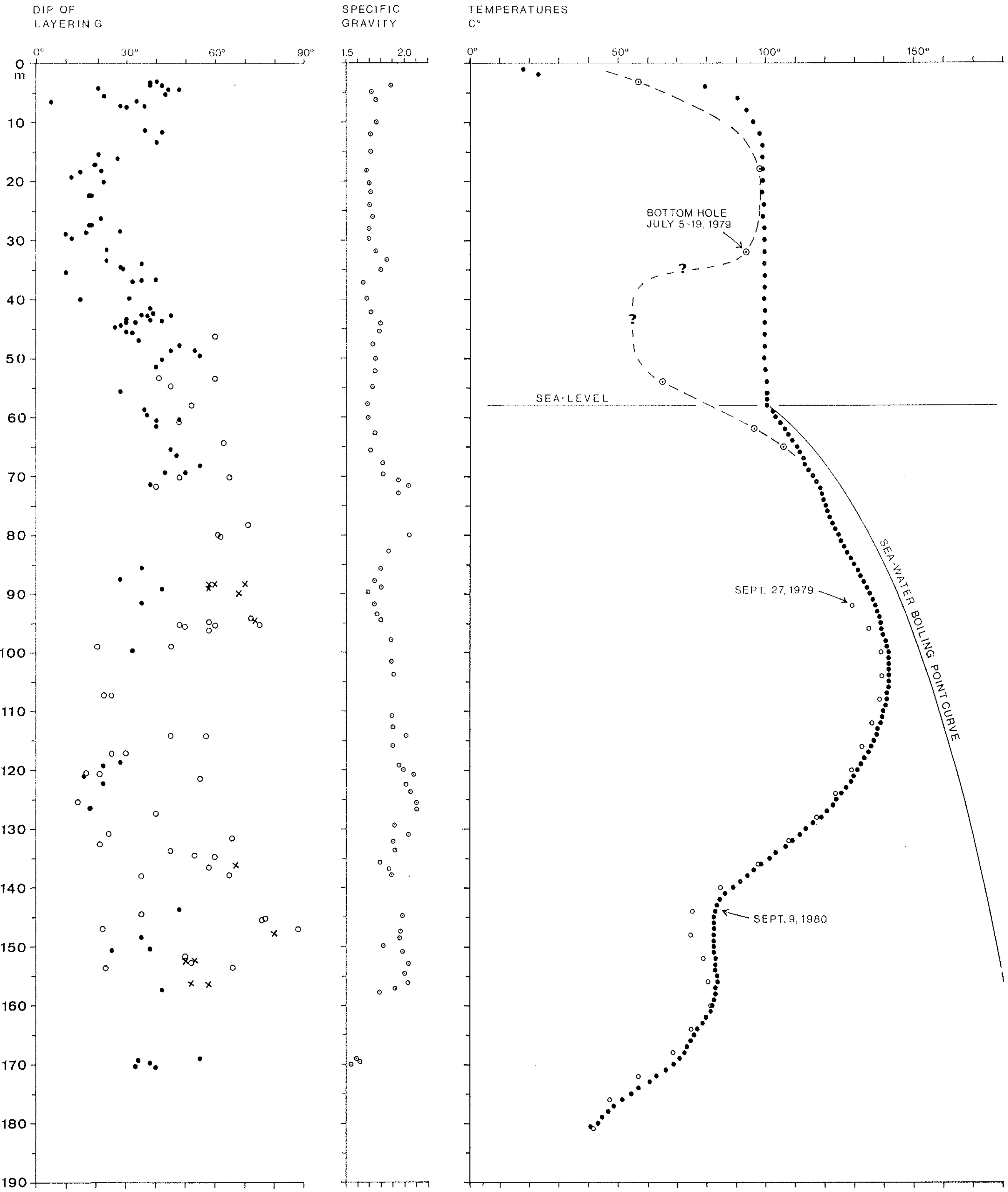


Fig. 7. Graphic core log. Water loss is indicated by large circles (complete loss of drilling fluid), and small circles (partial to heavy loss). Alteration is shown by thickness of alteration rims on sideromelane and olivine grains; above 50 μm measurements are inaccurate. Distinction is made between two types of layering: primary bedding (black dots), presolidification slumping planes (open circles); postsolidification shear planes are also indicated (crosses). Also shown is wet specific gravity of solid core, along with temperature measurements of July 1979, September 1979 and September 1980.


