

Volumetric evolution of Surtsey, Iceland, from topographic maps and scanning airborne laser altimetry: 1968 – 1998

JAMES B. GARVIN¹, RICHARD S. WILLIAMS JR.²

JAMES J. FRAWLEY³ & WILLIAM B. KRABILL⁴

¹NASA's Goddard Space Flight Center, Code 921, Bldg. 33, Room F326, Greenbelt, MD 20771 USA

²U. S. Geological Survey, Woods Hole Field Center, 384 Woods Hole Road, Woods Hole, MA 02543 USA

³Herring Bay Geophysics, And Raytheon-STX, at NASA's GSFC, Code 921, Greenbelt, MD 20771 USA

⁴Observational Sciences Branch, Code 972, NASA's GSFC, Wallops Flight Facility, Wallops Island, VA 23337 USA

ABSTRACT

The volumetric evolution of Surtsey has been estimated on the basis of digital elevation models derived from NASA scanning airborne laser altimeter surveys (20 July 1998), as well as digitized 1:5,000-scale topographic maps produced by the National Land Survey of Iceland and by Norrman. Subaerial volumes have been computed from co-registered digital elevation models (DEM's) from 6 July 1968, 11 July 1975, 16 July 1993, and 20 July 1998 (scanning airborne laser altimetry), as well as true surface area (above mean sea level). Our analysis suggests that the subaerial volume of Surtsey has been reduced from nearly 0.100 km³ on 6 July 1968 to 0.075 km³ on 20 July 1998. Linear regression analysis of the temporal evolution of Surtsey's subaerial volume indicates that most of its subaerial surface will be at or below mean sea-level by approximately 2100. This assumes a conservative estimate of continuation of the current pace of marine erosion and mass-wasting on the island, including the indurated core of the conduits of the Surtur I and Surtur II eruptive vents. If the conduits are relatively resistant to marine erosion they will become sea stacks after the rest of the island has become a submarine shoal, and some portions of the island could survive for centuries. The 20 July 1998 scanning laser altimeter surveys further indicate rapid enlargement of erosional canyons in the northeastern portion of the partial tephra ring associated with Surtur I. Continued airborne and eventually spaceborne topographic surveys of Surtsey are planned to refine the inter-annual change of its subaerial volume.

INTRODUCTION AND BACKGROUND

The topographic evolution of isolated volcanic islands has been uniquely observed at Surtsey, classified geomorphologically as a table mountain (e.g., Williams *et al.* 1983). Aerial photography acquired during the volcanic constructional phase of island development (15 November 1963 through 5 June 1967) (Thórarinnsson 1965, 1967, 1968) has continued on a near-annual basis until present, thanks to the efforts of the Surtsey Research Society and the National Land Survey of Iceland. While qualitative assessment of the subaerial landscape evolution of Surtsey has been described by Norrman and associates (e.g. Norrman 1980, Calles *et al.*, 1982 and Norrman & Erlingsson

1992), it has previously been difficult to estimate quantitatively the change in subaerial island volume. A number of studies have estimated the rate of erosion by area (Thórarinnsson 1965, 1968, Calles *et al.* 1982, Jakobsson *et al.* 1998). Because Surtsey represents an unprecedented opportunity to evaluate the volumetric evolution of a recently formed volcano in an isolated, marine setting, we have focused on measuring its volumetric change using newly available remote-sensing methods. Here we present the first high-resolution digital elevation model (DEM) of Surtsey acquired exclusively by means of NASA-based scanning airborne laser altimetry (SALA). The laser-altimeter-based DEM provides ~ 20 cm vertical accuracy across all of the sub-

