Journal of Volcanology and Geothermal Research 401 (2020) 106902

Contents lists available at ScienceDirect

Journal of Volcanology and Geothermal Research

journal homepage: www.elsevier.com/locate/jvolgeores

Exploring the human-nature dynamics of Hunga Tonga Hunga Ha'apai, Earth's newest landmass

Emily B. Hite [a,1,*], James B. Garvin [b], Dan A. Slayback [b,c], Emily A. Burke [a], Grace Callahan [a], Paul Joyce [a], Kerry Whittaker [a]

[a] Sea Education Association, 171 Woods Hole Rd, Falmouth, MA 02540, United States of America.
[b] NASA Goddard Space Flight Center, 8800 Greenbelt Road, Greenbelt, MD 20771, United States of America
[c] Science Systems & Applications, Inc, 10210 Greenbelt Road Suite 600, Lanham MD 20706

ARTICLE INFO

Article history:
Received 29 February 2020
Received in revised form 21 April 2020
Accepted 22 April 2020
Available online 30 April 2020

Keywords:
Hydromagmatism
Experiential education
Seascapes
Oceania
Biological colonization
Tombolo
Collaboration

ABSTRACT

This paper examines the human-nature dynamics of volcanic eruptions through a multidisciplinary exploration of the recently-formed Hunga Tonga Hunga Ha‘apai (HTHH) landmass in the Kingdom of Tonga. HTHH was formed in early 2015 in the Ha‘apai island group in southwestern Tonga. This landmass has persisted longer than expected, providing a rare opportunity to examine pathways of erosion and biological colonization, and offering a glimpse into the cultural dynamics of a continuously changing Polynesian seascape. In 2018 and 2019, a collaborative partnership between the Kingdom of Tonga, Sea Education Association (SEA), and the United States National Aeronautics and Space Administration (NASA) ran expeditions to HTHH to calibrate satellite observations via field, ship, and drone-based measurements. In accessing HTHH via SEA's sailing school vessel (SSV) the *Robert C. Seamans*, a team of scientists and students combined fieldwork in anthropology, oceanography, and physical volcanology to study micro- and macro-scale dynamics of this classical surtseyan eruption site. In this pathfinding paper, we discuss the value of involving students in the process of real-time scientific discovery with on-the-fly adaptive hypothesis testing; this collaborative project provided mutual benefit to initiatives in science and education by offering robust data collection, while expanding environmental and cultural literacy. Additionally, we integrate collaborative research on HTHH with ethnographic research to understand how this ever changing “sea of islands” or intimately interconnected island spaces impact social-cultural relations within Oceania. We emphasize the importance of such multidisciplinary research in understanding the complexity of human-nature relations in a rapidly changing world.

1. Introduction

This paper examines the human-nature dimensions of volcanic eruptions through a multidisciplinary exploration of a newly formed volcanic island landmass, Hunga Tonga Hunga Ha‘apai (HTHH), in the Kingdom of Tonga. HTHH[3] was constructed in early 2015 during an approximately month-long, predominantly explosive volcanic eruption that ultimately connected the islands of Hunga Tonga (HT) to the north east and Hunga Ha‘apai (HH) to the south west via a 1.9 km^2 tuff cone (Garvin et al., 2018) (Fig. 1). This rapidly-evolving landmass (now a tombolo) has persisted longer than expected (Garvin et al., 2018, 2019), providing a rare opportunity to examine pathways of erosion and biological colonization, and offering a glimpse into the cultural dynamics of a continuously changing Polynesian seascape. HTHH is one of the very few newly formed volcanic islands to persist for several years during the current era of commercial sub-meter resolution optical remote sensing satellites that became available in 1999 (Garvin et al., 2017, 2018). Therefore, HTHH offers a valuable opportunity to examine, in real time and on human scales, the quantitative details of erosion and dynamics of mechanical stability allowing new landscapes to evolve and persist here on Earth, and on other planets such as Mars, which is one motivation for the interest of the United States National Aeronautics and Space Administration (NASA) in studying this island as a planetary analogue.

Since 2015, NASA has conducted scientific research on HTHH using satellite and drone-based remote sensing to characterize its geological dynamics via a time series of meter-scale topographic models (Digital Elevation Models, DEM) together with a collaborative 2016 study of the sonar bathymetry of the larger underwater Hunga caldera in partnership with

* Corresponding author.
E-mail addresses: emily.b.hite@colorado.edu (E.B. Hite), james.b.garvin@nasa.gov (J.B. Garvin), dan.slayback@nasa.gov (D.A. Slayback), gcallah2@wellesley.edu (G. Callahan), pjoyce@sea.edu (P. Joyce), kwhittaker@sea.edu (K. Whittaker).
[1] Present address: University of Colorado Boulder, 1350 Pleasant Street, Boulder, CO 80302, United States of America.

[3] HTHH is a temporary name. Officially naming of the new landmass has cultural and political significance to the people of the Kingdom of Tonga. While suggestions have been made by members of the Tonga Geological Service, naming the landmass is ultimately the King of Tonga's decision.

https://doi.org/10.1016/j.jvolgeores.2020.106902
0377-0273/© 2020 Published by Elsevier B.V.

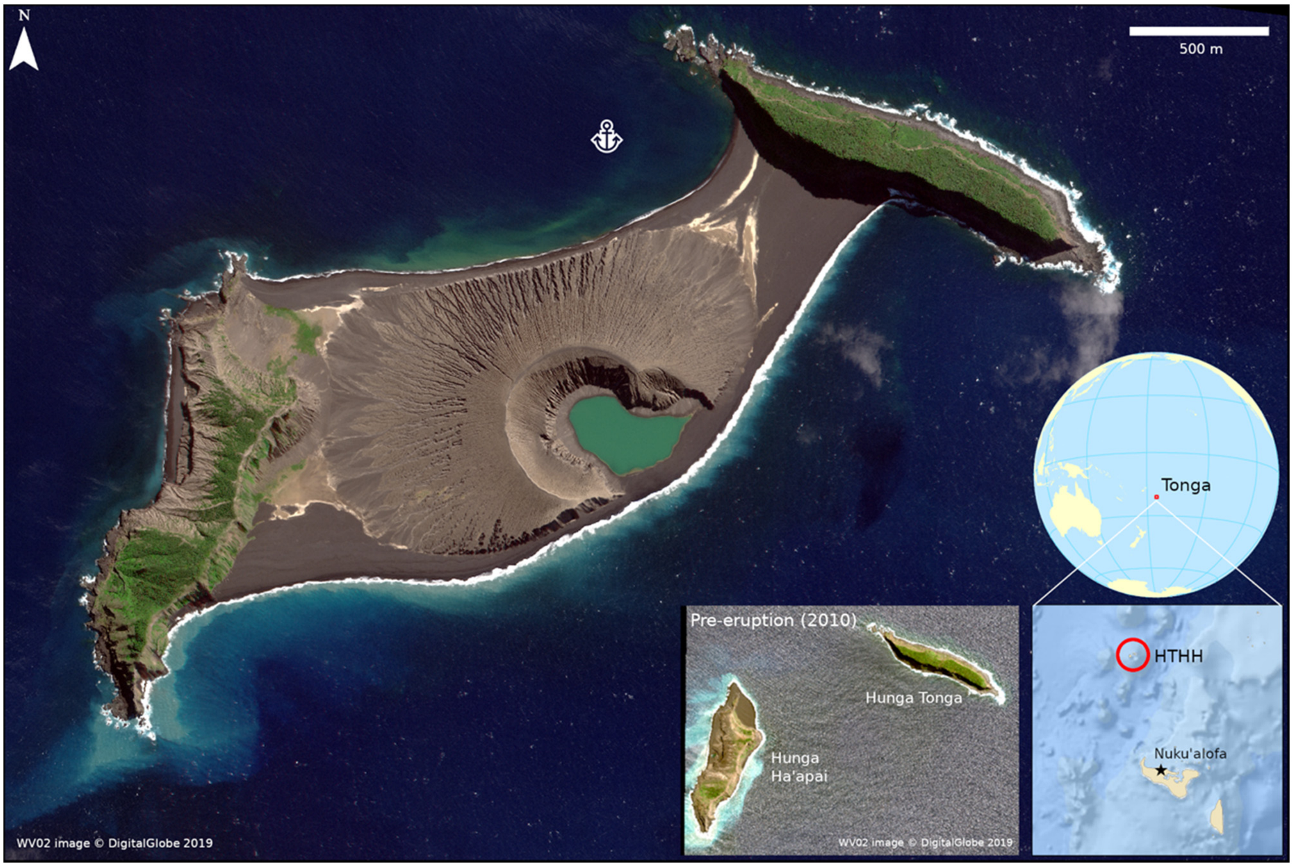

Fig. 1. Image of HTHH tombolo, situated in the southern Pacific in the Kingdom of Tonga, north of the capital Nukuʻalofa on the island of Tongatapu. Newly formed tuff cone edifice with crater lake in the middle of the landmass, with connected islands of Hunga Tonga to the northeast and Hunga Haʻapai to the southwest. The "pre-eruption" inset illustrates the two islands prior to the January 2015 eruption that ultimately connected them. The anchor symbol indicates the location of the *SSV Robert C. Seamans* during in situ research.

Schmidt Ocean Institute's (SOI) Research Vessel or R/V Falkor and Columbia Lamont-Doherty Earth Observatory (LDEO) (Garvin et al., 2017; Garvin et al., 2018). The NASA science team (Garvin, Slayback, Ferrini, Asrar, and other colleagues) hypothesized in June 2015 that the volcano could survive as an intact island landform for ~15–20 years on the basis of their observations of erosion rates over the first 6 months of the island's existence. Additionally, research has shown that slow hydrothermal mineralization could convert packets of basaltic-andesite tephra (ash) into palagonite, as occurred at Surtsey in Iceland (Jakobsson and Moore, 1986); this could increase mechanical resistance of marine abrasion and pluvial erosion at the new edifice. Such palagonization was not anticipated at HTHH until field reconnaissance and laboratory analyses provided evidence.

