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Key Points:
- Volumetric erosion for new hydromagmatic island is approximately 0.0026 km^3/year
- Demonstrated first meter-scale documentation of landscapes and topography for a new volcanic island over its initial stages of erosional evolution (approximately 3 years)
- Satellite-based measurements of new island predict lifetime of up to approximately 42 years

Supporting Information:
- Supporting Information S1
- Figure S1
- Data Set S1
- Table S1
- Table S2

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Monitoring and Modeling the Rapid Evolution of Earth's Newest Volcanic Island: *Hunga Tonga Hunga Ha'apai* (Tonga) Using High Spatial Resolution Satellite Observations

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Abstract We have monitored a newly erupted volcanic island in the Kingdom of Tonga, unofficially known as *Hunga Tonga Hunga Ha'apai*, by means of relatively frequent high spatial resolution (~50 cm) satellite observations. The new ~1.8 km^2 island formed as a tuff cone over the course of a month-long hydromagmatic eruption in early 2015 in the *Tonga-Kermadec* volcanic arc. Such ash-dominated eruptions usually produce fragile subaerial landscapes that wash away rapidly due to marine erosion, as occurred nearby in 2009. Our measured rates of erosion are ~0.00256 km^3/year from derived digital topographic models. Preliminary measurements of the topographic expression of the primary tuff cone over ~30 months suggest a lifetime of ~19 years (and potentially up to 42 years). The ability to measure details of a young island's landscape evolution using satellite remote sensing has not previously been possible at these spatial and temporal resolutions.

Plain Language Summary A new volcanic island in the southwestern Pacific Ocean was monitored via high-resolution satellite imaging over ~30 months since its time of formation in early 2015. This island, unofficially named Hunga Tonga Hunga Ha'apai (HTHH), was not expected to persist as land for more than a few months, but our observations have documented its lifetime for at least 36 months. Using topography derived from high-resolution satellite images, the above sea level volume of the island was measured over time, leading to a "volumetric" erosion rate that was compared with other oceanic islands. The HTHH island is disappearing much faster than Surtsey, but far slower than recent nearby activity indicates. Regional submarine topography shows that shallow-water topology may be an important factor in explaining the unanticipated lifetime of this new island, together with internal strengthening by hydrothermal mineralization. The stages of erosion at the HTHH island may have implications for similar landforms discovered on Mars and their evolution in association with surface water levels. The range of plausible lifetimes for this Tonga island system ranges from about 19 to 42 years, at our measured current rates of erosion (0.0026 km^3/year).

1. Introduction and Background

Starting around 19 December 2014, a surtseyan eruption was observed near 20.5°S, 175.4°W in the *Tonga-Kermadec* Islands volcanic arc (Bulletin of the Global Volcanism Network, 2015), followed by the emergence of a new island (Hunga Tonga Hunga Ha'apai, HTHH) by early 2015 (Woolaston, 2015). Initial high spatial resolution satellite observations by Airbus' Pléiades illustrated the resulting island with a total new land area of ~1.74 km^2 (1.94 km^2 including the interior crater lake) and relief of ~120 m (Figure 1, left). The new island formed between two older Tonga islands (*Hunga Tonga* to the NE and *Hunga Ha'apai* to the W; Figure 1), on the rim of the ~5 km diameter submarine *Hunga Caldera* (Bryan et al., 1972). A 2009 eruption (Vaughan & Webley, 2010) that produced a smaller area of new land to the southwest of *Hunga Ha'apai* washed away due to intensive marine abrasion after ~6 months. The lifetime of the 2009 island and others that formed via hydromagmatic processes in this region prompted local experts to suggest that the 2015 HTHH would face a similar demise (Luntz, 2015).

