Subsidence of Surtsey volcano, 1967–1991

James G Moore[1], Sveinn Jakobsson[2], and Josef Holmjarn[3]

[1] US Geological Survey, Menlo Park, CA, USA
[2] Icelandic Museum of Natural History, Reykjavik
[3] Icelandic Energy Authority, Reykjavik

Abstract. The Surtsey marine volcano was built on the southern insular shelf of Iceland, along the seaward extension of the east volcanic zone, during episodic explosive and effusive activity from 1963 to 1967. A 1600-m-long, east-west line of 42 bench marks was established across the island shortly after volcanic activity stopped. From 1967 to 1991 a series of leveling surveys measured the relative elevation of the original bench marks, as well as additional bench marks installed in 1979, 1982 and 1985. Concurrent measurements were made of water levels in a pit dug on the north coast, in a drill hole, and along the coastline exposed to the open ocean. These surveys indicate that the dominant vertical movement of Surtsey is a general subsidence of about 1.1 ± 0.3 m during the 24-year period of observations. The rate of subsidence decreased from 15–20 cm/year for 1967–1968 to 1–2 cm/year in 1991. Greatest subsidence is centered about the eastern vent area. Through 1970, subsidence was locally greatest where the lava plain is thinnest, adjacent to the flanks of the eastern tephra cone. From 1982 onward, the region closest to the hydrothermal zone, which is best developed in the vicinity of the eastern vent, began showing less subsidence relative to the rest of the surveyed bench marks. The general subsidence of the island probably results from compaction of the volcanic material comprising Surtsey, compaction of the sea-floor sediments underlying the island, and possibly downwarping of the lithosphere due to the laod of Surtsey. The more localized early downwarping near the eastern tephra cone is apparently due to greater compaction of tephra relative to lava. The later diminished local subsidence near the hydrothermal zone is probably due to a minor volume increase caused by hydrous alteration of glassy tephra. However, this volume increase is concentrated at depth beneath the bottom of the 176-m-deep cased drillhole.

Introduction

Surtsey Volcano was built from the sea floor (depth 130 m) at the southern end of the eastern volcanic zone of Iceland from November 1963 to June 1967. The volcanic island is about 1.5 km in diameter and lies 30 km south of the south coast of the main island of Iceland (Fig. 1).

The eruption that built Surtsey apparently began during the interval 8–12 November 1963, and the island first appeared above the sea surface on 15 November (Thorarinsson et al. 1964). Phreatic explosions from the initial primary vent on the east built a basaltic tephra cone until 31 January 1964. At that time explosive phreatic activity switched to a new vent 400 m northwest and built a pyroclastic cone until 4 April 1964, when explosions waned and lava began overflowing from the western vent. This effusive activity built a lava field south of the cone before ceasing on 17 May 1965 (Fig. 2). The
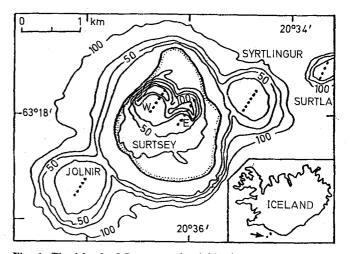

Fig. 1. The island of Surtsey and neighboring submarine volcanoes in July 1968 (modified from Norrman 1970). *Dotted lines* are approximate positions of original eruptive fissures with east (*E*) and west (*W*) vents of Surtsey designated; contour interval is 25 m. *Arrow* (on the inset map) locates Surtsey off the south coast of Iceland
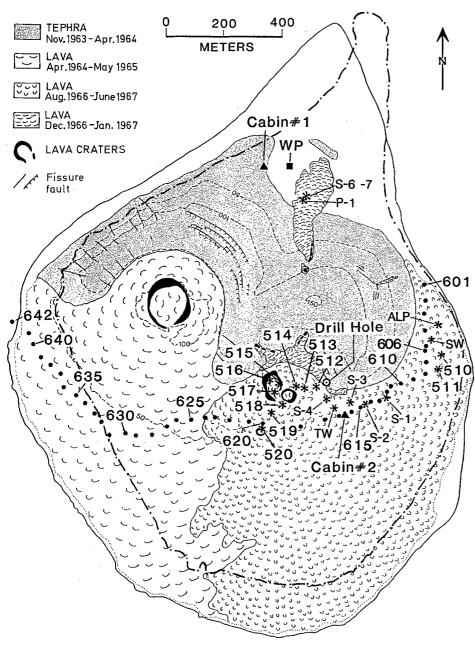
Correspondence to: JG Moore