As part of their ongoing research, in 2018, NASA joined a collaborative partnership with the government of the Kingdom of Tonga and the Sea Education Association (SEA) to visit HTHH to collect an array of measurements to document its current erosional state and to provide a basis for future measurements. The SEA sailing school vessel (*SSV*) *Robert C. Seamans* offered direct access to the remote island and an opportunity to involve students in ground truthing ex situ observations from high resolution satellite remote sensing (e.g., DigitalGlobe WorldView and Canadian Space Agency Radarsat-2). The Kingdom of Tonga has a vested interest in understanding and predicting the geological stability of HTHH, in part because volcanic activities have directly impacted people's daily lives and activities throughout time by transforming their spaces and places. Ultimately, frequent eruptions and the emergence of new landmasses are a significant component of human-nature relationships for people living in the region and therefore inform their cultures, ontologies, and epistemologies.

In this pathfinding paper, we discuss the value of involving students in the process of real-time scientific exploration and discovery with on-the-fly adaptive hypothesis testing; this collaborative project provided mutual benefits to initiatives in science and education by offering robust data collection, while expanding environmental and cultural literacy for undergraduate students from the United States and abroad as well as our research partners. This collaborative project combined research in physical volcanology and oceanography to study a variety of micro- and macro-scale dynamics of this classical surtseyan eruption site (i.e., Surtsey in Iceland as the type-locality of such hydro-magmatic eruptions). Additionally, students conducted ethnographic research, including participant observation and interviews, as part of their anthropological studies throughout Tonga to understand how this ever changing "sea of islands" or intimately interconnected island spaces (Hau'ofa, 1994) has impacted social-ecological relations of the people of Oceania.

First, we elucidate the regional setting and physical features of HTHH with references to Garvin et al. (2018). Then we discuss the roles of each partner and describe the collaborative processes that made this research possible. Next, we outline the mission, explaining data collection objectives and achievements, followed by a discussion of our preliminary findings. In conclusion, we highlight future directions for research and broadly argue for the importance of collaborative multidisciplinary fieldwork to understand the increasingly complex, globalized, and rapidly changing world.

1.1. Regional setting

HTHH is located in the Haʻapai island group, roughly in the center of the Kingdom of Tonga in the Southwest Pacific in the western part of the

Kermadec-Tonga back arc. It is located approximately 63 km NNW of Nuku'alofa, the capital of Tonga on the island of Tongatapu (see Fig. 1). The Ha'apai island group covers an area of over 109 km^2. It comprises a series of 51 islands, and countless shoals and reefs; only 17 of the groups' islands are inhabited. Hunga Tonga, Hunga Ha'apai, and the new tombolo, are uninhabited (currently and within historical knowledge); the pre-existing HT and HH landmasses are associated with steep and rugged volcanic terrain. HTHH lies along the Kermadec-Tonga subduction zone, a convergent plate boundary between the Pacific and Indo-Australian plate stretching over 3000 km from the islands of Tonga to New Zealand (Contreras-Reyes et al., 2011), which forms the Tongan trench, the second deepest oceanic trench on Earth (Smith and Demopoulos, 2003).

Bryan et al. (1972) have described the volcanic history of this region in the southwest Pacific, with attention to styles of eruption and petrology. Documented historical eruptions prior to the current episode discussed here occurred in 1912, 1937, 1988, and 2009. The most recent event occurred from late December 2014 to late January 2015, and potentially produced 0.4 km^3 of new materials with about 0.070 km^3 as a new subaerial tuff cone edifice (Garvin et al., 2018), with the form of a classical tuff cone (Németh and Kereszturi, 2015; Németh and Kósik, 2020; Wohletz and Sheridan, 1983).

1.2. Collaborative partnerships: Kingdom of Tonga, SEA, and NASA

The multidisciplinary research at HTHH was made possible through a unique partnership between the government of the Kingdom of Tonga, Sea Education Association (SEA), and the United States National Aeronautics and Space Administration (NASA). Multidisciplinary research has become an accepted norm in academia in the past few decades, in light of attempts to understand complex systems and global issues, such as climate change. Arguably, studying interconnected, overlapping, and integrated social-ecological systems as a whole provides much more realistic and multi-dimensional information than can be found studying each system individually (Liu et al., 2007).

The unique collaborative scientific mission conducted at HTHH was catalyzed by the remoteness of the island, challenge of access, and overlapping objectives of the Kingdom of Tonga, SEA, and NASA. Waters surrounding the new landmass remain uncharted, and landing on the island requires ship resources with mapping and small boat capabilities. In 2016, the SOI R/V Falkor collected valuable sonar bathymetric data (providing regional context), but did not land, and stayed beyond the 30 m isobath. There was much more to gain with respect to the subaerial expression of the new island by accessing the island directly including educational, scientific, and exploratory benefits.

Coincidentally, in 2018, SEA began pursuing the possibility of visiting HTHH as a stop along their annual sailing cruise track in the South Pacific region for an undergraduate SEA Semester© program that voyages yearly from American Samoa to New Zealand via Tonga and Fiji. In assessing the risk, safety, and navigational potential of visiting HTHH in 2018, SEA contacts led to the ongoing work of James B. Garvin and Vicki Ferrini, at NASA and LDEO, respectively. A new partnership was formed as a result of these discussions, and was guided by the NASA-funded work of Garvin, Slayback and Ferrini (which commenced in September 2015 via NASA's RRNES program in Earth Sciences). The team organized and executed a "proof-of-concept" visit to HTHH in 2018 aboard the *SSV Robert C. Seamans* to begin baseline observations and assess the feasibility of continuing in situ research on the newly formed landmass. The visit included a team comprised of SEA crew, faculty, and students, and NASA field scientist Dan Slayback. A repeat visit between October 7–11, 2019, as discussed herein, allowed for extended time on the island. Not only were we collectively able to conduct research described below, but we set forth discrete research and education goals, that include additional connections to operational benefits for the NASA Mars Exploration Program and its upcoming 2020 rover mission, now called Perseverance (with its Mars Helicopter Technology Demonstration experiment and its cameras [MHTD]).

1.2.1. The Kingdom of Tonga

The Kingdom of Tonga's King Tupou VI, the Geological Service, Tongan Ministry of Foreign Affairs, and the Ministry of Lands, Survey, and Natural Resources (MLSNR) were key actors in this research. Scientific permits are required for oceanographic and terrestrial sampling within the exclusive economic zone of any nation; the process of applying for scientific permits is complex, with each nation setting forth unique reporting guidelines and requirements. To obtain permits in Tonga, permission from the King is essential. Once his permission is granted, permits are distributed from MLSNR, as they are responsible for managing resources for the benefit of all its stakeholders, as well as developing and implementing programs for the environment. Lord Ma'afu, Minister for MLSNR and the Minister for Environment and Climate Change, granted SEA and NASA these permits for both the 2018 and 2019 expeditions.

One requirement of permitting is that all scientific data be shared with the Kingdom of Tonga and MLSNR. SEA and NASA provided all raw data to each partner group and the collaborative group is working on co-authored academic articles (Garvin et al., 2018, for example) and other methods to share this information to a broader public audience. The second permitting requirement was that SEA accommodate a scientific observer onboard for the duration of the HTHH visits in 2018 and 2019. Observers participate in research and data collection and provide mission oversight. In turn, the involvement of Tongan observers offered a benefit to the broader mission goals by providing an opportunity for cultural exchange and interaction with students, crew, and scientists by sharing their expert cultural, ecological, and geological knowledge. In 2018, Mafoa Penisoni, Assistant Geologist at MLSNR, joined as an observer for the HTHH mission, contributing to sailing and the educational and scientific work with SEA and NASA. As the native Tongan representative, Mafoa was the first person to set foot on the island during the team's visit, as is culturally appropriate in the region. Upon arriving at HTHH for the first time, Mafoa explored the landmass and gave thanks to the island before giving his blessing for research to begin, at which time NASA and SEA researchers landed on the island.

In 2019, Penikolo Vailea sailed as the second Tongan observer and research partner in this joint venture. Both Penikolo and Mafoa not only contributed to the scientific mission, but they became deeply integrated into the shipboard community. They also acted as liaisons for cultural exchange upon the ship's arrival in Vava'u and Nuku'alofa, offering opportunities for greater networking between SEA and NASA scientists, students, and local Tongans. As such, the scientific permitting process functions to advance research capacity, facilitate positive international collaboration, and develop equitable knowledge sharing processes. Scientific information on HTHH is important to the Kingdom of Tonga for navigational and survey purposes, and offers a deeper understanding of land formation processes within the highly geologically active region. Interviews indicated that it could also be a source of economic expansion for the tourism industry.

1.2.2. Sea Education Association (SEA)

SEA is non-profit organization offering field-based environmental education. SEA offers high school and adult programs in interdisciplinary ocean studies and sail training, and semester-long undergraduate programs, known as SEA Semester©. SEA is internationally recognized for its teaching, learning, and research dedicated to the exploration, understanding, and stewardship of marine and maritime environments. Participants actively sail aboard one of two 134-ft brigantine-rigged tall ships that are designated Sailing School Vessels (SSV): the *SSV Robert C. Seamans*, sailing in the Pacific Ocean or the *SSV Corwith Cramer*, sailing in the Atlantic Ocean. SEA Semester programs foster ocean stewardship through a trans-disciplinary approach that encourages ocean science and ocean literacy (understanding the reciprocal relationship between people and the ocean), principles identified for future sustainable development (e.g., Visbeck, 2018). Through SEA, a core value of leadership learning is woven into all elements of shipboard life and scientific collaboration.