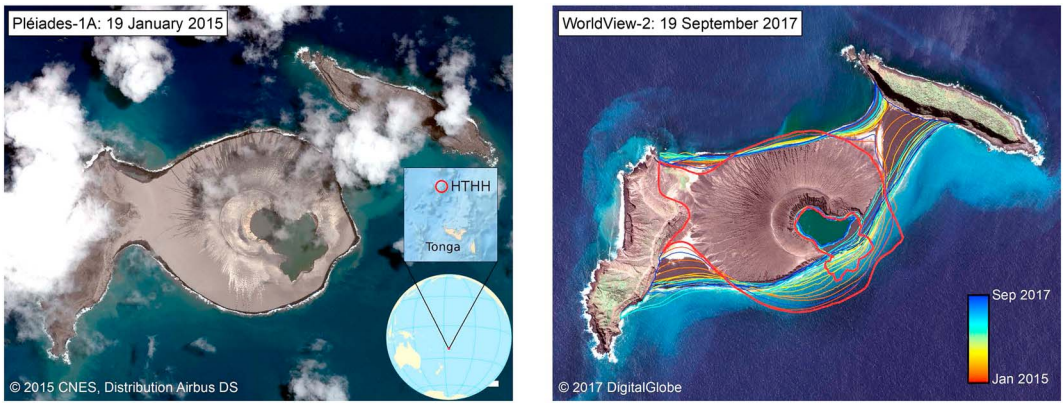

Figure 1. The Airbus Pléiades-1A image (left) at the end of the eruptive stage (19 January 2015). This is the initial, preerosional expression of the new island (Hunga Tonga Hunga Ha'apai) with an inset showing its location (red circle). The current state of the island 2.75 years later (right) is shown in a *DigitalGlobe* WorldView-2 image obtained on 19 September 2017. The evolution of the coastline is depicted in the outlines, with colors ranging from red for January 2015 (early) to blue for September 2017 (latest).

Given the apparent dominance of ash in this surtseyan style eruption (Cronin et al., 2017), early indications suggested that the island would wash away in a few months due to intensive marine abrasion, as was observed at the nearby 2009 eruption (location marked in Figure 3; Vaughan & Webley, 2010). Because typical ash-dominated eruptions rarely produce island landscape systems that survive for more than several months (Nunn, 1994), we organized a coordinated satellite observation effort involving the *Canadian Space Agency* (CSA) Radarsat-2 Synthetic Aperture Radar (SAR) and *DigitalGlobe* WorldView (WV) high-resolution (~50 cm panchromatic) visible imagery (via the U.S. Government's *EnhancedView* contract) to document what was believed to be the anticipated "death of the island" by the end of 2015.

Our initial sequence of satellite observations suggested that the island could persist and offer an opportunity to quantitatively document the stages of erosion and ultimate destruction in ways not previously possible at such spatial and temporal scales (Figures 1 and 2). We hoped to evaluate whether island volumetric changes due to natural causes at meter scales (NRC ES Decadal Survey, 2007) could be effectively measured. Preliminary results (Figure 1) suggested the following approach:

1. Using *meter-resolution* satellite observations, document the volumetric rates of change of the overall island for the purpose of accurately projecting island survival timelines
2. On the basis of volumetric erosion models developed for other oceanic islands (Garvin et al., 2000; Berrocoso et al., 2012; Ramalho et al., 2013; Perron, 2017), quantify the observed island erosion to investigate geologic processes that stabilize such fragile landscape systems, such as *hydrothermal alteration* (e.g., Jakobsson, 1978)

The continuing survival of the HTHH tuff cone (i.e., ~1.74 km^2 in coastline-defined area; Figure 1) over the past ~36 months motivated our development of an island lifetime prediction model using measured volumetric erosion rates (Perron, 2017).

Figure 2 illustrates the initial (post construction) state of the island (March 2015) from ~2 m spatial resolution SAR in comparison with its current appearance (February 2018). Deposition of eroded material to the northeast produced a spit that eventually formed an isthmus connected to the preexisting *Hunga Tonga* island. This is defined by specific strandlines identifiable in the high-resolution SAR backscatter data (Figure 2), which are indications of discrete erosional-depositional pulses.

2. Materials, Methods, and Context

As described in Nunn (1994) and other compilations about volcanic island evolution (Perron, 2017; Ramalho et al., 2013), there are multiple pathways by which newly formed landscapes erode, due to factors including geologic setting, local bathymetry, climatological patterns, and predominant composition of the materials involved. *Surtsey* offers a well-documented example that has been described comprehensively

