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Phreatomagmatic Eruption Deposits on the Seafloor Record Cataclysmic Caldera Formation on Axial Seamount, Juan de Fuca Mid-Ocean Ridge

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PHREATOMAGMATIC ERUPTION DEPOSITS ON THE SEAFLOOR RECORD
CATACLYSMIC CALDERA FORMATION ON AXIAL SEAMOUNT, JUAN DE
FUCA MID-OCEAN RIDGE

A Thesis

Presented to

The Faculty of the Department of Geology

San José State University

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

by

Jacob M. Danielsen

December, 2019

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The Designated Thesis Committee Approves the Thesis Titled

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CATACLYSMIC CALDERA FORMATION ON AXIAL SEAMOUNT, JUAN DE
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ABSTRACT

PHREATOMAGMATIC ERUPTION DEPOSITS ON THE SEAFLOOR RECORD CATAclySMIC CALDERA FORMATION ON AXIAL SEAMOUNT, JUAN DE FUCA MID-OCEAN RIDGE

by Jacob M. Danielsen

The physical and compositional characteristics of a unique ash-rich hydrothermal sediment, *hydrothermal muddy tuff* (HMT), on Axial Seamount, Juan de Fuca Ridge, suggest that it formed by phreatomagmatic eruptions during caldera formation. Deposit thickness trends away from the seamount summit and the presence of 68% primary volcaniclasts and 32% secondary lithics suggest a source from along caldera ring-faults deep in the crust. Lithic geothermometry indicates that the source was subject to low-temperature (<150 °C) alteration, consistent with a provenance as deep as 600 – 800 m below the seafloor. At this depth, just above the critical point of seawater, the brittle fragmentation of magma upon interaction with deep-circulating hydrothermal fluids triggered molten fuel coolant interaction (MFCI) and the production of highly angular and very fine grained (100 µm) glass shards. The resulting phreatomagmatic eruption was dispersed over 3.5 km away from the caldera by eruption plume fall-out, ocean bottom currents, and dilute gravity-flows. The result is a unique volcaniclastic deposit that has never been described in mid-ocean ridge settings. This study provides the framework for future studies to further explore fragmentation and dispersal mechanisms within the context of deep-marine volcanic setting.

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LIST OF ABBREVIATIONS

C/S – Interstratified Chlorite/Smectite - (Corrensite)

CVX – Convexity

EDX – Electro-dispersive Spectroscopy

HMT – Hydrothermal Muddy Tuff

Int. M – Intensity mean

Int. SD – Intensity standard deviation

JdFR – Juan de Fuca Ridge

LPA – Lower Pillow Alteration Zone

LPT – Limu o' Pele Tuff

LZD – Lithologic Transition Zone

mbsf – meters below the sea floor

mbsl – meters below sea level

MFCI – Molten fuel-coolant interaction

MGS – Morpho-grainsizer

MLML – Moss Landing Marine Laboratory

MOR – Mid-Ocean Ridge

MPa – Megapascal

PC – Push Core

PSA – Particle Size Analysis

SB – Scoop Bag

SEM – Scanning Electron Microscope

SLD – Solidity

TM – Tuffaceous Mud

TO – Tuffaceous Ooze

UPA – Upper Pillow Alteration Zone

XRD – X-ray Diffraction

ZZ – Zeolite Alteration Zone

INTRODUCTION

Deep-sea caldera systems provide the necessary structural elements (e.g. ring faults) to permit interaction between the lithosphere and hydrosphere (Mueller et al., 2009). These structures increase the porosity of the seafloor up to 33% (Gilbert et al., 2007), allowing for circulation of warm seawater (Cole et al., 2005) that precipitates authigenic minerals (Inoue, 1995). Deeply eroded submarine calderas show that dikes extend between their parent magma chambers to ring faults at the surface (Browning and Gudmundsson, 2015). This plumbing system provides access for seawater to seep deep into the crust where it can interact with the magmatic system (Mueller et al., 2009; Portner et al., 2015).

The potential for magma-seawater interaction results in phreatomagmatic style eruptions (Geshi et al., 2002; Zimanowski et al., 2015; Liu et al., 2017). This study restricts the term *phreatomagmatic* to only include subsurface magma-seawater interaction and does not include interaction between magma and seawater above the seafloor. Phreatomagmatic eruptions are driven by the expansion of boiling seawater to steam and are therefore limited to relatively shallow crustal depths where pressures are <30 MPa. At depths greater than this, seawater behaves as a supercritical fluid that lacks the expansion force required to drive phreatomagmatic eruptions (Bischoff and Rosenbauer, 1985). Phreatomagmatic eruption deposits often result in a heterogeneous mixture of primary volcaniclasts, broadly including fresh glassy shards (vitriclasts) from the

erupting magma, and non-primary volcanic fragments (lithics) that are stripped from conduit walls during the eruption (Barberi et al., 1989).

Although many studies on phreatomagmatic eruptions have been conducted in subaerial volcanic settings, very little is understood about them in deep-marine settings. Moreover, few studies have investigated the potential for magma-seawater interaction along submarine caldera systems despite its potential importance in producing ancient volcanogenic massive sulfide deposits where fault patterns mimic caldera ring structures and dikes (Large et al., 1992; Galley et al., 2007; Mueller et al., 2009). Due to the potential source of mineral resources (e.g. copper, gold, zinc), modern seafloor massive sulfide (SMS) deposits in active hydrothermal systems are of growing interest for natural resource extraction (Murray, 2019).

This study addresses magma-seawater interaction in submarine caldera systems and how it can influence deep-sea volcanic processes by characterizing a volcanoclastic succession on Axial Seamount (Fig. 1). An active submarine volcano, Axial Seamount lies on the Juan de Fuca Ridge (JdFR) approximately 1,500 meters below sea level (mbsl). Axial Seamount is one of the most well-mapped and abundantly sampled deep-marine volcanoes in the world, which when coupled with the presence of a large caldera and up to 65 centimeter-thick volcanoclastic unit extending several kilometers away from caldera margins, provides an excellent opportunity to study how deep-sea calderas influence volcanic, hydrothermal, and volcanoclastic processes.

Figure 1. Regional map showing location of Axial Seamount and other segments on the Juan de Fuca Ridge (JdFR), Cobb Eickelberg Seamount chain, and other structural features. Locations of structural segments based on Van Ark et al. (2007). Inset shows regional map relative to major cities on the west coast of North America.

This study focuses on a unique *hydrothermal muddy tuff* (HMT) lithofacies found near the caldera margins on Axial Seamount. The lithology of HMT was chosen due to its importance in potentially recording caldera formation (Portner et al. 2015). In contrast to typical ‘black smoker’ hydrothermal vent sediments that are generally sulfide-rich and lack vitriclasts, the HMT lithofacies found on Axial Seamount is composed of mostly non-sulfide bearing ash-rich hydrothermal sediment. By using lithostratigraphy, granulometry, componentry, and morphometry, this study tests the hypothesis that HMT formed during phreatomagmatic eruptions as a result of caldera collapse on Axial Seamount.

Research Objectives

This study has two primary research objectives:

1. Determine the physical association between Axial Seamount’s caldera and HMT lithofacies through stratigraphic analysis of the volcanoclastic succession.
2. Identify the provenance of HMT and understand its volcanoclastic origin by characterizing deposit granulometry, componentry, and morphometry.

The methodological approach used to address these objectives and some terminological clarification are explained below.

Lithostratigraphy

Lithostratigraphic trends of the volcanoclastic succession on Axial Seamount were evaluated to determine the source of HMT. Associations of lithofacies to caldera ring faults were evaluated using deposit thickness trends. Relationships

of lithofacies thicknesses to each other provide insight into modes of origin and deposition, and ultimately, their association or non-association to the seamount caldera system. Lithostratigraphic analysis is therefore used to provide insight into lithofacies source(s), transport, and deposition on the seafloor.

Granulometry

Granulometry refers to grain-size distribution, which is important in understanding eruptive processes as grain-size is directly related to total kinetic energy when fragmentation occurs in the presence of water (Wohletz et al., 1986; White, 1996). Granulometry also helps reveal sedimentary structures (e.g. grading and laminations), which can be used to understand dispersal. For example, graded bedding in the submarine environment forms by turbulent fluid flows where larger and less buoyant particles settle first, while smaller, more buoyant particles settle at a slower rate (Barreyre et al., 2011). These differences in hydrodynamic properties influence settling velocity and are also linked to particle morphology. Granulometry analysis was conducted to evaluate grain-size distributions with regards to fragmentation energy and sedimentary structures to explore transport mechanisms.

Componentry

Componentry refers to the material and components of bulk sediment subsamples (including mineralogy) and the chemical makeup of individual particles. Components within HMT may be divided into three main categories that include: primary volcaniclasts, non-primary volcaniclasts, and authigenic

hydrothermal minerals (Fig. 2). In this study, the term “primary volcanoclast” is used to refer to a particle that is magmatically associated with erupting magma and includes vitriclasts (Fig. 2A and B), monocrystalline volcanic minerals (e.g. plagioclase, olivine), and phyric fragments.

Conversely, the term “non-primary volcanoclast” refers to a fragment that is not associated with erupting magma, but instead, incorporated from the external environment during eruptions (e.g. conduit walls, volcano flanks; Fig. 2-C1 – C5; C8 – C11). The term “authigenic hydrothermal mineral” refers to minerals that precipitate from hydrothermal fluids (e.g. clays, sulfates, sulfides; Fig. 2-C6 and C7) associated with the eruption plume and are also non-primary to the erupting magma, but also not volcanic. Both non-primary volcanoclasts and authigenic hydrothermal minerals are therefore considered secondary particles (e.g. lithics).

Secondary components within HMT are of particular interest as chemical alteration of volcanic material results in clay minerals, which are abundant in hydrothermal environments (Utada, 1980; Inoue, 1995). Alteration mineral identification provides insight into the temperature controls and source-depth of potential phreatomagmatic eruptions (Alt et al., 1986). Additionally, authigenic hydrothermal mineralogy is indicative of temperature and chemical controls of hydrothermal fluids (Blount et al., 1977; Ellis and Mahon, 1977; Murnane and Clague, 1983; Inoue, 1995). Componentry analysis was therefore conducted to understand the provenance of non-vitric (e.g. secondary) HMT sediment.

Figure 2. Componentry typical of HMT lithofacies. Red scale bars are 500 μm . **(A)** Primary vitriclasts with angular/blocky morphologies. **(B)** Primary vitriclasts with a variety of fluidal morphologies including limu o' Pele and Pele's hairs. **(C)** Non-primary volcaniclasts (lithics). (C-1) Green fibrous mineral. (C2) Green other. (C3) Crystalline basalt. (C4 and 5) Red particles. White other. (C6 & C7) Green authigenic hydrothermal aggregate. (C8 – C11) White particles. Images enhanced for better color contrast.

Morphometry

Morphometry refers to the texture (e.g. size, shape, vesicularity, surface features) of individual particles, and for the purpose of this thesis is restricted to vitriclasts only. Vitriclast morphometry is highly dependent on the rheologic state of the material being expelled and the environment in which it forms (Büttner et al., 2002; Zimanowski et al., 1997). Vitriclasts may be broadly characterized as either angular / blocky or fluidal. Angular / blocky shards (Fig. 2A) form when magma fragments while in a brittle state (Porreca et al., 2014) and may be described as *dense* or *blocky* with sharp, angular edges and generally rigid surfaces. Fluidal shards (Fig. 2B) have smooth surfaces that form when magma solidifies while in a ductile state. Fluidal vitriclasts include limu o' Pele which are considered bubble-wall shards, but their mode of formation is highly debated (Clague et al., 2009b; Schipper and White, 2010). Nevertheless, vitriclast texture is influenced by the magma fragmentation process and external environmental conditions (Büttner et al., 2002; Liu et al., 2017; Wohletz, 1986; Zimanowski et al., 1997). In a submarine environment, magma-seawater interaction is of particular importance because it can form unique particles with entirely different morphologies based on state of the magma (brittle or ductile) during fragmentation. Morphological analysis was conducted in an effort to determine fragmentation mechanisms and thus, eruption style.

Axial Seamount Background

Axial Seamount lies on the active Juan de Fuca mid-oceanic ridge off the coast of Oregon and Washington States (Fig. 1). It is the youngest volcanic structure of the Cobb-Eickelberg seamount chain, a range of seamounts formed by the Cobb hotspot, which extends 1,800 km northwest to Alaska. Mid-ocean ridge (MOR) rift zones extend to the north and south of Axial Seamount as part of the Juan de Fuca Ridge (JdFR). The seamount has a well-expressed summit caldera that is approximately 8 x 3 km trending generally north-south.

Geophysical data suggest that outward dipping ring faults, that extend down to the magma chamber ~2 km beneath the seafloor, accommodate caldera inflation and deflation between eruption episodes (Wilcock et al., 2018).

Geophysical monitoring of Axial Seamount began in 1987 (Fox, 1990). In 1996, the National Oceanic and Atmospheric Administration (NOAA) implemented the New Millennium Observatory (NeMO) to record interactions between hydrothermal venting and volcanic activity using time-series data (Hamond et al., 2015). In 2014, the Ocean Observatories Initiative (OOI) completed the Axial Seamount cabled array, a network of numerous scientific instruments allowing for real-time observation (Kelley et al., 2014; Delaney et al., 2016). The extensive network of scientific monitoring recorded data during three eruptions in 1998, 2011, and most recently in 2015. Ocean bathymetry and geophysical data reveal that an increase in seismicity, bottom pressure, and caldera inflation coincide with eruptions (Wilcock et al., 2018). Implementation of

this extensive scientific monitoring network has resulted in Axial Seamount becoming one of the most well-studied deep-sea volcanoes in the world.

In addition to scientific monitoring, volcanic rocks and seafloor sediment retrieved from Axial Seamount has been analyzed in numerous studies. Seafloor mapping near the caldera indicates that the majority of volcanic activity is effusive (non-explosive) as evident by extensive lava flows (Clague et al., 2013); however, vitriclast deposits around the caldera margin indicate that some eruptions were explosive (Helo et al., 2011; Portner et al., 2015). The summit lavas on Axial Seamount are chemically distinct from lavas erupted on the adjacent ridge axis. The presence of the Cobb hot spot along the axial segment of the ridge results in an increased supply of hot-spot derived magma that is slightly more primitive and enriched in incompatible elements (e.g. TiO_2) compared to typical mid-ocean ridge basalt (MORB) lavas found along adjacent rift zones on the JdFR (Chadwick et al., 2005; Dreyer et al., 2013).

Magmatism throughout Axial Seamount's recent (<2 kyr) eruptive history exhibits at least three chemically distinct periods. Variations in MgO , K_2O and TiO_2 , which are good proxies for distinguishing primitive magma (high MgO wt. %) from slightly more evolved (low MgO wt. %) magma compositions (Sun, 1982; Arevalo and McDonough, 2010) support this. A shift from a compositionally diverse transitional (T)-MORB with low (<8.0 wt. %) MgO to normal (N)-MORB containing higher (>8.0 wt. %) MgO occurred approximately 900 years ago followed by another transition back to T-MORB with low MgO about 600 years

ago (Dreyer et al., 2013). This chemical stratigraphy observed in lavas is also observed in vitriclasts within the volcanoclastic succession around the caldera (Beth Johnson pers. comm.).

A 45 thousand-year (Kyr) record of volcanism and sedimentation on Axial Seamount is preserved in a <1-meter-thick volcanoclastic sequence around the summit (Clague et al., 2013; Dreyer et al., 2013). This sequence of sediment has been categorized into four different lithologic facies based on the composition, grain-size, chemical heterogeneity and stratification style (Portner et al., 2015). Lithofacies include a tuffaceous mud (TM), hydrothermal muddy tuff (HMT), limu o' Pele tuff (LPT), and tuffaceous ooze (TO), all of which formed in the same environment (mid-ocean ridge) but are inferred to indicate different eruption styles and dispersal processes. Table 1 summarizes lithofacies characteristics described by Portner et al. (2015) and incorporates visual observations of 25 cores described in this study. Detailed descriptions based on visual observations in this study are presented in *results*.

Table 1. Lithofacies described on Axial Seamount (modified from Portner et al., 2015).

Lithofacies	Described Composition	Components (approx. bulk %)	Modal Ash Range (%)	Grain-Size	Fabric	Interpreted Mode of Origin	Described Matrix Color
Tuffaceous Mud (TM)	Ashy mud	60 – 30 Mud (clay) 40 – 20 Angular vitriclasts 30 – 10 Fluidal vitriclasts 10 – 2 Lithics <2 Biogenic	10 – 45	Fine to coarse grained; very poorly sorted	Diffuse to defined lamination; bioturbation	Pelagic fall-out and distal gravity flow	Moderate brown (5YR 5/6) Or Moderate yellowish brown (10YR 5/6)
Hydrothermal Muddy Tuff (HMT)	Sandy mud to Muddy sand (with ash)	40 – 30 Angular vitriclasts 30 – 20 Fluidal vitriclasts 30 – 20 Mud (clay) 20 – 10 Hydrothermal Lithics <2 Volcanic mineral fragments & Lithics	10 – 60	Fine to very fine grained; well sorted	Normal grading with “normal-to-reverse graded” section; well-defined laminations resulting in “reverse-to-normal graded” sections.	Phreatomagmatic plume fall	Light Olive Grey (5Y 5/2)
Limu o Pele (LPT)	Ash	60 – 20 Fluidal Vitriclasts 40 – 70 Angular vitriclasts 6 – 2 Volcanic mineral fragments 5 – 1 Volcanic Lithics	>90	Medium – very coarse grained; moderately to well sorted	Normal grading; planar grain fabric; rip-up clasts of TO	Proximal gravity flow	None (Black)
Tuffaceous Ooze (TO)	Ashy mud	>90% Foraminifera <10% Angular vitriclasts	5 – 10	Fine grained; Very well sorted	Structureless	Pelagic fall-out	Greyish orange (10YR 7/4) Or Yellowish grey (5Y 7/2)

METHODS

Nearly 370 sediment push cores and scoop bags have been retrieved by remotely operated vehicle (ROV) from Axial Seamount during five expeditions between 2006 and 2016. This study primarily focuses on subsamples retrieved from push cores, but scoop bag subsamples are used for dataset comparison. Cores are stored at San Jose State University (SJSU), Monterey Bay Aquarium Research Institute (MBARI), and the United States Geological Survey (USGS) in Santa Cruz. A subset of longer (>20 cm) push cores were split at the USGS in Santa Cruz. Core and scoop bag sample locations on Axial Seamount used in this study are shown in Figure 3. A summary of methods and their application(s) used in this study are provided in Table 2. A log of methods used for each core and subsample are presented in Table 3.