DIP OF
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BOTTOM HOLE
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SEA-LEVEL
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SEA-WATER BOILING POINT CURVE
SEPT. 9, 1980

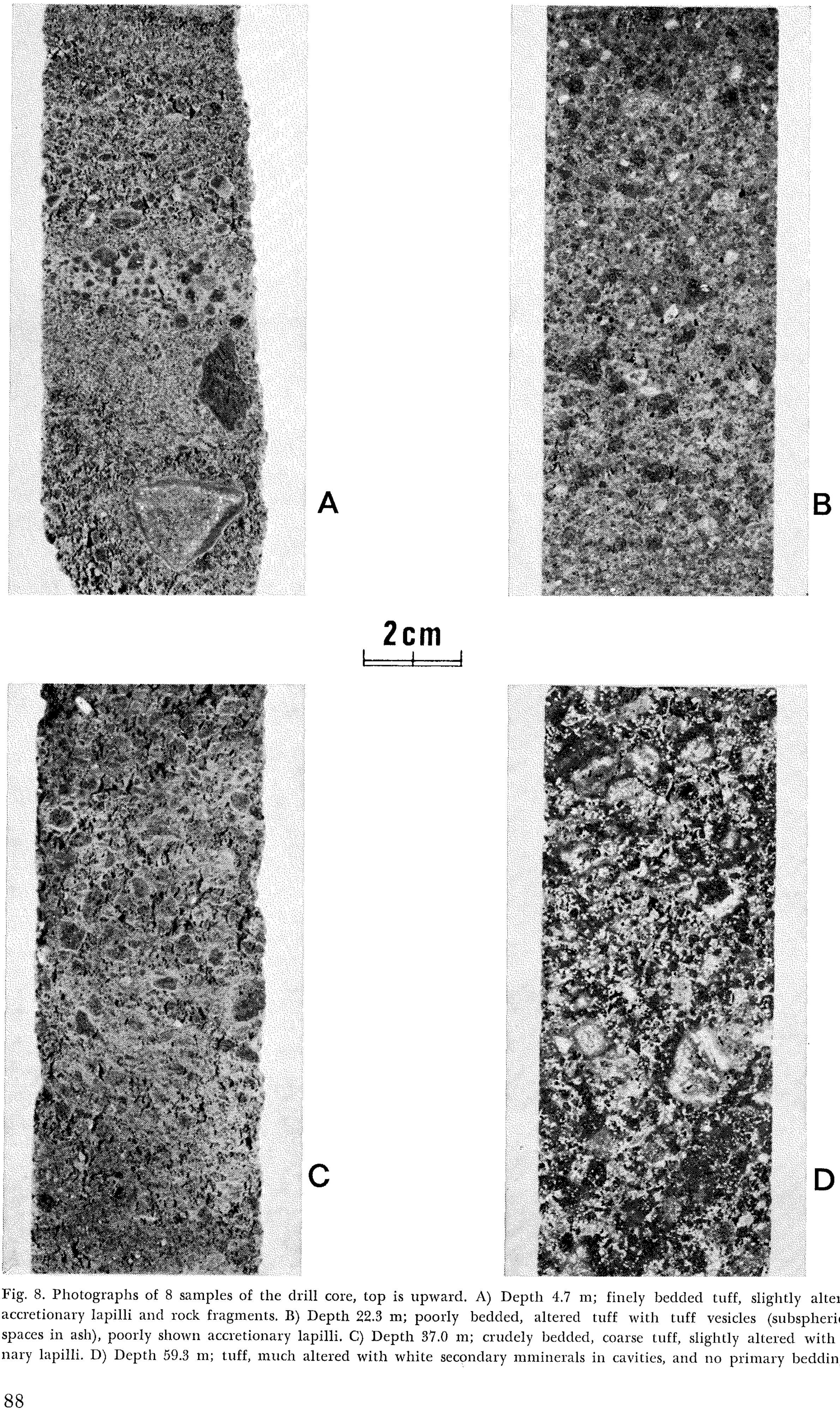
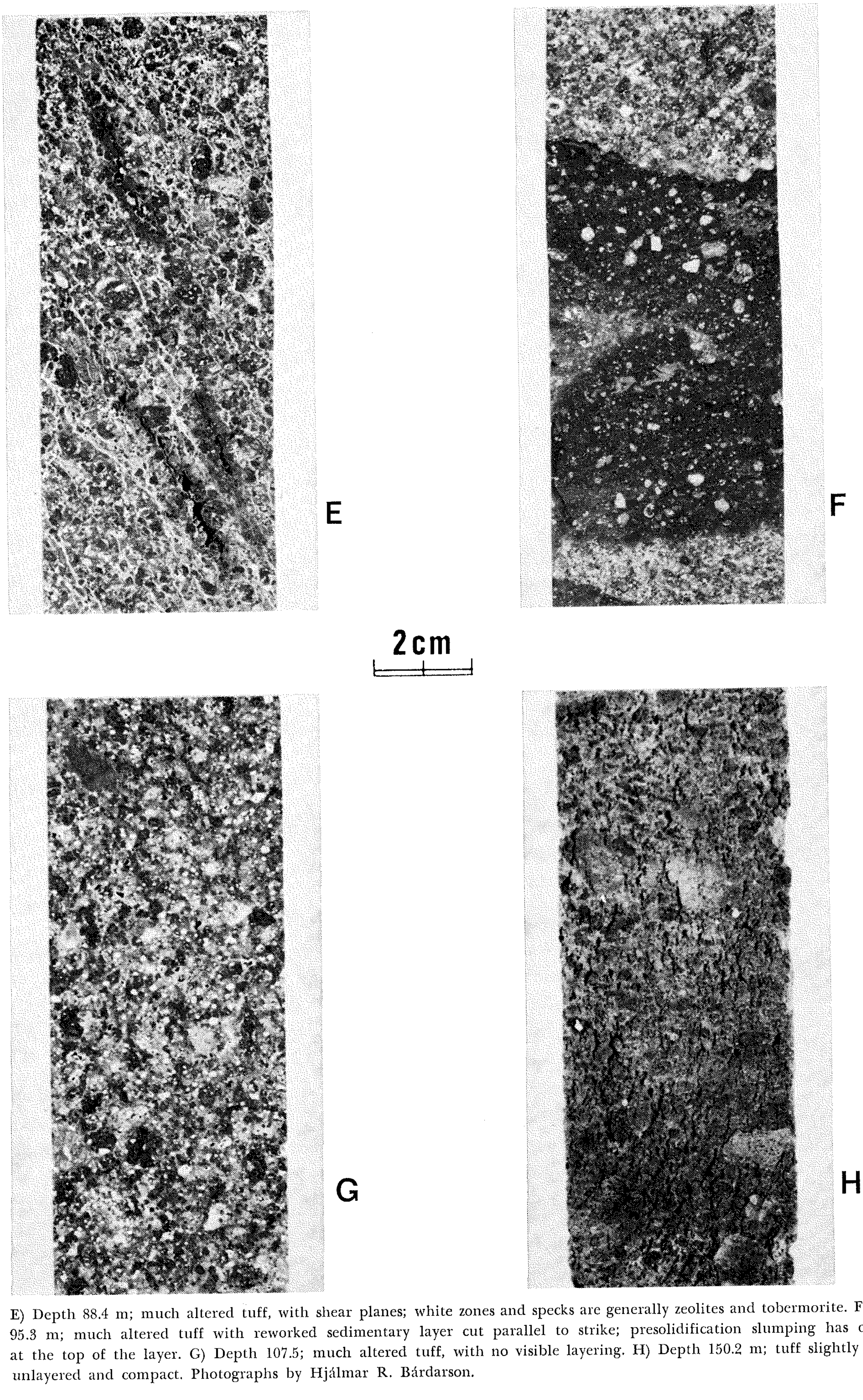


