Deep Ash Plumes Signal Ongoing or Recent Submarine Volcanic Eruptions, and Demonstrate a Syn-eruptive Process for Dispersing Fine Ash to Distal Sediments.

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Abstract

The considerable challenges of accessing unpredictable events at remote seafloor locations make submarine eruptions difficult to study in real time. The serendipitous discovery of two persistently active sites (NW Rota-1 in the Mariana arc, at ˜550 m, and West Mata in the NE Lau basin at ˜1200 m) resulted in multi-year, multi-parameter studies that included water column plume surveys and direct (ROV) observations. Intense magmatic-hydrothermal plumes rose buoyantly above both sites, while deep particle plume layers, dominated by fine ash and devoid of hydrothermal tracers, were found dispersing laterally on isopycnal surfaces at variable depths below the eruptive vents and above the seafloor. The presence or absence of deep ash plumes was directly correlated with explosive activity or quiescence, respectively. An estimated 0.4-14.6 x 105 m3/yr of fine ash entered the water column surrounding these volcanoes and remained suspended at distances exceeding 10's of km. We show that deep ash plume layers in the water column are a common feature of explosive submarine eruptions at other sites as well, and that they demonstrate a syn-eruptive mode of transport for fine ash that will result in deposition as "hidden" cryptotephra or fallout deposits in marine sediments at distances greater than previously predicted. Cruise FK171110 extended the time series of observations at West Mata, and resulted in discovery of new lava flows emplaced after September 2012, with one constrained between March 2016 and November 2017. ROV dives confirmed that West Mata was quiescent during this expedition, but widespread deep ash plumes were present. Turbidity in the deep ash plumes decreased by 80% over a 25-day period, with an average loss of 3% (0.15-0.6 g/m2) per day, suggesting the eruption that formed the 2016-2017 eruptive deposits had occurred within 8-121 days prior to the FK171110 expedition. Future studies of submarine volcanic processes will depend on improved exploration and event detection capabilities. In addition to recognizing the characteristic hydrothermal event plumes rising into the water column above actively erupting sites, widespread ash plumes dispersing at depths deeper than eruptive vents can also be diagnostic of ongoing, or very recent, eruptions. We infer the eruptive status at other sites based on these criteria.