SEA has a nearly 50-year history of contributing scientific data to, and involving students in, the process of impactful and meaningful broad-reaching scientific discovery. During each SEA program, students contribute to a range of oceanographic and social scientific research projects; they participate in a research design phase during onshore learning at the SEA campus in Woods Hole, Massachusetts and execute field research during the second portion of the semester. Students represent diverse backgrounds and majors from universities across the United States and internationally, and therefore bring unique perspectives, interests, and foci to SEA research projects. They work alongside SEA staff scientists, who are carrying out long-term, time-series data collection across repeat cruise tracks, revealing the dynamics of change in the ocean and on our planet, meaning that several projects are being conducted at any one time (see for example Bower et al., 2004; McClennen and Meyer, 2002). Students learn to collect empirical evidence, test their critical thinking, and interact with complex field data. Examples of the types of oceanographic research conducted by SEA include studies of the abundance and distribution of plankton, ocean plastic pollution, the biology of thermal fronts, the geology of carbonate banks and islands, physical and chemical oceanography of the regions, and the comparative ecology of shallow productive banks among others.

Each research vessel is equipped with oceanographic research laboratories, which were funded in part by the United States National Science Foundation, to collect and analyze data. Standard scientific sampling while underway includes continuous water column profiles of current magnitude and direction via Acoustic Doppler Current Profiler; continuous single-beam measurements of bathymetry; continuous surface seawater measurements of temperature, salinity, colored dissolved organic matter fluorescence, beam transmittance, and chlorophyll fluorescence; conductivity, temperature, and depth profiles of upper water column; discrete water samples collected by Niskin bottle for chemical analysis, surface and near-surface zooplankton biodiversity and abundance assessed by net tow and dip net (333 and 1000 μm mesh, respectively); surface and near-surface phytoplankton biodiversity and abundance assessed by drifted phytoplankton net (64 μm mesh); and sediment sampling by shipek grab and/or gravity core. Students also conduct hourly visual surveys (0600–1900 h) of marine debris, marine mammals, seabirds, fish, and sea turtles. Enumeration of marine debris and fauna is augmented with aerial surveys using a drone equipped with a digital recording device (e.g., Phantom 3 or similar model ~400 m range) and a hydroacoustic device to record the ocean soundscape, including marine mammal vocalization and anthropogenic noise.

Oceanographic research was combined with anthropological research as part of SEA's interdisciplinary program called SEA Semester: Sustainability in Polynesian Island Cultures and Ecosystems (SPICE). Through SPICE, students study the dynamic relationships between peoples and their environments with a focus on understanding cultural and ecological sustainability. Therefore, in addition to Nautical Science, Maritime Environmental History, and Oceanography, students are introduced to anthropological theory and methods in Maritime History and Culture and Cultural Landscapes and Seascapes, the latter of which is centered on learning about "Sense of Place."

In 1992 UNESCO introduced the designation of "cultural landscapes" to acknowledge places where "combined works of nature and humankind … express a long and intimate relationship between peoples and their natural environment" (see Rössler, 2006). More recently, the Ocean Health Index (OHI), a collaborative project that assesses global ocean health in order to advance ocean policy and protect marine ecosystems, has adopted the phrase "Sense of Place" to try to capture the "cultural, spiritual and aesthetic benefits that people value for a region" (OHI, 2019). Both organizations encourage preservation through knowledgeable action.

In anthropology, "place" is a central component of understanding peoples' relationships to specific landscapes and seascapes. Those locations are inscribed with culturally specific histories and meanings that inform peoples' identities, behaviors, and beliefs (Basso, 1996; Gupta and Ferguson, 1992; West, 2005). The people of Oceania have a unique relationship with place, as their identity is intimately centered on being of and from the sea (see Gegeo 2001; Kahn, 2011; McKinnon et al. 2016; Na'puti 2019; Oliveira 2014; Panelli and Tipa 2007; Smith 2004; Thaman 1985). Tongan anthropologist Epeli Hau'ofa refers to the Polynesian region as a "sea of islands," a concept that counters previous notions of the people of Oceania as being helplessly scattered throughout a vast sea of disconnected islands, dependent on foreign powers (Hau'ofa, 1994). Instead, through this concept we come to understand peoples, places, and cultures of the region as being an intimately interconnected web of seascapes where generations of independent peoples explore, live, and thrive with agency and self-determination. Sense of Place therefore is utilized within the context of SEA's SPICE program to develop a deeper understanding of the human-nature relationships throughout Oceania with the aim of enhancing cultural literacy and encouraging students to critically engage with broader social-ecological issues surrounding conservation, resource management, and cultural and ecological sustainability. More broadly, understanding the region as a sea of islands is an essential component of facilitating an equitable collaboration among research partners.

In 2019, SPICE Captain Chris Nolan, Chief Scientist Kerry Whittaker, and Chief Anthropologist Emily Hite worked onboard the *SSV Robert C. Seamans* with three professional sailing crew, three assistant scientists, two engineers, and a steward. Collectively, they led 26 undergraduate students in class S288 (designating the **S**eamans 288th class) from across United States' universities to sail between American Samoa and New Zealand, with port stops in Tonga and Fiji. They were joined by Tongan observer Penikolo Vailea, Fijian observer Sovaia Lewanavanua, and NASA scientist Dan Slayback for portions of the voyage.

As part of their anthropological projects, students worked with local collaborators to learn about cultural revitalization with professor and master artists specializing in *siapo* or tapa cloth in American Samoa, assisted in beach cleanups and removed invasive crown of thorns (*Acanthaster planci*) from coral reefs with the Vava'u Environmental Protection Association, planted mangroves in Nuku'alofa with the Tongan Department of Environment's Ministry of Lands, Environment, Climate Change and Natural Resources, and participated in cultural and scientific exchanges with students at local schools, including the International School of Suva and the University of South Pacific in Suva, Fiji. Also during port stops, students conducted independent and group projects on kinship, development, religion, navigation history, and conservation that entailed conducting interviews with our collaborators and participant observation to better understand various human-nature dynamics.

1.2.3. United States National Aeronautics and Space Administration (NASA)

NASA's participation was spearheaded by the Goddard Space Flight Center's Chief Scientist James Garvin (Jim) and Research Scientist Dan Slayback, . The NASA work at HTHH commenced in August 2015 in response to the January 2015 surtseyan eruption, with the intention of providing satellite-based monitoring data relevant to the erosional evolution of the new island, as well as connections to how small conical volcanoes on Mars may have evolved in the presence of standing bodies of water in the long-distant past (Brož and Hauber, 2013). NASA's Earth Sciences priorities are guided by the most recent National Academies Decadal Survey (Charo and Abdalati, 2018), with attention to volcano-climate connections, and to landscape evolution as part of the Surface Topography and Vegetation (STV) sub-element. Quantifying pristine landscape erosional rates using satellite data, ground truth via field calibration and validation, was a central theme of the NASA effort, precipitated by long-standing studies at the island of Surtsey using topographic remote sensing (e.g., lidar and SAR).

HTHH represents a rapidly evolving new landscape system for which satellite-based monitoring could offer insights and boundary conditions for physical models applicable to other newly-formed oceanic islands in an era of rapid sea-level rise. NASA's goals and objectives for studies of HTHH (Garvin et al., 2018) centered on mechanisms by which the tephra-dominated surtseyan eruption that formed the island could lead to its longer-term survivability as an island, given the typical evolution of such hydro-magmatic islands in this region (Vaughan and Webley, 2010). Understanding the mechanisms by which such small oceanic islands survive for decades and beyond at a locality other than Surtsey is a central theme that requires access to carefully-collected field samples for mineralogical assessment, measurement of shallow water bathymetry associated with the formation and erosion of the new volcano, and for on-site analysis of "ground control points" (GCP) using differential GPS surveying methods to formally control the nearly two dozen satellite based DEMs that NASA and partners have produced since 2015 for HTHH (and with SOI R/V Falkor sonar in 2016). Field-access to the island to produce the required GCPs, collect relevant samples (with associated documentation), and to search for signs of hydrothermal mineralization was essential to the NASA research hypotheses at the new tuff cone.

Table 1
Mission groups, objectives, and purposes linked to level 1 requirements.

Mission Group	Objective	Purpose
Geodetic Installations	Install geodetic markers at base station, at crater rim, and on Hunga Ha'apai.	Provide ground control at <10 cm levels for satellite and drone imagery and derived DEM products.
Drone Flights	Distribute optical targets to provide control points for drone imagery. Collect GPS points at targets and geodetic monuments. Fly drone mapping missions to collect imagery covering the entire island.	The targets provide visual reference points for processing of drone and satellite imagery into elevation models (DEMs), which are used to evaluate 2018–2019 erosion rates and document landscape changes.
Thermal FLIR	Locate areas with geothermal activity above background levels with hand-held FLIR instrument from NASA GSFC NDE (non-destructive evaluation) lab.	Identify evidence for continued geothermal activity, which may be contributing to stabilization and palagonization of ash and other volcanic materials.
Crater Lake	Quantify the lake bathymetry using simple COTS sonar system (LOWRANCE™). Phytoplankton studies. Collect sediment and water samples for microbial community analyses.	Identify vent structures that could support an effusive lava phase prior to surtseyan activity (island platform building). Determine hydrologic connectivity between crater lake and proximal seawater. Determine genetic diversity of crater lake microbes.
Flora and Fauna	Document area and types of vegetation, birds, and other fauna. Study coral (re)growth using an underwater remotely operated vehicle (ROV) and snorkel surveys.	Characterize early stage ecological colonization processes. Assess extent of landmass stability possibly provided by increased vegetation. Inform understanding of coral resiliency post volcanic disturbance in the absence of direct human impacts (nutrient pollution, overfishing, chemical pollution, etc.).
Geology	Locate spindle bombs and other types of diagnostic ballistic features. Study palagonization. Collect sediment and water samples for microbial community analyses. Study spectral anomalies tied to mineralogy.	Understand eruption stages (energetics). Document the vertical configuration of the primary edifice to refine Finite Element Analysis of the gravitational stress and creep within the volcano. Describe microbial diversity and colonization patterns of the landmass vs. pre-existing islands. Locate unique features or minerals.
Marine Debris	Collect debris and transport to Nuku'alofa for proper disposal.	Apply environmental stewardship values with practical actions.