Fig. 2. Geologic map of Surtsey
showing location of leveling
bench marks. Original 1967
marks are shown by *solid circles*,
and those added 1979–1988 by
stars. The site of water-level
measurements on the north cape,
first at an existing pond and later
in a dug pit, is indicated by the
square *WP*. Topography and
shoreline is from 1975 photo-
graphs (Norrman 1978) and geo-
logy from Jakobsson and Moore
(1982); August 1991 shoreline is
shown by *dash-dot line*. In Figs.
3, 4, 5, 8 and 9 bench marks gen-
erally west of BM 609 are pro-
jected onto a west-east line, and
the remainder to the north are
projected onto a south-north line

Surtsey vents remained dormant for more than a year
while eruptive activity switched to nearby submarine
vents and short-lived islands. On 19 August 1966 effu-
sion resumed from the original (east) Surtsey vent and
continued until 5 June 1967, building a lava field to the
south which partly overlapped that from the western
vent. During the construction of this extensive lava
field, new vents became active on the eastern cone (both
high on the inner crater wall and on the north flank) and
fed small lava flows intermittently during December
1966 and January 1967 (Fig. 2). All activity on Surtsey
stopped on 5 June 1967 (Thorarinsson 1968).

The leveling surveys and attendant water-level meas-
urements were originally conceived and conducted be-
cause of the opportunity to measure, from its inception,
the deformation of a newly built marine volcano. A sec-
ondary purpose was to establish the elevation of the

Surtsey drillhole collar to provide a reference to inter-
pret drill core and for downhole measurements (Jakobs-
son and Moore 1982, 1986).

History of leveling surveys

Ten leveling surveys with attendant water-level measure-
ments have been conducted on the island from 1967 to
1991; one period of measurement of water level in 1980
was unaccompanied by leveling (Table 1). The initial
leveling line was established in June 1967, shortly after
cessation of volcanic activity at Surtsey, and consisted
of 42 bench marks laid out in an arcuate east-west line
on the southern lava plateau (Tryggvason 1968). The
brass bench marks, cemented in holes drilled in lava,
were numbered from 601 to 642 from east to west along

Table 1. Survey periods

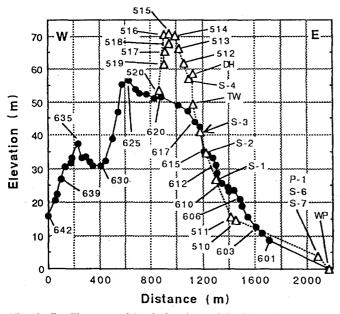| Date	Tidal range, cm		Tidal lag, min		Reference
	Pit	Drillhole	Pit	Drillhole	
1967, 21–22 June					Tryggvason 1968
1967, 9–12 August					Tryggvason 1968
1968, 25–28 June					Tryggvason 1970
1969, July					Tryggvason 1972
1970, June					Tryggvason 1972
1979, 28 July–16 August	13		349		Moore 1982
1980, 9–12 September	2.5	205	458	72	Tomasson and Snorrason 1980
1982, 8–11 August	5	170	360	48	This report
1985, 2–6 August	20	210	250	55	This report
1988, 6–11 August	23	190	280	55	This report
1991, 7–9 August	29	250	300	54	This report

Fig. 3. Profile across island showing original bench marks installed in 1967 (*solid circles*), and bench marks added in 1979 and 1982 (*open triangles*). WP indicates pit where water-level measurements were made on the north cape. Bench mark positions are projected to base lines as described in Fig. 2 and as shown in Figs. 3, 4, 5, 8 and 9

the line (Figs. 2 and 3). The line was releveled in August 1967, and in the summers of 1968 (Tryggvason 1970), 1969 and 1970 (Tryggvason 1972). This line was tied in elevation to the water level of a small lake on the north cape in 1967 and 1968. The pond eventually filled with sediment deposited by high surf. At the time of each subsequent survey a pit was redug at approximately the pond site to provide a place for measurement of the ground water level.