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1. Introduction

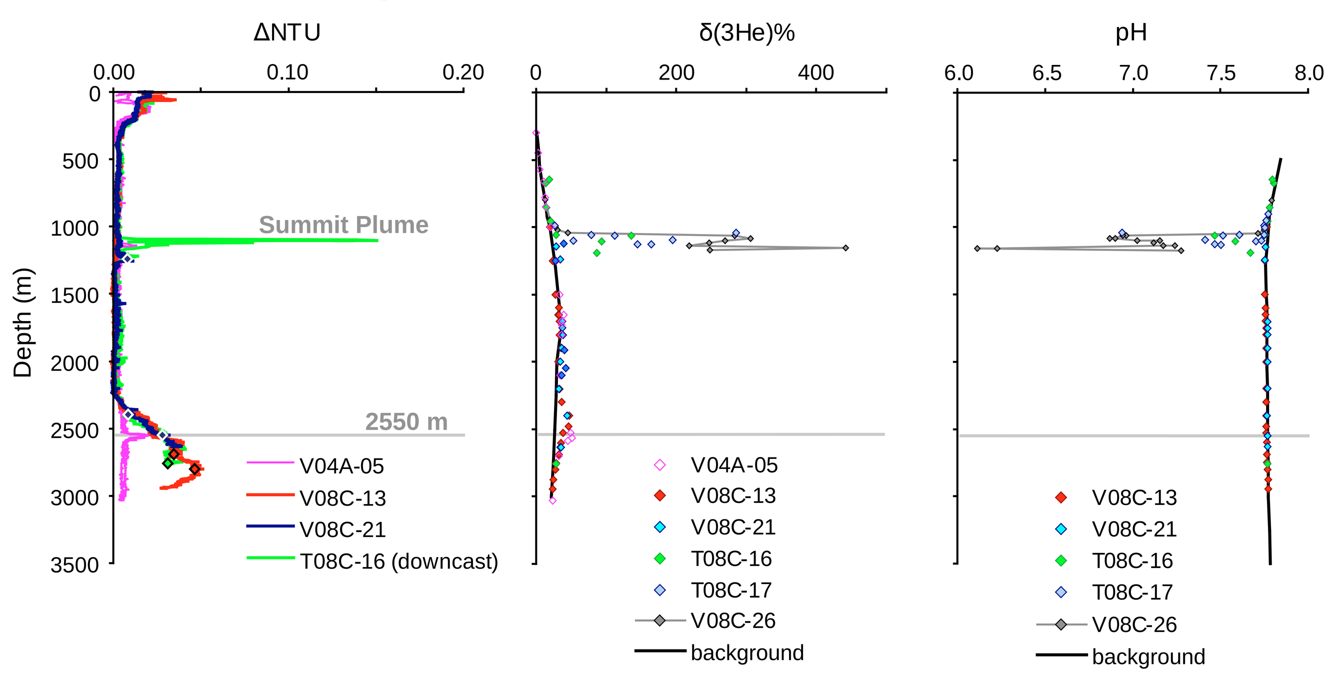
Submarine volcanic eruptions are difficult to study in real time due the considerable challenges of accessing unpredictable events at remote seafloor locations. The discovery of two persistently active sites (NW Rota-1 in the Mariana arc, explosively erupting at ~550 m; and West Mata in the NE Lau basin where the eruption at ~1200 m was both explosive and effusive) resulted in multi-year, multi-parameter studies that included water column plume surveys, direct (ROV) observations, repeat bathymetric surveys, and hydroacoustic monitoring.

Intense magmatic-hydrothermal plumes rose buoyantly above both sites, while deep particle-only plume layers, dominated by fine ash and devoid of hydrothermal tracers, were found dispersing laterally on isopycnal surfaces in the water column surrounding these volcanoes at variable depths below the eruptive vents and above the seafloor. The distribution of deep ash plumes suggests they are emplaced by sediment gravity flows of variable intensity.

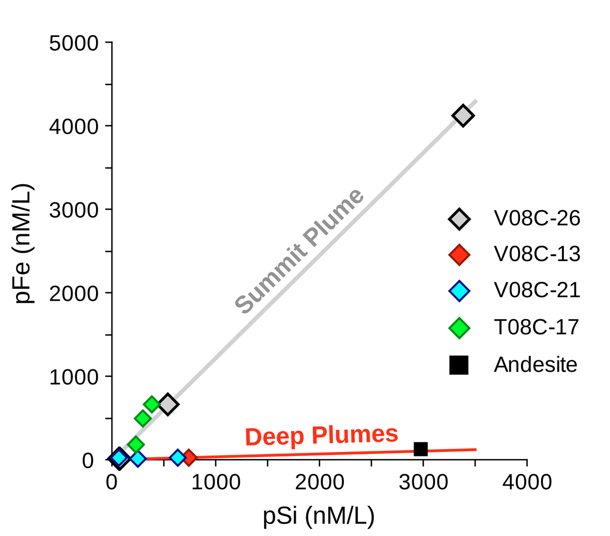
We estimate that fine ash was emplaced into the water column for lateral transport by local currents at rates of 0.4-14.6 x 10^5 m^3/yr during eruptive phases. Depending on particle size, height of the plumes above the seafloor, and local current speeds, individual particles might travel 10's to 100's of km before settling from suspension into the sediment record as "hidden" cryptoptephra or thin fallout deposits.

Deep ash plumes in the water column demonstrate a syn-eruptive mode of transport for fine ash to distances greater than previously predicted. They also represent a different kind of event-related plume that can be diagnostic of ongoing, or very recent, eruptions.