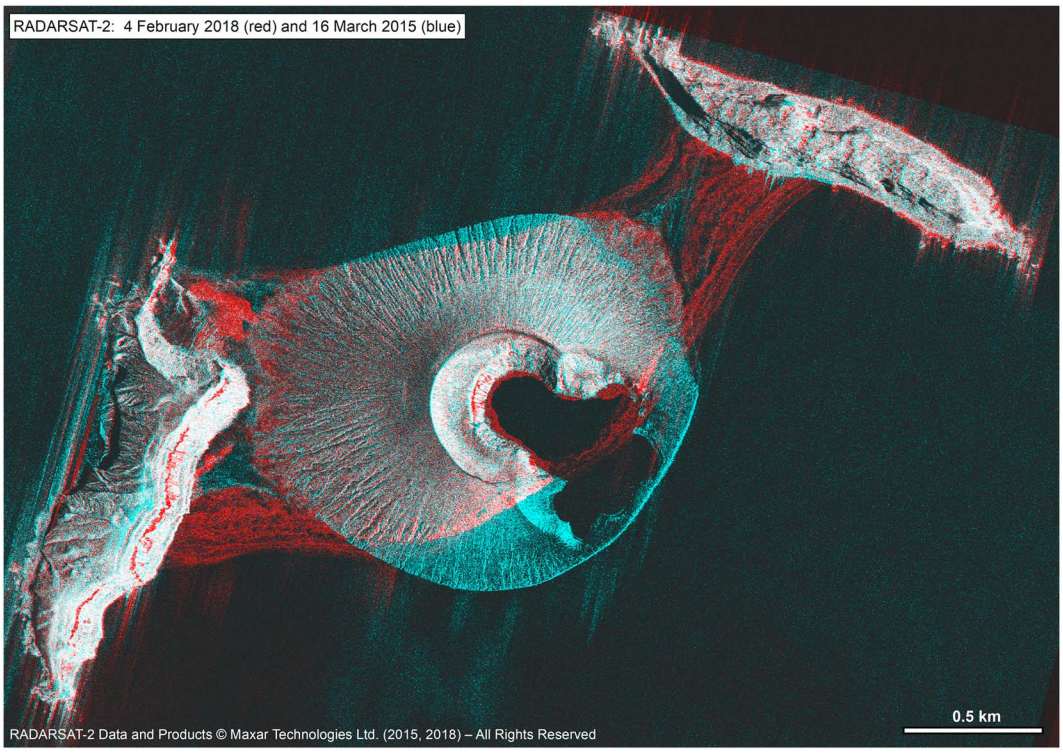

Figure 2. Canadian Space Agency Radarsat-2 *Spotlight* SAR images from 16 March 2015 (blue) and 4 February 2018 (red) at ~2 m spatial resolution (C-band HH at 44° incidence), orthorectified using DEMs generated from DigitalGlobe acquisitions close in date. The loss of ~20% of the island's initial area from marine erosion over time is evident, with redeposition as isthmus deposits (in red) to the NE and SW. Zones of incipient slope failure can be observed on the inner crater walls in *blue*. RADARSAT-2 Data and Products © Maxar Technologies, Ltd. (2015, 2017)—All Rights Reserved. RADARSAT is an official mark of the Canadian Space Agency.

by Thorarinsson (1975) and Jakobsson (1978), and it was adopted as a test case (Garvin et al., 2000) for quantifying volumetric erosion rates. The results of these studies demonstrate how island stabilization at Surtsey was enabled via low-temperature palagonitization over time (Jakobsson, 1978). This Surtsey erosional history prompted our investigation of how the new Tongan island would respond to southwestern Pacific Ocean erosional conditions applied to a basaltic-andesite composition (Cronin et al., 2017).

Opportunities for integrating topographic measurements at landscape scales with meter-class spatial resolution satellite images (e.g., CSA Radarsat-2 SAR, DigitalGlobe WV, and Airbus Pléiades) for a rapidly evolving, newly formed island have been rare; thus, our study offers a test case for a sustained monitoring program relevant to classical evolution models (Wohletz & Sheridan, 1983).

Previous studies (e.g., Surtsey) required multiple aerial photography missions, intensive field work, and episodic sampling over long periods (Thorarinsson, 1975; Jakobsson et al., 2000) to yield significant results. Our efforts at HTHH have exploited meter-resolution satellite-based observations with stereo-derived Digital Elevation Models (DEMs) to constrain above sea level island volume versus time. Given that the island's anticipated survival was expected to be only a few months (Cronin et al., 2017; Luntz, 2015), there was a sense of urgency in order to capture its erosional progression. Why the ash-dominated HTHH island has survived in a relatively intact state (as a tuff cone) for 3 years (Figures 1 and 2) is a key question (Garvin et al., 2017).