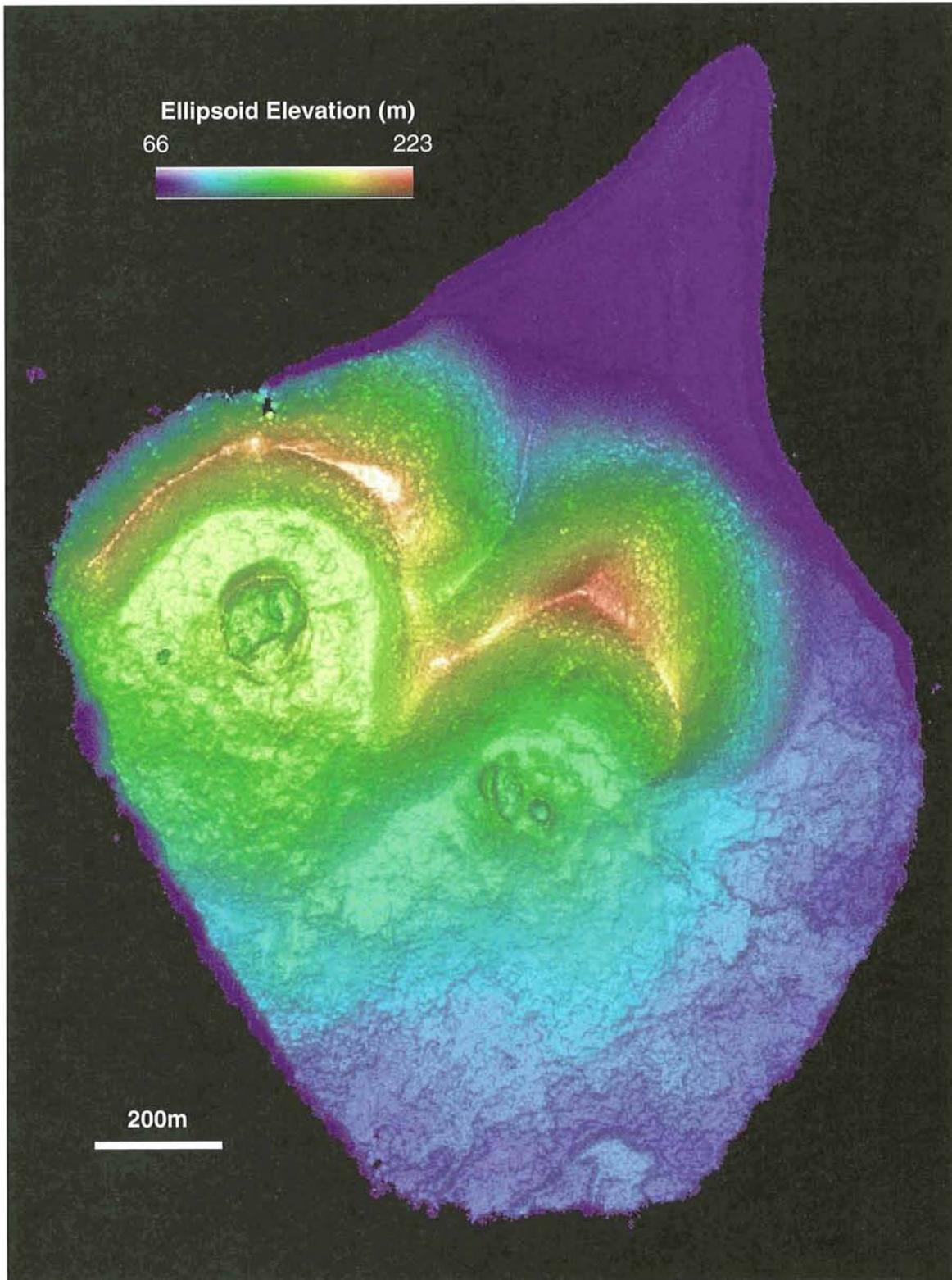


Figure 1. Digital Elevation Model (DEM) of Surtsey acquired 20 July 1998 via scanning airborne laser altimetry using the NASA ATM sensor. Colors represent elevation relative to mean sea level. Shading is based upon local topographic gradient computed from the DEM. The spatial resolution of this image is 3 m, while the vertical accuracy is ~ 20 cm RMS. Colors range from near sea-level (blue) to ~ 150 m (red). Corner coordinates are as in Jakobsson (1998). North is up in this image. Mean sea level corresponds to an ellipsoidal elevation of 66 m.

aerial landscapes of the island and permits computation of whole-island subaerial volumes at unprecedented accuracy. We have taken the SALA-based DEM (Fig. 1), acquired on 20 July 1998, and compared it to independently-derived DEM's from 6 July 1968, 11 July 1975, and 16 July 1993. All of the DEM's prior to 20 July 1998 were generated by digitizing contours on high-resolution topographic maps (Norrman & Erlingsson 1992) and by subsequently converting the data to a rasterized DEM format on a uniform spatial grid. Inter-DEM comparisons were facilitated only after careful co-registration at pixel-scales as fine as 2-3 m (spatial) and less than 1 m (vertical). The temporal evolution of the subaerial volume (V) and of the true surface area (SA) of Surtsey from 6 July 1968 to 20 July 1998 can then be assessed. Here we distinguish projected basal area (i.e., the coastal outline of the island) from true surface area, in which the local relief is utilized in the computation of area.

It is our intent to discuss the evolution of the subaerial volume of Surtsey in the context of those erosional processes presently known to be at work (Norrman 1980, Calles *et al.* 1982, Jakobsson *et al.* 1993). This report develops the remote-sensing methods that were utilized and treats the preliminary interpretation of the volumetric history of the island. Finally, simple predictions about the future erosional evolution of the subaerial expression of Surtsey are presented. We acknowledge that additional data are needed, including repeat SALA surveys, to adequately refine and interpret the geomorphic history of the island. However, we assert that the trends presented herein are valid and useful in the context of landscape-erosion rates in high latitude environments. There are additional surtseyan landforms within Iceland, Jan Mayen, and elsewhere whose present state of erosion can be better understood on the basis of the results for Surtsey that are presented in this paper.