2. Identifying Deep Ash Plumes

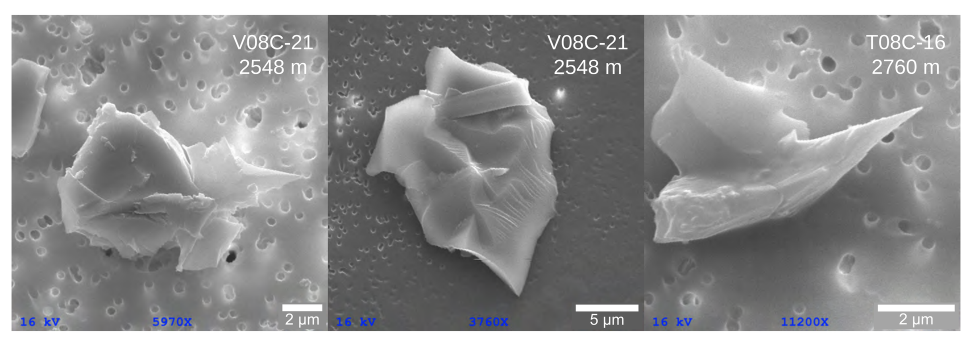


The intese turbidity (ΔNTU), ORP, helium (δ(3He)%), hydrogen, and pH anomalies of the plume over the summit of West Mata characterized it as a magmatic-hydrothermal plume. The deepest turbidity layers had none of these anomalies. A single profile in 2004 suggested at least one unidentified (at that time) deep hydrothermal source, and since then, many additional active hydrothermal sites have been located in the region (see #3).

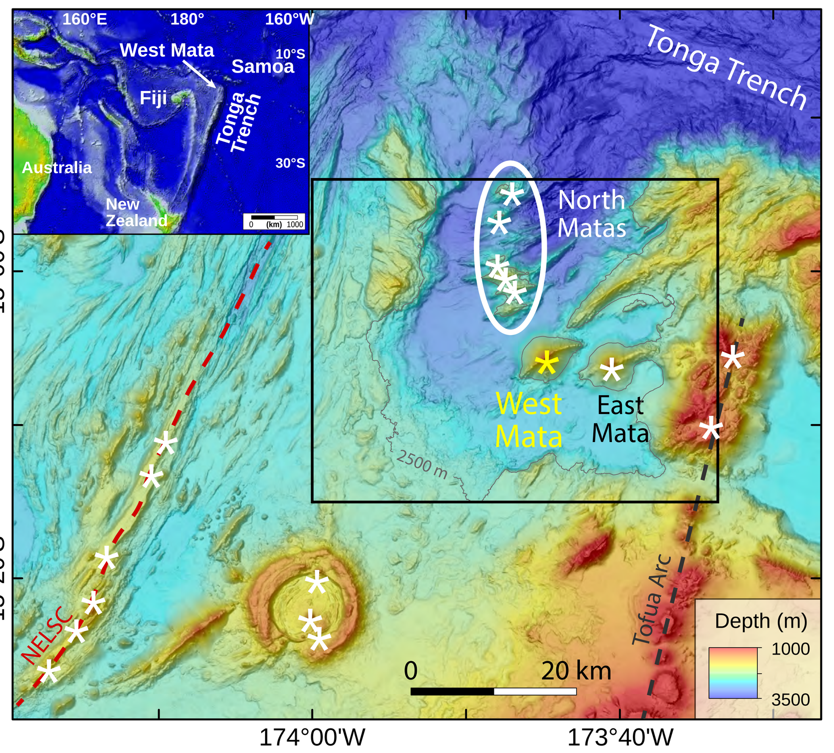


The particulate chemistry in the deep plumes was also distinctly different from that of the hydrothermal particles found in the plume over the summit of West Mata. In contrast to the enrichment of iron in the hydrothermal particles, the Fe/Si ratio of the deep plume particles was similar to boninite, the primitive andesite lava that was erupting at West Mata.