2.1. Previous Work at Surtsey

Garvin et al. (2000) studied the evolution of Surtsey (63°18′N, 20°36′W, in a mid-ocean ridge setting) using airborne and satellite remote sensing data. A volumetric erosion model was developed on the basis of a time series of DEMs from digitized high-resolution Icelandic maps and National Aeronautics and Space

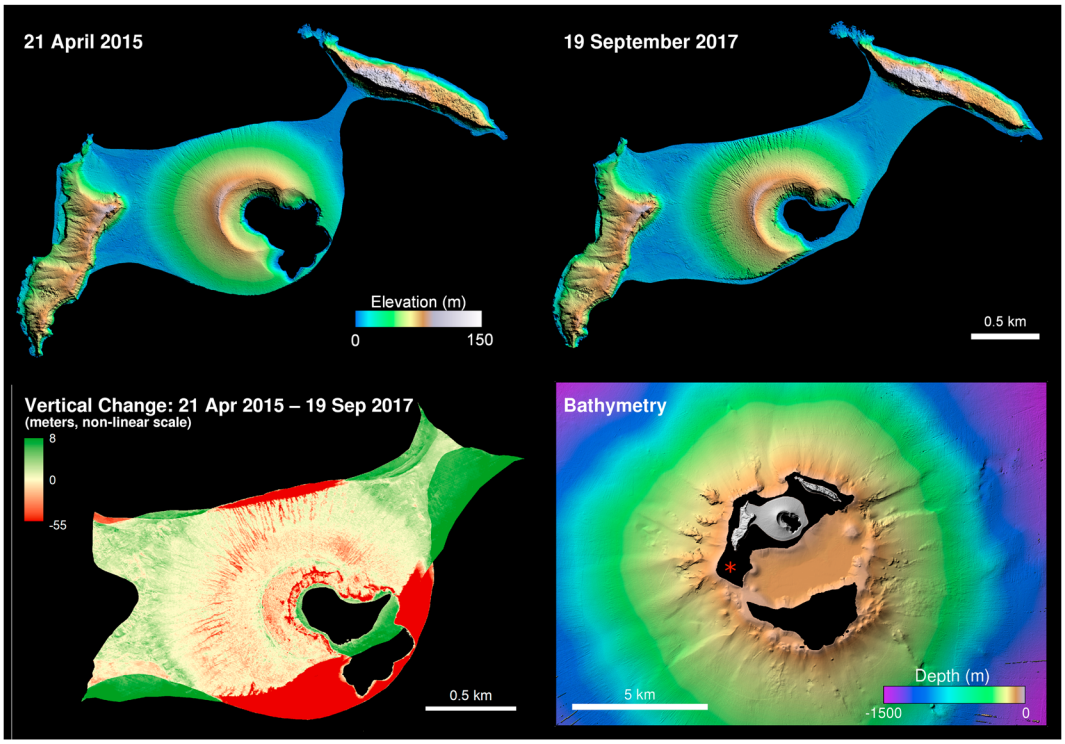

Figure 3. Initial (upper left) and 2017 (upper right) DEMs of Hunga Tonga Hunga Ha'apai at 1-m ground sample distance. The April 2015 DEM indicates a volume of 0.0479 km^3, whereas the September 2017 DEM (upper right) indicates a volume of 0.0430 km^3, a loss of 0.0049 km^3 in 2.5 years. If this simple volumetric erosion rate holds constant, the island will disappear in ~18.7 years. The lower left panel illustrates the difference of the two DEMs illustrated above (top), with areas of erosion in *red* and accretion in *green* (with levels shown in meters); it reflects −0.004272 km^3 lost in the major cliff erosion zones, leaving another 0.00087 km^3 (17%) of loss within the rest of the DEM. The lower right panel depicts the bathymetry (5 m ground sample distance) of the Hunga Tonga Hunga Ha'apai island vicinity as measured from the R/V *Falkor* in April 2016. Total estimated edifice volume above caldera floor (at −155 m) is ~0.50 km^3, with ~11% of that above mean sea level. The basal diameter of the edifice is ~1.5 km, with total relief above this submarine base of ~280 m (relative to the interior of the *Hunga* caldera). The red asterisk indicates the location of the 2009 eruption (Vaughan & Webley, 2010) which washed away after a few months.