Moreover, a potential connection to Mars was established on the basis of evidence that fields of 100 s of similar-appearing small conical volcanoes (on Mars) could have formed via hydro-magmatic eruptions when persistent, standing bodies of water were present and stable, only to survive when the conditions for stable liquid water waned, perhaps 1–2 Ga ago (Brož and Hauber, 2013). Thus, quantifying the time-variable topography of HTHH as it evolves at meter-scales with geodetic (GPS) control requires field-based measurements and ancillary drone-based observations, as a newly available element in research that connects the rapidly evolving Earth to past conditions on worlds such as Mars (e.g., NASA Strategic Plan and National Space Policy SPD-1 and related framework documents).

NASA was first connected to the SEA via co-investigator Vicki Ferrini (LDEO) who has worked as a team member with NASA since 2015. Ferrini connected the NASA PI (Garvin) with the senior leadership at SEA in Spring 2018 about possible joint activities near HTHH. The 2018 voyage to HTHH was thus a pathfinder that set in motion the more comprehensive plans for the 2019 field activities and objectives described herein. Prior to the voyage, NASA scientists James Garvin and Dan Slayback visited SEA campus to provide the context for the HTHH-scientific activities supported by NASA via their RRNES (rapid response to natural Earth events) program. Dan Slayback joined the crew onboard the *SSV Robert C. Seamans* between Vava'u, Tonga and Suva, Fiji to coordinate in situ research and conduct on the ground observations in 2018 and 2019.

2. HTHH mission objectives and purpose

An HTHH mission planning workshop took place in September 2019 on the SEA campus in Woods Hole, Massachusetts. During this full day workshop held in collaboration with SPICE students, formal mission science objectives were discussed and refined, as well as methods for achieving all mission goals within our allotted time frame in October given uncertain weather and sailing conditions. Garvin and Slayback also gave a public lecture focused on HTHH and its relation to ongoing Earth and Mars research as a continuous effort to inform broad audiences of scientific research. In this section, we detail the 2019 mission objectives and purpose, followed by examples of accomplishments; major scientific findings will be submitted once available on the basis of calibration and modelling, which is underway at the time of this writing.

2.1. Objectives

The 2019 collaborative Tonga-SEA-NASA research at HTHH was arranged as a mission of measurement discovery to enable a next-level of understanding of this unique island in a way that was not fully possible at locations such as Capelinhos in Azores, Portugal (erupted 1957–1958) or at Surtsey (erupted 1963–67). Involving students in the process of scientific mission planning, fieldwork, documentation, data collection, and discovery are key primary objectives for furthering environmental and scientific literacy. Thanks to ~4.5 years of satellite remote sensing via DigitalGlobe WorldView (WV) and Canadian Space Agency's Radarsat-2 synthetic aperture radar (SAR), the detailed time series of observations of the evolution of HTHH (Garvin et al., 2018) prompted key questions tied to specific measurements, which became "level one" requirements. This is the approach NASA uses for robotic science missions of discovery. The overarching mission objectives are summarized in Table 1.

To accomplish these objectives at HTHH, students were divided into mission groups and were led by Tongan, SEA, and NASA scientists and crew. The mission required careful scheduling and management of human resources; teams of students and professional crew were transported by inflatable boats to the island, while a cohort remained aboard the *SSV Robert C. Seamans* to keep the ship safely anchored and maintain shipboard operations. After establishing base camp on HTHH, each mission group set off to complete their designated tasks. There were two groups assigned to each mission per day, one in the morning and one in the afternoon. With no freshwater source on the island, no coverage for shade or rain shelter, and often extreme conditions hiking over rugged and unstable terrain, the elements presented a challenging environment for research and could at times be considered a limiting factor in this research project. Each day, the captain and faculty assessed the weather conditions and modified research plans accordingly, ensuring safety as a first-priority for all participants given the remote location of this research. Daily debriefs allowed for increased efficiency of mission operations over time, and the opportunity for participants to communicate accomplishments and challenges following each day. Reports via satellite telephone and email links to the science "back room" at NASA were used to adapt daily plans on the basis of results and in situ conditions.

3. Results: accomplishments and preliminary assessment

Teams collected and documented an extraordinary amount of data in the five-day excursion. Specific analyses are ongoing; however, some extremely-preliminary findings can be discussed herein. These observations will guide the longer-term scientific analyses once the datasets are calibrated, validated, and archived. This information is summarized visually in Fig. 2 and in Table 2, and described in further detail below.

3.1. Geodetic installations

Mission teams successfully installed three geodetic markers, surveyed via differential GPS methods. A permanent geodetic marker was installed on a large boulder near Hunga Tonga, which is the base station (Fig. 3). Two semi-permanent geodetic markers were also installed: one at the crater rim (near location in Fig. 4) and one near the peak of Hunga Ha'apai.

3.2. Field GPS surveys

On day one of the field research, teams spread across HTHH and placed drone targets for controlling eventual drone-based DEMs (Fig. 5). GPS control points (GCP) were also established for the entire edifice, which will allow high precision inter-DEM registration with vertical levels of control at ~10 cm, consistent with required precisions from which to accurately measure the volumetric history of erosion from early, post-construction to present (and going forward). This GCP frame of reference is critical for quantitative assessment of time-variable erosion rates and volumes for this unique volcano using both satellite based DEMs (from DigitalGlobe WV, as in Garvin et al., 2018) and drone-based DEMs.

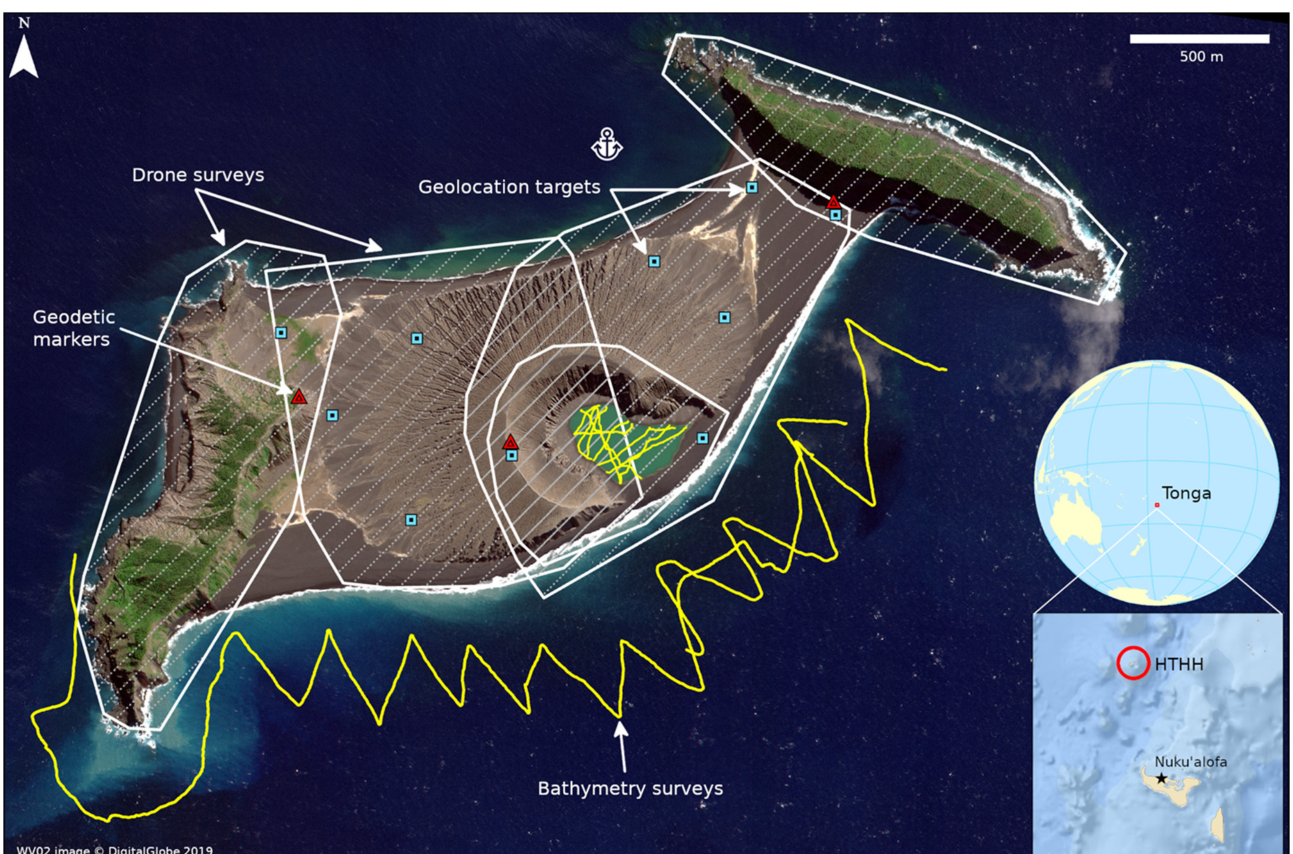

Fig. 2. Image (from DigitalGlobe WorldView-2) of HTHH illustrating the diverse array of surveys completed in October 2019. White polygon outlined regions with diagonal shading highlight the five regions covered in the drone surveys. The three red triangles symbolize locations of geodetic markers. The 10 blue squares indicate where the geolocation targets were placed. The yellow lines within the crater lake and along the south shore of HTHH represent the bathymetry surveys carried out by the LOWRANCE™.

