Observations on the Structure of Surtsey, Iceland, and its Basaltic Lapilli Tuff

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Summary

New investigations of the 1979 and 2017 cored boreholes coupled with observations of the dynamic surface of Surtsey have modified concepts of the subsurface structure of the volcano, an oceanic island that erupted from 1963–1967 on the insular shelf of the south coast of Iceland. Temperature anomalies in the 2017 vertical and inclined boreholes closely resembled each other in shape and magnitude even though they are ~100 m apart horizontally. The peak temperature of the vertical hole anomaly immediately after drilling was 124 °C at 105 m below surface (m b.s.) and the inclined hole anomaly 127 °C at 115 m b.s. The paucity of coherent basalt in the 2017 cores casts doubt on a previous concept — that the heat anomaly in the 1979 borehole, 141 °C at 100–106 m b.s., was due to nearby intrusions. The new observations suggest instead that top-down heating from the subaerial lava shield may have contributed to the thermal anomaly. In August 1966–June 1967, lava flows rapidly filled the Surtur vent crater to 80 m b.s. and overflowed to the south and east. Conduction of heat from the cooling shield into the water-saturated substrate would have been influenced by the material characteristics of the underlying lapilli tuff, but the mechanisms of downwards heat transfer are not clear. In the zone of tidal flux centred at ~58 m b.s., the tuff was highly porous in 1979 and it remains porous and permeable 38 years later. Boiling of interstitial water below sea level could have produced steam that rose and warmed the porous and permeable tephra adjacent to the lava shield, where it produced broad areas of palagonitized tuff. Other heat sources are also under consideration.

Abundant granular and microtubular structures occur in fresh glass of the original 1979 thin sections at 107 m b.s. (141 °C in 1980). These resemble endolithic microborings. They are perhaps indicative of an early, short-lived episode of functional microbial activity at <120 °C.

A geometrical analysis of layering in unrolled digital scans of the 2017 cores indicates that the relation of the apparent dip to the true dip of layering in the core inclined 55° from horizontal is such that steep dips are more common in westerly true dips, and gentle dips are more common in easterly true dips. The measurements indicate that near-surface layering in both the vertical and inclined cores dips westerly, suggesting that the boreholes are located inside the Surtur crater. In this proximal setting, the section of lapilli tuff may be almost entirely composed of facies resedimented from unstable depositional sites and/or recycled through the vent perhaps multiple times.

High porosity, high water absorption and low unit weight in certain sub-seafloor lapilli tuff samples are associated with vesicular cavities in the altered vitric matrix and pyroclasts with narrow ash rims. These reflect complex eruptive processes: sub-seafloor explosions, subsidence and down-slumping of previously erupted tephra.

Overall, the new observations support the hypothesis that a broad conduit and vent filling deposits underlie Surtur crater.

THE ORIGIN AND EVOLUTION OF THE TEMPERATURE MAXIMUM AT 100-120 m b.s. REMAINS UNCLEAR.
TUBULAR MICROBORINGS IN THIS ZONE GREW TO 30 μm LENGTHS IN 12 YRS, 141°C IN 1979.

1979 and 2017 Surtsey Boreholes

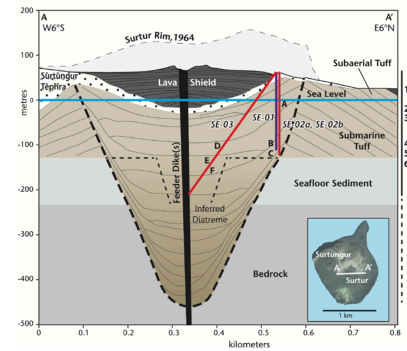


Figure 1. 1979 (SE-01) and 2017 (SE-02A, SE-2B, SE-03) boreholes. No intact sea floor deposits have been traversed by Surtsey drill cores. A postulated diatreme (Moore, 1985) is supported by the 2017 drilling results. The form and depth of subsurface basaltic deposits remain unclear (Jackson et al., in press, *Surtsey Research*) but a layered structure suggests downslumping of previously erupted tephra towards the central vent (Figs. 5–8). A–F show sites of petrographic micrographs (Fig. 11).