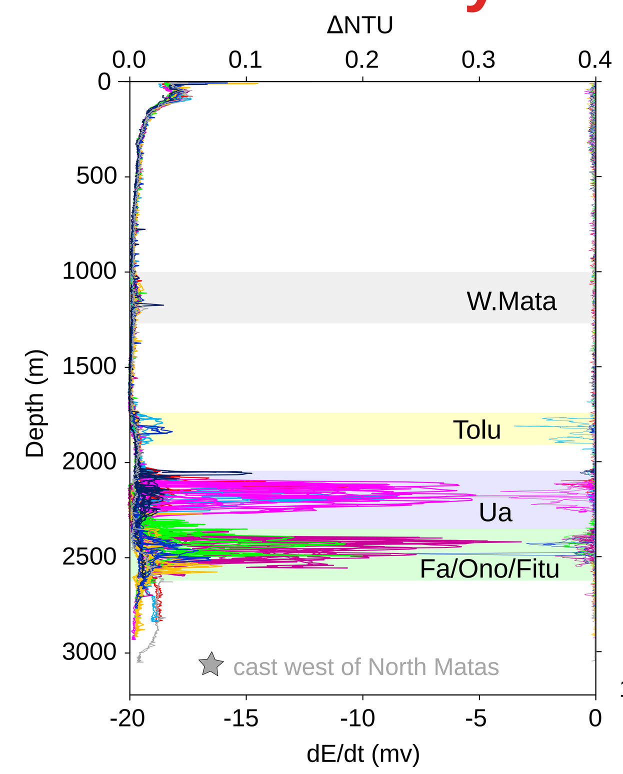
The deep plumes were dominated by fine ash shards with sharp edges and chonchoidal fractures, linking them to the ongoing eruption at West Mata.