Figure 3. Bathymetric map of Axial Seamount showing location of caldera (black line), fissures (red lines), and location of push cores and scoop bag samples analyzed in this study. Bathymetric data are from AUV and ship-based seabeam EM300 data acquired by MBARI. Caldera rim and fissures were drawn in by colleagues at MBARI pers. Comm.

Table 2. Methods and their application used in this study for lithofacies characterization.

Characteristic	Method	Application	# analyzed
Lithostratigraphy	Core Descriptions	Litho-stratigraphic associations to the caldera	25 ^a
Granulometry (Grain-size)	Laser diffraction	Primary method for grain-size analysis	66 ^b
Componentry (mineralogy & chemistry)	Point counts	Bulk HMT component proportions	27 ^b
	XRD	Analysis of bulk & clay mineralogy	10/4 ^c
	EDX	Chemical analysis of hydrothermal particle	28 ^d
Morphometry (particle shape)	Point counts	Proportions of vitriclast morphology (qualitative)	5 ^b
	SEM	Visually analysis of high-resolution images of individual glass particles	77 ^d
	MGS	Vitriclast morphology analysis (quantitative)	41 ^b

^a25 cores described.

^bSubsamples

^c10 subsamples used for “bulk” XRD; 4 subsamples used for clay XRD analysis.

^dIndividual particles analyzed

Table 3. Log of core and subsamples and the methods used in this study.

Core	Sample depth (from top of core)	Subsample Name	Core described	PSA	Point count	XRD "bulk"	CXRD (clay)	SEM mount	MGS (point count)
D515-PC74L			X						
D516-PC61XL			X						
D522-PPC1			X						
	9.0	D522-PPC1_9.0				X	X		
D522-PC62L			X						
	3.0	D522-PC62L_3.0						X	
	10.0	D522-PC62L_10.0		X					
	11.5	D522-PC62L_11.5				X			
	13.0	D522-PC62L_13.0		X	X				
	15.0	D522-PC62L_15.0			X			X	X
	16.0	D522-PC62L_16.0		X					
	19.0	D522-PC62L_19.0		X					
	21.5	D522-PC62L_21.5				X	X		
	23.0	D522-PC62L_23.0		X	X				
	26.0	D522-PC62L_26.0		X					
	27.0	D522-PC62L_27.0						X	X
	28.0	D522-PC62L_28.0		X	X			X	
	29.0	D522-PC62L_29.9				X			
	31.0	D522-PC62L_31.0		X					
	32.0	D522-PC62L_32.0						X	
	34.5	D522-PC62L_34.5		X					
	35.5	D522-PC62L_35.5		X					
	36.0	D522-PC62L_36.0		X					
	37.5	D522-PC62L_37.5		X	X				
	38.5	D522-PC62L_38.5		X					
	39.0	D522-PC62L_39.0		X					
	40.0	D522-PC62L_40.0		X					
	41.0	D522-PC62L_41.0		X	X				
	42.5	D522-PC62L_42.5		X					
	44.5	D522-PC62L_44.5		X					
	46.5	D522-PC62L_46.5		X	X				
	48.5	D522-PC62L_48.5		X					
D522-PC66			X						
	6.5	D522-PC66_6.5		X					
	8.0	D522-PC66_8.0		X	X				
	10.0	D522-PC66_10.0		X					
	11.0	D522-PC66_11.0		X					
	12.0	D522-PC66_12.0		X	X				
	14.0	D522-PC66_14.0		X					
	15.5	D522-PC66_15.5		X					
	17.0	D522-PC66_17.0		X	X				
	19.0	D522-PC66_19.0		X	X				
	19.0	D522-PC66_19.0		X					
D524-PC47XL			X						
	10.0	D524-PC47XL_10.0						X	
	22.5	D524-PC47XL_22.5		X					
	24.5	D524-PC47XL_24.0		X					
	27.0	D524-PC47XL_27.0		X	X				
	27.0	D524-PC47XL_27.0						X	X
	29.5	D524-PC47XL_29.5		X					
	32.0	D524-PC47XL_32.0						X	
	41.0	D524-PC47XL_41.0						X	
	48.0	D524-PC47XL_48.0						X	
D525-PPC2			X						
	17.0	D525-PPC2_17.0		X					
	19.0	D525-PPC2_19.0		X					
	21.0	D525-PPC2_21.0		X					
	23.0	D525-PPC2_23.0			X			X	
	24.0	D525-PPC2_24.0		X					
	26.5	D525-PPC2_26.5		X					
	28.5	D525-PPC2_28.5						X	
	29.5	D525-PPC2_29.5		X	X				
	29.5	D525-PPC2_29.5						X	
	32.0	D525-PPC2_32.0						X	
D528-PPC72			X						
D655-PPC43			X						

Table 3. Continued.

Core	Sample depth (from top of core)	Subsample Name	Core described	PSA	Point count	XRD "bulk"	CXRD (clay)	SEM mount	MGS MGS	MGS (point count)
D655-PPC49			X							
D655-PC67			X							
	13.5	D655-PC67_13.5			X				X	X
D655-PPC79			X							
	7.0	D655-PPC79_7.0				X				
	15.5	D655-PPC79_15.5		X						
	17.5	D655-PPC79_17.5		X	X					
	19.5	D655-PPC79_19.5		X						
	20.0	D655-PPC79_20.0				X	X			
	22.0	D655-PPC79_22.0							X	
	23.0	D655-PPC79_23.0		X	X					
	26.0	D655-PPC79_26.0		X	X					
D875-PC75			X							
	3.0	D875-PC75_3.0		X						
D876-PC66			X							
	13.0	D876-PC66_13.0		X						
	15.0	D876-PC66_15.0		X						
	16.0	D876-PC66_16.0		X						
	17.0	D876-PC66_17.0		X						
	19.5	D876-PC66_19.5		X						
D876-PC75			X							
	18.0	D876-PC75_18.0			X				X	
	21.0	D876-PC75_21.0							X	X
D878-PC44			X							
D878-PC53			X							
	5.0	D878-PC53_5.0		X						
	5.5	D878-PC53_5.5				X				
	8.0	D878-PC53_8.0		X						
	10.0	D878-PC53_10.0		X						
	12.0	D878-PC53_12.0				X	X			
	12.0	D878-PC53_12.0		X						
	14.0	D878-PC53_14.0		X	X					
	14.0	D878-PC53_14.0							X	
	16.0	D878-PC53_16.0		X	X					
	18.0	D878-PC53_18.0		X	X					
D878-PC58			X							
D878-PC62			X							
D878-PC63			X							
D878-PC66			X							
D878-PC75			X							
	4.0	D878-PC75_4.0							X	
	9.0	D878-PC75_9.0		X						
	11.0	D878-PC75_11.0		X						
	11.0	D878-PC75_11.0				X				
	13.0	D878-PC75_13.0		X						
	15.0	D878-PC75_15.0		X	X				X	X
	17.0	D878-PC75_17.0		X	X					
	17.0	D878-PC75_17.0				X				
	18.5	D878-PC75_18.5							X	
D878-PC76			X							
	10.0	D878-PC76_10.0		X						
	12.0	D878-PC76_12.0		X						
D878-PC78			X							
D881-PC72L			X							
	1.5	D881-PC72L_1.5		X						

Lithostratigraphy

Characteristics of 25 representative push cores were visually described. The selection preference of cores used for descriptions was based on their ability to be described (core accessibility and preservation), lithology, volcanoclastic features, location around the caldera (cardinal direction), and proximity to caldera margins. Distinct lithofacies were identified, separated based on criteria outlined by Portner et al. (2015), and measured for thickness.

Core descriptions include: lithofacies designation, grain-size, ash content, ash morphology, sorting, components (primary / non-primary volcanoclasts, authigenic hydrothermal minerals), structures (laminations, grading, etc.), unit contacts, color (using the Munsell color system), and geophysical logs (when available). Components and modal ash percent within each lithofacies were visually estimated. Geophysical characteristics of push cores, including seismic velocity, bulk density, and magnetic susceptibility, were measured at the USGS in Santa Cruz. Magnetic susceptibility, which measures the magnetic field strength of a material, aided in defining HMT contacts due to the high magnetic susceptibility of some hydrothermal minerals (Luyendyk and Melson, 1967; Airo, 2002).

Thickness of HMT measured in core descriptions was used to create thickness profiles and an isopach map. Although thickness measurements were based on core descriptions, observations of ROV video reveal that in situ volcanoclastic lithofacies are thicker. During the coring process, de-watering and

compression causes the lithofacies to compress approximately 25%. References to lithofacies thickness henceforth refers to thickness measured in the split core.

Subsample Preparation

Subsamples were extracted from representative cores approximately every other centimeter throughout the HMT lithofacies to be analyzed for granulometry, componentry, and morphometry. Altogether, 97 subsamples were extracted from 13 of the 25 described cores. Subsamples were consistently named using a location-based scheme. For example, subsample *D522-PC62L_27.0* refers to *Doc Ricketts ROV* dive (D) number “522”, push core (PC) number “62” (the “L” denotes a long core >20 cm), and “27.0” for the subsample depth of extraction (measured from the top of the core). Some cores have a PPC for piston push core, others just have PC for a short (<20 cm) core barrel. The selection of cores used for subsampling was based on their proximity to the caldera: proximal (<100 m from caldera rim), medial (100 m – 1000 m), and distal (>1,000 m).

Cores were subsampled from all margins surrounding the caldera, and along an outward transect orthogonal to the eastern caldera margin. This transect combined two smaller sub-transects that are offset by ~2.5 km (Fig. 4), thus allowing for detailed observations of volcanoclastic and lithostratigraphic changes with increasing distance from the caldera rim. Additionally, one core (*D881-PC72L*), which sits on a high pillow cone located approximately 42 km south of the summit of Axial Seamount (Fig. 5), was analyzed for grain-size distribution as

a baseline for “ambient” background sedimentation. The base of *D881-PC72L* was dated to be >40 kyr (Chen and Clague, 2015).

Figure 4. Map showing east side of the caldera where two transects (A – A'; B – B'), offset by about 2.5 km, are combined to create a full transect. Bathymetric data is from AUV and ship-based seabeam EM300 data acquired by MBARI. Caldera rim and fissures were drawn in by colleagues at MBARI pers. Comm.

Figure 5. Bathymetric map showing location of Axial Seamount in relation to core *D881-PC72L* used for “background” sedimentation granulometry analysis. Bathymetric data is from AUV and ship-based seabeam EM300 data acquired by MBARI. Caldera rim and fissures were drawn in by colleagues at MBARI pers. Comm.

All subsamples, regardless of the method to be used, were extracted from the core and weighed (wet). The mass required for subsamples varied depending on the method to be used for analysis, but a typical subsample contained ~ 6g of wet material that was dried overnight at 60-70°C. Dried samples were then weighed and soaked in 80 ml of a solution of 500 ml DI water and 70 mg of sodium hexametaphosphate (deflocculant). The sediment / deflocculant mixture was left overnight in the solution and then sonicated for 30 minutes to fully disaggregate clay flocs. Once the initial sample preparation procedure was complete, subsamples were selected for granulometry, componentry and morphometry.

Analytical Techniques

Particle Size Analysis (PSA)

Bulk subsamples were analyzed for grain-size distribution using laser diffraction particle size analysis (PSA) at the USGS in Santa Cruz, CA. Bulk subsample mass needed for the laser diffraction method was >3 g wet. Subsamples for the laser diffraction method were sieved to <1000 µm to prevent large particles from clogging the instrument. The mass of particles >1000 µm was recorded, normalized based on mass percent, and eventually re-combined with <1000 µm PSA results. Prepared <1000 µm subsamples in de-flocculent solution were taken to USGS in Santa Cruz to be analyzed using a Beckman Coulter LS 13 320 laser diffraction particle size analyzer. The subsample was diluted in 400 – 500 ml of DI water and mixed using an agitator for 3 – 5 minutes.

The solution containing the subsample was transferred to the instrument using a pipet (extracted from a consistent depth for each subsample) until laser obscuration reached 8 – 12%. The instrument sonicated the solution while measuring grain-size to reduce particle aggregates. This method measures vol. % of particles by the diffraction of light (McCave et al., 1986).

A total of 66 subsamples from 11 cores were measured for grain-size using the laser diffraction method. Pre-existing grain-size analysis results (using wet-sieving techniques) of TM and LPT from Portner et al. (2015) were used for comparison. Grain-size data using the laser particle diffraction method was plotted using the two grain-size plots: vol. % plotted against grain-size (μm) and cumulative vol. % plotted against grain-size. Combined laser diffraction ($<1000 \mu\text{m}$) and sieving PSA data ($>1000 \mu\text{m}$) was input into Gradistat (Blott and Pye, 2001) to calculate a variety of grain-size statistics including mean grain-size, peak mode, sorting, and skewness (Folk and Ward, 1957).

Point Counts

All subsamples used for point counting grains were sprinkled onto a 1x1 cm grid-paper and particles were only counted if they fell on the grid line to eliminate selective particle bias. For all samples, 500 grains / subsample ($n = 500$) were counted and tallied manually. To determine the appropriate grain-size for point counts, an initial point count was conducted using representative subsample *D522-PC66_19.0* (retrieved from HMT) in three different size-fractions including 63 – 125 μm , 125 – 250 μm , and 250 – 500 μm . The 125 – 250 μm size-fraction

was chosen because it includes representative mixture of the three primary components (primary volcaniclasts, non-primary volcaniclasts, and authigenic hydrothermal minerals), and is coarse enough for easy visual identification. Twenty-six additional subsamples, extracted from cores with a variety of proximities to the caldera and depths within HMT, were point counted in the 125 – 250 μm size fraction.

A summary of particle descriptions used during point counts are presented in Table 4. Agglutinate particles are presumed to be authigenic hydrothermal clay aggregates coated in sideromelane. Therefore, these may be considered hybrid particles in that they consist of both authigenic hydrothermal minerals primary vitric material. For the purposes of point counts, they were counted in the *authigenic hydrothermal minerals* category.

Table 4. Summary of point count categories and description of particles counted within each category.

Primary Volcaniclasts	Non-primary volcaniclasts	Authigenic Hydrothermal Minerals
Angular vitriclast	Altered glass (angular)	Green aggregates
fluidal vitriclast	Altered glass (fluidal)	Yellow aggregates
Vesicular (angular) vitriclast	Crystalline basalt/diabase	Pure sulfide
Vesicular (fluidal) vitriclast	Spherulitic	Agglutinate ^a
Plagioclase	Red/orange particles	
Olivine	Green fibrous	
Phyric	Green other	
	White fibrous	
	White other	

^aAgglutinate particles were counted as “authigenic hydrothermal minerals” however the hybrid nature of these particles means that they could also be considered “primary volcaniclasts”.

SEM/EDX

Scanning electron microscope (SEM) / energy dispersive X-ray spectroscopy (EDX) was used to examine vitriclast morphologies and the chemical composition of non-vitric grains. Representative particles ranging from 125 – 250 μm were selected by hand during point counts and mounted on standard 15 mm SEM stubs. These grains include the full range of components observed within HMT. Two mounts were created and gold-coated (to reduce electron charging) using a Polaron E5400 sputter coating system.

SEM mounts were analyzed using a Hitachi S-3400N scanning electron microscope equipped with an Oxford Instruments X-Max X-ray probe located at Moss Landing Marine laboratory (MLML). The SEM was operated using the variable pressure vacuum setting set to 6.0 Pa. Accelerating voltage was set to 30.0 kV for all acquired images, probe current was set between 60.0 – 70.0 mAmps based on the required strength of acquiring EDX spectra and so that measured deadtime was greater than 12%. Working distance was set between 10.0 – 10.2 mm for all EDX spectra. Prior to spectra collection, the EDX probe was calibrated using a copper standard and verified by collecting spectra on known basaltic grains which were compared to San Jose State University basalt standard spectra (Fig. 6).

Figure 6. Basalt (N-MORB) EDX spectra standard from the northern East Pacific Rise. MgO in standard is ~7.56 wt.%, which is comparable to HMT vitriclast geochemistry on Axial Seamount.

Grains selected for EDX point chemistry were selected based primarily on mineral morphology. Multiple “regions of interest” were selected for EDX analysis and spectra were taken from 3 – 7 points within each region of interest. Chemistry results were analyzed using INCA “Point & ID” software and filtered by hand to remove elements shown with overlapping peaks (not likely to be in the subsample). Mineral identification of points of interest were aided by SEM images (particle morphology), and measured spectra compared to known spectra of minerals using “SEM Petrology Atlas” (Welton, 2003).

XRD

Nine subsamples were analyzed for “bulk” subsample (non-glass) mineralogy using powdered X-ray Diffraction (XRD). Clay mineralogy was determined using two subsample preparations: (i) a <2µm random powder diffraction mount and (ii) a thin film peel mount of <2 µm clays from representative subsamples. The latter was modelled using computer software. Full subsample preparation and methods are outlined below.

“Bulk” Analysis

Subsamples selected for “bulk” XRD were first run through a Frantz magnetic separator to filter out glass particles to reduce the effect of broad baseline humps (obscuring mineral peaks) that result from the non-crystalline nature of glassy material. For “bulk” XRD analysis, non-magnetic minerals (e.g. plagioclase) needed to be separated from glass (low magnetic susceptibility) and grouped with minerals with a high magnetic susceptibility (e.g. pyroxene) to produce a subsample that excluded volcanic glass.

The Frantz magnetic separator was set to a 15° tilt and each subsample was run through the instrument three times with increasing magnetic susceptibility. The first run was set to 0.25 amps, the second run was set to 0.50 amps, and the third run was set to 1.00 amps. After runs one and two, the magnetic constituents were separated, and the non-magnetic material was re-run at the higher magnetic susceptibility setting (1.00 amps) to filter glass from non-magnetic minerals (e.g. plagioclase). After this run, the glass was separated out while the

non-magnetic constituents (e.g. plagioclase) were recombined with previously separated magnetic material to be analyzed for XRD. The remaining material (magnetic susceptibility-filtered bulk) was gently crushed to a powder in a mortar and pestle for XRD analysis.

Magnetic susceptibility-filtered bulk subsamples were taken to USGS (Santa Cruz) for XRD analysis. Powder mounts were prepared using a back-fill disk method. All subsamples were run using a copper anode with $k\alpha \lambda = 1.540598$. Divergence slits were fixed at 19mm. A continuous scan was performed at 2θ angles between $3 - 70^\circ$. Diffraction results were analyzed by hand using several in-print powder diffraction manuals including: *Selected Powder Diffraction Data for Minerals* (Berry, 1974), *Mineral Powder Diffraction File Search* manual (Bayliss et al., 1986) and on-line resources (Lufuente et al., 2015). Rigaku PPXL-2 XRD mineral-search software (V. 2.8.4) was used to confirm mineralogy using the auto-search / match functions at SJSU and MLML.