Fig. 8. Photographs of 8 samples of the drill core, top is upward. A) Depth 4.7 m; finely bedded tuff, slightly altered, with accretionary lapilli and rock fragments. B) Depth 22.3 m; poorly bedded, altered tuff with tuff vesicles (subspherical open spaces in ash), poorly shown accretionary lapilli. C) Depth 37.0 m; crudely bedded, coarse tuff, slightly altered with accretionary lapilli. D) Depth 59.3 m; tuff, much altered with white secondary mminerals in cavities, and no primary bedding visible.



E) Depth 88.4 m; much altered tuff, with shear planes; white zones and specks are generally zeolites and tobermorite. F) Depth 95.3 m; much altered tuff with reworked sedimentary layer cut parallel to strike; presolidification slumping has occurred at the top of the layer. G) Depth 107.5; much altered tuff, with no visible layering. H) Depth 150.2 m; tuff slightly altered, unlayered and compact. Photographs by Hjálmar R. Bárdarson.

grayish brown. Below 53.8 m traces of white secondary minerals appear, and at 58.5 m they make up more than 1 volume percent, and rapidly increase downwards. Below about 57.4 m the tuff is highly altered and assumes a greenish hue, and at 59.5 m the rock is distinctly greenish gray, cf. Fig. 8D. The uppermost reworked sedimentary layer occurs at 58.0 m depth, but between 53.1 and 58.0 m a few „muddy“ layers occur. The shallowest distinct slumping plane occurs at 53.3 m, however, there is possibly one at 46.4 m depth. An apparent transition occurs at about 72 m depth below which the tephra may be deposited as „slush“ in water.

71.9 – 84.8 m

Dikes, irregular; dipping about 60°-80°; the tuff is intercalated between the dikes at 72.6 – 73.0 m, 78.4 – 78.8 m, 79.2 – 80.4 and 82.1 – 82.8 m, and is mostly brownish black and only slightly altered (Fig. 7). The dikes are unaltered alkali olivine basalt, with phenocrysts of Cr-spinel, olivine and plagioclase and are petrographically indistinquishable from the lava at 1.0 – 2.7 m depth. The dikes show quenched glassy margins against the tuff.

84.8 – 138.1 m

Tuff; poorly layered, dense, much altered, greenish gray with white specks (cf. Fig. 8 E,F,G). A few blocks and pumiceous fragments occur. Many reworked sedimentary layers (Fig. 8F) and slumping planes are present. This unit grades into brownish unaltered tuff at the bottom.

138.1 – 143.8 m

Tephra (sand?); unconsolidated and unaltered; no sample was collected between 138.1 – 140.0 m, as all the drilling fluid was lost, and only cuttings were obtained between 140.0 – 143.8 m. More resistant layers may be present in this unit, as indicated by variations in the drilling rate.

143.8 – 148.5 m

Tuff; poorly layered, dense, much altered, greenish gray. Brownish and unaltered at contacts with units above and below.

148.5 – 149.7 m

Tephra (sand?); unconsolidated and unaltered; only drill cuttings are available.

149.7 – 150.4 m

Tuff; poorly layered and porous, unaltered and brownish (Fig. 8H).