Table 2
Accomplishments and preliminary analysis.

Mission Group	Accomplishments	Preliminary Analysis
Geodetic Installations	Permanent geodetic marker installed at boulder near HT (base station), and semi-permanent geodetic markers installed at crater rim, and near peak of Hunga Ha'apai.	Ongoing – being used as geodetic control for drone-based Structure-from-Motion computations of digital topography (DEM).
Drone	Drone mapping covering HTHH; 56 drone flights recording visual footage of HTHH at nadir and oblique at variable altitudes.	Ongoing – drone-based DEMs produced and now in validation with sub 10 cm grid scales (10× finer than from orbit).
Thermal	Hand-held NASA FLIR measurements taken at crater's lakeshore and in gullies, gullies along east flank of HTHH, crater rim, "hot spots" along lakeshore, gullies and washes on north slope of HTHH. Student discovery of putative geo-thermal hotspots.	Warmer (40–50 °C) spots located around the interior crater lake at irregular intervals, concentrated along the NE beach terrace of the lake (possibly tied to geothermal circulation within the edifice).
Side-scan Sonar bathymetric Mapping of Crater Lake	27 side-scan sonar transects completed: 8 across the lake to determine possible vent structure; 19 along southern coast to examine shallow water shelf structure were erosion has been most intensive.	"U"shaped cross-sectional bathymetry and connectivity with proximal seawater, with preliminary indications (from LDEO and NASA) of possible vent topology.
Flora	5 surveys completed; Rough estimates of area and 10 species documented; Medicinal species present	Diverse array of flora spreading outwards from HT and HH onto HTHH.
Birds	6 surveys completed around HTHH: 12 species identified; 5 unidentified species.	Increased diversity of bird species on HTHH found nesting at different locations than previously documented.
Other Fauna	Numerous species recorded: rats at south western region of HTHH and on HH. Hermit crabs, one skink at north eastern areas of HTHH and HT. Insects (moths, cockroaches, spiders) throughout HTHH. Sea snake (yellow lipped sea krait, *Laticauda colubrina*) by sea cave of HH. Countless humpback whale cows and juveniles swimming and breaching on north and south sides of HTHH. Juvenile whale shark observed near surface on southern slope of caldera.	Expansion of diversity and abundance of fauna spread throughout the HTHH landmass.
Coral	ROV (provided by James Cook University) and snorkel surveys utilized to photograph coral along northern edges of HT. Coral re-growth observed, including diverse, healthy, and abundant juvenile coral heads.	Supporting evidence of coral re-growth on north side of HT.
Geology	48 unique rock specimens, including samples for validation of multi-spectral (VIS, NIR, SWIR) anomalies, were photographed, located, and described. Innumerable volcanic bombs were observed. No spindle bombs observed. Soil samples from diverse environments for microbial community analyses.	Palagonitized ash observed; pumice and pristine lavas were also acquired and are undergoing SEM, x-ray Computer Tomography analyses at NASA Goddard.
Marine Debris	Collected an estimated 600 cubic feet of trash and transported it to Nuku'alofa for proper disposal.	The southwestern shoreline of HTHH near HH collects the most debris due to the ocean and wind currents. Fishing buoys, flip flops, and plastic bottles were the primary debris sighted and collected.

Essentially the entire landmass of HTHH was mapped (Fig. 2), illustrating that HTHH is evolving at multiple temporal and spatial scales; some features visible in October 2018 are already transformed or "missing", indicating various styles of erosion as a function of location (and hence volcano sub-unit) (Garvin et al., 2018, 2019). The summit region of the tuff cone (at ~120 m) is geochemically cemented and "stable" and does not yet show development of hot cracks or fissures as are seen at Surtsey and Capelinhos. Field reconnaissance at Capelinhos (made possible by GLEX 2019 and Portugal) and Portugal now permits direct comparison of the eroding tuff cones there to HTHH via similar datasets.

3.3. Crater Lake survey: "hot spots" and side scan sonar

A team conducted side-scan sonar mapping with a small bathymetric sonar device, the LOWRANCE™ (HDS 12), and temperature readings with a hand-held FLIR instrument. The LOWRANCE™ was used to generate three-dimensional mapping of the interior crater lake floor and small portion of the 5 km scale larger caldera on the south side of HTHH. Within the crater lake, the team deployed the LOWRANCE™ using two inflatable in-line Alpacka pack rafts; one team paddled and towed the second raft with a scientist and the LOWRANCE™ (Fig. 6). Over the course of five days, 27 side-scan transects were performed; 8 across the lake to determine submarine topography (bathymetry) and 19 along southern coast to examine eroded volcano flank structure. This sonar bathymetry demonstrated that the lake has a "U" shape in cross-section with maximum depths of ~15 m consistent with a collapsed volcano vent topology (e.g., Surtur II at Surtsey for example), but more work needs to be done to computationally model this shape to understand its evolutionary implications, after the LOWRANCE™ data are properly calibrated for roll and pitch effects. Initial analysis by Garvin, Ferrini, and Slayback using raw bathymetry, illustrates the potential for mapping vent structures, but ongoing work to correct for roll and pitch variations in the data are not yet completed for verification.

The LOWRANCE™ was also employed to investigate the shallow shelves on the southern shore of HTHH where most of intensive marine abrasion has eroded a significant portion of the 2015 tuff cone edifice (subaerial part). The instrument was mounted to the transom of a power-driven boat about 3 m in length and bathymetric data were collected along a series of transects. This mapping builds on the work of the SOI's R/V Falkor (see Garvin et al., 2018). The small boat launched from the *SSV Robert C. Seamans* surveyed the coastline in depths ranging from 30 m to 8 m. The data collected from this side scan sonar project can contribute to better understanding of the new island's near-coastal bathymetry and provide a baseline for future studies of erosional processes.

Fig. 3. Geodetic marker installed on HTHH at the request of the Kingdom of Tonga. It reads "Ministry of Land and Natural Resources, Tonga Geological Services, 2019." Photo Credit: SEA.

Within the crater lake, temperature, salinity, and phytoplankton measurements suggest high hydrographic connectivity with proximal seawater. The lake appears to be tidally influenced and contains marine plankton including diatom species and barnacle larvae. Temperature and salinity of the crater lake are close to those of ambient local seawater (17 °C and 32 ppt, respectively).

SEA mission groups recorded hand-held FLIR measurements at the interior crater's lakeshore and gullies, gullies along the east flank of HTHH, on the crater rim, at "hot spots" along the lakeshore, and in the gullies and washes on the north slope of HTHH. While no definitive geothermal "hot spots" could be measured using the COTS FLIR sensor (with very good resolution of a few degrees C) via systematic surveys, student explorers discovered "hot spots" in the shallow sediment of the crater lake floor that were patchily distributed, but concentrated primarily along the northeast rim of the crater lake/vent system and could be

Fig. 4. Mission team on the crater rim. Photo facing northeast with HT off to the right and the *SSV Robert C. Seamans* anchored in the center background of the photograph. The foreground illustrates rilles in high-standing layered tephra deposits, with detachments due to mass-wasting. Photo Credit: Captain Chris Nolan at SEA.

Fig. 5. Penikolo Vailea (L) and Dan Slayback (R) lay drone targets on HTHH. Photo Credit: Captain Chris Nolan at SEA.

detected about 5–15 cm beneath the surface sediment layer. The discovery of crater lake geothermal activity was made opportunistically, when a student and co-author of this paper, Grace, fell into the lake following a sonar survey, thereby detecting sub-surface warming of the lake sediment with her feet. Such observations support the concept of a geothermal circulation system within the tuff cone edifice, as has been documented at Surtsey.

Fig. 6. Students paddle across the crater lake, towing the LOWRANCE™ equipment in a second raft while conducting transects for bathymetric sonar readings. Photo Credit: Catherine Czajka, SEA class S288.

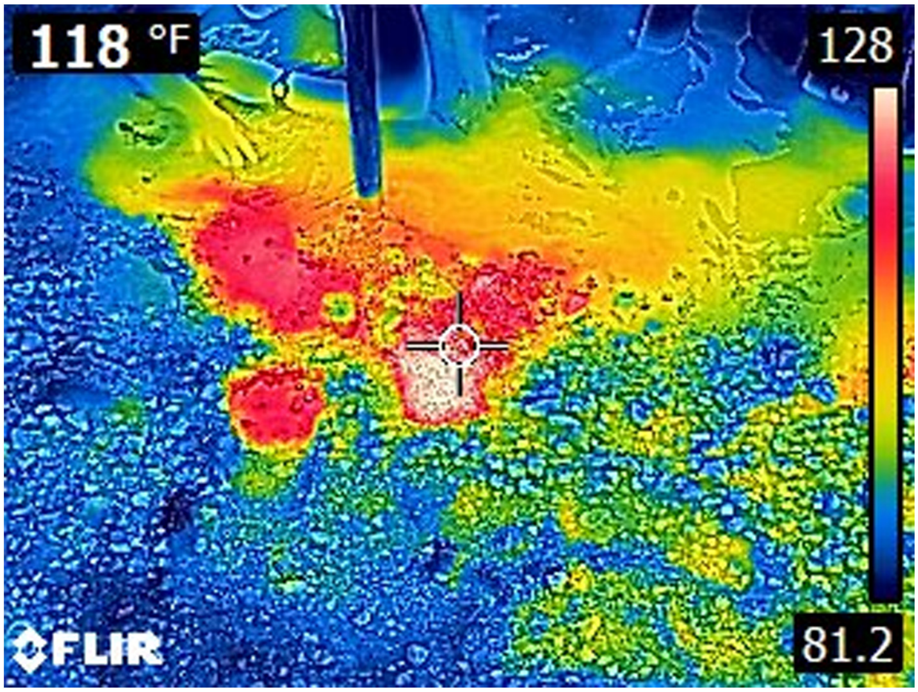

Fig. 7. FLIR imaging at one of the marked hotspots on the shore line of the crater lake, with students in the background searching with their hands and feet for other "hot spot" locations. FLIR instrument and imagery courtesy of NASA Goddard Code 541 NDE laboratory.