Geometrical Analysis of Layering, 2017 Inclined Borehole SE-03

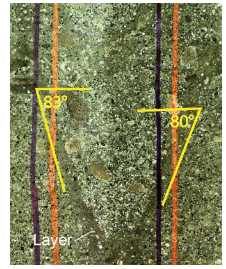
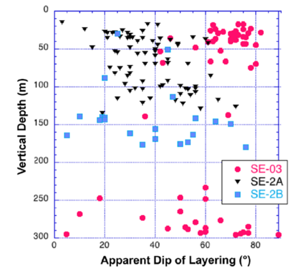


Figure 5. Unrolled digital scan (20 cm across) of 2017 SE-2A core, 38.3 m b.s. A planar dipping dark ash layer is expressed as a sine curve. The apparent dip is the angle between each of the steep parts of the curve and a plane normal to the core axis. The average dip is 71°.



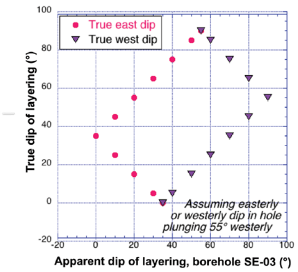


Figure 6. Dip of layering in boreholes SE-02A, SE-02B, and SE-03 as measured from unrolled digital scans.

Figure 7. Relation between the apparent dip of bedding in inclined borehole SE-03 that plunges 55° W and the true dip, assuming that the dip is either easterly or westerly. Gentle apparent dips in the drill core generally indicate true easterly dips and steep apparent dips generally indicate true westerly dips.

All figures after Moore & Jackson, in press, *Surtsey Research*

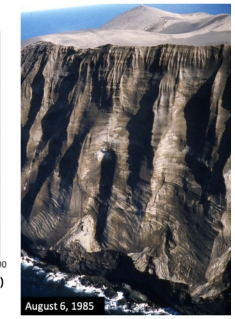


Figure 8. The 140 m-high seacliff on the west side of Surtsey. The east-dipping tuff layers apparently belong to the west side of the postulated diatreme beneath the Surtungur vent complex. Note that the dip of layering becomes steeper downward. After Jakobsson et al. (2013).

LAYERING DIPS SYSTEMATICALLY WESTWARD IN LAPILLI TUFF DEPOSITS ABOVE ~70 m b.s.
THIS SUPPORTS THE CONCEPT OF A WIDE CONDUIT WITH A RIM EAST OF THE BOREHOLES.

Porous Layers and Sub-Seafloor Microstructures

THE SUBSEAFLOOR DEPOSITS HAVE STRONGLY HETEROGENEOUS MATERIAL PROPERTIES. POROUS ZONES WITH LOW UNIT WEIGHT (1.4–1.6 gr/cm^3) AND HIGH WATER ABSORPTION (19–21 %) HAVE LARGE VESICLES AND PYROCLASTS WITH NARROW ASH RIMS (RS 22, 24-26, 30) (Fig. 11 E, F). COMPACT ZONES WITH HIGH UNIT WEIGHT (2.13–2.19 gr/cm^3) AND LOW WATER ABSORPTION (8–9 %) HAVE A DENSE ASH MATRIX AND FEW VESICLES (RS 27, 28, 32).

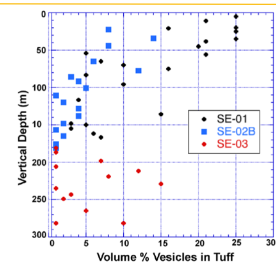


Figure 9. Volume % vesicles in lapilli tuff measured in thin sections, SE-01, SE-02B, and SE-03. After Moore & Jackson, in press, *Surtsey Research.*

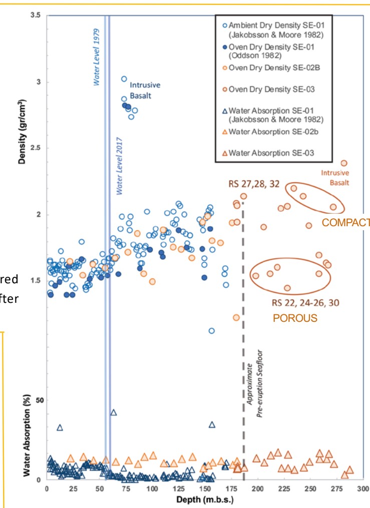


Figure 10. Water absorption and rock density of Surtsey lapilli tuff and basaltic intrusions, based on measurements by Jakobsson & Moore (1982), Oddson (1982), and Jackson et al. (2019a). After Jackson, in press, *Surtsey Research.*

