Measurements of the inclination of the SE-03 Borehole on Surtsey Volcano

TOBIAS BJÖRN WEISENBERGER[1*], MAGNÚS TUMI GUDMUNDSSON[1], BJARNI STEINAR GUNNARSSON[2,3], STEFFEN L. JØRGENSEN[4] AND MARIE D. JACKSON[5]

[1] Institute of Earth Sciences, University of Iceland, Reykjavík, Iceland (tobias.weisenberger@t-online.de)

[2] Verkís Consulting Engineers, Reykjavík, Iceland

[3] ÍSOR, Iceland GeoSurvey, Kópavogur, Iceland

[4] Centre for Deep Sea Research, Department of Earth Science, University of Bergen, Bergen, Norway

[5] Department of Geology and Geophysics, University of Utah, Salt Lake City, Utah, USA

*corresponding author

ABSTRACT

The inclined SE-03 borehole drilled in 2017 provides a unique opportunity to further examine the stratigraphy and submarine structure of Surtsey. The borehole was drilled towards west (azimuth 264°) with inclination of 35° from vertical. Downhole measurements conducted in August 2021 using a STP-8 inclinometer confirmed that any discrepancy in the orientation of the borehole is minor and does not affect the overall interpretation of the location of the SE-03 drill core. The average inclination of the borehole from vertical is 33.4±0.2°. The bottom of the borehole at 354.05 m measured depth corresponds to a total vertical depth of 294.7±1.2 m. This is 4.7 m deeper than the designed borehole path. The horizontal length from the well head to the point vertically above the bottom of the borehole is 195.1±1.0 m, which is about 8 meters less than the designed borehole path (203.1 m). Correcting for this 1.4-1.8° discrepancy between the planned inclination and the actual value gives greater accuracy in the location of the units cored. The results confirm the location of an intrusion directly beneath the Surtur crater, considered to be the feeder dyke for its eruption in 1966-67.

INTRODUCTION

In the summer of 2017, the International Continental Scientific Drilling Program (ICDP) SUSTAIN project drilled three cored boreholes through Surtsey at sites about 10 m from a cored borehole drilled in 1979 (Jackson *et al.* 2019; Weisenberger *et al.* 2019). Two of the holes were vertical (SE-02a and SE-02b) and one (SE-03) was inclined i.e. drilled at an angle. Drilling of all three holes through the still hot subsurface was conducted from the same drilling platform, adjacent to the 1979 hole (SE-01, Jakobsson & Moore 1982). Table 1 provides a summary of the 1979 and 2017 boreholes.

The purpose of the cored SE-03 borehole was to study the existence of a possible diatreme underlying Surtur crater (Moore 1985) through examining tephra deposits, dykes and other vent facies that can provide additional information on deep stratigraphy and submarine structure. It was planned as 300 m long inclined hole with steel casing (Jackson *et al.* 2015). SE-03 was the last hole drilled during the drilling campaign in 2017; coring took place between August 28th and September 4th. The hole was directed towards west (azimuth 264°) and had an angle of 35° from vertical. It reached a measured depth of 354.05 m, giving a presumed 290 m vertical depth under the eastern sector of Surtur crater. The core thus traverses the deep conduit and intrusions (feeder dyke) of the Surtur eruptions (McPhie *et al.* 2020;

Table 1: Boreholes drilled in Surtsey in 1979 (SE-01) and 2017 (SE-02a, SE-02b, SE-03) (based on Weisenberger *et al.* 2019).

Bore-hole name	Hole ID	Coordinates (WGS84)	Flange height (m a.s.l.)*	Reference level during drilling (m a.s.l.)*	East** North** (m)	Horizontal Distance from SE-01 (m)	Depth** * (m)
SE-01	73552	63° 18.09749'N 20° 35.98221'W	58.40	-	419756.79 311669.86	0.00	180.6
SE-02a	73553	63° 18.09659'N 20° 35.99063'W	58.01	57.57	419749.70 311668.38	7.08	152.01
SE-02b	73554	63 18.09739'N 20° 35.99020'W	57.86	57.65	419750.11 311669.85	6.86	191.85
SE-03	73555	63° 18.09649'N 20° 35.99170'W	58.13	57.65	419748.81 311668.22	9.92	354.64

* a.s.l.: above sea level; ** Reference coordinate system: ÍSN93; *** SE-03 is inclined 35° from vertical; depth is along hole axis.