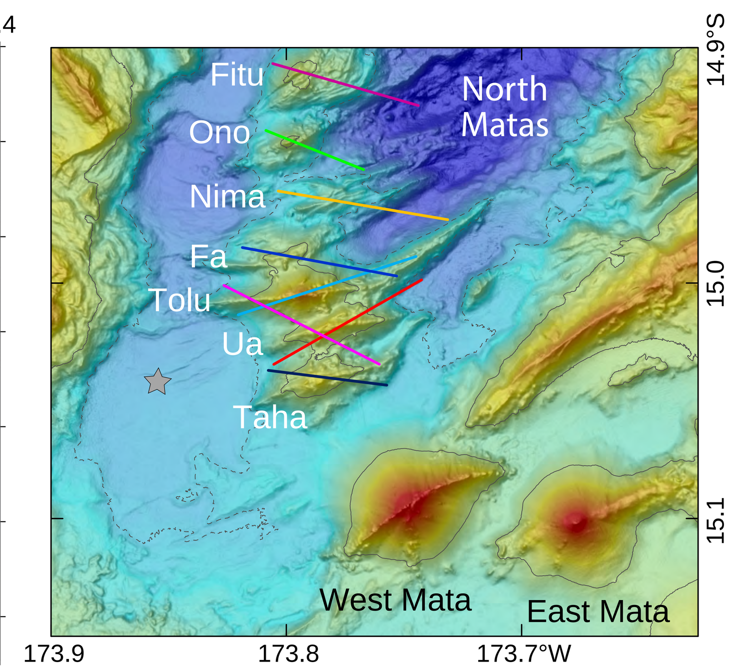


3. Differentiating Deep Ash Plumes from Hydrothermal Sources



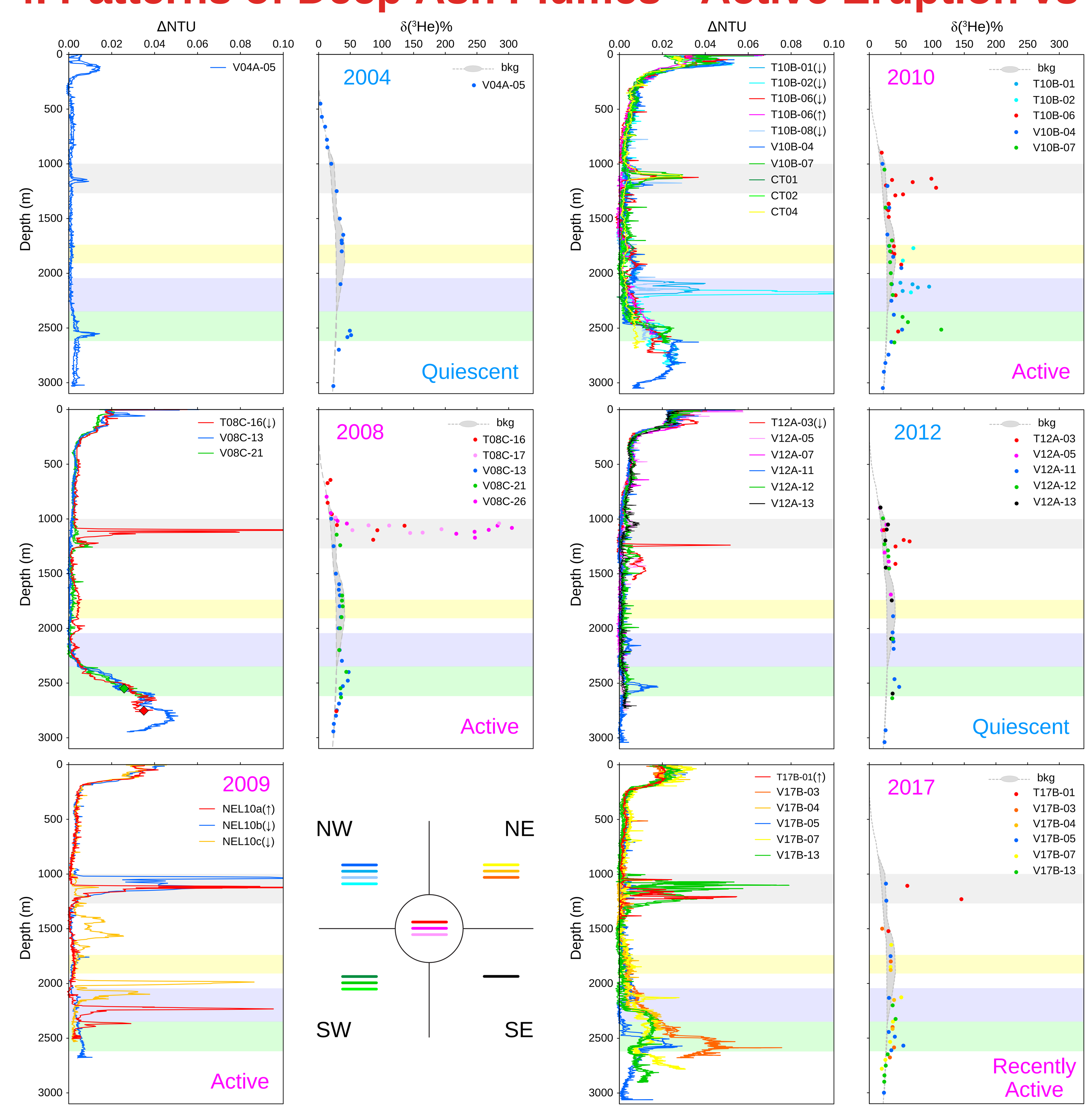
West Mata (yellow star) is located in the NE Lau basin, a complex tectonic and diverse volcanic region where several other hydrothermal sites (white stars) are located along the Tofua vocanic arc, the NE Lau back-arc spreading center (NELSC), and at rear-arc volcanoes. Due to their location and depth, plumes from the North Mata hydrothermal sites are most likely to commingle with the deep ash plumes from West Mata.