Administration airborne geodetic lidar altimeter measurements. Continuing analysis of Surtsey erosion suggests a two-stage history (early, rapid response versus later, slower evolution). This most-recent analysis results in the following relationships, based upon DEMs:

$$V_{\text{early}}\ (1968\text{–}1993) = 131.4 - 0.132\ t + 0.000029\ t^2,$$

and

$$V_{\text{later}}\ (1994\text{–}2015) = 0.46 - 0.00019\ t,$$

where volumes (V) are in km^3 and t is in calendar year format. These relationships estimate a lifetime for Surtsey of at least ~146 years, consistent with independent projections (Jakobsson et al., 2000). The early-to-late erosional stage "break" at 1993/1994 was established via optimization of volume versus time relationships by maximizing correlation coefficients ($R^2 > 0.80$) across the widest possible range of solutions.

2.2. Application to HTHH

We determined the initial volume and surface area of HTHH from an early DEM derived from late April 2015 WorldView-3 stereo images (Figure 3). The values are

$$V\ (\text{above local mean sea level}) = 0.050\ \text{km}^3$$

$$\text{SA}\ (\text{above local mean sea level}) = 1.80\ \text{km}^2$$

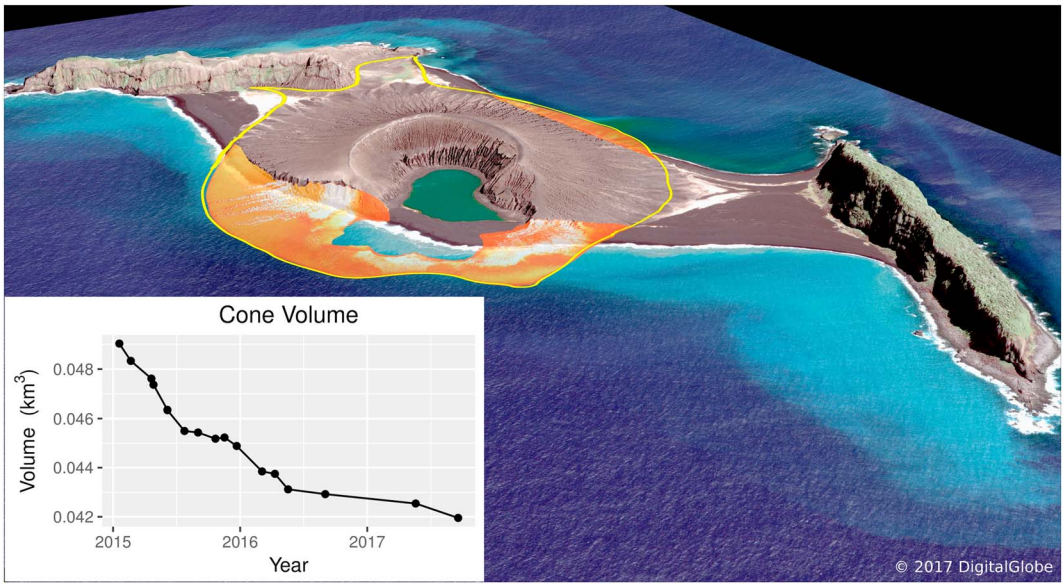

Figure 4. Perspective view of the 19 September 2017 *DigitalGlobe* WorldView-2 image as viewed from the southeast, with superimposed outline of the late January 2015 coastline and reconstructed initial topography. The tan/orange region is the footprint of the preerosional primary tuff cone that formed Hunga Tonga Hunga Ha'apai island, before a land-bridge connected it to the older *Hunga Tonga* (right). Marine erosion due to wave action from the south and SE in this near-shore shallow-water region is dominantly responsible for the pattern of island system response, with deposition of most of the eroded materials on the widening northeastern isthmus. The inset graph illustrates the volumetric change over time since January 2015. See text for details (Table 1 and Figure S1).

where these parameters have uncertainty levels of ~10% due to tidal variations. From these initial values and those estimated from the ensuing 2.5 years, we see evidence of an approximate mass balance developing within the overall land area (now a tombolo). Materials from the eroding southern flank of the tuff cone are being continuously redeposited in shallows to the NE and SW (Figures 2 and 3). This particular balance is difficult to anticipate, as it strongly depends on the near-shore bathymetry (Figure 3: lower right), and on the role low-temperature mineralization could be playing within the edifice (Fisher & Schmincke, 1984).