After a 9-year interruption in leveling, a new set of bench marks was established in 1979 to control leveling from the sea and from the water-level pit to a new drillhole on the east margin of the east vent (Jakobsson and Moore 1982; Moore 1982). These marks were tagged steel concrete nails driven in cracks in the lava (numbered S-1 to S-4 near the drillhole site and S-6 and S-7

on the small 1966–1967 lava flow near the northern field station, Fig. 2). Leveling of this line was repeated in 1982, when a series of nine new bench marks (numbered 512–520) was laid out on the flanks and crater of the eastern vent. The original 1967 line was not reoccupied in 1979 or 1982 except for the bench marks extending from the eastern shore to the vicinity of the drillhole site.

In 1985 all of the post-1967 bench marks were leveled as well as all those of the original 1967 survey line that could be found. Only one bench mark was added (marked P-1) near, and above, S-7 on the northern lava flow because the destruction of the nearby S-6 by storm waves indicated that S-7 was also in jeopardy.

By 1988 only 12 of the original 42 bench marks could be located and occupied. The 12 on the west end of the original line were lost because the sea cliff had receded 250 m (Fig. 2). Of the other missing 18, five were eroded or covered on the eastern margin of the island and 13 were apparently covered by windblown sandy tephra. In 1991, 14 of the original bench marks were measured; bench marks 609 and 627 were re-exposed by sand movement.

During the 1979–1991 surveys the groundwater level was measured in the drillhole and in pits dug on the north cape, which were filled and obscured each winter by storm waves. In addition, open ocean tidal measurements were made during 1979, 1985 and 1988. The measurements prior to 1991 generally included only a few tidal cycles. In 1991 from 10 August to 1 September an automatic device in the dug pit continuously recorded the water level through 83 tidal peaks.

Changes in level line

In order to compare the relative changes in elevation between the bench marks connected by the leveling survey, the elevation changes of each bench mark from one survey to the next are compared assuming that the elevation of a single bench mark has not changed during the history of leveling. In this method bench mark elevations are not compared with water-level measurements which are less accurate. Bench mark 606 near the east end of the

line was held constant, because it was included in all the leveling surveys and generally has shown small relative changes when compared with other bench marks, especially with those on the stable west side of the island.

The elevation change of each bench mark, relative to bench mark 606, for each successive survey may be compared with either (1) the elevations determined for the prime survey of 9–12 August 1967, or (2) the elevations determined for the preceding survey. Method (1) compares *cumulative* changes from the first survey through each subsequent survey and consequently only considers the original bench marks established in June 1967. Method (2) compares the *incremental* changes between each pair of surveys and hence considers changes in elevation of any bench mark occupied on two successive leveling surveys.

The cumulative plot (Fig. 4) indicates that from 1967 to 1970 deformation of the east–west line was dominated by marked relative subsidence of three zones of several bench marks each (compare with Fig. 3) centered at about 600 m (BM 625), 1050 m (BM 618 and BM 619), and 1400 m (BM 608). This pattern was recognized by Tryggvason (1970, *his* Fig. 1). By 1970 these zones had subsided a total of about 0.4, 0.2, and 0.1 m respectively relative to BM 606 (Fig. 4).

The western zone of subsidence occurs at the highest part of the original survey line (Fig. 3) close to the tephra shoulder marking the west rim of the east crater (Fig. 2). The central zone likewise occurs close to the tephra shoulder marking the east rim of the crater. These relations suggest that the buried tephra rim is closest to the surface at the zones of subsidence, and their relative
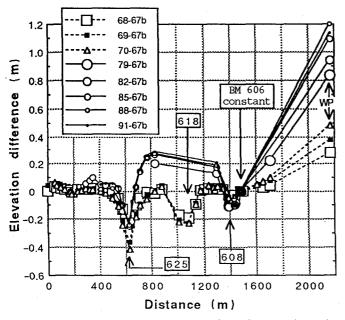