Weisenberger *et al.* 2019). Investigations of the SE-03 core will further clarify the internal structure and facies architecture of the type locality of Surtseyan volcanism (Thorarinsson 1967).

Due to logistical issues no downhole logging apart from temperature measurements could be carried out in 2017 after drilling of SE-03. However, as the orientation of the hole is an important parameter when it comes to locating the core within the internal structure the Surtur crater and diatreme, measurements of the inclination of the borehole were conducted on August 5th, 2021.

BOREHOLE SE-03

The 2017 drilling was carried out by DOSECC Exploration Services of Salt Lake City, Utah, USA, using an Atlas Copco CS-1000 drill rig assembled on site after having been transported to the Surtsey island in parts by helicopter from the Icelandic Coast Guard vessel Þór moored offshore.

The SE-03 cored borehole was pre-drilled at 35° from vertical and azimuth 264° with a 6⅛" tricone rotary drill bit to a measured depth of 12.6 m. After lowering the 4½" HWT conductor casing to a casing shoe depth of 11.91 m, the conductor casing was cemented in place. After waiting on cement,

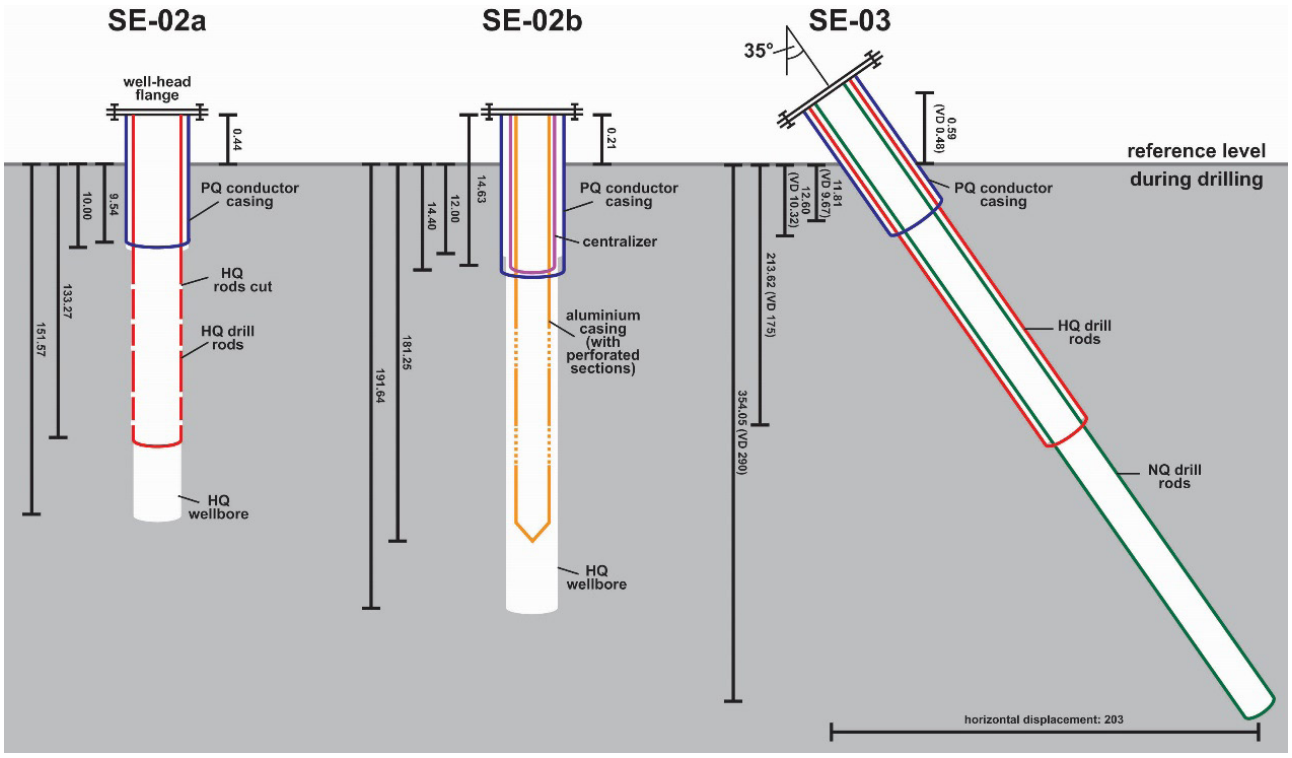

Figure 1. Schematic drawing of boreholes drilled on Surtsey in 2017. The inclined borehole dimensions are based on the planned 35° inclination (adapted from Weisenberger *et al.* 2019).

drill coring with a HQ3 bit tagged top of cement at 11.39 m. HQ coring (outer diameter: 88.9 mm, inner diameter: 77.8 mm) continued to 213.89 m measured depth, when the supply of HRQ drilling rods was fully exhausted. The HQ rods remain in the borehole to a measured depth of 213.62 m. Coring continued with an NRQ string (outer diameter: 69.9 mm, inner diameter: 60.3 mm). Coring with a NQ3 