Clay Analysis

Four representative subsamples were selected for clay mineralogy analysis using XRD. Subsample preparation followed the millipore transfer method outlined by Moore & Reynolds (1989). Selected powders from bulk XRD were measured to 2.00 g (dry) and added to 100 mL of deflocculant solution. The subsample-solution mixture was sonicated for 15 minutes to disaggregate clay particles. To separate the $<2 \mu\text{m}$ size fraction, the solution was centrifuged using an international clinical safeguard centrifuge (model CL) on setting #1

(approximately 1475 rpm). The subsample was centrifuged for 30 seconds once the centrifuge reached full speed (about 1 minute in total). Once the centrifuge slowed to a complete stop, the $<2\ \mu\text{m}$ fraction was decanted into a beaker and sonicated for another 5 minutes. Clay particles were separated from solution onto filter paper using a vacuum filtration device. The clay particles on the filter paper were gently rolled onto a petrographic slide, allowed to air dry, and stored in an ethylene glycol chamber. The resulting clay peel film ensures that all clay minerals are oriented with their crystallographic C-axis perpendicular to the surface of the petrographic slide.

Once clay peel films were prepared, they were scanned following the recommended clay XRD analysis (Poppe et al., 2001) from $2^\circ - 50^\circ 2\theta$ at a step of 0.03, using a Rigaku XRD instrument with a copper anode ($k\alpha\ \lambda = 1.540598$) located at MLML. A series of XRD treatments were performed on each subsample including untreated, treated with ethylene glycol, 400°C heat treatment, and 550°C heat treatment. Changes to peaks characteristics (e.g. expansions, collapses, destroyed) were used to identify specific clay minerals based on the *Clay Mineral Identification Flow Diagram* (Poppe et al., 2001). Although specific peak locations ($\text{\AA}$) are important in identifying clay minerals, slight variations are common and may occur due to ambient measurement conditions (e.g. laboratory humidity), treatment process (e.g. flooding subsample with glycol, temperature variations during heat treatments), or chemical coordination of clays. Therefore, clay peak locations discussed in results are

referred to as the general peak location identifiable for clay minerals (e.g. a 16.7 Å will be generalized and inferred to be a 17 Å peak).

The modeling software NEWMOD, developed in 1985 by R. C. Reynolds Jr., has been the standard method for quantifying clay mineral mixtures using XRD diffractograms (Yuan and Bish, 2010). NEWMOD modeling software was used in this study to replicate results of unknown XRD spectra by defining specific stoichiometric clay compositions. XRD spectra of glycolated <2µm subsamples, prepared with the clay peel film technique, were imported into NEWMOD to be modeled. Clay components were modeled by matching d-spacing and peak intensity in unknown subsamples to model output in NEWMOD. Once interstratified clays and reicheite ordering were defined and associated peaks identified, clay component mixtures were modeled iteratively until all clay peak positions and relative heights were present. Cation abundances for individual clay species and clay mixture abundance percentages were manually manipulated to help match peak intensities.

Morpho-grainsizer (MGS)

A Morphologi G3S (MGS) was used to quantitatively measure particle shapes. The instrument is designed to quantify the shape of individual particles based on high-resolution two-dimensional images and provides statistical analysis without operator bias. Analysis of 41 subsamples from 8 cores using the MGS was conducted at the Laboratoire Magmas et Volcans, Université Clermont

Auvergne in Clermont-Ferrand, France following the method outlined by Leibbrandt and Le Pennec (2015).

To focus on primary volcaniclast (e.g. vitriclasts, free crystals) morphologies, subsamples from the 250 – 500 μm and 500 – 1000 μm size fractions were run through a Frantz magnetic separator to filter particles that were not volcanic glass. The process of separation is different than that used for XRD separation as this method aimed to exclusively separate out primary volcaniclasts. The Frantz was set to a 15° tilt and the first run was set to 0.35 amps. The magnetic material was set aside, and the non-magnetic material was re-run at a setting of 0.5 amps. After this run, the magnetic material were mostly non-volcanic glass particles, and was therefore separated. This process was repeated twice further to ensure exclusion of all magnetic material. Once Each size fraction had been filtered, they were ready to be analyzed by the MGS for particle shape.

Two methods of dispersal were available to spread subsamples onto the glass slide: automatic and manual. The automatic dispersion unit (ADU) was used for most subsamples and used an air compressor to inject air into the contained subsample. The air pressure was set to 1.2 bars, the injection time (T_i) was set to 40 ms, and the settling time (T_s) was set to 20 seconds. These settings worked for particle sizes $>125 \mu\text{m}$. If particles to be measured were $<125 \mu\text{m}$, the air pressure was reduced to 1.0 bars, T_i was reduced to 80 ms, and T_s was increased to 40 seconds. After automatic dispersion, the particles were visually checked to verify a good dispersion (e.g. few particles touching). For

particles >500 μm , particles were manually dispersed by sprinkling them onto the glass slide and manually separating any particles that were touching. The manual dispersal method was preferred for the 500 – 1000 μm size-fraction because particles were large enough to visibly move into position (minimizing the chances of touching particles), allowing the operator to scan a larger area resulting in more particles scanned. 2.5x and 5.0x optics were tested to compare image quality, but always yielded similar results for the 250 – 500 μm size fraction. Therefore, after testing numerous runs, it was determined that using the 2.5x objective with the 250 – 500 μm size-fraction was the preferred combination as the 2.5x optics scanned the desired area considerably faster without compromising image quality and results.

Diascopic lighting (bottom light) was used to give better contrast of particles. The scans did not overlap and particles on the edges were automatically stitched together allowing the MGS to count all grains within the scanned boundaries. The focus was manually set on a representative particle of intermediate thickness prior to scanning. Differential z-stacking was enabled with one additional focus level above and below (196 μm above; -196 μm below for 2.5x optics) to obtain best image resolution and focal depth for particles of different thicknesses.

Lighting was manually configured by setting the lamp power (LP) and exposure. The LP ranged from 51 to 82 and the exposure ranged from 0.31 to 1.74. Gamma lighting correction was fixed at 1.0. The LP was configured to provide maximum contrast between the background and particles. The threshold

determines the separation of particles from the background and ranges from 0 to 255 (black to white). Various subsamples were scanned in order to determine the optimal threshold range to be between 120 – 160. The lower the threshold the better the results for particle shape parameters; however, if abundant fluidal particles are present, the thin particles will not be separated well from the background (Fig. 7). For this reason, most subsamples were scanned using a threshold between 140 – 150.

Figure 7. Differing MGS threshold values and their effect on particle scans. **(MGS View)** showing a thin particle in the middle and several thicker vitriclasts surrounding in plane light view. **(Threshold 120)** shows the thin particle cannot be separated from the background. **(Threshold 135)** the outline of thin particle is separated from the background, but a hole is present. With the *hole filling* option set to “on”, this particle will be scanned. Thicker vitriclasts have a slight grey shadow on their boarder. **(Threshold 150)** completely separates the thin particle yet the thick vitriclasts have a noticeable grey “halo” which may skew shape parameter results.

For automatically dispersed subsamples, the default scan area was used (5541.769 mm²). For manually dispersed subsamples, the scan area was manually set to cover the area of manually placed particles. Hole filling, which allows a particle to be properly scanned as long as the perimeter is completely separated from the background (even if the middle of the particle is not separated), was enabled to properly scan fluidal particles at lower thresholds (Fig. 7: threshold 135). Automatic filters were set to exclude particles with CE diameter <100 µm for all scans of subsamples >250 µm.

MGS Data Processing

Once scans were complete, additional manual filtering was required to exclude touching particles, improperly stitched particles, or dust (Fig. 8). The manual filtering process excludes approximately 6 – 25% of the total scanned particle population (excluding the <100 µm automatic filter). Subsamples dispersed using the ADU method required a larger proportion of scanned particles to be excluded whereas subsamples that were dispersed manually required considerably less particles to be excluded. Five steps were taken to ensure unusable particles were filtered out:

1. Plotting particle area (µm²) on the x-axis and the solidity parameter on the y-axis (Fig. 8a), particles were excluded based on the particle area parameter. For the 250 – 500 µm size fraction, particles with an area >500,000 µm² were filtered out, thereby removing large particle aggregates. Conversely, particles with an area <50,000 µm² were

excluded, thereby filtering small, improperly stitched / scanned particles and dust.

2. Using this same plot, outlier particles with low solidity (<0.7) were visually inspected and manually discarded if they were determined to be unusable. Some of this group were pele's hairs and thus were not discarded; however, most images in this exclusion category included grains that were touching.
3. Plotting circularity on the x-axis and solidity on the y-axis, outlier particles with low circularity (<0.6) were visually inspected and manually excluded if determined to be unusable (Fig. 8b). Elongate particles including pele's hairs fall into this category and were not filtered.
4. Using convexity on the x-axis and CE diameter on the Y-axis, particles with low convexity (<0.8) were visually inspected and manually discarded if they were determined to be unusable (Fig. 8c).
5. Particles remaining after the above filtering steps were individually examined. Any particles deemed unusable requiring exclusion (e.g. touching particles, improperly stitched) were manually discarded.

Figure 8. MGS particle filtering procedure. Particles falling within red hatched area were filtered out for all subsample scans. **(A)** Particles are separated by size with smaller particles being improperly stitched (I) and larger particles being aggregates of multiple particles (e.g. II, III, IV). Other filtered particles include those scanned debris on the stage (V) or improperly separated from background (VI). Particle aggregates also had a low solidity (e.g. III & IV) and were therefore also excluded. **(B)** Particles with low circularity values were improperly scanned particles (e.g. I) and particle aggregates (e.g. II, III, IV) were filtered out. **(C)** Particles with low convexity values were found to be touching/overlapping particles (e.g. I, II, IV) or improperly stitched (III) and were subsequently filtered out.

Data Parameters

MGS datasets were examined using a variety of calculated shape parameters and instrument measurements. Many methods of calculating shape parameters exist. This study uses shape parameters that were automatically calculated by Malvern's "Morphologi" software. A summary of shape parameters used in our study and a comparison of other methods are presented in Table 5. After testing various combinations of plotting data using shape parameters, four primary measurements were found to be most useful: *convexity* (CVX), *solidity* (SLD), *intensity mean* (Int. M), and *intensity standard deviation* (Int. SD).

Convexity is a measure of particle "edge roughness" while *solidity* is a measure of "morphological roughness" (Fig. 9; Liu et al., 2015). Shape parameters CVX and SLD were chosen because these shape parameters have been used extensively in previous ash morphology studies (e.g. Buckland et al., 2017; Leibrandt and Le Pennec, 2015; Liu et al., 2015; Nurfiani and Bouvet de Maisonneuve, 2018). *Intensity mean* and *intensity standard deviation* are not measurements of particle shape, but instead measurements of light transmission through a particle. *Intensity Mean* measures the intensity of light passing through a particle whereas *Intensity standard deviation* measures the range of light intensity that passes through a particular particle (Fig. 10).

Table 5. Various shape parameters used in ash morphology studies along with the mathematical formula, sensitivity, and alternative names (table modified from Leibrandt and Le Pennec, 2015 and Liu et al., 2015).

Shape Parameter	Abbreviation	Formula	Symbols	Sensitivity	Alternative Names
Aspect Ratio	AR	$\frac{W_b}{L_b}$	Wb: Width (μm) Lb: Length (μm)	Form	Aspect ratio Ellipse aspect ratio Ellipticity
Elongation	E	1-AR	AR: Aspect ratio	Form	N/A
Convexity ^a	CVX	$\frac{P_{ch}}{P}$	Pch: Circle equivalent perimeter (μm) P: Perimeter (μm)	Textural roughness	Roughness
Circularity	Cc	$\frac{2\sqrt{\pi A}}{P} \quad \frac{P_{ce}}{P}$	A: Area (μm^2) P: Perimeter (μm) Pce: Circle equivalent perimeter	Form & roughness	Shape factor Particle irregularity
HS Circularity	HCc	$\frac{4\pi A}{P^2}$	A: Area (μm^2) P: Perimeter (μm)	Form & roughness	Form factor Sphericity Roundness
Solidity ^a	SLD	$\frac{A}{A_{ch}}$	A: Area (μm^2) Ach: Circle equivalent area (μm^2)	Morphological roughness	N/A

^aDenotes shape parameter used in this study

Figure 9. Plot showing examples of *convexity* and *solidity* for several primary volcaniclasts from subsample *D522-PC62L_27.0 (HMT)*. **(A)** Basic metrics and calculations of convexity and solidity. See Table. 9 for definitions and abbreviations. Modified from Leibbrandt and Le Pennec (2015) **(B)** Plot showing examples of particles with differing values of *solidity* (x-axis) and *convexity* (y-axis). Refer to Table 5 for mathematical definitions of *solidity* and *convexity*.

Figure 10. Plot showing examples of particles with differing values of *intensity standard deviation* (x-axis) and *intensity mean* (y-axis). Particles are primary volcaniclasts from subsample *D522-PC62L_27.0* (HMT).

Data Visualization

Convexity frequency distribution curves were used to show variations in *convexity* between different subsamples. Additionally, plots of individual particles using traditional plots of *solidity* vs. *convexity* (SLD vs. CVX), argued to be useful for comparing ash morphologies (Liu et al., 2015), were implemented into this study to compare Axial Seamount subsamples with other known eruptions. Plots of *intensity standard deviation* value on the x-axis and *intensity mean* on the y-axis, a new method that has not been used in ash morphology studies, were used to evaluate proportions of fluidal and non-fluidal vitriclasts. We henceforth use the term "Int. STD vs. Int. M" to describe these plots.

Int. STD vs. Int. M plots were created to estimate and compare the relative abundance of free crystals (e.g. plagioclase), fluidal vitriclasts (limu o' Pele), and angular / blocky vitriclasts, to other subsamples. To create known fields of particle morphologies (fluidal, angular / blocky, and crystals), 100 representative particles of each field from four different subsamples were selected by hand to ensure correct identification. Fields were manually drawn around the spread of representative points (Fig. 11). While there is some overlap in vitriclasts and crystals fields, this method works well for differentiating limu o' Pele, which is the dominant style of fluidal vitriclasts in subsamples from Axial Seamount.

To test the reliability of using Int. STD vs. Int. M fields to determine abundance of fluidal particles, five subsamples used in the MGS method were also point counted using 300 grains / subsample. During these point counts,

three categories were counted: *angular / blocky vitriclasts*, *fluidal vitriclasts*, and *other*. Particles that were not vitriclasts (e.g. plagioclase, crystalline basalt) were counted in the “other” category. Fluidal particles were calculated as a percent.

Figure 11. Plot of Intensity standard deviation vs. intensity mean. One-hundred known particles of fluidal vitriclasts (**blue**), angular/blocky vitriclasts (**grey**), and crystals (**orange**) were plotted. Representative particles, with corresponding colored outlines, and their locations on the plot are shown. Fields were drawn around particles to create particle population fields (shaded regions).

To calculate the percentage of fluidal particles using the MGS method, points falling in the “fluidal” field were manually counted and divided by the total number of particles scanned. Fluidal particles from both methods were consistent with the largest variation between the MGS and point counting method being less than 3% of the total particles (Table. 6). Although there is some overlap in particle morphology fields, particularly between angular / blocky vitriclasts and crystals, the MGS method works well for differentiating limu o’ Pele, which is the dominant style of fluidal vitriclasts in subsamples from Axial Seamount.

Table 6. Particle morphometry results comparison using MGS method and traditional point count.

Sub-sample	Fluidal Particles (MGS)	Total Particles (MGS)	Percent Fluidal (MGS)	Percent Fluidal (Point Counts)	Percent Difference
D522-PC62L_15.0	80	1385	5.78%	4.00%	1.78%
D522-PC62L_27.0	228	2077	10.98%	11.30%	0.32%
D524-PC47XL_27.0	211	2118	9.96%	11.00%	1.04%
D876-PC75_21.0	115	1772	6.49%	4.30%	2.19
D878-PC75_15.0	526	1862	28.25%	28.00%	0.25%

Point Density Plots Using ArcGIS

Particle parameter data from MGS scans was exported from “Morphologi” software. To express the high number of data points (single grain analyses) for any individual subsample scan, point density plots were created using both SLD vs. CVX and Int. STD vs. Int. M plots to express the 68.2% (1 σ) and 95.4% (2 σ)

confidence field of all data points. Depending on the type of plot, specific parameters (e.g. CVX, SLD) were selected, and imported into ArcGIS, and plotted as a spatial point dataset (vector data). Spatial analyst toolbox, in ArcGIS, was used to create a point density raster of each dataset. The “neighborhood” setting was set with a radius that covered the most continuous and representative field of input data points. The radius of the “neighborhood” setting depends on the standard deviation of the input data. After testing various radii (Fig. 12), a radius of 18 (cell units) was selected for SLD vs. CVX plots, and a radius of 20 was used for Int. STD vs. Int. M plots. These settings were chosen because they were found to most accurately represent the data compared to higher and lower settings.

Once the point density fields were created, they were re-classified to display 3 regions (1σ , 2σ , and $>2\sigma$) using break percentages of points. These segments were set to 100, 31.8, and 4.6, thus creating 3 fields containing 68.2% (1σ); 95.4% (2σ); and 100% of data points. The classifications were colored to display the 1σ field as a dark color, the 2σ field as a light color, and $>2\sigma$ was displayed as no data. Therefore, the shaded boundary contains 95.4% (2σ) of data points. Using these steps, point density plots of MGS data were displayed as fields of 1σ , and 2σ . Density plots were created for both SLD vs. CVX plots (Fig. 13) and Int. SD vs. Int. M plots (Fig. 14).

Figure 12. Plots comparing point density radii settings. Plots of *intensity standard deviation* vs. *intensity mean* (left) and *solidity* vs. *convexity* for subsample *D522-PC62L_27.0 (HMT)*. Red points are individual particles whereas colored fields represent point density plots. Darker field represents 68.2% (1σ) of points while lighter colored field represents 95.4% (2σ) of data points. Points falling outside of shaded regions are $>2\sigma$ and are considered outliers. Top plots show point density plots with a radius = 2. Middle plots show point density plot with radii = 20 and 18 for intensity standard deviation vs. intensity mean and *solidity* vs. *convexity* plots, respectively. Bottom plots show a radius=38.

Figure 13. *Solidity* vs. *convexity* point density plot of subsample *D522-PC62L_27.0* (HMT) showing data points (**orange**). Data density fields are shown in green where the **dark green** field represents 1σ (68.2% of all data points) and the **light green** field represents 2σ (95.4% of all data points). Representative particle images and plot locations are shown.