The National Aeronautics and Space Administration (NASA) is interested in advanced orbital and airborne remote-sensing approaches that permit direct measurement of landscape rates of change in response to natural forcings such as climate, severe meteorological phenomena, volcanic eruptions, and others. NASA is presently operating an orbital laser altimeter to map the topography of landscapes on Mars (Smith *et al.* 1999), and has flown similar instruments in Earth orbit aboard the Space Shuttle (Garvin *et al.* 1998). Near-term plans call for Earth-orbiting

laser altimeters to be launched in the 2001-2002 for the purpose of documenting the dynamics of terrestrial ice sheets, as well as for measuring the relief of vegetation on a global basis. Scanning airborne laser altimeters (SALA) such as the Airborne Topographic Mapper (ATM) are presently used to provide "airborne ground-truth" for local areas in anticipation of future orbital monitoring efforts (Krabill *et al.* 1995). At present, SALA systems such as the NASA Wallops Flight Facility ATM can acquire spatially-dense (i.e., measurements every meter) topographic sampling over local areas on the basis of laser pulse repetition frequencies exceeding 3000 pulses per second. We operated the ATM sensor at 5000 pulses per second (i.e., 5000 Hz) at an altitude of approximately 500 m (above mean sea level) in order to acquire adequately dense spatial sampling to facilitate construction of a 3-m (per DEM grid cell) digital elevation model for Surtsey. This was accomplished by flying the ATM sensor in a NASA Wallops Flight Facility P-3B aircraft, together with differential GPS equipment, at an altitude that maximizes instrument swath width (i.e., $0.5 \times \{P-3 \text{ altitude}\}$), while minimizing laser ranging errors. Thus, we required 13 passes to exhaustively map the topography of Surtsey on a 3 m grid (Fig. 1). In places, the ATM scans overlapped to allow for dynamic cross-over error analyses. We have assessed some of these and the data from independent swaths agree to within 20 cm (RMS) under most circumstances. For more details concerning NASA's aircraft laser altimetry efforts, the reader is referred to Krabill *et al.* (1995), Garvin (1996), and to Garvin & Williams (1992). Additional details concerning the ATM sensor system can be found at the following web site: <http://aol.wff.nasa.gov/aoltm.html>.

Detailed characterization of the topographic evolution of isolated, small islands is largely unknown in the extant literature. Surtsey affords an ideal target for undertaking such an experiment on the basis of its isolation, as well as the wealth of existing data about the island since the time of its formation. Prior to the 1998 SALA surveys, we conducted profiling laser altimeter experiments at Surtsey to understand the meter-scale topographic characteristics of its key landscape features, including for example the volcanic collapse crater Surtur I, the northern ness, and the primary tephra rings (Garvin & Williams 1992). Improvements in laser transmitter technology and in differential GPS tracking