150.4 – 157.4 m

Tuff; poorly layered and dense, much altered, greenish gray. Brownish and unaltered at the contact with the unit below.

157.4 – 168.6 m

Tephra (sand?); unconsolidated and unaltered; only drill cuttings are available.

168.6 – 170.0 m

Tuff; layered, porous, slightly altered and brownish.

170.5 – ~176.5 m

Tephra (sand?); unconsolidated, unaltered; only drill cuttings are available, expect at 171.0 – 171.4 m and 172.6 – 174.9 m, where no samples were collected.

~176.5 – 180.6 m

Sand or tephra; unconsolidated and unaltered, no samples below 180.1 m as all the drilling fluid was lost; only coarse sand, no fines came up with the drilling fluid.

Accretionary lapilli and vesiculated tuff.

Accretionary lapilli or mud balls (Moore & Peck 1962) are common in the Surtsey tephra, especially in the inner slopes of the tephra rings (Lorenz 1974a). They are also common in the core at depths between 2.7 – 17.3 m and 32.4 – ~57.0 m (Fig. 8A and C). Between 57.0 – ~72 m depth accretionary lapilli are less common, and below about 72 m they are apparently scarce. However, alteration and compaction at deeper levels makes positive identification of accretionary lapilli difficult. The accretionary lapilli generally contains a core of a single grain of glass or basalt around which is an accreted layer of very fine ash, commonly about 0.10—0.25 mm thick, but on a few larger lapilli up to 0.6—2 mm thick. The fine accreted layers are believed to have formed when wet lapilli nucleii were thrown into an ash cloud containing abundant steam. It is noteworthy that accretionary lapilli do not seem to occur in tuff layers with dip less than about 22° (Fig. 7). The rather abrupt change in the occurence at about 72 m depth may indicate the transition from tephra deposited subaerially to tephra deposited as „slush“ in water.

Vesiculated tuff is commonly found in surface layers on Surtsey (Lorenz 1974a), and is common at depths between 2.7 – 32.4 m (Fig. 8B).