Figure 14. *Intensity standard deviation vs. intensity mean* point density plot of subsample *D522-PC62L_27.0* (HMT) showing data points (orange) and data density fields are shown in green where the **dark green** field represents 1σ (68.2% of all data points) and the **light green** field represents 2σ (95.4% of all data points). Morphology fields (fluidal, crystals, and angular) are represented by colored dashed fields (**blue = fluidal**; **orange = crystals**; **grey = angular**). Representative particle images are bordered with their respective morphology color and their location on the plot is shown.

RESULTS

Core Descriptions

Visual observations of 25 cores were described and build on those reported by Portner et al. (2015). Modified lithofacies descriptions based on cores observed in this study are summarized in Table 1. General observations reveal that the individual beds of LPT and HMT are normal graded (coarser material near the bottom fining upwards) whereas TM is structureless. This is true regardless of whether other lithofacies are present, or proximity of the core to caldera margins. Foraminifera are found in TO, LPT (in rip-up clasts of TO), and TM, but are notably absent in HMT. Bioturbation is common within all lithofacies except LPT, which sometimes distorts boundaries and / or structures. Although characteristics are variable from core to core, general descriptions and overall trends of each lithofacies are outlined below, with an emphasis placed on HMT. Figure 15 shows representative cores and associated characteristics from proximal, medial, and distal locations. Individual core descriptions are presented in Appendix A. Core logs were created using sedimentologic descriptions and geophysical properties measured from the cores (Appendix B).

Tuffaceous Mud (TM)

Tuffaceous mud (TM) is composed of orange / brown mud with fine ash – medium lapilli-sized vitriclasts and is poorly sorted. Visually estimated modal percentage of ash ranges from 10 – 45%, making this unit mud-matrix supported. Vitriclasts consist of a mixture of both fluidal and angular / blocky shards, with

Figure 15. Figure showing representative proximal, medial, and distal cores accompanied by identified lithofacies, sedimentary structures, magnetic susceptibility, grain-size, and point count results. For grain-size, red circles represent sampling points while black line show trends. Point counts are shown at sampling depths to show relative abundance of components (blue = primary volcaniclasts; red = non-primary volcaniclasts; green = authigenic hydrothermal minerals). **(A)** Proximal core D522-PC62L. **(B)** Medial core D522-PC66. **(C)** Distal core D878-PC53. Core images enhanced for better contrast.

fluidal vitriclasts being more common in laminations. Beds are generally structureless, but variably contain diffuse laminations of concentrated vitriclasts and / or laminated mud where ash is absent. Vitriclasts are predominantly fresh / clean, but some altered Fe-oxide coated shards are present. Other components present in low abundance include biogenics, free crystals (e.g. plagioclase), and red / orange Fe-oxide particles. Overall color was described as either moderate brown (5YR 5/6) or moderate yellowish brown (10YR 5/4).

Hydrothermal Muddy Tuff (HMT)

Hydrothermal muddy tuff (HMT) is composed of intermixed fluidal to angular / blocky vitriclasts, free crystals (plagioclase, olivine, pyritic fragments), crystalline basalt / diabase, altered oceanic crust fragments (e.g. actinolite / tremolite), the sulfide mineral pyrite, and clay aggregates. Beds are generally are generally fine to very fine grained. Clay aggregates comprise most of the fine-grained mud within the unit along with sulfides, namely pyrite. Visually estimated modal ash percent ranges from ~10 - 60%. Several proximal (<100 m from caldera margins) and medial (100 – 1,000 m) cores containing HMT tend to have a higher visually estimated modal ash abundance near the bottom and top of lithofacies.

Laminations (both well-developed and diffuse) are common, range in thickness from ~1 mm – 10 mm and generally consist of medium- to coarse-grained fluidal ash. Well-developed laminations are common in proximal and some medial cores. Distinct laminations within distal cores (>1,000 m) are less prevalent. Diffuse ash laminations are present in medial (Fig. 15B) and some

distal cores (Fig. 15C). Many laminae exhibit “reverse-to-normal graded” grain-size distributions (Fig. 15A). A distinct “pale green” lamination observed near the top of HMT exists in 10 of the described cores, all of which are either proximal or medial, and often marks the boundary of HMT and overlying TM. Overall color of the HMT is light olive grey (5Y 5/2). Geophysical characteristics show that HMT has high magnetic susceptibility compared to other lithofacies due to abundance of magnetic material (Fig. 15).

Limu o’ Pele Tuff (LPT)

Limu o’ Pele tuff (LPT) is primarily composed of fresh glass shards (>90%) with the remaining constituents consisting of plagioclase, olivine, phyric glass, and crystalline basalt / diabase. Vitriclast morphology is a mix of angular / blocky and fluidal. Angular / blocky grains tend to occur near the base of the lithofacies while fluidal shards are more common near the top. Grain-size ranges from coarse ash to medium lapilli and the beds are normal graded. LPT is normal graded and also generally grades from abundant angular / blocky vitriclasts near the bottom of the lithofacies to fluidal vitriclasts in the top of the lithofacies. Rip-up clasts from underlying muddy units are sometimes present. Geophysical characteristics of LPT show it has generally higher density compared to other lithofacies due to the predominance of glass particles and lack of silt / clay.

Tuffaceous Ooze (TO)

Tuffaceous ooze (TO) is comprised of >90% foraminifera mixed with small abundances of orange / brown mud and fine – medium ash that is predominantly

angular / blocky. Larger fluidal vitriclasts (medium – coarse ash) are sometimes present. This lithofacies is structureless and highly bioturbated.

Lithostratigraphy

Vertical Stratigraphic Sequence

A lithostratigraphic sequence is consistently observed throughout cores on Axial Seamount (Fig. 16). Age constraints have been placed on the current lithostratigraphy using ^{14}C chrono-stratigraphy from foraminifera (Clague et al., 2013; Portner et al. 2015; and unpublished data). Lithostratigraphy on Axial Seamount is complimented by vitriclast MgO variability from subsamples where 15 vitriclasts per a 2 cm thick slice of core were analyzed (Clague et al., 2013; B. Johnson pers. Comm.).

The top (youngest) of the stratigraphic sequence begins with TM (<800 ka), which overlies HMT, and is present at the top of all described cores. HMT (900 – 1,200 ka) overlies LPT lithofacies and was present in all summit cores except the furthest core from the caldera (*D878-PC62*; >3.5 km from caldera margin). LPT (1,200 – 1,500 ka) sits beneath, or within the lower portion of HMT (or TM if HMT is absent) and was absent in 8 summit cores that contained HMT (e.g. HMT was the basal unit). TO (> 1,500 ka) lies beneath the LPT lithofacies. The upper portion of this facies invariably shows increasing modal percentage of ash grading into the overlying LPT. Presence of TO is atypical near the caldera and was only observed in 5 of the 23 described cores (primarily distal cores).

Figure 16. Regional stratigraphy found on Axial Seamount. **(A)** Image taken from ROV looking towards a fissure **(B)** Image taken by ROV's showing the wall of fissure in (A) showing TM, HMT, and LPT lithofacies. Vertical yellow line is 30 cm. **(C)** Image of core D516-PC61XL, which was retrieved in the vicinity of image B, accompanied by visually described lithofacies. **(D)** table showing general regional stratigraphy correlated with ^{14}C chrono-stratigraphy and MgO chemo-stratigraphy. Bold MgO indicates a period of more primitive lava chemistry.

Lateral Stratigraphic Sequence

A clear lithostratigraphic association between the caldera margin and HMT lithofacies exists. Thickness observations of all lithofacies (Fig. 17) along the offset transect reveal variations in thickness associated with caldera margins. Results show greater HMT thickness near caldera margins (Fig. 18), which thins away as distance increases and overall thickness of HMT is asymmetric with regards to the caldera. The southeast side of the caldera rim, also the location of active fissures (Clague et al., 2013; Dryer et al., 2013), contains thicker sections of HMT while the northwest side is considerably less thick (Fig. 19). HMT laterally extends further on the southeast (>3.4 km) compared to the northwest (1.5 km) side of the caldera rim and tends to follow contours of seafloor bathymetry.

Results of LPT are similar to that of HMT where the lithofacies is thicker near caldera margins in proximal cores and thin as distance away from the caldera increases. Conversely, TO is notably absent near caldera margins and only appears in distal cores more than 3.1 km away from the caldera. TM thickness remains consistent, or only slightly increases, with increasing distance away from the caldera. TM is the only facies observed on the caldera floor where sediment is entirely all younger than 800 kyr and <25 cm thick (Clague et al. 2013).

Figure 17. Select cores along offset-transect (including distance from caldera) and thicknesses of TM (orange field), HMT (green field), LPT (grey field), and TO (yellow field). HMT and LPT noticeably thins with increasing distance from caldera margin.

Figure 18. HMT thickness profile along offset transect. Thick black line shows profile of seafloor in meters below seafloor (no vertical exaggeration). Thick green line shows HMT thickness along the seafloor (vertically exaggerated 1000 times for clarity). Locations of cores are represented by circles with color corresponding to the dive number.

Figure 19. Isopach map showing thickness of HMT present around Axial Seamount. Thickness is based on described cores (white circles) with inferred isopach bounding lines. Thick black line outlines the caldera. Note that HMT is considerably thicker on the east side of the caldera and extends further away from the caldera towards the southeast. Caldera rim and fissures were drawn in by colleagues at MBARI pers. Comm.

Granulometry

Grain-size analysis focused on HMT lithofacies, but several subsamples within TM and LPT, and an off-summit subsample (TO) were also analyzed for comparison. Results are consistent with the overall grain-size trends observed qualitatively in the core descriptions (above). All three lithofacies are notably coarser than the off-summit (TO) subsample analyzed for “background sedimentation”. HMT contains the finest mean grain-size and peak mode compared to TM and LPT, while LPT is significantly coarser than TM and HMT (Fig. 20A). Further grain-size analysis within HMT reveals some variability based on proximity of a core to the caldera, and depth within a core (Fig. 20B). Distal cores generally consist of finer grain-sizes in the top of the lithofacies whereas proximal cores have greater variability. Average peak modes in the bottom and middle of subsamples from distal HMT cores are slightly coarser than proximal and medial cores. This is consistent with core observations where proximal and medial cores have distinct laminations (which presumably constrains coarse material) whereas distal cores lack distinct laminations resulting in a dispersal of coarse material throughout the entire lithofacies.

No notable distinction in sorting, skewness (peak symmetry) or kurtosis (peak sharpness) could be discerned between HMT and TM. All subsamples were *poorly sorted* or *very poorly sorted* and either *symmetrical*, *fine skewed* or *very fine skewed*. Kurtosis was variable and included leptokurtic, mesokurtic, and platykurtic. Results are presented in Tables 7 and 8 and summarized below.

Figure 20. Graph showing variation in the range and mean grain-size. **(A)** Range of grain-size for subsamples analyzed from different lithofacies (**Orange = TM**; **Green = HMT**; **Grey = LPT**). Vertical red line represents mean grain-size of all subsamples. **(B)** Range and mean of grain-size for all subsamples analyzed from HMT. Subsamples are separated by proximity to the caldera, and whether the subsample was retrieved from the top, middle, or bottom of HMT.

Table 7. Results of PSA and analysis based on identified lithofacies.

Litho-facies	# Sub-samples	Average Peak Mode (μm)	Modal Distribution			Skewness				Kurtosis			Sorting				
			Unimodal	Bimodal	Trimodal	Coarse skewed	Symmetrical	Fine skewed	Very Fine skewed	Mesokurtic	Leptokurtic	Platykurtic	Very well sorted	Moderately well sorted	Moderately sorted	Poorly sorted	Very poorly sorted
TM	11	335	3 (27%)	5 (46%)	3 (27%)	0 (0%)	2 (18%)	5 (46%)	4 (36%)	2 (18%)	7 (64%)	2 (18%)	0 (0%)	0 (0%)	1 (8%)	5 (46%)	5 (46%)
HMT	54	100	46 (83%)	8 (15%)	1 (2%)	0 (0%)	2 (4%)	39 (71%)	14 (25%)	16 (29%)	36 (66%)	3 (5%)	0 (0%)	0 (0%)	0 (0%)	34 (63%)	20 (37%)
LPT	12	831	11 (92%)	1 (8%)	0 (0%)	0 (0%)	4 (33%)	3 (25%)	5 (42%)	1 (8%)	5 (42%)	6 (50%)	2 (17%)	1 (8%)	4 (33%)	5 (42%)	0 (0%)

Table 8. Results of HMT PSA analysis based on proximity to the caldera.

HMT Proximity	# Sub-samples	Average Peak Mode (μm)	Modal Distribution			Skewness				Kurtosis			Sorting	
			Unimodal	Bimodal	Trimodal	Coarse skewed	Symmetrical	Fine skewed	Very fine skewed	Mesokurtic	Leptokurtic	Platykurtic	Poorly sorted	Very poorly sorted
Proximal	34	98	30 (88%)	3 (9%)	1 (3%)	0 (0%)	2 (5%)	19 (56%)	13 (39%)	24 (71%)	8 (24%)	2 (5%)	21 (62%)	13 (38%)
Medial	9	97	6 (66%)	3 (33%)	0 (0%)	0 (0%)	0 (0%)	5 (56%)	4 (44%)	3 (33%)	5 (56%)	1 (11%)	5 (56%)	4 (44%)
Distal	11	107	9 (82%)	2 (18%)	0 (0%)	0 (0%)	0 (0%)	9 (82%)	2 (18%)	4 (36%)	7 (64%)	0 (0%)	8 (73%)	3 (27%)

Summit Lithofacies

Grain-size analysis reveals distinct differences in grain-size metrics between each lithofacies. TM is highly variable with peak mode ranging from 30 μm – 1,500 μm (5.1 ϕ – -1.5 ϕ) with the average falling near 446 μm (1.1 ϕ ; Fig. 21A). TM grain-size generally decreases with increasing distance away from the caldera which is consistent with core description observations where higher modal percent of coarse ash is more abundant in proximal cores. HMT is generally fine grained with peak modes ranging from about 30 – 170 μm (5.1 – 2.56 ϕ) and the average falling near 100 μm (3.3 ϕ ; Fig. 21B). HMT grain-size tends to be more variable in proximal cores due to the presence of more well-defined ash laminations, and more homogenous in distal cores. LPT is much coarser grained than TM and HMT with peak modes ranging from approximately 300 μm to >2000 μm (1.75 ϕ – -1.0 ϕ ; coarse ash) and the average falling near 875 μm (0.19 ϕ ; Fig. 21C). Greater range of LPT grain-size is present in proximal cores and is well to moderately-well sorted for any individual subsample.

Off-Summit

In addition to grain-size analysis of each lithofacies, the off-ridge core *D881-PC72L* (approximately 42 km S. of the caldera) was subsampled and analyzed for "ambient sedimentation" and is considered to be from TO lithofacies. Grain-size analysis results reveal ambient sedimentation is significantly finer-grained than that of average TM, HMT, and LPT subsamples.

Figure 21. Grain-size distributions analyzed from different lithofacies. Dashed purple line represents “background sedimentation” from off-summit core D881-PC72L (TO) approximately 42 km S. of the caldera. **(A)** Grain-size distributions from TM lithofacies. **(B)** Grain-size distributions from HMT lithofacies. **(C)** Grain-size distributions from LPT lithofacies.

Componentry

Visual Observations

Three major components were visually identified within HMT including primary volcaniclasts, non-primary volcaniclasts, and authigenic hydrothermal minerals (Table 4). Primary volcaniclasts include vitriclasts, ranging from unaltered (fresh basalt glass) to slightly altered (<20% altered by visual estimation). Vitriclasts are predominantly angular / blocky (Fig. 2A), but fluidal vitriclasts are also present (Fig. 2B). For further information regarding vitriclasts, see *morphology* below. Primary volcaniclasts also include free crystals (plagioclase and olivine) and phyric glass shards. Non-primary volcaniclasts (Fig. 2C-1 – 11) include oceanic crust (unaltered or altered) fragments: crystalline basalt / diabase, green blocky? (pyroxene?), green fibrous (actinolite?), white fibrous (tremolite?), white zeolites (?), red particles (iddingsite?), and moderately to completely altered vitriclasts, which are identified by a coating of various colors. Authigenic hydrothermal minerals (Fig. 2C-6 and C7) are made up of green / yellow clay aggregates and yellow hydrothermal sulfides (e.g. pyrite). Vitric “agglutinate” particles are unique in that sideromelane (basalt glass) has presumably stretched and coated hydrothermal clay aggregates and may be considered both primary and authigenic in origin.

Point Counts

Representative HMT subsample *D522-PC62L 46.5* shows that finer size fractions have considerably less primary volcaniclasts than the coarser size

fraction (42% vs. 79%, respectively), which considerably less non-primary volcanoclasts and authigenic hydrothermal minerals. Abundance of non-primary volcanoclasts increase from 16% in the coarser size-fraction to 30% in the finer size-fraction while authigenic hydrothermal minerals increase from 5% to 21%. Results of the 125 – 250 μm size-fraction are similar to the coarse size-fraction (250 – 500 μm). In addition to differences in the three major components, vitriclast morphology also varies with grain-size (Fig. 22B). Fluidal shards make up more than 12% of all vitriclasts in the 250 – 500 μm size fraction whereas the 63 – 125 μm size fraction contains only 4.25%.

Results of 27 representative subsamples in the 125 – 250 μm size fraction from HMT are presented in Table 9 and plotted on a ternary diagram (Fig. 23A). An average of all 27 subsamples reveal that primary volcanoclasts are the most abundant (70%), non-primary volcanoclasts make up 24%, and authigenic hydrothermal minerals are the least abundant (6%). Abundance of authigenic hydrothermal minerals shows little variation (2% to 13%). Conversely, primary and non-primary volcanoclasts are more variable (56% to 81% vs. 15% to 34%, respectively).

To further investigate primary vs. non-primary volcanoclast variability, subsamples were separated and re-plotted based on subsample characteristics including depth within HMT lithofacies, proximity of core in relation to the caldera, and subsample mean grain-size (Fig. 23B – D). No relation exists between componentry and proximity to caldera, depth within HMT, or subsample mean

grain-size, implying that HMT componentry of the 125 – 250 μm size fraction is relatively homogenous.

Figure 22. Point count ternary plots of HMT. **(A)** Results of various grain-size fractions ($n=500$) from subsample *D522-PC62L 46.5* (Fig. 15). Decrease in grain-size results in a decrease in primary volcaniclast abundance. However, primary volcaniclasts are still prevalent ($>40\%$) in fine grain-size fractions. **(B)** Bar charts show percent of fluidal vs. angular/blocky vitriclasts. Coarser size-fractions are more abundant in fluidal shards whereas the fine size-fraction contain more angular/blocky vitriclasts.

Table 9. Results of point counts (n=500) in the 125 – 250 µm size fraction of HMT.