3. Results From Monitoring and Modeling HTHH Evolution

Using a time series of satellite observations through February 2018 encompassing ~36 months of modification, in combination with our derived DEM time series (Figures 3 and S1), we investigated erosional changes using estimated volumes as a proxy for mass (Table S1).

We acquired a series of 75 very high resolution images from *DigitalGlobe* (Worldview-1, -2, and -3 satellites; 72 images), and Airbus (Pléiades-1A satellite: three images). Although 65 of these were image pairs taken in a stereo acquisition mode and thus potentially suitable for generation of DEMs, most were too cloudy to be useful; in the end, we generated 16 DEMs from this series, using PCI Geomatica's Orthoengine module (version 2017; Table S1, Data Set S1, and Figure 3). Lacking geodetic ground control from a site visit, we instead created an initial DEM (21 April 2015) from the DigitalGlobe level-2A product (orthoready), without ground control. The resulting DEM was then used to create an ortho image, and the two (orthoimage and DEM) were then adopted as control for processing all other DEMs (e.g., ground control points and elevations were obtained from this initial set). Even so, some of the resulting DEMs exhibited unrealistic vertical offsets, which became apparent in the scatter in a plot of volume over time (Figure 4: inset). To control for these vertical errors, we selected a bare and visibly unchanging patch of *Hunga Ha'apai* to normalize elevations across all DEMs, resulting in a much less noisy volumetric time series (Figure 4 and Table S1). Our primary criterion for selecting this control patch (among several evaluated) was that the resulting time series show only decreases (or no change). Figure 4 shows a 3-D perspective of a satellite image from 19 September 2017

Table 1
Model Fits for Total Tuff Cone Volumes V_{tc} (in km^3) From Full Time Series of All 16 DEMs

Model	Intercept	Slope	R^2	Lifetime
Linear	0.0477	−0.00256	0.84	18.7 years
Log	0.0444	−0.00195	0.93	[a]
Piecewise linear—first segment	0.0488	−0.00451		—
Piecewise linear—second segment	0.0449	−0.00108	0.97	41.7 years

Note. Time is in years, starting at 1 January 2015. For the piecewise linear model, values are provided for each segment, with the optimal breakpoint found at 16 February 2016. The R^2 goodness of fit values listed is the overall R^2 of both temporal segments (see also Figure S1).
[a]The logarithmic model does not converge to a zero-crossing (end of island state) given the present data and its uncertainties (Table S1).

draped over its DEM, with the rendering of the initial tuff cone (January 2015) superimposed to illustrate areas where it has since eroded away, together with a graph of the change in volume over time (Figure S1).

The rate of volumetric landscape change is well-known at Surtsey and we have established this rate for HTHH using the time series of 16 DEMs over the past ~30 months (Figures 3 and 4 and Table S1). From these DEMs, we computed tuff cone volume (V_{tc}), using a basal contour defined by the initial island posteruption coastline (green contour line in the lower-left panel of Figure 3). This was adopted in order to maintain a common basis of reference for measured volumes. By interpolating the April 2015 DEM (Figure 3) back in time to match the coastline of the island in late January 2015, we determined an approximate initial volume of ~0.050 km^3 above sea level, as shown in Figure 4.

It is clear from our time series of DEM-based volume measurements (Figure 4 inset and Table S1) that an early stage linear model does not predict island evolution reliably. Indeed, if we were to use only the initial ~6 months of volume estimates, a linear "early stage" model projects island lifetime of ~7.2 years, a value not consistent with the current state of the island topography (Figure 3).

By examining the full sequence of volumes from the 16 DEMs extending out to September 2017 (Table S1), we can fit linear, log linear, and piecewise linear models to this time series, as illustrated by the equations in Table 1 (also Figure S1). Piecewise linear approximations provide an effective "temporal" separation of the initial rapid erosion trajectory (mentioned above), with the slower ongoing trajectory, but only future measurements will inform how this trend will ultimately evolve. Table 1 lists the estimated lifetimes for these fits.

On this basis we conclude that the primary tephra/lava tuff cone will persist at least for another ~18.7 years and possibly up to ~42 years. More accurate projections of tuff cone lifetime require DEMs with submeter geodetic control, over a longer temporal baseline. While the primary tuff cone may degrade from its present subconical form in ~18.7 years, it is likely that a low-relief "land bridge" between *Hunga Ha'apai* to the SW and *Hunga Tonga* to the NE will persist for much longer (~42 years), subject only to the frequency and intensity of tropical cyclonic storms (e.g., *Gita* on 11 February 2018) that could wash over the barrier-island-like landscapes. Thus, the volumetric evolution of the primary tuff cone at HTHH illustrates the stages of erosion for an ash-dominated basaltic-andesite volcano in a setting dominated by marine erosion.