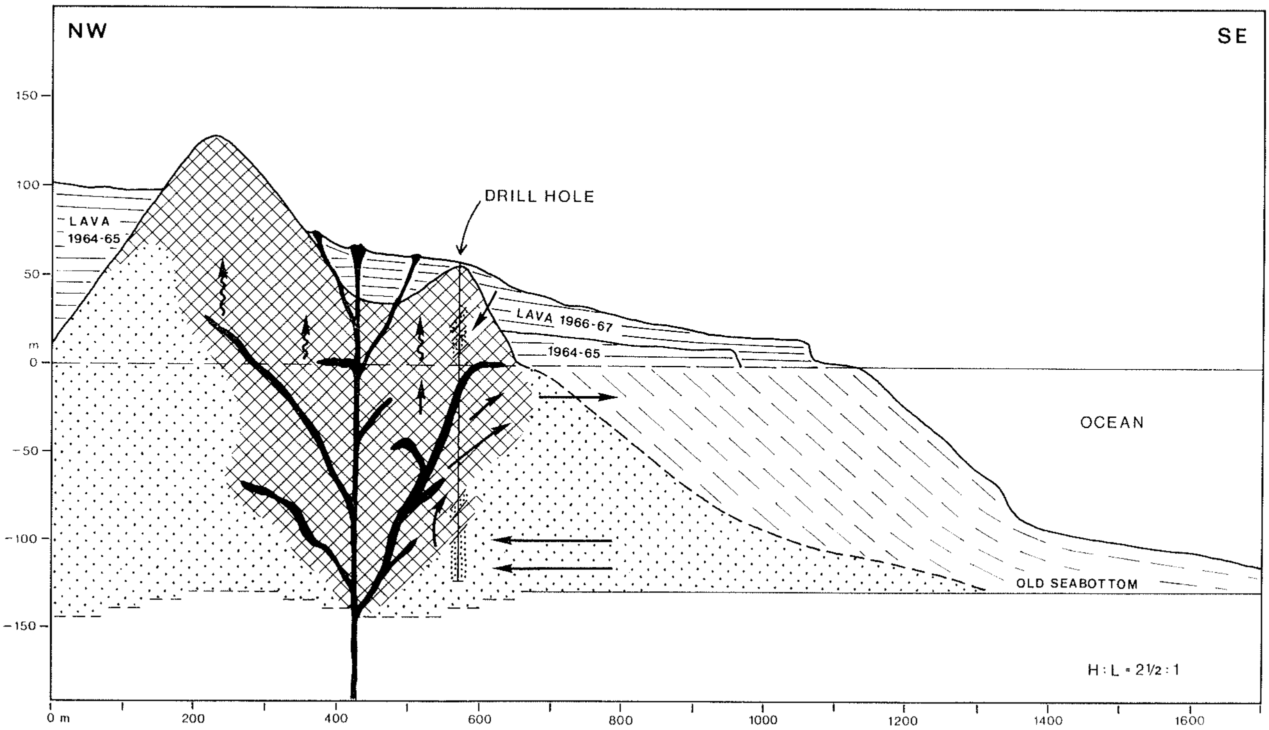


Fig. 9. Profile through the eastern tephra and lava craters, and the drill hole, from NW to SE. The pyroclastic material formed between November 14, 1963 and April 4, 1964 and is dotted, and the estimated distribution of consolidated rock is cross hatched. The coarse permeable tephra layers encountered in the hole are shown by fine stippling and feeder dikes and other instrusions of 1966-1967 are black. Arrows indicate suggested flow direction of water (straight arrows) and steam (undulating arrows) in the southeasternmost part of the island. See text p. 92 for discussion.

The vesicles are most conspicuous at 17.3 — 32.4 m depth, i.e. where the tephra layers dip less than 30°, and where there are no accretionary lapilli. Vesiculated tuff is considered an indicator of phreatomagmatically formed base surges (Lorenz 1974b). The vesicles are up to several mm in size and are commonly rounded, though irregular in shape and are moulded against the margins of larger pyroclasts. They are apparently produced by steam and other gases included in wet ash.

Planar structures

Distinction is made between three types of planar structures: primary layering or bedding (defined by crude size sorting), slumping planes, and faults formed after partial or complete consolidation of the layers. Dip measurements on all easily recognized layers are plotted in Fig. 7. Plotted dips assume the hole is vertical; direction of dip is unknown in the unoriented core.

The dips of the primary bedded layers range from 5°-55° (89 measurements), and average 33°. Primary layering is less common below about 72 m depth (Fig. 7). Above this level the average dip decreases regularly from about 45° at 72 m depth to about 18° at 20-25 m depth, where it rises again to an average of 40° at the surface.

Secondary planes, which clearly indicate slumping in soft, wet layers occur below 40 m depth, and are especially common below 94 m depth. These slump planes are commonly associated with reworked sedimentary layers (Fig. 8F). The dip of these planes are usually considerably steeper than that of the primary layers (Fig. 7). The dip ranges from 14° to 89° (50 measurements), and average 48°.

In 13 places, between 88-157 m depth, secondary planes occur which are indicative of shearing (faulting) in semiconsolidated material (Fig. 8E). These shears occur in zones, commonly with open fractures, partly filled with secondary minerals. The faulting appears to have occurred before most of the secondary minerals were formed and before complete alteration and compaction of the tuff.

Density and porosity measurements

Specific gravity of the drill core was determined by weighing and measuring the volume of sections of the drill core and determining the loss of weight when immersed in water. Since it was not possible to entirely dry much of the core, all of the reported values are the specific gravity of wet core. The specific gravity generally compares directly with the degree of alteration of the core (compare Fig. 7). Down to about 70 m it averages 1.7–1.8. From 70–160 m depth it averages about 1.9. The short segment of relatively unaltered core at 170 m depth averages about 1.7.