Fig. 5. Change in elevation of bench marks for six consecutive leveling periods; only bench marks measured during consecutive leveling periods are included. Data are plotted with BM 606 assumed to have undergone no change. The groundwater level on the north cape is the point on the right (*WP*)
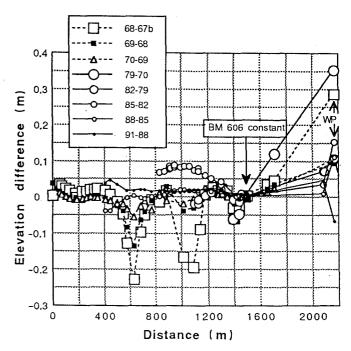
subsidence is related to greater compaction of tephra relative to lava.

The cumulative plot relative to BM 606 (Fig. 4), however, indicates that by 1985 (and possibly by 1982) the pattern had changed and points within the western zone of depression had risen (relative to BM 606) as well as points on either side of the middle zone of depression. Unfortunately many of the original points were not occupied in the 1979 and 1982 surveys and none of the original bench marks in the middle zone of depression survived past 1970. The smaller, eastern zone of depression maintained its subsided condition.

The incremental plots relative to BM 606 (Fig. 5) show additional details that clarify this late deformation. The 1982–1985 leveling epoch of the newer bench marks in the central part of the eastern crater shows a marked apparent uplift up to about 8 cm relative to BM 606. The 1985–1988 epoch shows a relative uplift of about 2 cm, and the 1988–1991 epoch indicates a further reduction of this apparent uplift.

Measurement of the water table on the north cape

During all surveys, either the groundwater level in a pit dug in sand, or the surface of the earlier small pond, on the north cape was measured, and the average water level was tied by leveling surveys to the east end of the line of bench marks. The water level at this site, which is 100–200 m from the beach (Fig. 2), is affected by ocean tides that are attenuated and delayed relative to the tides in the open ocean (Table 1). The nature of the tidal fluc-

Fig. 4. Cumulative change in elevation of bench marks for eight leveling periods, all relative to the initial survey in August 1967; only bench marks in the initial leveling survey are included. Data are plotted with BM 606 assumed to have undergone no change. The groundwater level on the north cape is the point on the right (*WP*)
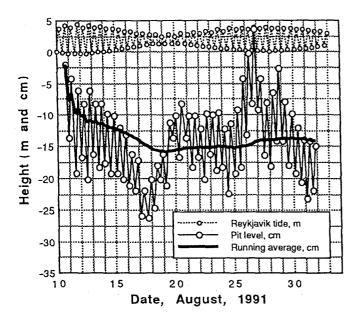
Fig. 6. Record of 83 high and low water levels measured by a recording pressure sensor in pit on the north cape of the island during the period 10 August–1 September 1991. Upper *dotted line* is predicted tidal cycle at Reyjkavik in m. *Thin solid lines* shows tidal extremes in pit, and *heavy line* is running average of water level in pit since 10 August, both in cm. No absolute elevation relation between Reyjkjavik and dug pit water levels is implied

Fig. 7. Elevation of BM 606 relative to water table in dug pit (and pond) on the north cape of the island from 1967 to 1991

tuations in this pit are shown by the 22-day record of 10 August–1 September 1991 (Fig. 6). The overall height of the water table in the dug pit is affected by the monthly tidal cycle, such that the average water level stands higher during the fortnightly period of spring tides and about 5 cm lower during the neap tides.

Sea-level measurements at the coast indicate that the groundwater table is somewhat higher than the average tide level in the ocean. In 1967 measurements indicated that the water level in the small pond near the site of the dug pit on the north cape was about 10 cm above that of a larger tidal pond near the north shore, which probably more nearly approached the elevation of sea level (Tryggvason 1972). In 1979 sea-level measurements using a tide staff on the beach on the northeast side of the northern cape for a period of 5 h indicated that the average water level in the dug pit was 25 ± 15 cm above mean sea level at the coast. In 1985 sea-level measurements using a pressure transducer on the east coast near BM 601 (Fig. 2) indicate that the average water level in the dug pit stood 25 ± 15 cm above that in the ocean. In summary, the average groundwater level is apparently always somewhat above mean sea level and fluctuates in elevation depending on rainfall and other factors.