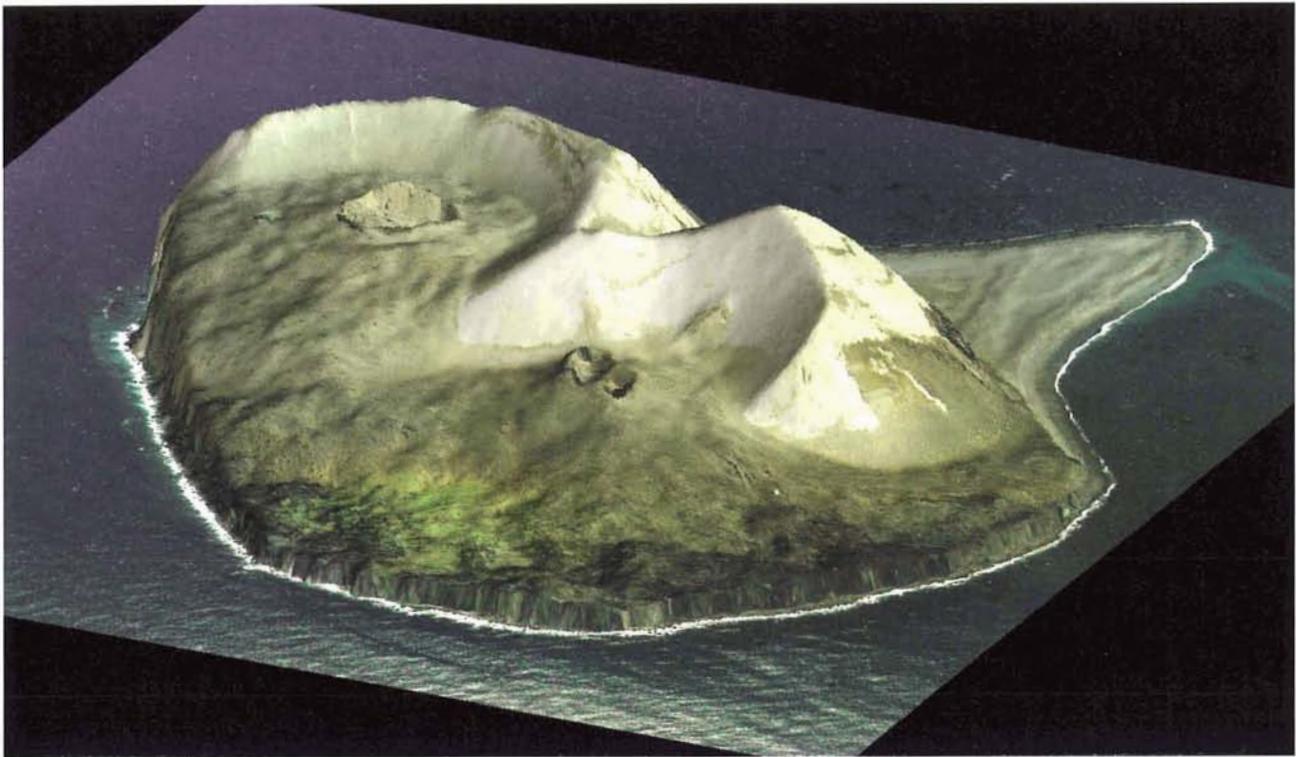


Figure 2. Aerial photograph of Surtsey draped atop the DEM that is illustrated in Fig. 1. The 23 August 1998 aerial photograph was acquired by the Iceland Geodetic Survey (photo ID: O-9542) and digitized by NASA, before being "ray traced" atop the DEM, and then converted to a perspective view from the southeast. The resolution of this image is equivalent to that of the DEM in Fig. 1 or 3 m per pixel. Special thanks to the National Land Survey of Iceland (courtesy S. M. Thorvaldsson, Permit no. 216). Vertical exaggeration is ~20:1.

methods have now allowed us to adopt the SALA approach to completely characterize the landscapes of the entire island in three dimensions. On 20 July 1998, we conducted the ATM surveys of Surtsey under excellent conditions. What follows is a brief description of the data and our preliminary interpretations of it in comparison with previous topographic mapping data from independent sources.

THE LASER-ALTIMETER DIGITAL ELEVATION MODEL

By combining more than a dozen SALA swaths of topographic data, and correcting for aircraft motion, radial position, and other factors, a seamless DEM can be constructed, as depicted in Fig. 1. This false-colored topographic map combines more than one million independent laser measurements into one image in which color represents elevation above mean sea level. In Fig. 1, the "colder" colors such as blue represent the lowest elevations, while the "hotter" colors such as red indicate the greatest relief. We have modulated the topography with a shaded rendition of the topography of Surtsey derived from the DEM to provide texture on the image. This texture reflects

the 3 m scale "roughness" of the surface as measured from the local distribution of slopes at 3 to 6 m horizontal scales. Other than a berm of wave-emplaced boulders, the northern ness appears lower and smoother than all other regions on Surtsey. Individual flow fronts and other crenulations related to the emplacement of the lavas that form the carapace covering the southern half of the island are readily visible. Several topographic/roughness "units" can be observed from the DEM displayed in Fig. 1. First, the depositional northern ness appears as a smooth, low unit, with few features except the berm of boulders that outlines its margins. Second, the middle of the island is dominated by arcuate tephra-rings that extend for 180 degrees in an "m-shaped" pattern. These high-standing features appear to be flanked by aprons of mass-wasted material that transitions into the northern ness lowlands to the north. The third major surface unit is that of the lavas and collapse craters that dominate the southern 40% of the island. Surtur II, to the west, is most clearly expressed as a nearly cylindrical volcanic "pit crater" reminiscent of many similar landforms in the Kilauea region of Hawaii. The lava flow fields that encircle Surtur II appear to form a discrete,