Grace describes her accidental discovery, stating:

At the end of the final [LOWRANCE™] transect, I stumbled out of the inflatable raft into water up to my chest, much deeper than I had anticipated. The fine gravel under my feet was loose, and my feet sunk about a foot below the sediment. I instantly felt warmth surrounding my feet, and as I moved my feet around, the feeling became more noticeable. I extracted one of my feet from the gravel, confirming that yes, the lake water was distinctly cooler than whatever was below the surface. I immediately told the other students about the hot spot,

Fig. 8. Vegetation survey from HH looking northeast towards HTHH tuff cone. Variable patches of sedge grass in the foreground with denser grass, shrubs, and morning glory in background closer to the base of HTHH. Photo Credit: SEA.

and they waded in to investigate and confirm its presence. Because it had been cold and rainy that day and the warm water appeared to be in small, discrete patches, I guessed that it could be geothermal activity warming up water within the gravel instead of residual solar radiation. Excited, we returned to the ship to report our observations and share our questions.Returning to the crater lake the next day, I was worried that we would not be able to find the hotspot again and our mission group would prove to be a waste of time. But after about fifteen minutes of wading along the shoreline and digging into the sediment, we found first one hotspot and then many more, scattered unevenly across the basin. It was thrilling to know that we were discovering something new and unexpected about the island.

The following day, a group of students and staff were deployed to survey and investigate these "hot spots" along the interior land component of the crater lake, to confirm their presence and to search for additional locations. The group waded through the clay-rich volcanic 'muds', manually using their feet and hands to detect thermal anomalies, which were then measured using a YSI temperature probe and hand-held FLIR imaging camera (Fig. 7). GPS coordinates of all thermal anomalies and "hot spot" regions were noted.

A team returned to the crater lake at night (2100 h) with the FLIR thermal imaging camera to measure thermal anomalies in the absence of peak day-time solar heating and to confirm "hot spot" locations identified around the shoreline rim of the crater lake. Temperatures measured with the FLIR during the day and the night were over 40 °C, with some around 50 °C, which is consistent with possible geothermal activity. These relative small spots are spatially variable, suggesting a putative hydrothermal circulation system that connects residual thermally active areas at depth to cracks in the crater lake floor (possibly suggesting sites of a former vent or a fracture system through which lavas were erupted) and probably within cracks (as mechanical failures) within the overall edifice. These observations are tantalizing and suggest that better-calibrated and systematic thermal IR mapping ideally with a drone-based FLIR type system be conducted in the future, together with higher sensitivity field surveys conducted during predawn hours (to minimize calibration issues).

3.4. Flora

During five vegetation surveys, field teams photographed and recorded descriptions of numerous species. The majority of vegetation cover documented included various sedge grasses in the Cyperaceae family, sunflowers in the Asteraceae and Crepidioides families, and the silky jackbean in the Fabaeae family (Fig. 8). Species from all three of those families were common on the flanks of HT and HH, and were growing towards the HTHH base. Additionally, a variety of ferns and mosses were growing in cracks and crevices throughout the HTHH landmass. The largest patch of mixed vegetation was growing at the southwest end of the landmass in an area over 300 m long and almost 100 m wide, coming from the base of HH and spreading towards HTHH. There is a similar patch growing on the northwest end of the landmass. There were also patches of sedge grasses on the southwest face of HTHH. Guava trees were noted growing on the steep hillsides as well as a variety of Tongan medicinal plants. Since 2018, vegetation has noticeably expanded in the lower reaches of the volcano with the possibility of erosional stabilization on the flanks.

3.5. Fauna

We recorded and positively identified twelve species of birds during six surveys. Positively identified birds include one pacific golden plover (*Pluvialis fulva*), a few Polynesian starlings (*Aplonis tabuensis*), and a small group (under 10) of ruddy turnstones (*Arenaria interpres*). There was an abundance of brown boobies (*Sula leucogaster*), red-footed

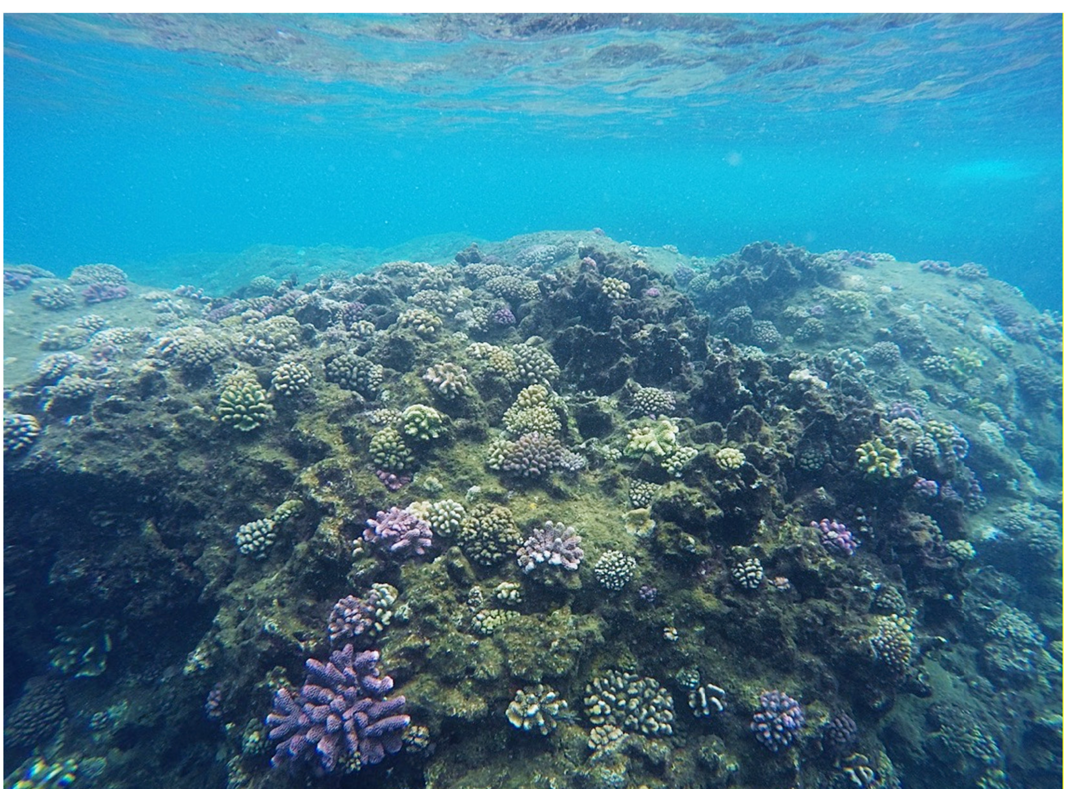

Fig. 9. Coral regrowth is observed on the northeastern coast of HTHH, off the northern edges of HT, an area that was blanketed in ash during the 2015 eruption. Photo Credit: Frank Wenninger, SEA class S288.

boobies (*Sula sula*), red-tailed tropicbirds (*Phaethon rubricauda*), white-tailed tropicbirds (*Phaethon lepturus*), and great and lesser frigatebirds (*Fregata minor* and *ariel*, respectively), primarily nesting on the cliffs of HT and HH and flying over the beaches of HTHH. There were two barn owls (*Tyto alba*), spotted together in a cave at HH and one more (or possibly the same individuals) documented on the other end of HTHH on the banks of HT. There were colonies of hundreds of sooty tern adults and chicks (*Onychoprion fuscatus*) located at the southeast end of HTHH near the base of HT. There were also groups of brown noddies (*Anous stolidus*) scattered throughout HTHH. Petrels documented at both HT and HH cliffs facing HTHH are preliminarily identified as Phoenix Petrels (*Pterodroma alba*), an endangered species. Additionally, two small songbirds were seen fluttering between bushes on the cliffs of HT, but eluded identification. One marsh bird (seen in the large vegetation patch at HH) and a pigeon on HH were recorded also, but cannot be further identified at this time. Bird diversity appears to have increased and nesting sites have shifted since baseline observations were made in October 2018.

Additionally, a sea snake (*Laticauda colubrine*) was documented at the sea cave on the west end of HH, as well as hermit crabs, rats, spiders, moths, and cockroaches throughout the landmass. Countless humpback whale cows and calves were observed within 100 m of the HTHH coastlines on the north and south sides of the landmass. One juvenile whale shark was also documented during sonar scans of the south coast of HTHH. A reef shark and diverse fish species were also observed while snorkeling on the north side of HTHH during coral surveys.

A remotely operated vehicle (ROV), provided by partners from James Cook University in Australia, and snorkel surveys by students and crew of SEA, collected video and photographic evidence of coral re-growth following the 2015 volcanic disturbance (Fig. 9). ROV and snorkel surveys of coral reefs on the north shore of HH show high diversity and re-growth consistent with that observed in previous surveys (Smallhorn-West et al., 2019). The corals of HTHH demonstrate high recruitment and resilience following the hydro-magmatic volcanic disturbance of the 2015 HTHH eruption. The resilience of HTHH coral populations has been attributed to their remoteness and freedom from anthropogenic stressors such as nutrient or chemical pollution, sedimentation, or overfishing (Smallhorn-West et al., 2019). Future coral monitoring will be valuable in tracking the re-growth process of this relatively pristine coral system, post volcanic disturbance.