The 1985 ocean measurements during three high and two low tides indicate that the tidal cycle at Surtsey occurs 45 ± 5 min before that at Reykjavik, whereas published tide tables indicate that at Heimaey harbor (22 km northeast of Surtsey) the cycle occurs 43 min before that at Reykjavik. Hence, the ocean tide at Surtsey is essentially synchronous with that at Heimaey.

Data from six periods of water-table measurement in the dug pit, from 1979 to 1991, indicate a tidal range
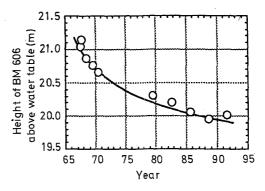
varying from 2.9 to 29 cm with cycles delayed 250–458 min from the predicted tidal cycle at Heimaey (Table 1). The common tidal range of the water table between successive high and low tides is 5–10 cm.

The level of the ground water at the dug pit has risen a total of about 110 cm relative to the apparently most stable bench marks (such as BM 606) during the surveys (Fig. 7). The rise of the groundwater level was about 15–20 cm/year in 1967–1968, 5 cm/year in 1969–1970 (Tryggvason 1972), and is currently (1991) about 1–2 cm/year.

Absolute elevation changes

The groundwater level in the dug pit, as measured for a few days to a few weeks during each leveling survey, averages approximately 10 cm above mean sea level. It is subject to the same processes that alter short-term measurements of sea level in an ocean tide gage, such as the lunar cycle, changes in sea temperature and salinity, wind patterns, barometric pressure, etc. It is also subject to the processes which affect the groundwater level on the north cape relative to the adjacent sea level such as changes in rainfall on the island, height of waves breaking on the beach, temperature of ground water including hydrothermal fluxes, permeability of the ground materials, character of onshore winds, and distance to the shoreline.

The measured total subsidence of the original bench marks relative to the water table from August 1967 to August 1991 is 80–130 cm (Fig. 8). This subsidence is 2–3 times larger than the maximum cumulative relative changes of elevation between the individual bench marks across the island, and hence subsidence is regarded as the dominant elevation change on Surtsey. This subsidence is also much larger than the long-term variations of sea level as recorded at the Reykjavik tide gage 110 km northwest of Surtsey, where an average apparent rise of sea level of 0.37 cm per year was recorded during 1958–1983 (Emery and Aubrey 1991). Such a rate corresponds to about a 9 cm rise during the 24-year period of the leveling surveys.

The nature of subsidence is best seen in plots where the water table (as defined by the average water level in
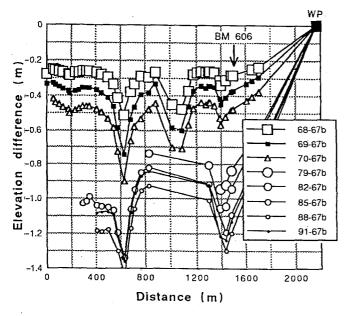
Fig. 8. Cumlative change in elevation of bench marks for eight leveling periods all relative to the first survey in August 1967; only bench marks in the initial leveling survey are considered. The water table as measured in the dug pit on the north cape (point *WP* on right) is assumed to have undergone no change
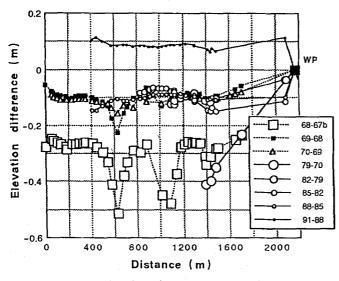