Hydrothermal plumes from the North Mata volcanoes were differentiated from deep ash plumes because they were clustered into three distinct depth ranges and characterized by hydrothermal tracers including helium, temperature, and oxidation-reduction potential (ORP) anomalies (dE/dt) coincident with increased turbidity. The hydrothermal components were relatively consistent from year to year, while the turbidity-only layers were highly variable, overprinting the hydrothermal signal as well as extending deeper (see below).

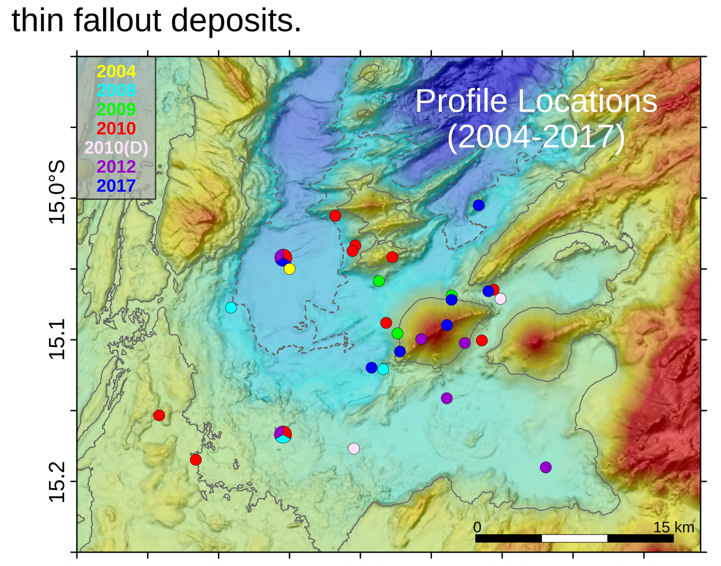
4. Patterns of Deep Ash Plumes - Active Eruption vs Quiescence (2004-2017)



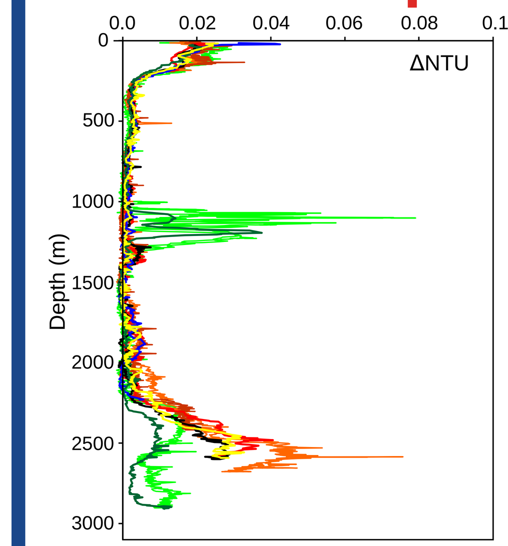
The eruptive history (1996-2017) at West Mata is known from repeat bathymetric surveys, hydroacoustic monitoring, plume chemistry, and direct observations. Deep ash plume presence or absence was correlated with active and quiescent eruptive phases, respectively. We interpret these plumes as volcaniclastic ash produced by the eruption with subsequent downslope and lateral transport through the surrounding water column via sediment gravity flows with variable intensity, runout, and liftoff dynamics.