Reworked sedimentary layers

About 40 silty layers were encountered between 58.0 and 153.6 m depth (Fig. 7). The thickness of these layers varies between 0.3 and 3.6 cm for all but two layers, which measure 10.5 and 22 cm. The average thickness of the layers is 1.9 cm, and the total vertical thickness is 76 cm. The layers are commonly associated with slump planes which have an average dip of 48°.

These layers (Fig. 8F), which are made up of the same consituents as the primary tephra, show considerable sorting; the finest and coarsest-grained fractions have disappeared leaving silty material. Rarely, single large grains or parts of unsorted tephra layers are present in the layers. At 53.4–57.7 m depth there are several „muddy“ layers. These have no sharp contacts and are often vesicular. The layers may be interpreted as mud spatter from the tephra crater.

The reworked sedimentary layers may have formed when slumping of the water-saturated tephra pile occurred at the time of deposition. These layers tend to be regularly spaced (Fig. 7). Many of the layers are 4.5 – 6.5 m apart, although a spacing of <1 m between layers is not uncommon. Slumping apparently occurred rythmically as the pile gradually built up. Perhaps the periodic slumping was triggered by tidal currents.

THE HYDROTHERMAL SYSTEM

A general idea of the geometry of the hydrothermal system in the eastern part of Surtsey is based on observations during the eruption, surface geology, sea floor topography, and drill hole data (Fig. 9). The direction of dip of the tephra layers encountered in the hole is not known. The flatter dips near the surface may represent strata near the crest of the crater rim. Steeper dips at greater depth may represent strata deposited either within the crater or on the outer flanks. The close proximity of the drill hole to the eastern vent lava crater (140 m, Fig. 2) suggests that the strata dips southwest and hence was deposited within the crater on the inner crater walls. Likewise the dikes presumably also have a westerly dip so as to connect the main volcanic conduit beneath the vent center with the small flank eruptive vents active in 1966-67.

Porous unaltered tephra or sand layers were encountered at depths of 138.1 – 143.8 m, 148.5 – 149.7 m, 157.4 – 168.6 m, and 170.5 – 180.6 m (Fig. 7). In the bottom layer temperatures of 40°-60° C were recorded in 1979 and 1980, and since the other porous layers show only minor signs of alteration, similar temperatures may have prevailed in them. It is likely that cold sea water has entered the hydrothermal system through these deep porous layers, as also suggested by the high transmissivity observed at the bottom of the drill hole (Tómasson and Snorrason, 1982).

The zone of highly altered tuff below sea level corresponds closely with the zone of highest temperature measured in the hole (Fig. 7). Because of the growth of abundant secondary minerals in this heated environment, this rock has the lowest estimated permiability of any part of the hole (2.5×10^{-13} m^2) while the less altered tuff above sea level has a considerably higher permiability (1.4×10^{-10} m^2) (Axelsson et al., 1982).

Ground water, largely marine in origin, heated by contact with dikes and intrusions, produced this alteration and then rose and flowed probably eastsoutheast back to the sea near sea level. It is replaced by cold sea water flowing in from the bottom probably also largely from the east side of the island.

The temperature within the drillhole in a zone extending from sea level down for 40 m is only slightly lower than the boiling point curve (Fig. 7). Hence in this hot zone the ground water is no doubt boiling at certain favourable places and times depending on the state of the tide, the downflow of cool meteoric water, and other factors. Consequently a steam phase will rise through the tephra above sea level and will be concentrated in fractures and other favourable zones where it will heat the tephra to about 100° C.

During wet weather cold meteoric water from above will seep down especially through permeable layers. Perhaps the coarse tephra layers at 32.4 – 35.7 m and 40.4 – 52.5 m are only slightly altered because they served as channels for such descending cool, meteoric water.

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