Subsample	Primary Volcaniclasts							Non-Primary Volcaniclasts								Authigenic Hydrothermal Minerals				Total (%)			
	Angular	Fluidal	Vesicular (Angular)	Vesicular (Fluidal)	Plagioclase	Olivine	Phyric	Altered Glass (Fluidal)	Altered Glass (Angular)	Crystalline Basalt	Spherulitic	Red/Orange Particle	Green Other	White Other	Green Fibrous	White Fibrous	Green Aggregates	Yellow Aggregates	Pure Sulfides	Agglutinate	Primary Volcaniclasts	Non-Primary Particle	Authigenic Hydrothermal minerals
D522-PC62L_13.0	286	7	0	0	59	2	9	0	33	38	4	10	3	22	0	0	1	24	2	0	72.60	22.00	5.40
D522-PC62L_15.0	238	12	0	0	41	3	13	1	85	43	0	8	9	21	0	0	6	26	0	2	60.43	32.87	6.69
D522-PC62L_23.0	191	4	0	0	68	3	15	0	94	35	1	8	16	16	0	2	7	38	1	1	56.20	34.40	9.40
D522-PC62L_28.0	307	11	1	0	48	0	4	0	58	23	5	5	2	16	0	0	1	17	2	0	74.20	21.80	4.00
D522-PC62L_37.5	263	12	1	0	40	5	12	67	0	33	4	6	5	20	0	1	3	25	3	0	66.60	27.20	6.20
D522-PC62L_41.0	281	10	0	0	51	4	21	0	55	44	5	9	0	8	0	0	0	11	1	0	73.40	24.20	2.40
D522-PC62L_46.5	316	15	0	0	21	0	9	1	45	20	0	11	1	19	0	0	0	41	1	0	72.20	19.40	8.40
D522-PC66_8.0	313	39	0	1	36	0	5	2	39	28	1	5	4	8	0	2	3	14	0	0	78.80	17.80	3.40
D522-PC66_12.0	242	3	1	0	48	2	4	0	77	29	0	14	3	16	0	0	5	53	0	3	60.00	27.80	12.20
D522-PC66_15.5	179	15	0	0	18	0	2	7	159	20	4	9	1	17	0	0	3	65	0	1	42.80	43.40	13.80
D522-PC66_19.0	267	31	1	0	63	4	4	1	52	35	0	4	4	15	0	1	4	11	0	3	74.00	22.40	3.60
D524-PC47XL_27.0	248	30	0	0	32	3	9	2	76	39	1	6	7	18	0	0	8	17	0	4	64.40	29.80	5.80
D525-PPC2_23.0	275	23	0	0	28	2	7	0	68	39	0	8	9	12	0	2	5	20	1	1	67.00	27.60	5.40
D525-PPC2_29.5	282	24	0	0	21	6	8	0	89	25	1	3	7	11	0	0	4	18	1	0	68.20	27.20	4.60
D655-PPC67_13.5	270	14	2	0	37	4	7	0	61	25	3	10	8	22	0	0	2	34	0	1	66.80	25.80	7.40
D655-PPC79_17.5	254	50	0	0	49	4	14	0	42	27	4	8	7	16	0	1	2	18	2	2	74.20	21.00	4.80
D655-PPC79_23.0	294	45	0	0	53	2	12	0	28	26	1	4	4	10	1	0	3	12	1	4	81.20	14.80	4.00
D655-PPC79_26.0	332	40	0	0	16	1	9	0	28	28	0	5	1	20	0	0	2	17	0	1	79.60	16.40	4.00
D876-PC75_18.0	282	41	0	0	52	13	6	1	46	27	4	2	3	2	0	0	7	14	0	0	78.80	17.00	4.20
D878-PC53_8.0	235	20	0	0	27	1	12	1	83	18	0	11	11	14	0	0	3	61	0	3	59.00	27.60	13.40
D878-PC53_10.0	251	20	0	0	45	1	12	0	63	12	0	12	6	26	0	1	4	44	0	3	65.80	24.00	10.20
D878-PC53_12.0	269	16	0	0	64	5	15	0	45	22	0	9	6	10	0	0	7	28	0	4	73.80	18.40	7.80
D878-PC53_14.0	264	18	0	1	33	2	1	3	80	35	0	5	7	21	0	1	5	24	0	0	63.80	30.40	5.80
D878-PC53_16.0	263	12	0	3	20	0	1	2	114	12	3	8	4	16	0	1	1	39	0	1	59.80	32.00	8.20
D878-PC53_18.0	289	26	0	2	41	3	3	4	60	29	1	5	2	13	0	0	4	15	0	3	72.80	22.80	4.40
D878-PC75_15.0	257	59	0	0	31	5	5	1	63	40	0	2	8	16	0	1	1	11	0	0	71.40	26.20	2.40
D878-PC75_17.0	281	42	0	0	33	1	4	0	54	35	0	13	2	12	0	1	0	21	0	1	72.20	23.40	4.40
Average	268	24	0	0	40	3	8	3	63	29	2	7	5	15	0	1	3	27	1	1	68.52	25.10	6.38

Figure 23. **(A)** Results of point counts from 27 subsamples ($n=500$) in the 125 – 250 μm size-fraction of HMT. Individual subsamples are shown by a blue “X” and an average of all subsamples is denoted by a red diamond. **(B)** Plot of subsamples based on proximity of core to the caldera (proximal = <100 m; medial = 100 – 1,000 m; distal = >1,000 m). **(C)** Plot of subsamples segregated by relative depth within HMT (top, middle or bottom of lithofacies). **(D)** Plot of subsamples based on subsample mean grain-size.

XRD

“Bulk” XRD Analysis

X-ray diffraction of 10 “bulk” subsamples from HMT and TM lithofacies were analyzed. Major peaks and intensities of each subsample were similar regardless of lithofacies (Fig. 24). Some minor differences are observed specifically in the “pale green” lamination observed near the top of HMT (subsample *D522-PPC1 9.0*) which shows a distinct peak near 9.48 Å that is absent in other subsamples, and a single peak near 2.517 whereas other subsamples have a “doublet” peak near 2.567 / 2.517 Å.

Identified unaltered volcanic minerals include amphibole (hornblende), Mg-rich pyroxene (augite, enstatite, diopside), plagioclase (anorthite), and olivine. Minerals identified that are typical of altered oceanic crust include amphibole (actinolite, tremolite), chlorite, epidote, and plagioclase (albite), zeolites (heulandite and laumontite) and clay minerals (see *clay mineral identification*). Additional minerals typical of deep-sea hydrothermal systems include quartz and pyrite. Table 10 summarizes major peaks and associated minerals. Minor mineral components are difficult to resolve due to overwhelmingly large abundances of aforementioned minerals.

Figure 24. X-ray diffractogram of representative glass-separated "bulk" subsamples *D522-PC62L_7.0* (TM), *D522-PPC1_9.0* (HMT pale green lamination), and *D522-PC62L_21.5* (HMT). Major peaks are labeled with d-spacing (Å) and with identified primary mineral(s). Mineral identification is summarized in Table. 10. Minerals are indicated by the following abbreviations: Am: Amphibole (actinolite, tremolite, hornblende); Ch: Chlorite; E: Epidote; O: Olivine; P: Plagioclase (anorthite, albite); Pr: Pyrite; Pyx: Pyroxene (diopside, augite); Q: Quartz; Sm: Smectite; Z: Zeolite (heulandite, laumontite).

Table 10. Summary of major identified XRD peaks and associated mineral(s).

d-spacing (Å)	Minerals	d-spacing (Å)	Minerals
14.100	Smectite	2.900	Pyroxene + Epidote
9.480	Zeolite	2.845	Olivine + Plagioclase
7.120	Zeolite	2.700	Pyrite + Epidote
6.460	Chlorite	2.567	Olivine + Pyroxene
4.560	Chlorite	2.517	Olivine
4.038	Plagioclase	2.235	Pyroxene
3.903	Plagioclase + Zeolite	2.139	Pyroxene
3.751	Plagioclase	2.037	Pyroxene + Chlorite
3.638	Plagioclase	1.885	Pyrite
3.560	Chlorite	1.834	Quartz
3.341	Quartz	1.765	Plagioclase
3.210	Pyroxene + Plagioclase	1.682	Pyroxene + Pyrite
3.180	Plagioclase	1.537	Smectite + Chlorite
3.110	Amphibole + Plagioclase	1.490	Smectite
2.996	Pyroxene + Plagioclase	1.414	Pyroxene
2.935	Pyroxene + Plagioclase + Zeolite	1.372	Quartz

Clay Mineral Identification

Four “bulk” XRD subsamples were analyzed for clay mineralogy: *D522-PC62L 21.5* is a proximal HMT subsample, *D522-PPC1 9.0* is a proximal subsample retrieved from the “pale green” lamination near the top of the HMT lithofacies, *D655-PPC79 20.0* is a medial HMT subsample, *D878-PC53 12.0* is a distal HMT subsample (Fig. 25). Refer to Figure 3 for core locations and Appendix B for subsample depth. Results of clay peaks observed in each subsample throughout the clay XRD treatment process are summarized in Table 11. The primary clay components include smectite, chlorite and interlayered smectite / chlorite.

Figure 25. XRD diffractograms of four <2 um subsamples of HMT analyzed for clay mineralogy. Various treatments of subsamples are shown (Blue: untreated; Green: glycolated; Purple: heat treated to 400 °C; Red: heat treated to 550 °C). Changes in XRD diffractograms are used to infer clay species and summarized in Table 11. Subsamples *D522-PC62L_21.5*, *D655PPC79_20.0*, and *D878-PC53_12.0* all have nearly identical patterns while *D522-PPC1_9.0* (pale green lamination) is notably different. Identified clay minerals are indicated by the following abbreviations: Am: Amphibole; Ch: Chlorite; Cor: Corrensite; P: Plagioclase; Pyx: Pyroxene; Sm: Smectite; Z: Zeolite.

Table 11. Flow table showing results of clay XRD treatment scans of <2 µm oriented clay subsamples. Numerical value represents major peak (Å). Arrows show peak changes after treatment. Peak expansion or collapse is represented by crossing arrows. Clay proportions modeled using NEWMOD are shown.

Subsample	Untreated	Glycolated	Heat Treatment (400 C)	Heat Treatment (550 C)	Identified Clays	NEWMOD Proportions (%)
D522-PC62L_21.5	29 → 16 → 14 → 7 →	30 → 17 → 14.4 → 7 →	27 → 14.4 → 10 → 7 →	29 → 14.4 → 10 → 7 →	Corrensite Chlorite Saponite/ Nontronite Chlorite	Corrensite: 21 Chlorite: 33 Smectite: 31/15 (Tri/Di)
D525-PPC1_9.0	29 → 17 → 14 → 7 →	29 → 17 → 14.4 → 7 →	27 → 14.4 → 10 → 7 →	29 → 14.4 → 10 → 7 →	Corrensite Chlorite Saponite/ Nontronite Chlorite	Corrensite: 23 Chlorite: 57 Smectite: 20/0 (Tri/Di)
D655-PPC79_20.0	29 → 17 → 7 →	30 → 17 → 7 →	27 → 14.4 → 10 → 7 →	29 → 14.4 → 10 → 7 →	Corrensite Chlorite Saponite/ Nontronite Chlorite	
D878-PC53_12.0	29 → 17 → 7 →	29 → 17 → 7 →	27 → 14.4 → 10 → 7 →	27 → 14.4 → 10 → 7 →	Corrensite Chlorite Saponite/ Nontronite Chlorite	

Discrete smectites are identifiable by the 14 Å untreated peak expanding to 17 Å after glycolation. Heat treatment results in a collapse to about 9.5 Å, which is consistent with nontronite. Additionally, the untreated 17 Å peak which is unchanged after glycolation, and collapses to about 9.5 Å. Although untreated subsamples containing smectites generally have a 001 peak at 14 Å, low-charge Fe²⁺ coordinated saponite has been described to have a 17 Å peak (Yeniol, 2007). This 17 Å peak is inferred to collapse to 10 Å after heat treatments. Identified smectite clays include nontronite and saponite.

Corrensite, a perfect 50 / 50 interlayering of smectite and chlorite, is identified by a peak located at about 29 Å for untreated scans. After glycolation, this peak remains unchanged, or expands only slightly to about 30 Å. Heat treatments at 400 °C and 550 °C result in a slight collapse to about 27 Å. Although the pattern of expansion to 30 Å and collapse to 27 Å is not a common pattern, it is consistent with corrensite as observed by Beaufort and Meunier, 1994. Additional peaks are attributed to other minerals (e.g. plagioclase, quartz, zeolites, pyroxene, amphibole). The peak near 9.34 Å is dominant in subsample *D522-PPC1 9.0*, but much smaller in the other subsamples, and is consistent with the zeolite laumontite. Other differences in peak locations and intensities between subsamples may be explained by different clay mixture proportions.

Identification of discrete chlorite is based on two peak evaluations. Untreated scans show peaks near 14 Å and 7 Å, which remain unchanged throughout the treatment process. Peak intensity does vary during heat treatments, which is

consistent with Fe^{2+} -bearing chlorite which tends to give a weaker 14 Å peak (Brindley, 1952).

XRD scans of <2µm powdered size fraction to evaluate the 060 reflection indicates dominance of tri-octahedral clays as evident by the peak near 1.536 Å (Fig. 26). The minor peak near 1.490 Å may indicate small proportions of di-octahedral clays. Based on the 060 results and the series of chemical and heat treatments, major identified clays include trioctahedral smectite (Mg and Fe^{2+} -coordinated saponite), corrensite (interlayered 50 / 50 mix of chlorite / smectite), and chlorite with minor proportions of dioctahedral smectite (Fe^{3+} -coordinated nontronite).

Figure 26. XRD diffractogram for randomly oriented <2 µm size fraction clay to determine the 060 peak location. Dominant peak at 1.536 Å indicates tri-octahedral clay species whereas slight peak at 1.490 Å suggests the presence of some di-octahedral clays. Minor peak indicated by “P” is plagioclase.

Clay XRD Modeling

Clay modeling software, NEWMOD, was used to model mixture percentages of the three major clay components (smectite, corrensite, and chlorite) based on glycolated XRD scans. Subsamples *D522-PC62L 21.5*, *D655-PC79 21.0*, and *D878-PC53 12.0* were nearly identical, therefore only subsamples *D522-PC62L 21.5* and *D522-PPC1 9.0* were modeled. Results are summarized in Table 11.

Models of glycolated XRD scans (Fig. 27) reveal that chlorite is the major component in both subsamples making up 33% in subsample *D522-PC62L 21.0* and 57% in subsample *D522-PPC1 9.0*. Tri-octahedral smectite makes up roughly 31% of subsample *D522-PC62L 21.0*, and about 20% in *D522-PPC1 9.0*. Subsample *D522-PC62L 21.0* also contains 15% of di-octahedral smectite. Proportions of corrensite are 21% and 23% in subsamples *D522-PC62L 21.0* and *D522-PPC1 9.0*, respectively.

Subsample *D522-PC62L_21.5* has relatively larger proportions of smectite and chlorite, and lesser amounts of corrensite. Conversely, chlorite is the major clay mineral component in *D522-PPC1_9.0* and contains less smectite and corrensite proportions. These subsamples differ in that *D522-PC62L 21.0* has overall higher proportions of smectite with both di- and tri-octahedral components present whereas *D522-PPC1 9.0* has overall smaller proportions of smectite and the di-octahedral component is absent.

SEM-EDX (Chemistry)

Major element geochemistry was evaluated using SEM-EDX from: partially altered vitriclasts (Fig. 28A-1 – 3), vitric agglutinates (Fig. 28B-1), green hydrothermal aggregates (Fig. 28B-2), yellow hydrothermal aggregates (Fig. 28B-3), green particles (Fig. R28C-1), red particles (Fig. 28C-2), fibrous particles (Fig. 28C-3), and white particles (Fig. 28D-1 – 3). Results are described below and summarized in Table 12.

Partially altered vitriclasts tend to contain areas of progressive alteration (Fig. 29). Smooth surfaces are consistent with basaltic glass. Areas of glass that have incipient alteration contain a pitted appearance under SEM, whereas areas of the grain that are encrusted with a white alteration product appear spongy. The alteration substance encrusting fresh basalt glass is consistent with palagonite or smectite based on SEM morphology, EDX spectra, and XRD diffractograms. Vitric agglutinate EDX chemistry are consistent with basalt glass standards indicating that these particle surfaces are sideromelane (Fig. 30). Chemistry is consistent regardless of whether EDX is retrieved from “sub-spherical” or smooth glass areas.

Green hydrothermal aggregates are dominated by clay (Fe^{2+} -bearing chlorite or saponite) and often contain small ($<20\ \mu\text{m}$) crystals of pyrite (Fig. 31A). Yellow hydrothermal aggregates also include small pyrite crystals but are dominated by nontronite clay and also tend to contain ilmenite (FeTiO_3), and iron-oxide (goethite?; $\text{FeO}(\text{OH})$) crystals (Fig. 31B). Green particles have a mixture of

Figure 28. SEM images of representative non-primary (A; C; D) and authigenic hydrothermal mineral components (B) in HMT. Insets show plane light image of the grain using a binocular microscope. Scale lines are 500 μm). **(A-1 – A-3)** selected altered vitriclasts. Yellow lines show contact between various stages of alteration [fresh basalt glass (bg), slightly altered (sa), and highly altered vitriclast encrusted with clays (ha)]. **(B-1)** vitric-agglutinate particle. **(B-2)** Green hydrothermal clay aggregate. **(B-3)** Yellow hydrothermal clay aggregate. **(C-1)** Green particle. **(C-2)** Red particle. **(C-3)** White fibrous particle. **(D-1 – D-3)** Various “white particles”.

Table 12. Summary of minerals identified on grains of interest using EDX.

Particle Type	EDX Spectra Reference	Overall Color	Morphology	Primary Constituent	Accessory Minerals
Agglutinate	Fig. 30	Black/dark color	Sub-spherical aggregates	sideromelane	None
Altered Vitriclasts	Fig. 29	Variable (white, orange, brown)	Variable (smoothed, pitted, spongy, vermicular/grooved)	Basaltic glass, palagonite, smectite	None
Green Aggregates	Fig. 31A	Pale/bright green	Sub-spherical aggregates	Smectite: saponite (Fe^{2+})	Pyrite
Yellow Aggregates	Fig. 31B	Pale yellow	Sub-spherical aggregates	Smectite: nontronite/saponite (Fe^{3+})	Fe-Oxides (goethite?); TiO (ilmenite)
Red particles	Fig. 33	Red	Variable	Iddingsite	Smectitic Clays (nontronite); Fe-oxides (goethite/hematite); ilmenite/titanomagnetite
Green Particles	Fig. 32	Dark green/black	Variable (euhedral faces, sub-spherical aggregates, and encrusting coatings)	Pyroxene	Smectitic clays (saponite)
Fibrous Particles	Fig. 34	White or pale yellow/green	Fibrous (prismatic)	Actinolite/tremolite	None
White Particles	Figs. 35, 36 and 37	Pure white or off-white/beige	Variable (euhedral crystals, prismatic fibers, curvaceous fibers, platy, smooth, blocky)	Phyric/plagioclase	Fe-Oxides (goethite/hematite); zeolites (heulandite, laumontite); pyrite; barite; ilmenite/ titanomagnetite

Figure 29. EDX spectra of altered glass. **Spectrum 1** shows high Si, Al, Ca and moderate Fe, Mg, consistent with basalt glass standards. **Spectrum 3** has lower abundances of Ca, Al with increased Mg which, in conjunction with the “spongy” texture, is consistent with clay. Presence of Ti likely indicates presence of titanium oxide minerals (bright white spots) near **spectrum 3**. Presence of Au is from gold coating used under the SEM to reduce electron charging.