drill bit reached a total measured depth of 354.05 m. This corresponds to a presumed 290 m vertical depth below the ground surface and a horizontal displacement of about 203 m (Fig. 1). The NRQ coring string was left in the hole as permanent casing, including the NQ3 bottom-hole assembly. An extension of the HWT conductor casing was added and a flange was installed, at 0.48 m above the reference ground level. This corresponds to an additional borehole length of 0.59 m. Table 2 provides a detailed overview of the borehole design.

METHODS

Inclination measurements were carried out on August 5th, 2021, by an ÍSOR logging engineer using tools transported by helicopter to Surtsey (Fig. 2). The equipment consisted of a trip unit that was suitable for counting depth, a wireline line, logging instrument, and processing unit. The instrument was operated using the electrical generator stored at the Pálsbær II hut.

Table 2. Borehole specifications (based on Weisenberger *et al.* 2019).

Well name	SE-03
Total measured depth (m)*	354.05
Well-head flange height above drilling reference level (m)	0.59 (0.48 vertical height)
Total measured depth (m)**	354.64
6⅛” tricone rotary drilling (m)*	0-12.6
HQ drilling (m)* coring	11.39-213.89
NQ drilling (m)* coring	213.89-354.05
Casing information	
HWT conductor casing shoe depth (m)* (OD: 114.3 mm, ID: 101.6 mm)	11.91
HRQ drill rods left in hole (m)* (OD: 88.9 mm, ID: 77.8 mm)	213.62
NRQ drill rods left in hole (m)* (OD: 66.9 mm, ID: 60.3 mm)	354.05

* Drilling reference level, ** Reference level: flange, abbreviations: OD: Outer diameter, ID: inner diameter

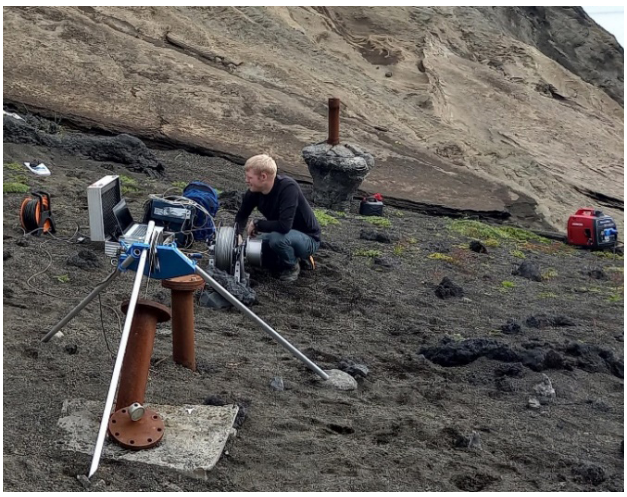

Figure 2. Photograph showing ÍSOR logging engineer conducting inclination measurements of the inclined borehole (SE-03) on August 5th, 2021.