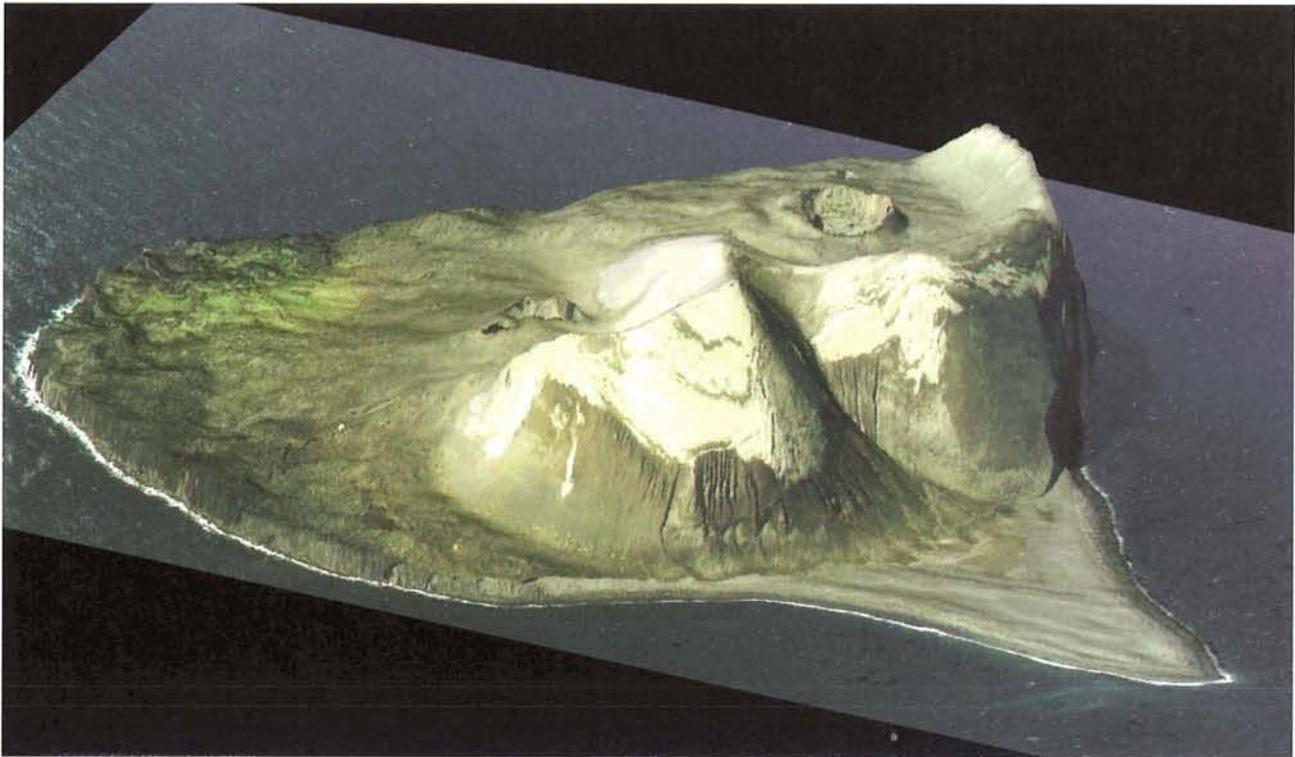


Figure 3. As in Fig. 2, but the perspective view is from the northeast to better feature the erosional canyons being formed in the tephra ring materials (palagonitized tephra). Observe how the albedo of surface materials correlates with the topography. There appears to be local topographic control of the erosional distribution of materials on Surtsey.

but now eroded, lava shield. The lavas associated with Surtur I to the east are multi-tiered, indicating multiple episodes of emplacement, and less association with a single circular vent. From the DEM displayed in Fig. 1, it is clear that intensive marine erosion has most strongly influenced the southwestern coast of Surtsey, leaving a linear coastline, with dramatic cliffs tens of meters in relief.

On the basis of the DEM illustrated in Fig. 1, one can analyze the recent geomorphic history of the island. This is best accomplished by employing multiple perspectives and by combining datasets. We have digitized vertical aerial photographs acquired on 23 August 1998 by the National Land Survey of Iceland and co-registered them to the SALA-derived DEM acquired on 20 July 1998. We can then “ray trace” the two-dimensional data from the vertical aerial photograph on top of a perspective view of the DEM to provide static views from different vantage points. Fig. 2 is an example of a ray-trace of the aerial photograph draped atop the DEM, as viewed from the southeast. In this view, one can visually correlate changes in surface albedo with topography at the same scale. For example, the

palagonitized tephra (Garvin & Williams 1992) that outcrops in the tephra rings appears as a higher albedo “tan” unit in Fig. 2, in contact with tephra-covered lavas to their south. Small debris flows can be seen along the eastern and northeastern margin of the tephra ring complex, indicating water-related transport and subsequent outflow. Grassy surfaces have been established in the wind-protected areas of the southern part of Surtsey on the basis of rapid ecological colonization facilitated by sea birds. Fig. 2 also suggests that periodic overflow of the northern ness has produced a series of subtle topographic ridges that outline patterns of deposition as the water receded (Calles *et al.* 1982). Overwash of this region appears to have influenced the position of albedo features associated with very subtle relief variations.

Fig. 3 presents an alternate perspective of Surtsey, as viewed from the northeast. In this case, the research hut is visible with its red roof. In addition, a series of rapidly developing erosional canyons, some of which are more than 5 m in width, can be observed all along the northern face of the tephra rings. Albedo markings associated with the lowest points of the northern