Fig. 9. Change in elevation of bench marks for eight consecutive leveling periods; only bench marks are considered which were measured during each pair of consecutive leveling epochs. Data are plotted with the water level in ponds or dug pits on the north cape assumed to have undergone no change. The groundwater level on the north cape is point WP

the dug pit) is held constant relative to all the bench marks (Figs. 8 and 9). The apparent upward movement of the bench marks relative to the water level from June 1967 to August 1967 and from August 1988 to August 1991 (Fig. 7) are anomalies that apparently reflect a 10 cm variation in the water level due to the spurious causes discussed above (see Tryggvason 1972, his Fig. 6).
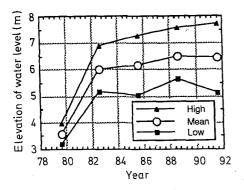
Incremental elevation changes of bench marks relative to the water table (Fig. 9) show an interesting pattern. Each of the leveling intervals shows a general subsidence of about 10 cm except for the first interval (August 1967–June 1968) and fourth interval (August 1970–August 1979) both of which show more than 40 cm of subsidence, and the last interval (August 1988–August 1991), which shows an apparent uplift of 10 cm. The first interval marks the first full year after cessation of volcanic activity and reflects the active subsidence immediately following the eruption. The fourth interval spans a 9-year hiatus in leveling and yields an average apparent subsidence of about 7 cm/year. The apparent uplift during the last interval apparently reflects an anomalous fall of water level in the pit due to short-term processes. The general similarity of the other subsidence rates results from the comparison of time increments of one year early in the leveling (1967–1970) with time increments of three years late in the leveling program (1979–1991).

Movement of the drill collar relative to adjacent bench marks provides information on the nature of subsidence after completion of the cased drillhole in 1979. The drillstring of the NCQ pipe (outside diameter 6.99 cm) became stuck in the hole at a depth of 176.5 m, and subsequent drilling to the final depth of 180.6 m was done inside the BQ pipe (outside diameter 5.56 cm) within the NCQ pipe (Jakobsson and Moore 1982). Hence the drill casing (the NCQ pipe) is presumably fixed to the hole walls at 176.5 m depth, some 13.5 ± 5 m above the level of the pre-Surtsey ocean floor. If there were any significant compaction (or expansion) of the tephra above that point between leveling surveys it should be reflected in a rising (or sinking) of the drill collar relative to the adjacent bench marks, which are anchored on surface lava flows. Elevation changes between the drill-pipe assembly and neighboring bench marks are small, generally less than 1 cm, and are commonly reversed during successive survey intervals. This fact suggests that compaction or expansion of the tuff in the vicinity of the drillhole has been minimal since the drillhole was completed, and post-drilling elevation changes result primarily from processes deeper than 176.5 m (i.e. 118 m below sea level).

Water level in drillhole

As soon as the drillhole reached the depth of the water table in July 1979, down-hole water-level measurements were made, and were continued during the period of drilling, and during each subsequent leveling survey. They show that the average water level rose about 4 m during drilling (Moore 1982), and an additional 2 m by the following year. The early rise resulted from the heating of water within the drillhole and the surrounding region during recovery from the introduction of large volumes of cold sea water into the drillhole during the drilling operation.

Continuous water-level measurements in the drillhole using a pressure transducer during September 1980 re-

Fig. 10. Height of average water level, and of high and low tide, in drillhole above that in the dug pit on the north cape of Surtsey

vealed a strong tidal character to the water-level fluctuations (Tomasson and Snorrason 1980) which had not been recognized in 1979 because of the perturbations induced by drilling and pumping cold seawater into the hole. The maximum tidal range was 2.05 m and the tidal cycle was retarded an average 72 min from that of nearby Heimaey as reported in tide tables. The leveling survey line was not reoccupied in 1980, and the relationship of the drillhole water level with the water table on the north cape was not determined.

Measurements in 1982, 1985, 1988 and 1991 indicated that tides in the drillhole averaged about 60% in amplitude of those as reported in tide tables for Reykjavik, and were retarded 48–55 min from the Heimaey tidal cycle as reported in tide tables (Table 1). The higher tidal amplitude and lower retardation of tides in the drillhole as compared with those in the dug pit (Table 1) indicate a much more permeable substrate at the base of the cased drillhole than around the dug pit (Tomasson and Snorrason 1980). This permeability difference no doubt reflects the unsorted, porous volcanic products extending from the base of the drillhole to the submarine flank of the volcano as compared to water-worked, sorted volcanic sands and silts comprising the upper levels of material comprising the north cape.