The inclination tool (SPT-08 inclinometer) is a product manufactured by SPT (Stockholm Precision Tools) with the following specifications: inclination (dip) from 0-360° to within ± 0.1°, gravity toolface from 0-360° ± 0.1°, magnetic toolface from 0-360° ± 0.2°, total magnetic field from 0-100,000 nT accurate to ± 50 nT, dip from -90° from horizontal within ± 0.2°, tool temperature (borehole temperature) from -40 °C to +125 °C accurate to ± 1 °C, pressure 80 MPa, and length dimension 1650 mm with outer diameter 42 mm (in the pressure barrel). The tool weighs 10 kg.

The logging run was planned based on the existing temperature conditions in the hole, indicating a temperature maximum of about 140 °C at a measured depth of about 145-150 m (Weisenberger *et al*. 2021).

The inclination was measured every twenty meters during the downhole logging, except for the interval between 100 and 200 m measured depth where no readings were taken. The high temperatures within this interval largely exceed the operational range of the instrument. To avoid any temperature related damage the tool was lowered through this interval as quickly as possible. This was successful as no damage occurred.

Individual measurements were also made on the outrun, which confirmed the data obtained during the inrun measurements.

RESULTS

The results of the inclination measurements are shown in Table 3 and Figure 3. The data show a slight deviation from the planned inclination of 35°,

Table 3. Inclination measurements conducted on August 5th, 2021, comparison with planned inclination of 35°.

Depth	Inclination (from vertical)	Vertical depth	Vertical depth 35°	Vertical error (m)	Horizontal displacement	Horizontal length (35°)	Horizontal error (m)
0.00	36.54	0	0	0.00	0	0	0.00
10.00	36.39	8.0	8.2	-0.15	5.9	5.7	0.21
20.00	36.32	16.1	16.4	-0.29	11.9	11.5	0.38
40.00	35.56	32.3	32.8	-0.48	23.5	22.9	0.53
60.00	34.88	48.6	49.1	-0.52	34.6	34.4	0.19
80.00	34.40	65.1	65.5	-0.45	45.5	45.9	-0.41
100.00	34.24	81.6	81.9	-0.32	56.4	57.4	-0.98
200.00	32.70	165.0	163.8	1.19	110.3	114.7	-4.42
220.00	32.21	181.9	180.2	1.68	118.1	126.2	-8.13
240.00	32.36	198.8	196.6	2.21	128.2	137.7	-9.47
260.00	32.40	215.7	213.0	2.71	139.2	149.1	-9.89
280.00	32.40	232.6	229.4	3.22	150.0	160.6	-10.57
300.00	32.48	249.5	245.7	3.71	160.9	172.1	-11.15
320.00	33.16	266.3	262.1	4.14	173.4	183.5	-10.10
340.00	33.44	283.0	278.5	4.47	186.7	195.0	-8.35
354.05*	33.44	294.7	290.0	4.68	195.1	203.1	-7.97