Figure 30. EDX spectra of agglutinate particle. **Spectrum 1** shows high Si with moderate proportions of Ca, O, Al, Mg and Fe, all of which are consistent with basalt glass (see Fig. 6). Presence of Au is from gold coating used under the SEM to reduce electron charging.

Figure 31. EDX spectra of hydrothermal clay aggregates. **(A)** green clay aggregate. **Spectrum 1** shows dominant peaks of S and Fe and relatively low abundances of other elements. High S and Fe and the euhedral mineral faces are consistent with pyrite (FeS_2). **Spectrum 3** shows spectra of the "sponge" textured material and shows high abundance of Si, O, and Fe consistent with clay. **(B)** Yellow clay aggregate. **Spectrum 2** (bright white spots) is consistent with Fe-oxide minerals (goethite?). **Spectrum 4** is rich in Si and Fe has a clay-like appearance, consistent with nontronite. Presence of Au is from gold coating used under the SEM to reduce electron charging.

euohedral crystal faces and clay textures and have chemistry consistent with pyroxenes (augite) at various stages of chemical alteration to clays (chlorite?; Fig. 32). Red particles are likely iddingsite, an alteration product of olivine at various stages of alteration (Smith et al., 1987), and may be coated in Fe^{3+} clays (nontronite) and include small crystals of iron oxide (hematite?; Fe_2O_3) and ilmenite and / or titanomagnetite [$\text{Fe}^{2+}(\text{Fe}^{3+}, \text{Ti})_2\text{O}_4$; Fig. 33].

Fibrous particles are split into two categories by color; white and pale-yellow / light green fibrous particles have similar EDX spectra showing roughly equal proportions of Ca, Mg, and Fe (Fig. 34; 06_41). Both types of fibrous minerals have continuous prismatic fibers as evident in SEM images. Based on chemistry, color and prismatic fibrous morphology indicate that these white and green minerals are tremolite and actinolite, respectfully (Fig. 34; 06_29 and 06_11-L4).

White particles are often polymineralic (Fig. 35 and 36) and are generally pure-white or pale white / beige in color, sometimes with areas of pale yellow / green, and often contain very small ($<20\mu\text{m}$) darker crystals within them. Based on EDX spectra and morphologies observed in SEM images, these components are euohedral plagioclase (albite) crystals and chlorite, respectively. Regions on white particles that contain areas of small ($<5\mu\text{m}$) white monomineralic crystals with a blocky morphology are consistent with the zeolite laumontite [$\text{Ca}(\text{AlSi}_2\text{O}_6)_2 \cdot 4\text{H}_2\text{O}$; Fig. 36]. Other white monomineralic $\sim 10\mu\text{m}$ crystals with a tabular / “coffin shaped” habit are consistent with heulandite [$(\text{Ca}, \text{Na})_{2-3}\text{Al}_3(\text{Al}, \text{Si})_2\text{Si}_{13}\text{O}_{36} \cdot 12\text{H}_2\text{O}$; Fig. 37]. One grain also has a spectra consistent with barite [BaSO_4 ; Fig. 35].

Figure 32. EDX spectra of a green particle. **Spectrum 1** was measured on a euohedral crystal face and has spectra consistent with pyroxene, showing high Si, Ca, and Mg. **Spectrum 2** was measured from an area on the particle with a green encrusting clay, and aggregate-like texture, and has spectra consistent with clay (high Si, moderate Fe, Al, and Mg. Presence of Au is from gold coating used under the SEM to reduce electron charging.

Figure 33. EDX spectra of a red particle. **Spectrum 1** was measured on a location with a “spongey” like texture and has dominant Fe, and Si, peaks which are consistent with di-octahedral (Fe^{3+} -rich) nontronite. **Spectrum 2**. Was measured on a sub-euhedral grain and has a very strong Fe signature and roughly equal parts Si and O. The strong Fe may be indicative of a Fe-O (hematite?) with Si coming from surrounding clay. **Spectrum 3** was measured on a bright white grain with sub-euhedral crystal faces and has a strong Fe and moderate Ti, and Si peaks. The presence of Fe, and Ti is consistent with titanomagnetite. Presence of Au is from gold coating used under the SEM to reduce electron charging.

Figure 34. EDX spectra of fibrous morphologies which consist of white prismatic fibrous minerals (**06_41**), slightly curved "fiber bundles" (**06_29**), and off white/green prismatic fibers (**06_11_L4**). Spectra consist of high Si with moderate Fe, Ca, and Mg. Fiber diameter is $>5\ \mu\text{m}$. Spectra and fibrous morphologies are consistent with amphibole (actinolite/tremolite). Presence of Au is from gold coating used under the SEM to reduce electron charging.

Figure 35. White particle 06_16 with 4 different locations of interest (L1-L4) with identified minerals at each location (Pyx: Pyroxene; B: Barite; FeO: Fe-oxide; Py: Pyrite). (L1) has spectra and morphology consistent with pyroxene. (L2) has strong S, O and Ba signatures consistent with barite (BaSO_4). (L3) **spectrum 1** has high Si, Mg, and Fe consistent with clay. **Spectrum 2** has high Fe and O signatures consistent with Fe-oxide mineral goethite? (L4) **spectrum 1** has spectra consistent with clay (high Mg, Si, O and Fe) while **spectrum 2** has abundant Fe and S consistent with pyrite. Botryoidal crystal shape consistent with framboidal pyrite. Presence of Au is from gold coating used under the SEM to reduce electron charging.

Figure 36. EDX of white particle 06_11-L5. **Spectrum 1** and **spectrum 3** show high Si and Al and moderate Ca and the morphology is consistent with the zeolite laumontite [Z(L)]. **Spectrum 2** was measured on tabular/"coffin-shaped" crystals of ~10 μm and have spectra showing high Si and Al and moderate Ca, consistent with the zeolite heulandite [Z(H)]. **Spectrum 4** was measured in a platy material which is high in Si, Al, Mg. The morphology and high levels of Mg are consistent with clay. Zeolites 1 and 2 are shown in Figure 37. Presence of Au is from gold coating used under the SEM to reduce electron charging.

Figure 37. EDX spectra of small (<10 μm) euhedral zeolite crystals on particle 06_11. Locations of zeolite 1 and zeolite 2 are shown in Fig. 36. Zeolite 1 shows strong Si, Al and Ca with moderate amounts of Fe and Ti. Zeolite 2 also contains strong Si, O, and Ca but contains some Na. Blocky morphologies and spectra of both zeolite 1 & 2 are consistent with the zeolite laumontite $[\text{Ca}(\text{AlSi}_2\text{O}_6)_2 \cdot 4\text{H}_2\text{O}]$. Presence of Au is from gold coating used under the SEM to reduce electron charging.

Dark crystals with a yellow metallic luster have chemistry consistent with pyrite (FeS_2) whereas dark crystals with a black / dark brown metallic luster are consistent with ilmenite and / or titanomagnetite. Dark brown crystals with an earthy luster have spectra and crystal morphology consistent with goethite ($\text{FeO}(\text{OH})$) and hematite.

Morphometry

SEM Observations

A SEM was used to observe surface features of fluidal and angular / blocky vitriclasts within HMT (Fig. 38). Fluidal shards have smooth faces and may be further subdivided based on morphology to include limu o' Pele (Fig. 38A-1 – 3), tubular (Fig. 38A-4), taffy (Fig. 38A-5), and Pele's hairs (Fig. 38A-6). Lim o' Pele dominate the fluidal shard population and characteristically have a thin, platy morphology, often flat but sometimes folded over. Faces of limu o' Pele sometimes contain microlites or enclosed bubbles protruding from the surface. Tubular vesicular vitriclasts have smooth surfaces but are vesicular on end margins resembling a tube. "Taffy-like" vitriclasts have a stretched-like "taffy" appearance. Pele's hairs are thin ($<100\ \mu\text{m}$ -diameter) and elongate, with smooth cylindrical margins resembling a hair. "Agglutinate" particles morphologically resemble clay aggregates typical of the hydrothermal environment, but are entirely coated in a thin, smooth basaltic glass as evident by EDX spectra.

Figure 38. SEM images of vitriclast morphologies. **(A)** Examples of fluidal vitriclasts. A-1 – A-3 show examples of limu o' Pele bubble wall shards. Bubble-texture on face may be microlite crystals enveloped in glass? A-4 shows a vitriclast with tubular vesicles. A-5 shows limu o' Pele with a taffy texture. A-6 shows a Pele's hair. **(B)** Examples of angular/blocky glass particles. B-1A shows an angular vitriclast with sharp edges and smooth glassy faces with conchoidal fracture patterns and radiating perpendicular step-fractures (B-1B). **B-2** shows angular vitriclast with step-fracturing on bottom face. B-3A shows an angular vitriclast showing conchoidal fracture smooth face with pitting (B-3B) in fracture rings. B-4 Blocky vitriclast displaying sharp margins with smooth glass faces and minimal vesicles.

Angular / blocky particles have sharp, well defined corner margins with semi-smooth surfaces that show brittle fragmentation features (e.g. conchoidal fracture fractures, step fracturing; Fig. 38B-1 – 4). Larger angular / blocky particles often contain small (20 – 50 μm diameter) vesicles that make up no more than 10% of the surface. Highly vesicular particles (containing ~40% vesicles) were only observed in <1% of vitriclasts according to point counts and were not observed under SEM.

MGS Subsample Population Results

Subsample Comparison Descriptions

Subsample MGS populations from volcanoclastic lithofacies on Axial Seamount (TM, HMT, LPT) were compared talus scoop bag subsamples collected from the summit of Axial Seamount (See Fig. 3 for locations).

Subsample *D522-SB23* was retrieved from a talus pile from a 2011 lava flow that cascaded over the caldera wall. Subsample *D526-SB12* was collected from an andesite pillow cone talus pile. Subsample *D880 -SB33* was collected from a sheet flow talus pile near a fissure. All scoop bag subsamples are inferred to have fragmented by autoclastic (non-explosive) fragmentation (D. Kapule pers. Comm.).

In addition to scoop bag subsamples, two subsamples from West Mata were also analyzed and compared to subsamples on Axial Seamount. Subsample *J2_r17_r28* is a proximal scoop bag and *J2-418_Sed7* is a distal scoop bag subsample, both of which contain boninite ash from the 2009 eruption in which

explosive style activity was directly observed by ROV (Resing et al., 2011). This subsample is therefore representative of ash fragmented by magmatic explosivity. These autoclastic and pyroclastic scoop bag subsamples are used to compare against MGS ash populations and discussed further in the *fragmentation and eruption style* section.

Point Density Plot Analysis

To differentiate ash morphologies on Axial Seamount, point density plots of TM, HMT, and LPT core subsamples were compared to scoop bag subsamples. Data plotted on SLD vs. CVX plots (Fig. 39) shows variation between core and scoop bag subsamples. Field value results are summarized in Table 13. Scans from TM and LPT show broad 2σ field ranges in both *solidity* (>0.7) and *convexity* (>0.7). HMT is more constrained overall with the 2σ field ranges for both *solidity* and *convexity* >0.8 . Slopes for TM, HMT, and LPT subsamples are all moderately-steep (1.54 – 1.88).

Talus scoop bag subsamples (*D526-SB12*; *D880-SB33*) have more constrained *convexity* 2σ field values (>0.85) while the *solidity* field range is variable and similar to that of TM, HMT, and LPT (>0.7). Trend lines based on 1σ slopes have much more gentle slopes (0.55 – 0.67). Subsample *J2-417_r28* (West Mata) shows a constrained *solidity* 2σ field (>0.8) and wider *convexity* value (>0.7) than Axial Seamount push core subsamples and has the steepest slope of all measured subsamples (2.22).

Figure 39. *Solidity vs. Convexity* point density plots. **(Top)** Results of representative subsamples from each lithofacies (TM, HMT, and LPT). **(Bottom)** Results of scoop bag subsamples *D526-SB12* and *D880-SB33*, and sample from West Mata, *J2-417_r28*. Dashed blue line through plots are the slope of 2σ data points. Results are summarized in Table. 13.

Table 13. Results of solidity vs. convexity plots 2σ field range values.

	SLD ^a	CVX ^a	Slope ^b
Talus 1 (D526-SB12)	>0.85	>0.73	0.55
Talus 2 (D880-SB33)	>0.87	>0.79	0.67
TM (D878-PC75_4.0)	>0.75	>0.73	1.54
HMT (D522-PC62L_27.0)	0.81 – 0.99	>0.80	1.82
LPT (D524-PC47XL_41.0)	0.73 – 0.98	>0.70	1.88
W. Mata (J2-417_r28)	0.73 – 0.96	>0.82	2.22

^aBased on 2σ field range values

^bBased on 1σ field range values

Plots of Int. SD vs. Int. M show differences in ash populations based on lithofacies and proximity to the caldera (Fig. 40A). The presence of 2σ density shading falling in a particular field (e.g. fluidal) implies a statistically significant amount of that particular particle style. For example, subsample *D878-PC75_4.0* (TM distal) has more 2σ shading occupying the “fluidal field compared to subsample *D522-PC62L_32.0*. (LPT proximal). Therefore, *D878-PC75_4.0* contains significantly more fluidal particles relative to *D522-PC62L_32.0*, which is consistent with core descriptions where distal TM tends to contain more fluidal vitriclasts than proximal LPT.

Figure 40. *Intensity Standard Deviation* vs. *Intensity Mean* point density plots. (A) Representative subsamples from each lithofacies (Orange = TM; Green = HMT; Grey = LPT) and from varying proximities to the caldera. (B) Representative scoop bag subsamples from varying proximities to the caldera. (C) subsamples from West Mata for comparison

All three lithofacies show that distal subsamples contain a higher proportion of fluidal particles and crystals compared to the proximal and medial subsamples. TM contains the highest proportion of fluidal particles followed by HMT, whereas LPT contains only a small percent of fluidal particles. TM and LPT tend to contain more crystals than HMT. In addition to scans from each lithofacies, three scoop bag subsamples (Fig. 40B) and two subsamples from West Mata (Fig. 40C) were also plotted for comparison. Scoop bag subsamples are highly variable with subsamples *D522-SB23* and *D880-SB33* containing both fluidal shards and crystals (2σ field “intensity mean” values >90) whereas the 2σ field for subsample *D526-SB12* is mostly constrained to the “angular / blocky vitriclast” field. Meanwhile, the proximal (*J2-417_r28*) and distal (*J2-418_Sed7*) subsamples from West Mata are vastly different. The proximal subsample spread is constrained primarily to the “angular” field whereas the distal subsample spread extends into the “fluidal” and “crystals” fields.

Convexity Distribution Frequency Curves

Distribution frequency curves of *convexity* (Fig. 41) show distinct differences between scoop bag subsamples (*D526-SB12* and *D880-SB 33*), representative HMT subsample (*D522-PC62L_27.0*), and other subsamples from TM (*D8789-PC75_4.0*), LPT (*D524-PC47XL_41.0*). Scoop bag subsamples have narrow asymmetric peaks <0.95 whereas the HMT curve is symmetrical with the peak falling between $0.92 - 0.95$. Subsamples from TM and LPT also have symmetrical peaks, but the distribution frequency is broader with peaks generally

falling <0.9 *convexity* values. Subsample types with inferred fragmentation mechanisms are similar (e.g. scoop bag subsamples; TM, LPT, West Mata), while HMT stands out as being notably different.

Figure 41. *Convexity* frequency distribution curves comparing representative subsamples from each lithofacies and scoop bags on Axial Seamount, and subsamples from West Mata.

DISCUSSION

Lithostratigraphy

Grain-size results comparing off-summit subsamples vs. other lithofacies suggest that products of volcanic eruptions are mostly constrained to Axial Seamount's summit, supporting the idea that the volcanoclastic lithofacies (LPT, HMT, and TM) source is on Axial Seamount's summit. General stratigraphy observed around the caldera indicates chronological control on the deposition of each lithofacies. Lithostratigraphy is discussed below based in chronological order from oldest (TO) to youngest (TM).

Absence of TO in proximal and medial cores may be caused by non-deposition, erosion by bottom currents and / or burial by lava flows. TO is interpreted to be background sedimentation (Portner et al., 2015), thus eliminating the idea of non-deposition. High bottom current circulation velocities constrained to the summit on Axial Seamount (Xu and Lavelle, 2017) may provide a mechanism to eradicate TO near the caldera. Additionally, TO only occurs in cores >1500 years old which coincides with volcanism and effusive volcanism (Clague et al., 2013), suggesting that older sedimentary deposits (e.g. TO) were buried by younger lava flows.

Observations of LPT and HMT show both lithofacies thin with increasing distance from the caldera (Fig. 18). This indicates that their eruptive source was near the current location of the caldera and primary eruptive vents (Caress et al., 2012; Chadwick et al., 2013). Caldera formation is important in that it effectively

increases the porosity of oceanic crust up to 33% (Gilbert et al., 2007) by way of ring faults around its margins. These structures allow for substantial seawater infiltration and ultimately magma-seawater interaction in the subsurface, which explains the thickening of HMT toward the caldera.

Formation of TM is marked by a notable absence of hydrothermal lithics seen in underlying HMT (e.g. authigenic hydrothermal minerals, altered oceanic crust) and fine-grained vitriclasts signifying the end of caldera formation. TM is interpreted to have formed by pelagic fall-out in conjunction with periodic eruptions with the same eruption style that produced LPT. TM lithofacies thickness is relatively consistent across the offset transect (Fig. 17), further suggesting primarily a pelagic fall-out origin from vents near and far from the caldera.

HMT Provenance

HMT is composed of (1) primary volcaniclasts produced by eruption and fragmentation of (juvenile) magma, (2) non-primary particles of fragmented oceanic bedrock (accessory lithics), and (3) authigenic hydrothermal particles that precipitate from hydrothermal fluids (accidental lithics). Non-primary particles that are incorporated into a plume of primary volcaniclasts as a result of volcanic eruptions are referred to as accessory lithics. Meanwhile, accidental lithics refer to particles that are locally entrained into a plume (e.g. authigenic hydrothermal minerals). Table 14 summarizes accessory and accidental lithics identified as

Table 14. Summary of lithics (accessory and accidental) identified on Axial Seamount and implications.