The mean water level within the drillhole has apparently risen from 1982 to 1991 relative to the water level in the dug pit (Fig. 10). Water-level measurements in the drillhole, however, are of lower accuracy than that in the dug pit because of the larger tidal range, the shorter measurement periods, and the constant boiling of water in the drillhole which complicates detection of the water surface 50 m down the pipe (Jakobsson and Moore 1982). This apparent rise of about 0.5 m in nine years is independent of subsidence of Surtsey because it is relative to the best absolute datum available, the average water level in the dug pit. The rise of water in the drillhole may be caused by expansion of the volume and depth of the zone of heated water associated with the hydrothermal system.

Mechanism of deformation

The primary vertical change at Surtsey is a general subsidence of about 1.1 ± 0.3 m since measurements began in

1967. During 1967–1968 the subsidence rate was 15–20 cm/year (Tryggvasson 1972), and by 1991 had slowed to 1–2 cm/year (Fig. 7). Long-term tide-gage data indicate that, in contrast, Reykjavik on the Iceland mainland is subsiding at 0.36 cm/year (Emery and Aubrey 1991). The greater subsidence rate at Surtsey is apparently largely caused by compaction of porous fragmental volcanic material, compaction of underlying sediment, and downbowing of the crust due to the addition of the mass of Surtsey on the pre-existing sea floor. Surtsey with a volume of 1.1 km^3, and assumed density equal to that of the average drill core of 1.8 g/cm^3 (Jakobsson and Moore 1982), represents a newly added mass to the crust of 2×10^{15} g. Part of the subsidence through 1970 was caused by compaction and consolidation of the new volcanic products which comprise the volcano, down to the level of the prevolcanic sea floor 130 m below sea level. The two zones of greatest early subsidence are in close proximity to the flanks of the eastern tuff crater, and perhaps are underlain by a thinner sequence of lava flows overlying tephra of the crater flanks (Moore 1985). Initially the cause of the depression of the two areas on the south lava plain from 1967–1968 was ascribed to a plastic flow of hot lava (Tryggvason 1968, p. 152). However, the continued subsidence of these areas in each leveling survey up to 1970 (Fig. 5) suggests that the subsidence results from compaction and consolidation of pyroclastic material.

Additional subsidence after 1970 was apparently dominated by compaction of prevolcanic sediment on the insular shelf of Iceland beneath the volcano, compaction of about 13 m of loose tephra below the drill casing, and possibly from minor downwarping of the crust as a result of the volcano's mass. These processes apparently dominated after the drillhole was completed in 1979 because of the lack of differential movement between the zones where tephra is thick versus thin, and between the top of the drill casing versus other neighboring benchmarks on tephra.

The zone of diminished subsidence, well established by 1985, of the inner part of the eastern crater is probably due to a minor volume increase caused by the alteration and hydration of glassy tephra within the hydrothermal system of Surtsey. The general zone of diminished susidence centered at 1000 m (BM 513, 514, 515) extends from 800 m (BM 622) to 1400 m (BM 609). This 600-m zone lies directly south of the hydrothermal area of the eastern vent as defined by the 20° ground-temperature isotherm (depth 20 cm) and the area of mapped palagonitized tephra (Jakobsson and Moore 1982). However, the lack of differential movement between the surface bench marks and the drill casing indicates that the bulk of the elevation changes result from alteration that is deeper than the base of the 176-m-deep drill casing.

Bjarni Kristinsson assisted with the leveling surveys in 1979, Hreinn Magnusson in 1982, Magnus Olafsson and John Norrman in 1985, Magnus Sigurgeirsson and Karin Eriksson in 1988, and Gudmundur Sverrisson and Thorvaldur Thordarson in 1991. Eysteinn Tryggvason provided digital data for his leveling surveys of 1967–1970. Water in the drillhole was measured by Omar Sigurdsson in 1982. Discussions with Roy Bailey, Paul Delaney, Herb Shaw, and Ross Stein were helpful, and reviews by RA Bailey, D Dzurisin, and DA Swanson have substantially improved the manuscript. The help of these colleagues and reviewers is appreciated.

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