*projected using same angle as at depth 340 m

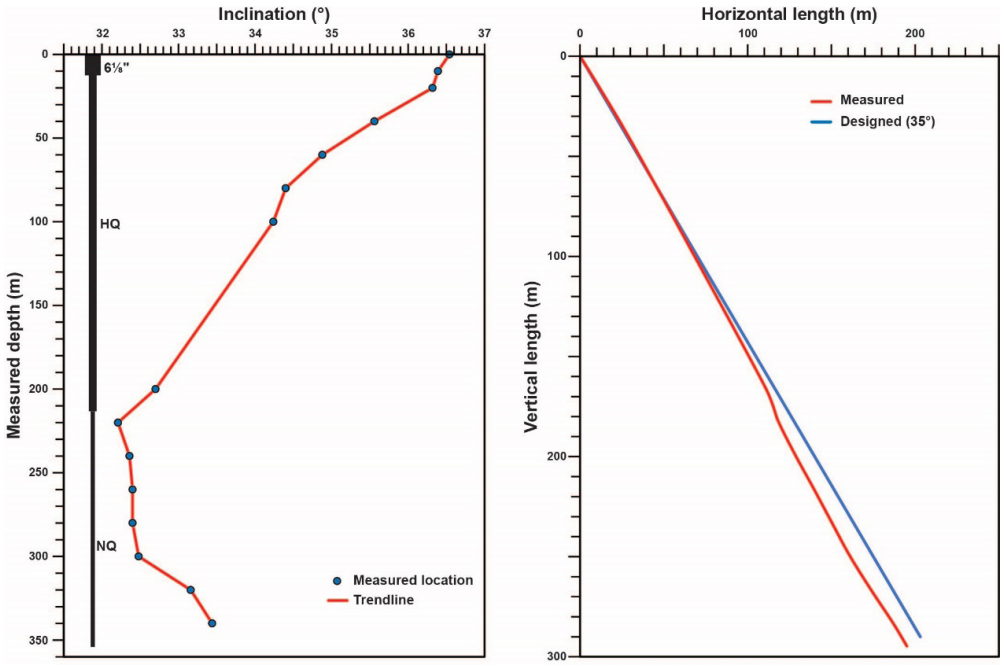

Figure 3. Diagram showing the measured inclination of the SE-03 borehole (left). The right graph shows the planned borehole path in comparison with the measured borehole path.

with the measured values ranging between 32.2° and 36.5°. This range is within the expected error margin for the drilling.

At the top, the borehole is inclined at a slightly higher angle, 36.5°, compared to the planned angle of 35°. With increasing depth and HQ drilling, the borehole inclination drops slightly by about 2° per 100 m measured depth. At 220 m measured depth the borehole has an inclination of 32.2°. The borehole inclination then increases again, at a rate of approximately 1° per 100 m measured depth. Overall, the average inclination is 33.4±0.2° from the surface to the bottom of the borehole. We cautiously assume that the average error in inclination may be 0.2°.