Lithic Type	Mineral Category	Mineral	Temperature Conditions ^a	Primary Alteration Zone	Oxidation Conditions	Cation Exchange
Authigenic / Altered	Clay	Saponite	Low	UPA	Reducing ^b	Fe ²⁺ , Mg ²⁺
		Nontronite	Low	UPA	Oxidizing	Fe ³⁺
		Corrensite	Medium	LPA	Reducing ^b	
		Chlorite	High	TZD		
Authigenic	Sulfide	Pyrite	Varies	N/A	Reducing	Fe ²⁺ and S
	Silicate	Quartz	Medium	N/A		Si
	Sulfate	Barite	Medium	N/A		Ba
Altered	Oxide	Goethite	Low	UPA	Oxidizing	Fe ³⁺
		Hematite	Low	UPA	Oxidizing	Fe ³⁺
	Zeolite	Heulandite	Low	ZZ		Al & Ca
		Laumontite	Medium	TZD		Al & Ca
	Greenschist	Actinolite	High	TZD		Fe ²⁺ , Mg ²⁺
		Tremolite	High	TZD		Ca, Fe ²⁺ , Mg ²⁺
		Epidote	High	TZD		Ca, Fe ³⁺
		Albite	High	TZD		Na, Ca

Notes:

^aTemperature conditions generalized

^bAssuming Fe²⁺ cation

Abbreviations:

UPA: Upper pillow alteration zone

ZZ: Zeolite alteration zone

LPA: Lower pillow alteration zone

TZD: Lithologic transition zone

N/A: Not applicable

part of the hydrothermal system and their implications. Components are separated based on their inferred provenance sources and are described below.

Primary Volcaniclast Origin

Primary volcaniclasts are characterized by fresh (unaltered) glass particles to slightly altered. Although the majority of fresh vitriclasts are juvenile, and are therefore discussed in the context of volcanic processes (see *fragmentation and eruption style*), the presence of slightly altered vitriclasts suggests that not all vitriclasts are magmatically derived. Fresh volcanic glass (e.g. vitriclasts) alters to palagonite (Stroncik and Schmincke, 2001; Stroncik and Schmincke, 2002), the first stable phase of mafic glass alteration (Peacock, 1926; Hay and Jones, 1972). Partially altered vitriclasts to palagonite are likely from previous eruptions (e.g. not juvenile vitriclasts) and are therefore considered cognate lithics.

MgO geochemistry of vitriclasts is important to understanding the provenance of glass shards within the erupted material. Homogenous geochemical signatures reveal that all vitriclasts are magmatically derived whereas heterogenous geochemical signatures imply that existing vitriclasts from previous eruptions may have been stripped from conduit walls and incorporated into the erupted material (Portner et al., 2014). Therefore, an understanding of vitriclast chemistry is pertinent to separating out juvenile vitriclasts from cognate lithics. Portner et al. (2015) concluded that vitriclasts in HMT are chemically heterogeneous, implying that a population of unaltered vitriclasts are cognate and were entrained from glassy wall rock during eruption. Future geochemical

analysis on HMT primary volcaniclasts is required to qualitatively make this distinction.

Non-Primary Volcaniclast Origin – Conduit Wall-Rock

Upwelling magma bodies and emplacement of new oceanic crust leads to significant heat-flow in mid-ocean ridge environments (Sclatter et., al 1981). High geothermal gradients near mid-ocean ridges results in thermal alteration of oceanic crust that includes clays, oxides, zeolites, and greenschist facies minerals (e.g. actinolite, epidote). Mineral assemblages provide insight into thermal alteration zones that occur at depth within a particular section of oceanic crust (Alt et al., 1986). These zones are characterized by the presence of specific minerals and include:

1. “Upper Pillow Alteration Zone” (UPA; 0-320 m) that generally consists of unaltered basaltic glass, crystalline basalts that contain unaltered pyroxenes and calcic plagioclase, with minor amounts of Fe-oxides (goethite), clays (saponite) and celadonite.
2. “Zeolite Alteration Zone” (ZZ; 254-290 m) that is a sub-zone of the upper pillow alteration zone and generally includes the first occurrence of zeolites (e.g. thomsonite; heulandite), in conjunction with clays (e.g. saponite) and celadonite.
3. “Lower Pillow Alteration Zone” (LPA; 320-624 m) consisting of slightly altered materials. Saponite often replaces olivine and plagioclase in this zone. Pyroxenes remain predominantly unaltered, with local alteration

consisting of chlorite, talc, and actinolite. In this section, volcanic glass is completely replaced by clay minerals.

3. “Lithologic Transition Zone” (TZD; 624-1076 m) that is characterized by abundant of greenschist minerals including chlorite, actinolite, epidote, laumontite, prehnite. Plagioclase has undergone albitization and is partially replaced by high-temperature zeolites (e.g. laumontite).

These zones, described by Alt et al. (1986), are defined from drill cores retrieved from a different setting than that of Axial Seamount. Due to Axial Seamount’s presence above a hotspot, it may have a higher temperature gradient, which would cause the depths associated with alteration zones to be shallower than described. Nonetheless, these alteration zones provide insight into relative depth and thermal conditions based on mineral assemblages in HMT. Alteration minerals observed in HMT are presented in Figure 42 and discussed below.

Clay Minerals

Clay minerals are a common alteration product resulting from warm hydrothermal fluids interacting with unaltered minerals in deep-sea hydrothermal. Clay minerals produced in mafic volcanic settings are generally rich in Fe and Mg, due to the leaching of Fe and Mg ions from mafic minerals, and often include saponite, nontronite, corrensite (C / S; interstratified chlorite / smectite), and chlorite, (Schiffman and Fridleifsson, 1991; Inoue, 1995). The formation of a clay mineral is sensitive to temperature. Therefore, the presence of a particular clay

Figure 42. Accessory lithics identified in HMT on Axial Seamount showing crustal depths and alteration zones as described by Alt et al., 1986. Mineral depth ranges are from Alt et al., 1986 and references within. Temperature ranges on Axial Seamount are likely very different due to the high geothermal gradient and therefore is not included; however, depth ranges of minerals relative to each other are the same.

species can provide reliable controls on depth of formation in oceanic crust where geothermal gradients are well-constrained (Utada, 1980; Schiffman and Fridleifsson, 1991; Inoue, 1995). Temperature, not pressure, is the primary control of the type of clay produced in deep-sea alteration, while oxidation state generally controls cation exchange (e.g. amount of Mg or Fe in saponite; Andrews, 1980; Yenioğlu, 2007).

Weathering of partly crystalline basalt at Low-temperatures (<100 °C) results in the alteration of glass selvages first to amorphous palagonite, which then crystallizes into smectite (nontronite or saponite). Intermediate temperature clay alteration begins above 100 °C and results in the recrystallization of smectite to interlayered chlorite / smectite until a 50 / 50 ratio is achieved in corrensite. As alteration evolves above temperatures of about 200 °C the chlorite / smectite interlayer ratio increases until corrensite entirely converts to discrete chlorite. Progression from low-temperature smectite, to intermediate temperature corrensite, and finally to high-temperature chlorite, occurs over a relatively narrow temperature range between 100 and 200 °C (Schiffman and Fridleifsson, 1991; Inoue, 1995).

SEM images of altered vitriclasts show a range of alteration including unaltered basaltic glass, slightly altered glass (palagonite), and smectite-altered glass (Fig. 28A-1 – 3). Results of clay XRD diffractograms (Fig. 25) reveal primary clay constituents within HMT include smectite, interstratified chlorite / smectite (corrensite), and chlorite. Smectite is predominantly tri-octahedral

(saponite) and may have significant Fe^{2+} cation coordination implying reducing conditions; however, small proportions of di-octahedral smectite (nontronite) is present, particularly on red particles (Table 12). Peak locations at various stages of clay XRD treatments suggest that chlorite is Mg^{2+} -rich, but that Fe^{2+} -bearing chlorite is also present. Cation coordination implies different oxidation states with Fe^{2+} saponite and chlorite forming under reducing conditions while Fe^{3+} nontronite forming under oxidizing conditions.

Three of the four subsamples selected for clay XRD analysis (*D522-PC62L_21.5*; *D655-PPC79_20.0*; *D878-PC53_12.0*) had nearly identical diffractograms throughout the clay treatment process suggesting that clays within HMT are mostly homogenous. The exception appears to be within the “pale green” lamination at the top of HMT (subsample *D522-PPC1_9.0*) where clay treatment diffractograms showed obvious differences. Most HMT subsamples consist of 33% chlorite, ~46% smectite, the majority of which was modeled as trioctahedral (saponite), and 21% corrensite. This combination covers a broad range of temperature conditions. The bimodal distribution of low and high temperature clays (Fig. 43) distinctly segregates low-temperature smectite from high-temperature chlorite suggesting different provenances.

HMT subsample analyzed from the pale green lamination contains higher proportions of high-temperature clays including 57% chlorite, 23% corrensite, 20% trioctahedral smectite (saponite). These models indicate the presence of predominantly high-temperature clays in the “pale green” lamination (Fig. 43).

High-temperature clays positioned stratigraphically at the top of HMT in proximal and medial cores suggests deeper parts of the hydrothermal system were ejected during volcanic eruptions.

Figure 43. Figure showing relative proportions of clay species (smectite, corrensite, chlorite, and serpentine) based on NEWMOD clay models of two subsamples.

Oxides

The most common oxide minerals in volcanic and hydrothermal settings include Fe-oxide hematite (Fe_2O_3), Fe-hydroxide goethite ($\text{FeO}(\text{OH})$). Ti-oxides ilmenite (FeTiO_3) and titanomagnetite ($\text{Fe}^{2+}(\text{Fe}^{3+}, \text{Ti})_2\text{O}_4$) are observed under

SEM in red particles (Fig. 33) but are not associated with thermal alteration. Hematite may be an accessory mineral in volcanic rocks or associated with alteration whereas goethite is exclusively associated with alteration. Oxide minerals are relatively low in abundance and therefore were not identified using XRD; however, SEM visual observations and EDX analysis show that Fe-oxides are present primarily on red lithics (Fig. 33) and yellow clays (Fig. 31B) but were also observed in a white particle (Fig. 35). Although it is difficult to differentiate hematite from goethite using SEM morphology (Welton, 2003), the presence of Fe-oxides implies alteration of shallow oceanic crust and oxidizing conditions in the UPA zone (Alt et al., 1986).

Zeolites

Zeolites are an important component of hydrothermal lithics because they are common in altered oceanic crust, are sensitive to temperature, and often replace volcanic glass and Ca-rich plagioclase (Coombs, 1954; Stewart, 1974; Boles, 1977). Common zeolite minerals found in deep-sea hydrothermal settings include: chabazite, clinoptilolite, heulandite, laumontite, mesolite, natrolite, scolecite, stilbite, thomsonite, and wairakite (Browne, 1978; Wirsching, U. 1981; Alt et al. 1986; Inoue, 1995; Neuhoﬀ et al. 2006). Each zeolite tends to have a unique crystal morphology (e.g. fibrous, platy, blocky), which when coupled with the high amounts of aluminum, allows for identification of specific zeolite minerals (Mumpton and Ormsby, 1976; Welton, 2003; Zhang et al. 2011).

Results of individual grains using SEM / EDX and XRD diffractograms show that Ca-rich zeolites, laumontite and heulandite, are present on Axial Seamount, and are likely replacing calcic plagioclase and basaltic glass. These are some of the most common zeolites found in low-grade metamorphic settings (Mumpton, 2018). Heulandite occurs at low temperatures (<150 °C) and is often replaced by laumontite at higher temperatures (Coombs, 1954). Figure 37 shows laumontite appearing to replace heulandite suggesting lithics were present at overlapping zeolite formation temperatures (100 – 200 °C) which is consistent with the C/S clay zone.

Hydrothermal Quartz

While quartz is not common in mafic volcanic settings, it is a common constituent in hydrothermal systems. In medium to high temperature hydrothermal systems (230 – 380 °C; Alt et al., 1986), Si enriched hydrothermal fluids seep into fractures and crystallize as quartz veins. Presence of quartz in HMT is likely a constituent of hydrothermal quartz veins stripped from conduit walls.

Greenschist-Grade Minerals

Greenschist-grade metamorphic minerals include chlorite, actinolite, tremolite, epidote, and albite. The presence of chlorite is discussed in detail above. Actinolite, tremolite, and epidote often replace amphiboles and pyroxenes whereas albite replaces Ca-rich anorthite (Alt et al., 1986). Although tremolite is generally associated with metamorphosed carbonate rocks and skarns, they are

also present in metamorphic mafic and ultramafic rocks in Mg-rich systems (e.g. Nisbet et al., 1977; Franceschelli et al., 2002). Greenschist minerals have previously been reported as occurring predominantly within the lower pillow basalt and sheeted dike sections of oceanic crust (Alt et. al, 1986). Presence of these minerals suggests high-grade alteration >600 m deep within the crust.

Non-Primary Volcaniclast (Accessory Lithic) Provenance

Non-primary volcaniclasts include crystalline wall-rock (e.g. basalt) and minerals associated with altered and unaltered oceanic crust including, plagioclase, pyroxene, amphibole, zeolites, chlorite, and epidote, all of which were confirmed by XRD and SEM-EDX analysis. Minerals indicative of shallow crust alteration, low temperatures include Fe-oxides, zeolites, and smectitic (nontronite & saponite) clays, iddingsite. Fe-oxides and Fe³⁺ nontronite are indicative of oxidizing conditions, perhaps in the water column or shallow oceanic crust. Conversely, Fe²⁺ saponite is indicative of reducing conditions suggesting that oxidation conditions progress from oxidizing to reducing with increasing depth.

Presence of heulandite and laumontite, particularly found on the same particle, imply that altered lithics formed near transition temperatures between each of these minerals (100 – 150 °C). Interlayered chlorite / smectite (corrensite) with the addition of zeolites and are indicative of temperatures between 100 – 170 °C. Presence of high-temperature altered minerals chlorite, epidote, actinolite and albite are representative of greenschist facies

metamorphism deeper (>500 m) within the crust. Additionally, pyrite-laden chlorite suggests reducing conditions at high temperature (above 200 °C) and depths > 600 m within the crust.

Hydrothermal quartz is also indicative of moderate to high hydrothermal fluid temperatures, which when coupled with the absence of typical high-temperature hydrothermal minerals (e.g. cubanite, chalcopyrite), suggests that quartz formed as hydrothermal fluid-filled veins within the crust and not as a black smoker deposit. Fragments discussed above are inferred to have been incorporated into HMT after being stripped from surrounding bedrock and conduit walls and therefore may be referred to as *accessory lithics*. The presence of low-temperature Fe-oxides to high temperature greenschist facies minerals indicate that accessory lithics were stripped as deep as the lithologic transition zone. Therefore, provenance of accessory lithics ranges from shallow unaltered crust to 600 – 800 m below the seafloor (mbsf).

Authigenic Volcaniclast Origin - Eruption Plume

Hydrothermal activity is commonly associated with deep-sea caldera systems (Cole et al., 2005). Increased oceanic crust permeability due to the presence of ring faults and fissures facilitates circulation of warm seawater resulting in authigenic minerals precipitated from expelled hydrothermal fluids. Minerals commonly associated with typical “black smoker” seafloor hydrothermal systems include pyrite, wurtzite, pyrrhotite, chalcopyrite, cubanite, and siderite, while clays are notably absent in these environments (Feely et al., 1987). Some metallic

sulfides (e.g. pyrite, sphalerite) are less sensitive to temperature conditions. Instead, these are influenced by chemical controls (cation abundance and availability; Utada, 1980), and oxidation state (Andrews, 1980; Alt and Jiang, 1981). Less common hydrothermal minerals include hydrothermal sulfates (e.g. barite), the stabilities of which are dependent on temperature, chemical conditions, and solubility controls (Blount, 1977; Jamieson et al., 2015). Minerals associated with hydrothermal fluid precipitation are shown with associated hydrothermal fluid temperatures (Inoue et al., 1995; Feely et al., 1987 and references within) in Figure 44 and summarized below.

Hydrothermal Clay Aggregates

Hydrothermal clay aggregates include clays that are inferred to precipitate from hydrothermal fluids, and unique agglutinate particles. Although clays are described above (see *Clay Minerals*) clays described here have unique aggregate morphologies and are different from clays formed by replacement. Clays are not common in typical “black smoker” hydrothermal environments; however, point count results reveal that HMT contains both yellow and green clay aggregates. Secondary minerals in green clay aggregates include small pyrite crystals suggesting that the trioctahedral clays are Mg^{2+} / Fe^{2+} -rich saponite. Conversely, yellow clay aggregates contain Fe-oxide (goethite?) crystals suggesting the clay is dioctahedral nontronite (Fe^{3+}).

Figure 44. Authigenic hydrothermal minerals (precipitated from hydrothermal fluids) observed within HMT and their relative temperature ranges and context to clay zones, compared to temperature ranges of minerals commonly found in "typical" black smoker style hydrothermal systems. Absence of high-temperature minerals and abundance of low-temperature clays implies a relatively low hydrothermal fluid temperature on Axial Seamount. Note, high-temperature chlorite is present within HMT, yet is not inferred to precipitate from hydrothermal fluids. Temperature ranges from Inoue et al., 1995; Feely et al., 1987 and references within.

Although both of these clays imply relatively low fluid temperatures (smectite zone; up to 100 °C), they represent very different oxidation conditions. Green clay minerals likely precipitated in reducing conditions within the vent or conduit while yellow clays likely precipitated under oxidizing conditions in the water column or in the plume. Agglutinate particles (Fig. 28B-1) are unique in that their morphology is similar to that of a low-temperature hydrothermally precipitated clay aggregate yet are coated in basalt glass (Fig. 30). While less prevalent than other clay aggregates, their presence within HMT suggests that basalt magma was interacting with hydrothermal fluids while in a ductile state within the conduit or near the top of the vent.