3.6. Geology and volcanology

Forty-eight unique rock specimens were photographed, located, and described using handlens scale observations (<100 μm). Some of these photographs were used to validate satellite multi-spectral imaging data from WV imaging over the past 4 years. Several ballistically-transported pyroclastic bombs were observed, but the field team found no evidence of aerodynamically shaped "bombs" such as the spindle variety, which is viewed as surprising. A putative layer of palagonitized or hydrothermally-altered (cemented) ash was observed, potentially pointing to the incipient development of this important stabilizing material to enable a prolonged lifetime for the volcano (Fig. 10). A set of 20 sediment samples, collected across the island, were sent to University of Colorado Boulder for downstream microbial community analysis.

Mission groups also collected 23 sediment samples from different environments around the island, near bird colonies, among vegetation, in the intertidal zone, on the crater rim and crater slopes, and from canyon walls and the crater lake (Fig. 11). The students collected samples using sterile equipment and techniques, utilizing their newly acquired GPS, mapping, photographic, and documentation skills to keep a detailed record of each of the samples.

3.7. Marine debris

Dedicated mission groups collected trash for five days and others picked up trash while working on their projects. An estimated 600 cubic feet of trash was collected and removed from HTHH (Fig. 12). It was disposed of in Nuku'alofa, Tonga. Unfortunately, the magnitude of trash on HTHH, which included PVC piping, large fishing buoys, kerosene tanks, and other heavy, large materials did not allow for complete

Fig. 10. Hand-sized palagonitized rock sample documented by geology mission group on HTHH. Photo Credit: SEA.

Fig. 11. Students collect samples for genetic analysis of microbial community composition. Photo credit: Emily Burke at SEA.

removal; the remaining marine debris was placed into piles above the high tide line in attempt to keep it from returning to the ocean.

4. Discussion: cultural and environmental literacy and the value of student involvement

The educational value of the 2019 HTHH collaborative mission cannot be overstated. Growing evidence points to the importance of hands-on interdisciplinary learning in fostering active citizens who can contribute creative solutions to global and complex issues such as climate change (e.g., McCauley et al., 2019; Kelly et al., 2019; Stone, 2009). The act of bolstering environmental and ocean literacy has been identified as essential to contributing to future sustainability (e.g., Rice and Robinson, 2012; Visbeck, 2018). In fact, the United Nations has identified ocean science and ocean and environmental literacy as factors in direct support of UN sustainable development goals.

To achieve scientific goals of the 2019 HTHH mission, twenty-six undergraduate students worked in collaboration with faculty, scientists, and crew from Tonga, SEA, and NASA. The group collectively surveyed unique aspects of the island, documented activities through photography and audio recordings, transported equipment, marked coordinates of significant findings, and also collected marine debris. Students were valuable assets in this mission, playing a vital role as active participants in the process of discovery and scientific questioning essential to the success of the mission. This mission demonstrates the value of human-driven scientific exploration and discovery of new landmasses, as compared to drone and rover-based surveys. The benefit of on-the-ground human participants is best exemplified by the events leading to the discovery of putative geothermal activity within the interior HTHH crater lake. The "hot spots" were discovered serendipitously that were not detected with hand-held FLIR imaging previously used to survey the area. This event demonstrates the critical value of human explorers in the exploration of new terrain, and could be used to argue for human-based exploration of deep sea habitats, remote Earth locations, or planets such as Mars. Furthermore, this finding directly involved students in the spirit of adventure that can only be captured in those rare moments of unexpected scientific discovery and realization with dynamic response in the field.

Students communicated their experiences in a cultural and educational exchange with Tongan and Fijian observers, and among students at the University of South Pacific and the International School of Suva, both in Fiji. With opportunities for follow-on communication of HTHH activities and cultural exchange among SEA students and students in Fiji, this project embraced the interdisciplinary value of the experience. It has been shown that participation in place-based scientific activities significantly increases participant knowledge, bolsters a connection to place and community, and increases awareness of anthropogenic impacts to environmental systems (Haywood et al., 2016; Haywood, 2019; Kelly et al., 2019). Through cultural exchanges, students, faculty, and crew learned about the importance of interconnected seascapes throughout the south Pacific region to the people of Oceania in conversations about historical navigation, cultural preservation and revitalization, and conservation initiatives in their constantly changing seascape.

The involvement of students in the HTHH mission also provided a framework for exploring the development of leadership skills among participants. Others have argued for the importance of leadership skill training among scientists to facilitate interdisciplinary collaboration and effective teamwork (Leiserson and McVinney, 2015). While the corporate and business sectors contribute assets to developing leadership and management skills among their employees, formal leadership training for scientists and academics is not widely available. SEA students learned about the process of adaptive sampling, data management and the importance of collaboration, and communication in accomplishing their goals. The rugged terrain of HTHH was demanding on the team, and required mission participants to take care of one another, advocate for personal needs, and communicate clearly. The environment demanded creative planning and flexibility due to weather and unknowns of the terrain. Additionally, students learned valuable

Fig. 12. Black bags of trash (on the left foreground of the photo) collected from HTHH sit on the dock at Nuku'alofa awaiting removal by the waste disposal authorities. In comparison, the small five compact trash bags on the right side of the photograph were refuse created by 40 students, faculty, and crew in a 2-week period aboard the *SSV Robert C. Seamans,* visible at the dock. Photo Credit: Captain Chris Nolan at SEA.

lessons regarding proper data management, organization, and analysis. The development of leadership skills among participants should be highlighted as one of the accomplishments of this mission as well.

5. Conclusion

Interdisciplinary research and collaboration is increasingly necessary to solve complex problems in a globally connected civilization. Traditional academic measures of success including data output and publication volume have been noted as barriers to interdisciplinary collaboration, particularly for early career scientists (Goring et al., 2014). In the case of this unique collaboration between the Kingdom of Tonga, SEA, and NASA, distinct but overlapping goals to study HTHH facilitated this fruitful interdisciplinary work. Measures of success focused not only on the data collection, but also the educational, leadership, and outreach value of the mission work and cultural exchange, increasing the potential for productive interdisciplinary collaboration.

There are numerous possibilities for continuing this mission and the related satellite and ongoing modelling efforts that can be facilitated over the next several years through this collaborative research partnership. Understanding HTHH and its evolutionary life history will illuminate Earth processes which are priorities in the National Academy of Sciences Earth Sciences Decadal survey (Charo and Abdalati, 2018), but also for a former time on Mars when persistent surface waters probably resulted in surtseyan eruptions similar to those that formed HTHH, but afterwards their erosional pathways were interrupted by the disappearance of the standing bodies of water (in a state of "arrested erosional development"). This work at HTHH can inform studies of such ancient Martian systems as well and integrate latest thinking in astrobiology to this new island, and connect to national US space police directives (SPD-1).

NASA's original hypothesis (from the Garvin and colleagues proposal to RRNES Program) that the volcano could survive as an intact island landform for at least 15–20 years appears to have been realistic. Much improved field data may extend this projection and be used to model the likely outcomes as HTHH moves out of its 2nd and 3rd life-stage into its next phase, perhaps with more gravitationally-induced stress failure or creep, changing its appearance (Garvin et al., 2018, 2019). Thanks to a first-ever time series of drone-based (SfM) DEM datasets (October 2018 – October 2019), NASA scientists are ready to measure and model erosion at scales as fine as 10 cm over an inter-annual time scale and compare with those over the ~5 year lifetime of this island. These measurements will facilitate examination of dozens of other preserved oceanic island volcanoes where the islands themselves are now presenting a much later stage of evolution, and are the subject of ongoing NASA-led research. As such this pathfinding work at HTHH is defining the early-stage erosional evolution of a whole class of terrestrial landforms (oceanic island volcanoes) to enable examination of trends throughout time and in the context of volcano-tectonic regimes.

From our observations and preliminary findings discussed here, we believe that HTHH will survive as an intact Surtsey-like volcano for a few decades at least, providing a natural laboratory for studies of the erosional evolution of a simple ocean island volcano in a unique geotectonic setting (Bryan et al., 1972). This provides opportunities for linking its geomorphic evolution to ecological influences, local micro-climate, sea-level variability, and astrobiology, offering valuable insight into the evolution of landscapes on Earth and on other planets such as Mars. Therefore, such continued collaborative research will be essential to continue monitoring the evolution of this island and its processes of ecological colonization, and gain further insight into the importance of new land masses within a "sea of islands."

Data availability

The field data collected on HTHH (drone nadir images for SfM-based DEMs, GPS, sample xCT scans, LOWRANCE™ sonar) are currently being processed and calibrated by scientific standards and as such, are not yet available. The Satellite full-res DigitalGlobe Data is also not available at this time, as it is a commercial dataset being used for pathfinding research by NASA and partners. While the NASA FLIR images are not fully calibrated to NASA thermal infrared standards, they can be used as “non-scientific calibrated data” to show trends. The large set of nadir-viewing drone images are not yet available given they were funded by the Mars Exploration Program for use in support of the Mars 2020 mission and will be fully released in March/April 2021 once the *Perseverance* Rover with the MHTD operates on Mars. Please direct questions regarding this data availability to the corresponding author.

To obtain unpublished oceanographic data collected aboard the *SSV Robert C. Seamans* during the full cruise track in the Pacific, contact the Chief Scientist Kerry Whittaker or SEA data archivist at Sea Education Association PO Box 6 Woods Hole, MA 02543. Phone: 508-540-3954 or E-mail: data-archives@sea.edu.

Funding

Participation by NASA was supported by NASA RRNES-20, NASA Mars Exploration Program Future missions, and NASA GSFC.