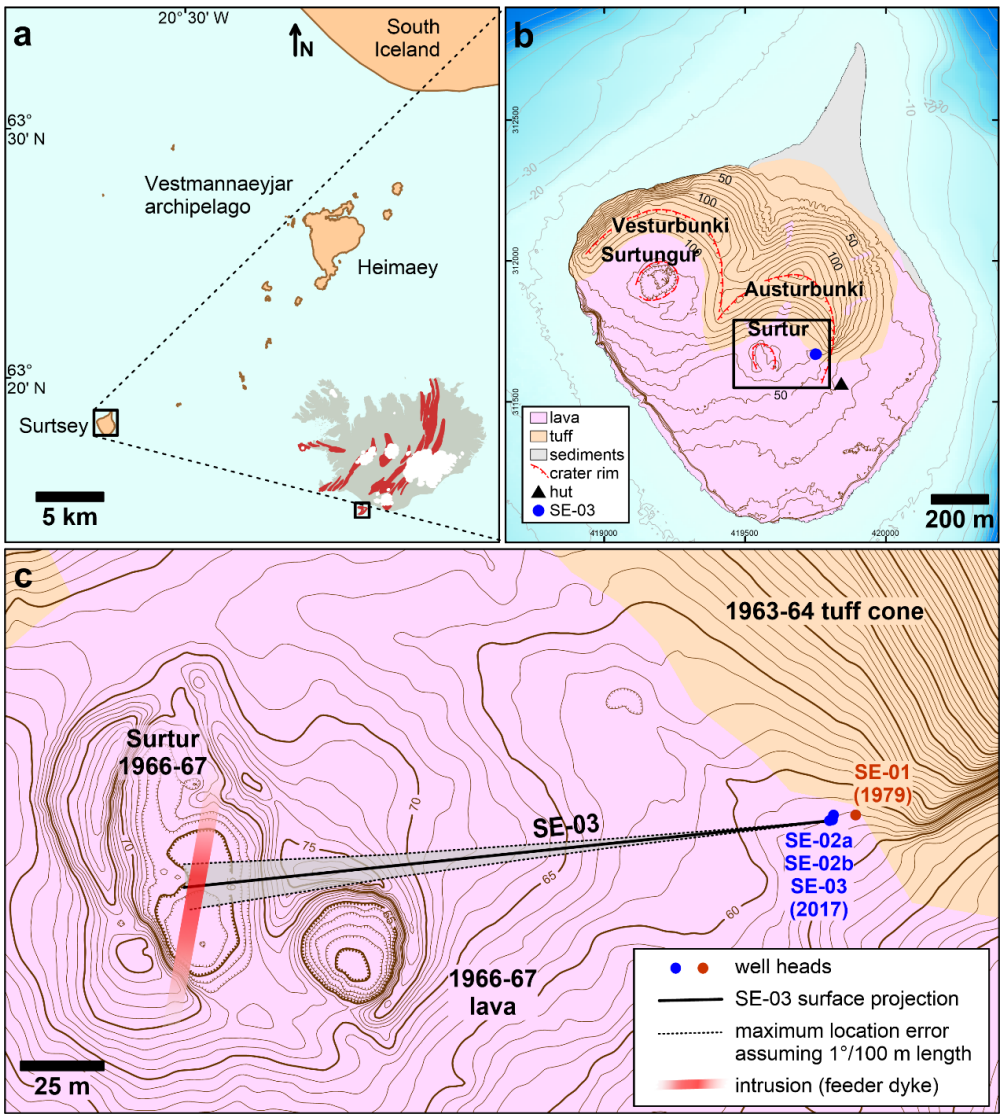

Figure 4. Location maps. (a) Vestmannaeyjar archipelago and Surtsey volcano. (b) The island of Surtsey. (c) Location of the inclined borehole SE-03 and its relation to the Surtur crater of 1966-67. The location of the intrusion encountered at 343-352 m measured depth is indicated with its likely orientation, based on Sigurður Þórarinsson's measurements of the 1966 volcanic fissure.

A build-up of inclination is observed within the section drilled with the smaller diameter NQ3 bit. The change of drilling diameter from HQ to NQ occurred at a measured depth of 214 m (Figure 3, Table 2). The change in the inclination trend from dipping to building up inclination at 220 m can apparently be related to the drilling activity and associated reduction of borehole diameter. The HQ drill pipe remained in the borehole, while drilling with the NQ3 bit commenced. Drilling with a smaller string and within a casing-supported upper section are plausible explanations for the observed change in inclination.

The measured difference in vertical orientation for the HQ section corresponds to an increase of 1.7 m at the end of the drilled section. A greater deviation in orientation results in a higher rate of vertical displacement for the NQ section. The corrected vertical depth at the bottom of the borehole is 294.7±1.2 m. This is 4.7 m deeper than the designed borehole path (Tables 2 and 3). The discrepancy in horizontal direction follows the same trend. The bottom of the borehole thus has a horizontal displacement of 195.1±1.0 m, about 8 meters less than the designed path of 203.1 m.

Figure 4 shows the surface projection of SE-03. The location of the approximately 5 m wide intrusion entered at a measured depth of 343-352 m (Weisenberger *et al.* 2019) is shown, using the initial trend of the eruptive fissure (N10°E) as measured by Sigurður Þórarinsson on August 20,1966 (Thorarinsson 1967) to indicate

its likely trend. The intrusion lies directly beneath the Surtur crater, consistent with it being the feeder dyke of the 1966-67 eruption. Again, using a maximum error of 0.2° for the average angle, the uncertainty in the dyke location is ±1 m.

SUMMARY

Measurements of the actual angle from vertical of the SE-03 cored borehole drilled on Surtsey in 2017 used a STP-8 inclinometer, carried out on August 5th, 2021. The results show that deviations from the planned angle of 35° from vertical are minor, with an average 33.4±0.2° inclination of the hole from vertical. The vertical depth of the bottom of the borehole at 354.05 m measured depth is 294.7±1.2 m and the horizontal length from the drill head to the point vertically above the bottom is 195.1±1.0 m. By correcting for the 1.4-1.8° discrepancy between the planned inclination and the actual value, greater accuracy in the location of the lithological units in the SE-03 core is achieved. However, this discrepancy is minor and does not affect the overall interpretation of the core. In particular, the results strongly support the interpretation that the intrusion at a measured depth of 343-352 m is the feeder dyke of the Surtur 1966-67 eruption.

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