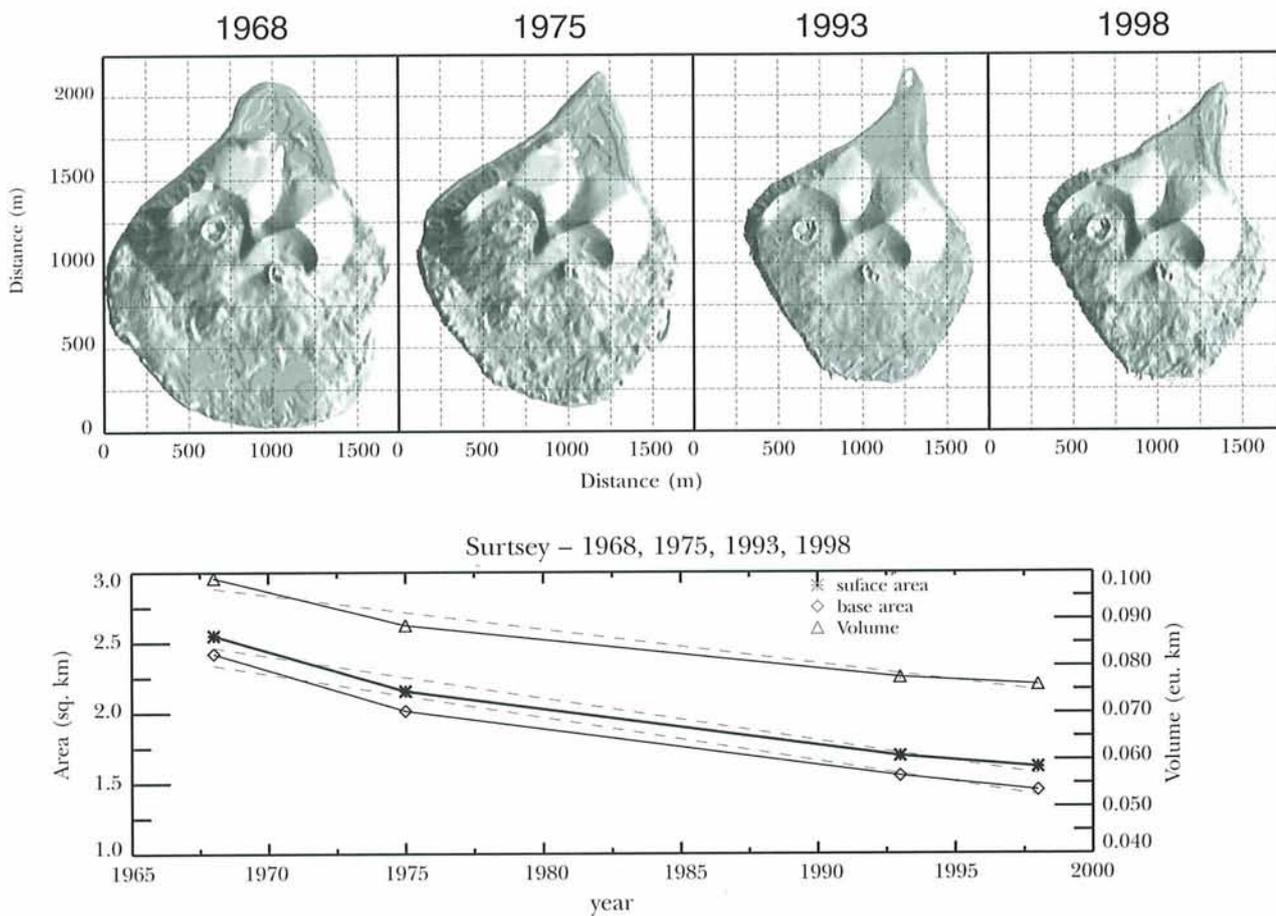


Figure 4. Graphical and pictorial representation of progressive erosion of the subaerial expression of Surtsey from 1968 through 1998. Shaded relief views of the topography of Surtsey in 1968, 1975, 1993, and 1998 are shown at the top, as derived from digitized topographic maps (1968, 1975, 1993) and from scanning airborne laser altimetry (1998). The time-history of the subaerial volume, true surface area (i.e., not projected onto a planar base), and basal area of the island is plotted against year (A.D.) at the bottom, illustrating the pattern of erosional loss over 30 years. More than 25% of the post-eruption subaerial volume of Surtsey has been lost to marine erosion and mass-wasting since 1968. See text for further details and for specific dates associated with each DEM.

ness can also be observed, near the cleft that separates that two sections of the central tephra ring complex. The evolution of the erosional canyons in the tephra rings has increased appreciably since 1991, when field measurements associated with NASA laser altimeter surveys were conducted by the senior author (Garvin & Williams 1992).