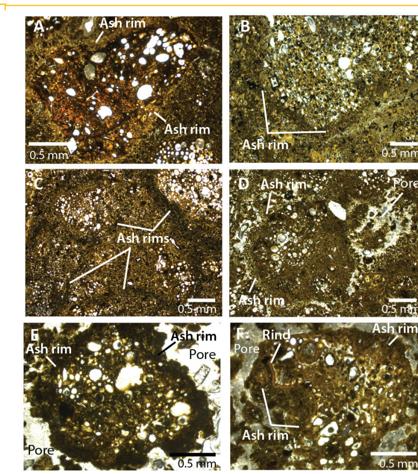


Figure 11. Petrographic images of coarse ash- and lapilli-sized particles with rims of fine ash in submarine and sub-seafloor lapilli tuff, 2017 Surtsey cores, plane polarized light except (A). A) Near water level, 65.8 m b.s., 110.3 °C in 1980, 102.8 °C in 2017; altered glass particle with rim of birefringent fine ash, SE-02B, cross polarized light. B) Near submarine inflow zone, 154.1 m b.s., 83°C in 1980, 82 °C in 2017, SE-02B; weakly altered glass lapillus with opaque, non-birefringent, altered fine ash rim. C) Lowermost submarine zone, 170 m b.s., 68.6 °C in 1980, 62.1 °C in 2017, SE-02B; clot of tephra agglomerations surrounded by dark gray ash rims. D) Sub-seafloor lapilli tuff, 220.4 m measured depth, 58 °C in 2017, SE-03 (RS19); altered glass particle with rim of angular fine ash, surrounded by narrow cavities filled with mineral cements. E) Sub-seafloor lapilli tuff, 258.9 m measured depth, 57 °C in 2017, SE-03 (RS24); altered glass particle with dense rim of fine ash, surrounded by open cavities. F) Sub-seafloor lapilli tuff, 267.2 m measured depth, 57 °C in 2017, SE-03 (RS25); altered glass particle with thick rim of sub-angular coarse and fine ash, surrounded by cavities filled with mineral cements. Temperature measurements from Jakobsson & Moore (1982), Jackson et al. (2019a). After Jackson, in press, *Surtsey Research.*

Hypothesized Lava Shield Heat Source

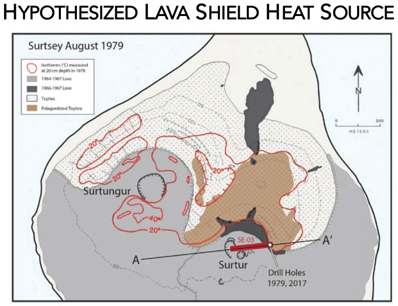


Figure 2. Map of Surtsey in 1979 shows 1964–1967 lavas in gray. Tephra is dotted and extent of palagonitized tephra is brown. Temperature of 1979 hydrothermal area measured at 20 cm depths shown by red isotherms. Profile of **Figure 1** is black line, with red segment the surface projection of 2017 inclined borehole SE-03. Vertical boreholes SE-01, SE-02A and SE-02B occur at the east end of the red segment. After Jakobsson & Moore (1982b), Jackson et al. (2019a), Moore & Jackson, in press, *Surtsey Research.*

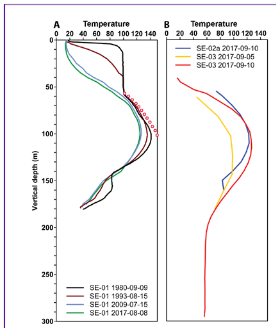


Figure 3. Temperatures in Surtsey boreholes. A) 1979 SE-01 temperatures, measured in 1980, 1993, 2009, and 2017; red dotted line is boiling point curve. B) SE-02a and SE-03 borehole temperatures, measured in 2017. After Jackson et al. (2019a).

1979 Endolithic Microborings

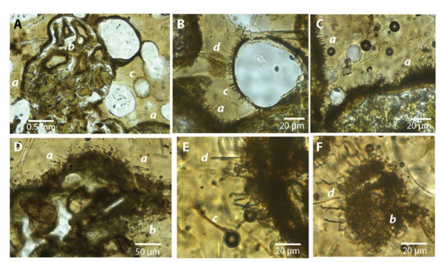


Figure 4. Petrographic images of microtubule and granular microstructures, interfacial zones with narrow protrusions, and possible endolithic microborings in glass lapilli of the original 1979 Surtsey thin sections (79S), plane polarized light. Labels a, b, c, d refer to sites of tubules and granular features. A, B, C) 79S, 36.4 m.b.s., 70.8 °C in 1980. D, E, F) 79S, 107.5 m.b.s., 140.8 °C in 1980. Temperature measurements from Jakobsson & Moore (1982), Jackson et al. (2019a). After Jackson, in press, *Surtsey Research.*

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