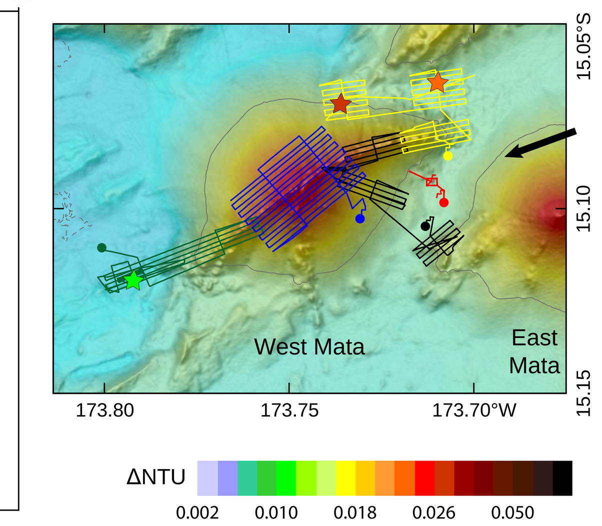
The near-uniformity of the plume distribution at 5 to 20 km from the slope break at the base of West Mata (e.g., 2008 & 2010), regardless of direction, is consistent with radial dispersal of sediment gravity flows. However the complex bathymetry surrounding West Mata appears to exert some directional control on the distribution of the plume relative to the eruptive sites.

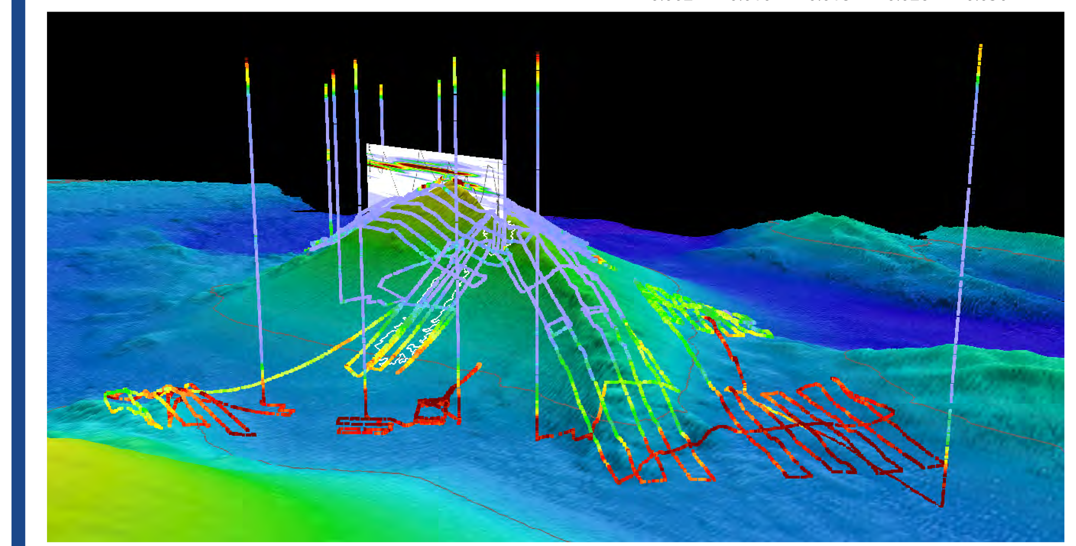
We estimate that fine ash was emplaced into the water column for lateral transport by local currents at rates of 0.4-14.6 x 10^5 m^3/yr during eruptive phases. Depending on particle size, height of the plumes above the seafloor, and local current speeds, individual particles might travel 10's to 100's of km before settling from suspension into the sediment record as "hidden" cryptoptephra or thin fallout deposits.