VOLUMETRIC ANALYSIS

The 20 July 1998 SALA surveys produced a geodetic quality DEM of Surtsey, with better than 20 cm vertical accuracy. We have used this dataset as the basis for quantifying the volumetric evolution of the island in a subaerial sense. The subaerial volume of the island was computed by numerical integration of the DEM, yielding a value of 0.075 km³, with an error budget of

less than 5%. By co-registering digital elevation models derived by digitizing three different topographic maps of Surtsey, we have been able to compute subaerial island volume for three other time steps. We digitized the 1993 topographic map (1:5000-scale) produced by the Iceland Geodetic Survey (Jakobsson *et al.* 1993) to provide a 3 m DEM for the island from 1993. In addition, we digitized the 1:2000-scale maps produced from aerial photographs acquired on 6 July 1968 and 11 July 1975 (Norrman 1980, Norrman & Erlingsson 1992) to provide additional time steps for reference. In order to accurately co-register four different DEM's to the same reference frame, we used our geodetic-quality 1998 data (i.e., acquired using sub-meter quality GPS positioning) as a reference base and dynamically adjusted each of the other maps so that fixed

features were co-aligned to within 1-2 m in a horizontal sense. Once we achieved adequate co-registration, we computed the subaerial volumes of Surtsey for each time step: 6 July 1968, 11 July 1975, 16 July 1993, and 20 July 1998. Fig. 4 illustrates how the topography of the island has evolved from 6 July 1968 to 20 July 1998, as well as how the volume has decreased since 6 July 1968. The true surface area, basal area, and subaerial volume (Fig. 4) all follow the same trend from 6 July 1968 to 20 July 1998. The reduction in subaerial volume from nearly 0.100 km³ to 0.075 km³ in only 30 years of sustained marine erosion from sub-arctic cyclones is remarkable. If one fits a linear relationship to the volume (V) data from 6 July 1968 through 20 July 1998, an equation of the form:

$$V = -0.0007279 t + 1.53$$

can be derived using least squares regression methods. In this equation, V represents subaerial volume in km³ and t is time in absolute years, such as 1968 and so forth. While it is clear that a linear relationship between volume and time is not expected, this equation fits the existing data with a high confidence factor of nearly 0.98 (i.e., R² correlation coefficient is 0.98). Using this volume versus time relationship, it can be shown that Surtsey's volume converges to ~0 km³ in only another 100 years. This is a highly simplistic view of the volumetric erosion of Surtsey, because it does not take into consideration that Surtsey itself sits on a submarine socle (Norrmann & Erlingsson 1992) and the erosivity of the indurated cores of the conduits of the Surtur I and Surtur II eruptive vents is unknown. However, it shows that the pace of erosion could easily reduce the island to a series of areally insignificant sea-stacks (e.g., indurated cores) in about a century (Jakobsson et al. 1998). Higher-order non-linear least squares regression analyses of the volume versus time data have also been conducted, with largely similar results. In the best-fitting polynomial solution, the subaerial volume of Surtsey approaches zero in approximately 106 years. Power law analysis of the relationship between volume and time involves fitting an equation of the form:

$$V = k t^{-n},$$

where k is the pre-exponential coefficient, and n is the power-law exponent. In this case we measure time t in years since 1960 and volume in km³ as before. When we adopt this approach, an equation of the form:

$$V = 0.137 t^{-0.160}$$

results, which suggests a much longer lifespan for the bulk of the subaerial island. However, this approach implicitly assumes that the relatively rapid pace of erosion Surtsey has experienced over the past 30 years will drastically diminish, allowing for a different style of volumetric erosion in the future. As yet, there is no evidence of a change in the style or magnitude of erosion on the island from recent field observations (Jakobsson 1998). While we believe the linear relationship discussed above is overly pessimistic with respect to the survival of the island, the power-law projection may be considered optimistic. A reasonable projection is likely to lie in between, suggesting a lifespan of several hundred years for the bulk subaerial volume of the island.

The best-fitting linear relationship between true surface area (SA) and time (t) suggests that the majority of the land surface of the island could be reduced to nearly zero in only 50 years. A more optimistic power-law solution (SA = 4.68 t^{-0.29}) would allow for hundreds of years of survival. While more data is needed and increasingly precise geodetic methods could be used to assess inter-annual change, our results suggest that the predicted lifetime of Surtsey as a unique locality for studying the evolution of an island may be limited. Unless the pace of subaerial erosion dramatically shifts, the life span of the island is probably limited to ~ 100 years, although the more resistant sea stacks could survive for centuries.

SUMMARY

We have used state-of-the-art airborne remote sensing methods to capture the topography of the land surface of Surtsey as of 20 July 1998. The resulting DEM provides more than one million point measurements of the elevation of the island in a geodetic coordinate frame, and facilitates direct computation of the subaerial volume. The subaerial volume computed from the SALA-derived DEM is 0.075 km³, which is ~ 25% less than the volume of the island just after the end of its volcanic construction phase (1968). The best-fitting linear relationship between island subaerial volume and time suggests that most of the island should be reduced to a volumetrically-insignificant group of sea stacks in approximately 100 years. While this prediction is based on very limited snapshots of island volume over a 30 year period, it suggests that monitoring the volumetric erosion of Surtsey over the next few decades could be an important

activity if volcanic island erosion patterns are ever to be quantified. Surtsey is unique in that a high-quality set of DEM's exist for the island since the terminal stages of its constructional phase. Over the past 30 years, there are four snapshots of island volume computed from independent DEM's (6 July 1968, 11 July 1975, 16 July 1993, and 20 July 1998) and prospects for generating new DEM's in future years both from aircraft and spaceborne methods are encouraging. Validating the current volumetric-erosion trend for the island by means of future laser altimetry surveys appears to be amply justified, if only to understand whether there are any shifts in the style or pattern of erosion in this sub-arctic environment.