4. Discussion

A time series of satellite observations was acquired to capture and analyze the volumetric evolution of the rapidly evolving landscapes and coastal outline of the new HTHH tuff cone in Tonga. This ~36 month-long study based upon a combination of WV optical and Radarsat-2 SAR observations has provided comprehensive documentation of the island's evolution throughout its early modification and subsequent adjustment stages. Our measurements from monthly Radarsat-2 SAR images (Figure 2), episodic WV optical observations (Figure 1), the Pléiades image (19 January 2015; Figure 1), and WV-based DEMs (Figure 3) allowed us to characterize the pattern and rate of erosional modification, as described above.

These efforts have produced the time series that documents HTHH coastline area and primary tuff cone volume (Figures 1–4). We have observed apparent pulses of deposition to the northeast on the isthmus

(connecting to *Hunga Tonga*) that developed initially as a spit in February–March 2015 after initial island formation (Figure 2). Our results suggest the following four stages of erosional development at HTHH:

Stage 1 Initial erosional response in which early development of a northeast trending spit from intensive marine erosion and deposition is first established. Timeline: from eruption to early April 2015 (approximately 3 months).

Stage 2 Stabilization (up to ~6 months after end of the eruption) with wash over of the low-relief southern bounding rim of the crater and subsequent closure due to sediment deposition via a shallow near-shore submarine shelf to the south. Timeline: April–June 2015.

Stage 3 Incremental erosion of island from the south via sustained marine erosion with episodic, pulsed deposition of a low-relief isthmus from the initial HTHH tuff cone to the older *Hunga Tonga* (NE). Timeline: June 2015 to present.

Stage 4 Future modification of the quasi-equilibrium (piecewise linear model) with partial inner crater wall collapse and eventual lowering of the tuff cone rim, combined with accelerated marine erosion from the south. Timeline: the duration of this island evolution stage is unknown, and not well constrained by any single-stage erosion model given frequency of extreme events such as typhoons (e.g., *Gita* in February 2018).

5. Summary and Conclusions

Evaluation of the sensitivity of relatively high temporal resolution monitoring at HTHH demonstrates the potential of this approach for characterizing volcano erosion rates. Wohletz and Sheridan (1983) have described the general stages of erosional evolution of volcanic tuff cones, and this work (HTHH) offers a sample of their erosional sequence as a snapshot in time. Field-based observations at HTHH (Grouille & Sabau, 2017) acquired samples guided by our satellite images, including an initial search for evidence of hydrothermal alteration products. We suggest that satellite remote sensing and associated analysis of volumetric evolution of new islands such as HTHH is relevant to landscape erosion on volcanoes in general (Perron, 2017), even if the HTHH tuff cone lifetime is as brief as ~19 years. Ultimately, these results have established a framework for scientific observations of ephemeral oceanic islands from which predictive models for island lifetimes and evolutionary pathways can be further refined. The results presented herein offer quantitative estimates for the pace of island erosion in one specific oceanic erosional regime for comparison with others. Our findings indicate that the shallow submarine bathymetry around the southern margin (shelf?) of the new HTHH edifice (Figure 3: lower right) plays a potentially significant role in the island's evolution and deserves detailed near-term characterization.

On the basis of our measurements and analysis it is likely that hydrothermal alteration of some form is mechanically supporting the primary HTHH tuff cone, allowing for a lifetime with a projected range of values between ~19 and 42 years. It is clear that HTHH is eroding at a rate many times faster (0.00256 km^3/year) than basaltic Surtsey, marking it as an important example of volcanic island erosion in action. Future studies of the predominant direction of swells to the south of the new island in association with the regional seafloor topography within the submarine *Hunga Caldera* (Figure 3, lower right) may further explain the survival modes of the primary tuff cone, especially if the near-shore bathymetry can be measured within ~500 m of the southern coast. Finally, application of these results to other volcanic island settings on Earth and potentially to Mars, where evidence of ancient (~2–3 billion years ago) hydrovolcanic eruptions has been documented (e.g., Broz & Hauber, 2013), is a potentially exciting next step.

Acknowledgments

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