5. 2017 Deep Ash Plume Decay: Evidence for Recent Eruption





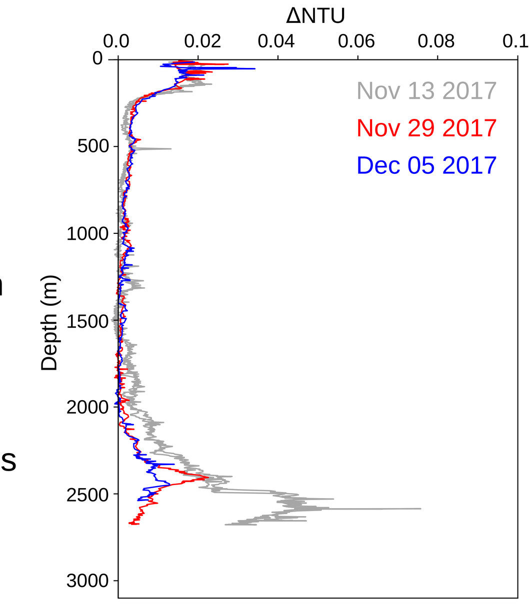


West Mata was quiescent during the 2017 expedition (FK171110) but deep ash plumes were present. Several new lava flows had been emplaced since 2012. One of these was located on the ENE rift zone and flank, and was constrained by repeat bathymetric surveys to have erupted between March 2016 and November 2017.

The deep ash plumes were distributed around the base of West Mata, mostly towards the northeast and east. These plumes decayed rapidly over a 25 day period (Nov 13 - Dec 05), loosing 80% of suspended mass (averaging ~3%, or 0.15-0.6 g/m^2, per day) due to either lateral transport or settling from suspension.

Given this rate of decay, the plume, as seen on November 13, could last for 8-121 days if not replenished, which implied the eruption that created the ENE rift zone deposits likely occurred within weeks to a few months prior to the FK171110 expedition.

Scan to view video of plumes at West Mata submarine volcano.



6. Deep Ash Plumes at Other Submarine Eruptions

The growing list of submarine eruptions where deep ash plumes have been observed suggests this mode of transport for fine ash may be common regardless of depth, lava type, or eruption style. Future studies of submarine eruption dynamics could benefit by including surveys for deep ash plumes.

Volcano	Geologic Setting (Location)	Eruption depth (m)	Lava Type	Eruption style	Year[1] surveyed	Flank slope (°)	Reference[2]
Kavachi	Forearc (Solomon Islands)	2-5	Andesite/ Basaltic-Andesite	Surtseyan, phreatomagmatic, explosive	2000	18	Baker et al. (2002)
NW Rota-1	Arc Mariana arc	550	Basalt/ Picro Basalt Basaltic-Andesite	Stombolian, explosive	2003-2012	31	Chadwick et al. (2008) Walker et al. (2008)
West Mata	Back-arc volcano NE Lau	1200	Boninite	effusive and explosive	2008-2017	>30	Resing et al. (2011) Walker et al., this work
NELSC	Back-arc spreading center NE Lau	1700	Theolitic basalt	effusive, probably some explosive	2008-2010	>30	Baker et al. (2011) Walker, unpublished data
Monowai	Arc Kermadec arc	~100	Basalt	explosive (T-phase hydroacoustic signals)	2004	>20	Wright et al. (2008) Walker et al. (2010)
Ahyi	Arc Mariana arc	100-200	Andesite/ Basaltic-Andesite	explosive (T-phase hydroacoustic signals)	2014	>30	Buck et al. (2018) Walker, unpublished data
Daikoku	Arc Mariana arc	~400	Andesite/ Basaltic-Andesite	Unknown	2015	>30	Walker, unpublished data

[1]Years when water column surveys were conducted.
[2]The first reference describes detection and style of the eruption; the second describes the deep ash plumes. Baker et al. (2002) describes both.

7. Summary

- Fine ash generated by submarine volcanic eruptions is emplaced episodically into the water column via dilute sediment gravity flows to form particle-only plumes that disperse laterally above the seafloor at depths deeper than the eruptive vents.
- Deep ash plumes demonstrate a process for transporting fine ash to regional and distal sediments that is not dependent on lofting volcaniclastic particles high into the water column in buoyant hydrothermal event plumes (aka "megaplumes").
- Deep ash plumes can be dispersed to distances >10s of km from the source eruption and will contribute to regional and distal sediments via settling of individual particles, which may appear as "hidden" cryptotephra or thin fallout deposit ash layers.
- Deep ash plumes are short-lived, making them useful indicators for the exploration and investigation of ongoing or very recent submarine volcanic eruptions.