ACKNOWLEDGEMENTS

We acknowledge the strong support of our colleagues on the Airborne Topographic Mapper instrument team, including Serdar Manizade, James Yungel, Robert Swift, and Earl B. Frederick. In addition, the Surtsey laser altimeter mapping experiment would not have been successful without the outstanding piloting skills of Virgil Rabine, who flew the NASA Wallops Flight Facility P-3B aircraft with great deftness to achieve the DEM that was generated. This research was funded in part by the NASA Office of Earth Sciences Solid-Earth and Natural Hazards program, under the leadership of Earnie Paylor. Additional support from the Earth Observing System Project Office (Michael King) and the NASA Goddard Space Flight Center Director's Discretionary Fund (DDF) are also gratefully acknowledged. Field validation of remote sensing data for Surtsey was enabled by Dr. S. P. Jakobsson, who granted research permits to the senior author in 1991 and 1998. We also wish to thank Larry Bergreen for his inspirational thoughts about our Surtsey research, and Jack Bufton for motivation associated with our laser remote sensing experiments in Iceland over the past 11 years. We would also like to acknowledge the work done by Cheryl L. Fenner, former Director, Geologic Information Visualization Center, Mary Washington College, Fredericks-

burg, VA, for digitizing the 6 July 1968 and 11 July 1975 topographic maps of Surtsey by John O. Norrman; and the application of the ANU-DEM software to these two maps and to the 16 July 1993 Serkort (National Land Survey of Iceland) of Surtsey by Michael J. Oimoen, Science and Applications Branch, EROS Data Center, U. S. Geological Survey, Sioux Falls, SD. Finally, the senior author wishes to thank his wife Cindy, son Zachary, and daughter Danica for their long-standing support of this activity.

References

- Calles B., K. Linde & J.O. Norrman 1982. The geomorphology of Surtsey Island in 1980. *Surtsey Res. Progress Rep.* 9: 117-132.
- Garvin, J.B. 1996. Topographic characterization and monitoring of volcanoes via airborne laser altimetry. *Geol. Society of London Special Publication* 110: 137-153.
- Garvin, J.B. & R.S. Williams Jr. 1992. Remote sensing studies of the geomorphology of Surtsey, 1987-1991. *Surtsey Res. Progr. Rep.* 10: 57-71.
- Garvin, J.B. & 5 others 1998. Observations of the Earth's topography from the shuttle laser altimeter (SLA): Laser-pulse echo-recovery measurements of terrestrial surface. *Physics and Chemistry of Earth* 23: 1053-1068.
- Jakobsson S.P. 1998. Surtsey 35 ára. *Náttúrufræðingurinn*, p. 83-86.
- Jakobsson, S.P., S. Fridriksson & E. Hauksson (eds) 1993. *Surtsey 30 ára, Surtseyjafélagið*, Reykjavik, Iceland, 16 pp. with enclosed 1:5000-scale topographic map from 16 July 1993 aerial photographs by the Iceland Geodetic Survey.
- Jakobsson S.P., J. G. Moore, & G. Gudmundsson 1998. Monitoring the Surtsey Volcanic island, Iceland. *Abstract, EOS, Trans. AGU* 79 (45), Fall Meeting Suppl., p. F55.
- Krabill, W.K., R.H. Thomas, C.F. Martin, R.N. Swift & E.B. Frederick 1995. Accuracy of airborne laser altimetry over the Greenland ice sheet. *Int. J. Remote Sensing* 16 (7): 1211-1222.
- Norrman, J.O. 1980. Coastal erosion and slope development on Surtsey Island, Iceland. *Zeit. fur Geomorph.* 34: 20-38.
- Norrman, J.O. & U. Erlingsson 1992. The submarine morphology of the Surtsey volcanic group, *Surtsey research progress report* 10: 45-56.
- Smith, D.E. & 18 others 1999. The global topography of Mars and implications for surface evolution, *Science* 284 (28 May 1999): 1495-1503.
- Thórarinnsson S. 1965. *Sitt af hverju um Surtseyjargosið*. (Engl. summary: Some facts about the Surtsey eruption). *Náttúrufræðingurinn*, 35(4): 153-181.
- Thórarinnsson, S. 1967. *Surtsey*, Viking Press, New York, 47 pp.
- Thórarinnsson S. 1968. *Síðustu þættir Eyjaelda*. (English Summary: The last phases of the Surtsey eruption). *Náttúrufræðingurinn*, 38(3-4): 113-135.
- Williams, R.S. Jr., S. Thórarinnsson & E.C. Morris 1983. Geomorphic classification of Icelandic volcanoes, *Jökull* 33: 19-34.