CRediT authorship contribution statement

Emily B. Hite: Methodology, Investigation, Writing - original draft, Writing - review & editing, Supervision. **James Garvin:** Conceptualization, Methodology, Validation, Project administration, Writing - review & editing, Funding acquisition. **Dan Slayback:** Conceptualization, Methodology, Software, Investigation, Writing - review & editing, Data curation, Project administration. **Emily A. Burke:** Resources, Writing - review & editing, Investigation. **Grace Callahan:** Writing - review & editing, Investigation, Methodology. **Paul Joyce:** Conceptualization, Supervision, Funding acquisition. **Kerry Whittaker:** Conceptualization, Methodology, Investigation, Writing - original draft, Supervision, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We would especially like to thank the Kingdom of Tonga, the Department of Lands and Natural Resources, the Tongan Geological Services, and the people of Tonga for making this research possible, offering valuable advice regarding research, and welcoming us to the country. Specifically, we thank our Tongan collaborators and research partners, Lord Ma‘afu, Minister for Lands, Survey, and Natural Resources and the Minister for Environment and Climate Change, and Taaniela Kula and Penikolo Vailea at Tonga Geological Services for their invaluable input, assistance sailing, and conducting research.

We would like to thank the students and professional crew of SEA Semester classes S282 and S288 for their dedication and scientific contributions to the HTHH 2018 and 2019 interdisciplinary missions. Special thanks to Captains Elliot Rappaport and Chris Nolan. We would like to thank Patrick Smallhorn-West for his contributions to our coral surveys and to Nick Dragone at the University of Colorado Boulder on his microbiome analyses.

We would also like to thank NASA Project Co—I Dr. Vicki Ferrini, NASA GSFC Center Director Chris Scolese, NASA HQ senior Earth scientists Jack Kaye and Gerald Bawden, NASA Engineering (NDE lead) Justin Jones, USRA's Dr. Ghassem Asrar and NCAR's Karen Andersen, Canadian Space Agency's Christine Giguere and the entire CSA Radarsat-2 Background Mission team with Andre Boyer and Jonathan Lajoie, and finally Dr. James J. Frawley of Herring Bay Geophysics (Herring Bay, MD).

References

Basso, Keith, 1996. Wisdom Sits in Places: Landscape and Language Among the Western Apache. University of New Mexico Press, Albuquerque, NM.
Bower, A., Zettler, E., Gawarkiewicz, G., 2004. Science Under Sail. Oceanography 17 (3).
Brož, P., Hauber, E., 2013. Hydrovolcanic tuff rings and cones as indicators for phreatomagmatic explosive eruptions on Mars. Journal of Geophysical Research: Planets 118 (8), 1656–1675.
Bryan, W.B., Stice, G.D., Ewart, A., 1972. Geology, petrography, and geochemistry of the volcanic islands of Tonga. J. Geophys. Res. 77 (8), 1566–1585.
Charo, A., Abdalati, W., 2018. The 2017-2027 National Academies Decadal Survey for Earth Science and applications from Space: An Overview of the Report. 42nd COSPAR Scientific Assembly, p. 42.
Contreras-Reyes, E., Grevemeyer, I., Watts, A.B., Flueh, E.R., Peirce, C., Moeller, S., Papenberg, C., 2011. Deep seismic structure of the Tonga subduction zone: Implications for mantle hydration, tectonic erosion, and arc magmatism. Journal of Geophysical Research: Solid Earth 116 (B10). https://doi.org/10.1029/2011JB008434.
Garvin, J.B., Slayback, D., Giguere, C., Frawley, J., Asrar, G., Andersen, K., Ferrini, V., 2017. The story of Hunga Tonga Hunga Ha'apai Island in the Kingdom of Tonga. Apogeo Spring 2017, 36–39.
Garvin, J.B., Slayback, D.A., Ferrini, V., Frawley, J., Giguere, C., Asrar, G.R., Andersen, K., 2018. Monitoring and modeling the rapid evolution of Earth's Newest Volcanic Island: Hunga Tonga Hunga Ha'apai (Tonga) using high spatial resolution satellite observations. Geophys. Res. Lett. 45 (8), 3445–3452.
Garvin, J.B., Slayback, D.A., Ferrini, V., Frawley, J., Giguere, C., Asrar, G.R., Andersen, K., 2019. *Monitoring and Modelling the Evolution of HTHH in Tonga*, presentation at NASA Senior management monthly review with the NASA Science Mission Directorate Assoc. Administrator (March 2019), reprised in presentation at fall 2019 AGU in Dec. 2019. Accessible at. https://svs.gsfc.nasa.gov/temp/l05888673/index.html.
Gegeo, David Welchman, 2001. Cultural Rupture and Indigeneity: The Challenge of (Re) visioning "Place" in the Pacific. Contemp. Pac. 13 (2), 491–507.
Goring, S.J., Weathers, K.C., Dodds, W.K., Soranno, P.A., Sweet, L.C., Cheruvelil, K.S., Kominoski, J.S., Rüegg, J.T., Thorn, A.M., Utz, R.M., 2014. Improving the culture of interdisciplinary collaboration in ecology by expanding measures of success. Front. Ecol. Environ. 12, 39–47.
Gupta, Akhil, Ferguson, James, 1992. Beyond “culture”: space, identity, and the politics of difference. Cult. Anthropol. 7 (1), 6–23.
Hau'ofa, Epeli, 1994. Our Sea of Islands. Contemp. Pac. 6 (1), 147–161.
Haywood, B., 2019. Citizen Science as a Catalyst for Place Meaning and Attachment. Environment, Space, Place 11, 126–151.
Haywood, B.K., Parrish, J.K., Dolliver, J., 2016. Place-based and data-rich citizen science as a precursor for conservation action. Conserv. Biol. 30, 476–486.
Jakobsson, S.P., Moore, J.G., 1986. Hydrothermal minerals and alteration rates at Surtsey volcano, Iceland. Geol. Soc. Am. Bull. 97 (5), 648–659.
Kahn, Miriam, 2011. Tahiti beyond the Postcard: Power, Place, and Everyday Life. University of Washington Press, Seattle, WA.
Kelly, R., Fleming, A., Pecl, G., Richter, A., Bonn, A., 2019. Social license through citizen science: a tool for marine conservation. Ecol. Soc. 24.
Leiserson, C.E., McVinney, C., 2015. Lifelong learning: Science professors need leadership training. Nature 523, 279–281.
Liu, Jianguo, Dietz, T., Carpenter, S.R., Alberti, M., Folke, C., Moran, E., Pell, A.N., Deadman, P., Kratz, T., Lubchenco, J., Ostrom, E., Ouyang, Z., Provencher, W., Redman, C.L., Schneider, S.H., Taylor, W.L., 2007. Complexity of coupled human and natural systems. Science 317 (5844), 1513–1516.
McCauley, V., McHugh, P., Davison, K., Domegan, C., 2019. Collective intelligence for advancing ocean literacy. Environ. Educ. Res. 1–12.
McClennen, C., Meyer, A., 2002. Transferable elements of the education program SEA semester. J. Geosci. Educ. 50 (3).
McKinnon, K., Carnegie, M., Gibson, K., Rowland, C., 2016. Gender equality and economic empowerment in the Solomon Islands and Fiji: a place-based approach. Gend. Place Cult. 23 (10), 1376–1391.
Na'puti, Tiara R., 2019. Archipelagic rhetoric: remapping the Marianas and challengingmilitarization from "A Stirring Place". Communication and Critical/Cultural Studies 16 (1), 4–25.
Németh, K., Kereszturi, G., 2015. Monogenetic volcanism: personal views and discussion. Int. J. Earth Sci. 104 (8), 2131–2146.
Németh, K., Kósik, S., 2020. Review of Explosive Hydrovolcanism. Geosciences 10 (2), 44.
Ocean Health Index, OHI. 2019. http://www.oceanhealthindex.org/about. Date accessed: December 20, 2019.
Oliveira, K.A.R., 2014. Ancestral places: Understanding kanaka geographies. Oregon State University Press.
Panelli, Ruth, Tipa, Gail, 2007. Placing Well-Being: A Māori Case Study of Cultural and Environmental Specificity. EcoHealth 4, 445–460.
Rice, R.E., Robinson, J.A., 2012. Transdisciplinary approaches for twenty-first century ocean sustainability communication. Public communication campaigns 231–244.
Rössler, Mechtild, 2006. World heritage cultural landscapes: a UNESCO flagship programme 1992 - 2006. Landsc. Res. 31 (4), 333–353.
Smallhorn-West, P., Garvin, J., Slayback, D., DeCarlo, T., Gordon, S., Fitzgerald, S., Halafihi, T., Jones, G., Bridge, T., 2019. Coral reef annihilation, persistence and recovery at Earth's youngest volcanic island. Coral Reefs https://doi.org/10.1007/s00338-019-01868-8.

Smith, Alisa, 2004. A Māori Sense of Place? Taranaki Waiata Tangi and Feelings for Place. 60(1). New Zealand Geographer, pp. 12–17.
Smith, C.R., Demopoulos, A.W.J., 2003. The deep Pacific ocean floor. *Ecosystems of the Worl*d, 179–218. https://link.springer.com/content/pdf/10.1007/BF02340472.pdf.
Stone, M.K., 2009. Smart by Nature: Schooling for Sustainability. Watershed Media, Healdsburg, CA.
Thaman, Konai Helu, 1985. The Defining Distance: People, Places, and Worldview. Pac. Viewp. 26 (1), 106.
Vaughan, R.G., Webley, P.W., 2010. Satellite observations of a surtseyan eruption: Hunga Ha'apai, Tonga. J. Volcanol. Geotherm. Res. 198 (1–2), 177–186.
Visbeck, M., 2018. Ocean science research is key for a sustainable future. Nat. Commun. 9, 690.
West, P., 2005. Translation, Value, and Space: Theorizing an Ethnographic and Engaged Environmental Anthropology. Am. Anthropol. 107 (4), 632–642.
Wohletz, K.H., Sheridan, M.F., 1983. Hydrovolcanic explosions; II, Evolution of basaltic tuff rings and tuff cones. Am. J. Sci. 283 (5), 385–413.