Metallic Sulfides

Pyrite (FeS_2) was the only sulfide identified using EDX and was observed both independently and accompanying green Fe^{2+} saponitic clay aggregates (Fig. 31A), and chloritic alteration clays (Fig. 32). Hydrothermal systems are often associated with pyrite as sulfur breaks and ionizes from H_2S gas from the volcanic system and compounds with Fe. Due to the broad temperature range of pyrite formation (Alt et al., 1986), it is not indicative of temperature; however, the notable absence of other sulfides that are otherwise abundant in typical “black smoker” hydrothermal systems (e.g. cubanite, chalcopyrite, pyrrhotite, sphalerite, wurtzite; Feely et al., 1987) implies a relatively low hydrothermal fluid temperature (<200 °C). The presence of pyrite is indicative of reducing conditions and presence of free Fe^{2+} and S^{2-} ions. Additionally, the presence of pyrite in

green chlorite alteration clays and in saponite clay aggregates supports an oxygen reducing environment perhaps deeper in the hydrothermal system and shallow conduit. Lack of pyrite in other yellow clay aggregates (nontronite; Fig. 31B) implies oxidizing conditions, perhaps in the plume above the vent (see *hydrothermal clay aggregates*).

Sulfates

Results show that hydrothermal barite is present in low quantities within the hydrothermal system on Axial Seamount. Barite is one of the most common authigenic sulfates found in hydrothermal environments and forms from the leaching of Ba from the alteration of basalt resulting in barite precipitating from Ba²⁺-rich hydrothermal fluids mixing with SO₄²⁻ in seawater (Blount, 1977; Kim and McMurtry, 1991). Formation of barite in deep-sea hydrothermal settings has been identified take place between 150 – 300 °C (Hannington et al. 1995). Barite has an extremely low solubility constant, ranging from 10⁻⁶ to 10⁻³ molal (Blount, 1977), which preserves barite in normal oceanic conditions and is not prone to further alteration (Paytan et al. 1993, 1996a, 1996b). Therefore, the presence of barite in HMT supports the idea that SO₄²⁻-rich seawater is interacting with altered basalt, thus leeching Ba²⁺ ions and precipitating as hydrothermal barite in moderate hydrothermal fluid temperatures on Axial Seamount. Barite was only observed on one grain in HMT. Paucity of barite in HMT suggests that hydrothermal fluid temperatures were near the minimum formation temperature for barite (150 °C).

Authigenic Volcaniclast (Accidental Lithic) Provenance

Weathering of mafic oceanic crust and glass results in a diverse chemical system by leeching many elements including Fe, Mg, Ca, Al, Ba, S, (among others), which later alter or precipitate authigenic hydrothermal minerals including smectite (saponite / nontronite), barite, and pyrite. Presence of the aforementioned minerals and a lack of typical high-temperature hydrothermal minerals (e.g. cubanite, chalcopyrite, pyrrhotite, sphalerite, siderite, wurtzite) implies relatively low hydrothermal fluid temperatures ranging from 40 °C up to about 170 °C (Fig. 44). Interestingly, smectite varieties include both trioctahedral (Mg^{2+} / Fe^{2+}) saponite (containing small pyrite crystals; Fig. 31A), and Fe^{3+} nontronite (containing small FeO crystals; Fig. 31B) indicating variable oxidation conditions. Nontronite may be precipitating above the seafloor in the water column whereas saponite may precipitate within the shallow crust before being incorporated into the ascending plume. Saponite is more common than nontronite suggesting authigenic clays precipitated predominantly in reducing conditions. Formation temperatures of authigenic hydrothermal minerals are consistent with shallow upper crust conduit / vent margins, or seawater / plume columns, which is very different from deep TZD sources of accessory minerals. Incorporation of these authigenic minerals into HMT is presumed to have occurred by an eruption plume in the conduit or just above the vent. The former is supported by agglutinate particles which are presumed to be authigenic clay

aggregates coated in basaltic glass. Authigenic hydrothermal minerals are therefore considered to be *accidental lithics*.

Fragmentation and Eruption Style

Fragmentation Style Background

Magma fragmentation may broadly be categorized as either effusive (non-explosive), or explosive. Various magma fragmentation styles have been linked to different eruption styles. Non-explosive magma fragmentation includes *autoclastic processes*, while explosive fragmentation styles include (1) *magmatic*, (2) *phreatic*, and (3) *phreatomagmatic explosivity* (Büttner et al., 2002; Liu et al., 2017; Wohletz, 1986; Zimanowski et al., 1997). Fragmentation style may be inferred from vitriclast texture and unique morphologies (Büttner et al., 2002; Wohletz, 1983; Zimanowski et al., 1997) and are tested against results presented in this thesis below.

Autoclastic Fragmentation

Autoclastic (non-explosive) fragmentation, broadly including thermal quench granulation, occurs when magma / lava behaves as a brittle material and fractures under applied stress supplied by a moving lava flow or a lava flow flowing down a steep slope (Porreca et al., 2014; Skilling et al., 2001). Thermal quench granulation, sometimes described as autoclastic fragmentation, occurs when magma is cooled on contact with water and contracts rapidly, quenching under stress and fragmenting.

Magmatic Explosivity

Magmatic explosivity is driven by volatile (namely SO₂, CO₂ and H₂O) degassing and rapid magma ascent (Sparks et al., 1977; Zimanowski et al., 1997; Clague et al. 2003). Coalescence of magmatic volatiles in low viscosity magmas (e.g. basalt) create large “slugs” that buoyantly rise through the conduit.

Explosivity is constrained by numerous factors including gas expansion and overpressures, magma viscosity, conduit properties, and, particularly in submarine environments, overlying hydrostatic pressure (Papalle et al., 1999; Wilson et al., 1980; Clague et al., 2003). Although the juvenile products of magmatically explosive eruptions can be recognized in part by highly vesicular ash and lapilli in subaerial eruptions (Sparks et al., 1977; Heiken and Wohletz, 1991), the presence of such deposits in submarine environment are lacking and therefore explosive eruptions on the seafloor are somewhat debated (Maicher et al., 2000; White et al., 2003; Schipper et al., 2013; Cas et al., 2003).

Nevertheless, active explosive eruptions on West Mata and NW-Rota-1 volcanoes in the Southwest Pacific conclusively show that explosive eruption can and do occur on the seafloor (Deardorff et al., 2011).

Phreatic

Phreatic eruptions are steam-driven explosive events that occur in the subsurface when water flashes to steam upon interaction with hot volcanic material (Barberi et al., 1992). Magmatic heat transfer to often circulating water sources (e.g. lakes, groundwater, shallow ocean) results in super-heated steam

explosions driven by vapor expansion (Barberi et al., 1992; Germanovich and Lowell, 1995). The result is a violent eruption that fragments the host rock without direct interaction of magma (Ollier et al., 1974). Products of phreatic eruptions therefore only include country rock fragments while juvenile volcaniclasts are absent.

Phreatomagmatic

Phreatomagmatic eruptions differ from phreatic eruptions in that they involve direct interaction of water with magma, resulting in a rapid transition from liquid to vapor (steam) bubbles. The result is a highly explosive eruption (Büttner et al., 2002; Zimanowski et al., 1997) driven by *molten fuel-coolant interaction* (MFCI; White, 1996). MFCI refers to interaction between a fuel (magma) and a coolant (water) resulting in a highly explosive fragmentation process which occurs in four distinct stages over several milliseconds (White, 1996). First, (i) contact between the fuel and coolant results in a stable vapor film. Next, (ii) the vapor film collapses resulting in transfer of thermal energy to mechanical energy driving fragmentation of fine, “primary” particles. Next, (iii) coolant expands explosively upon coolant “flashing” of bulk material mixing. During the last stage, (iv) “induced fragmentation” occurs when explosive expansion propels primary particles and melt into other particles resulting in “secondary” particles. These stages assume expansion of H₂O from liquid to gas. Extreme pressures in subaqueous environments reduce the potential for phreatomagmatic explosivity by lowering the expansion capacity of the liquid-to-gas phase transition of water

(Büttner et al., 2002; Zimanowski et al., 1997). MFCI is limited to the critical point of seawater (30 MPa; Bischoff and Rosenbauer, 1985; Portner et al., 2014), below which, heated seawater would behave as a supercritical fluid limiting any steam / vapor expansion.

In contrast to other eruption styles, which generally do not contain juvenile clasts and are highly vesicular (Heiken, 1972; Wohletz and Krinsley, 1982; McPhie et al., 1990), phreatomagmatic eruptions are generally characterized by fine-grained juvenile vitriclasts (Wohletz et al., 1986; White, 1996) that are “dense” or angular / blocky and often show brittle fragmentation features (e.g. step-fractures, pitting; Büttner et al., 1999; Büttner et al., 2002).

Phreatomagmatic explosivity and autoclastic fragmentation may occur together as seawater and magma interact resulting in an initial explosive fragmentation from steam-expansion and secondarily by thermal quench granulation (Van Otterloo et al., 2015).

HMT Eruption Style and Fragmentation Mechanism

Subsample Population Morphology

Ash particle shape analysis has been used extensively to infer fragmentation mechanism and / or eruption style (e.g. Dellino and La Volpe, 1996; Büttner et al., 2001; Riley et al., 2003; Maria and Carey, 2007; Leibrandt and Le Pennec, 2015; Liu et al., 2015; Buckland et al., 2017; Nurfiani et al., 2017). Representative datasets from Axial Seamount’s HMT subsamples were plotted using SLD vs. CVX plots and compared to other known eruptions including Surtsey, Mount St.

Helens, Tambora, and MOK seamount from the East Pacific Rise (Fig. 45). Table 15. summarizes sample comparisons to those analyzed from Axial Seamount and West Mata. Ash analyzed from phreatic (Surtsey) and magmatically explosive style eruptions (Mount St. Helens and Tambora) generally have lower solidity values and significantly lower convexity values indicating higher textural roughness correlating to higher vesicularities (Liu et al. 2015). Axial Seamount vitriclasts have similar solidity and convexity values to the MOK seamount data (>2000 m deep near the East Pacific Rise), analyzed by Maria and Carey (2007). High solidity and convexity values (>0.8 & 0.8 respectively) are indicative of “dense” particles with low textural roughness, which are consistent the low volumes of volatile exsolution common in deep-marine eruptions.

SLD vs. CVX comparison plots of lithofacies in push cores, scoop bags, and a subsample from the 2009 West Mata eruption, shows some variability (Fig. 39; Table 13). While data suggest that there is a difference in fragmentation style between subsamples collected from lithofacies (TM, HMT, LPT), scoop bag subsamples, and other submarine volcanic samples, SLD vs. CVX plots do not appear to differentiate between subsamples collected from TM, HMT, and LPT. To further explore difference in fragmentation mechanisms between push core and scoop bag subsamples, *convexity* frequency distribution curves were analyzed.

Figure 45. SLD vs. CVX plot of a representative HMT subsample (D522-PC62L_27.0) compared to other ash samples. Lower convexity values shallow-marine (Surtsey) and subaerial eruptions (MSH and Tambora) correlate to higher vesicularity (Maria and Carey, 2007). HMT shows high convexity and solidity values similar to ash from MOK seamount (yellow) on the East pacific Rise, both of which have low vesicularity. Refer to Table 15 for sample comparisons.

Table 15. Samples used for ash morphology comparison.

Location / Samples	Occurrence	Eruption year / age	Composition	Magma fragmentation process	Volcanic explosivity index (VEI)	Grain size analyzed (μ m)	Vesicularity (%)	References
Axial Seamount <i>TM</i> <i>HMT</i> <i>LPT</i> <i>Scoop Bags</i>	Submarine (>1400 m)	<1,500 ya	Basalt	Magmatic (TM) Phreatomagmatic (HMT) ^a Magmatic (LPT) Autoclastic (Scoop Bags)	N/A	250 - 500	<10	This study; Portner et al. (2015) and references within
West Mata <i>J2-417_r28</i> <i>J2-418_Sed7</i>	Submarine (1200 m)	2009	Boninite	Magmatic?	N/A	250 - 500	31.4	Resing et al. (2011)
MOK Seamount	Submarine (>2000 m)	N/A	Basalt	Autoclastic	N/A	250 - 500	<10	Maria and Carey (2007) and references within; Liu et al. (2015) and references within
Mt. St. Helens	Subaerial	1980	N/A	Magmatic	4	250 - 500	~79	Newhall and Self (1982); King and Cashman (1994); Liu et al. (2015) and references within
Tambora	Subaerial	1815	Trachy-andesite	Magmatic	7	350 - 500	~50	Newhall and Self (1982); Gertisser et al. (2011); Liu et al. (2015) and references within
Surtsey	Submarine (<100 m) / subaerial	1963 - 1964	Basalt	Phreatomagmatic ^b	2	250 - 500	~45	Newhall and Self (1982); Moore (1985); Liu et al. (2015) and references within
Tungurahua (2001) <i>TU2001-3</i> <i>TU2001-5</i>	Subaerial	2001	Andesite	Magmatic	2	250 - 300	N/A	Leibrand and Le Pennec (2012); Leibrand and Le Pennec (2015) and references within
Tungurahua (2006) <i>TU-2006-6</i>	Subaerial	2006	Andesite	Magmatic	3	250 - 300	N/A	Fee et al. (2010); Leibrand and Le Pennec (2015) and references within
Puy de Montchal <i>MC6ka-1</i>	Subaerial	6.6 ka	Basalt	Magmatic	N/A	250 - 300	N/A	Leibrand and Le Pennec (2015) and references within

Notes:

^a Arched in this study

^b Phreatomagmatic includes magma-water interaction above the vent

Abbreviations:

ka: thousand years ago

m: meters

N/A: Not described / not available

VEI: Volcanic explosivity index

ya: years ago

Convexity distribution curves were compared to subaerial volcanic ash samples of known eruption styles and inferred fragmentation mechanisms (Fig. 46A; Table. 15). Leibrandt and Le Pennec (2015) plotted convexity frequency distribution curves of four samples. Samples *TU2001-5* and *TU2001-3* are from the 2001 eruption of Tungurahua (andesitic stratovolcano in Ecuador), which is described as small-scale strombolian style eruption. The same volcano produced sample *TU-2006-6*, which was from a much more explosive plinian style eruption in 2006. The fourth sample, *MC6ka-1*, is from Puy de Montchal (basaltic scoria cone) in France, which formed from a strombolian style eruption. Axial Seamount vitriclast subsamples from TM, HMT, LPT, and subsamples from West Mata (*J2-417_r28* and *J2-418_Sed7*) were separated and plotted with similar distribution frequencies for comparison.

Subsamples from TM and LPT are similar to subsamples from West Mata (Fig. 46B), potentially suggesting a similar fragmentation style. Observations from West Mata show that the eruption was strombolian and produced vesicular and fluidal (limu o' Pele) vitriclasts (Resing et al., 2011; Clague et al., 2009a), suggesting that LPT and TM may also have formed by a similar eruption style. These subsamples are similar to ash sampled from Strombolian eruptions at Puy de Montchal.

The HMT subsample resembles ash analyzed from the 2006 eruption at Tungurahua (Fig. 46D), which is distinctly different from samples interpreted to have been fragmented by non-explosive (autoclastic) and explosive (pyroclastic)

Figure 46. **(A)** Convexity distribution curves for all subsamples from Axial Seamount compared to the West Mata subsample, and subaerial eruptions analyzed by Leibrandt and Le Pennec (2015). TU-2001 is from the 2001 eruption of Tungurahua (Andesitic stratovolcano in Ecuador). TU-2006 is from the 2006 Tungurahua eruption. MC6ka is a sample from Puy de Montchal (basaltic scoria cone) in France. **(B)** Scoop bag subsamples from Axial Seamount (autoclastic fragmentation) are similar to the 2001 eruption of Tungurahua. **(C)** West Mata subsample (strombolian eruption style) is similar to TM and LPT lithofacies subsamples from Axial Seamount. These also show a similar peak location to ash from Puy de Montchal. **(D)** HMT subsample is notably different from scoop bag subsamples, West Mata, and other lithofacies (TM and LPT). It also shows a similar distribution to the 2006 Tungurahua eruption. Note different scales used in B and D to show distribution curves more clearly. Refer to Table 15 for sample comparisons.

processes. The 2006 eruption at Tungurahua was more explosive (volcanic explosivity index: 3; Fee et al., 2010) compared to the 2001 eruption (volcanic explosivity index: 2; Le Pennec et al., 2012) resulting in a different ash morphology signature (Leibbrandt and Le Pennec, 2015). Therefore, the unique curve of HMT compared to other submarine subsamples may imply a different fragmentation mechanism is responsible compared to scoop-bag subsamples, TM / LPT lithofacies, and West Mata.

Although there are similarities in subsample convexity distributions compared to those measured by Leibbrandt and Le Pennec (2015), more work is required to better understand differences in ash morphology related to eruption style and fragmentation mechanisms in submarine vs. subaerial eruptions. Specifically, the practice of comparing submarine ash subsamples from Axial Seamount to subaerial eruptions may not be directly analogous due to entirely different magma compositions, volatile contents, vesicularities, conduit geometries, and ambient pressures at the vent surface. Nonetheless, similarities in convexity histograms of vitriclasts analyzed from Axial Seamount and West Mata (submarine) show distinct segregation, similar to differences in subaerial eruptions with different fragmentation mechanisms and eruption styles. The uniqueness of the HMT subsample compared to other lithofacies (TM and LPT), scoop bag subsamples, and strombolian style ash subsamples from West Mata supports the idea that ash within HMT was fragmented by a mechanism other

than autoclastic fragmentation or magmatic explosivity during strombolian-style bubble bursts.

Vitriclast Texture

The texture of juvenile vitriclasts (size, shape, and vesicularity) provides insight into fragmentation energy and mechanism (Wohletz et al., 1995; White, 1996; Deardorff et al., 2011). Point count results show that vitriclasts are the primary component of HMT lithofacies (~60%; Fig. 23). While vitriclasts dominate coarser grain-size fractions, fine grain-sizes (<125 μm) consist of >40% vitriclasts implying that PSA analysis of bulk HMT represents the vitriclasts fraction. The mean grain-size of HMT is about 100 μm (Fig. 20), which is consistent with high fragmentation energy and the likely involvement of external water (Wohletz et al., 1983; White, 1996). The fine-grained nature of HMT is therefore consistent with the highly energetic phreatomagmatic eruption style.

Texture is also strongly controlled by the physical state of the magma (liquid or solid) and fragmentation mechanisms. Vitriclasts may be divided into two distinct shapes, fluidal and angular / blocky. Fluidal vitriclasts occur when magma is fragmented while in a ductile state while angular / blocky vitriclasts occur once magma is in a brittle state after cooling below the glass-transition temperature (T_g ; Allen et al., 2010). The T_g is defined as a kinetic transition of a magma from a liquid to solid-like behavior (Porreca et al., 2014).

Point count and MGS results of vitriclast morphology (Figs. 22B and 40) reveal that the vast majority (>90%) of vitriclasts in the 125 – 250 μm size

fraction are angular / blocky while fluidal particles make up <10%. These results suggest that fragmentation styles predominantly occurred while magma was in a brittle-state. Moreover, the lack of fluidal vitriclasts in HMT argues against a magmatic explosivity fragmentation style (e.g. strombolian style), which has been the preferred submarine explosive eruption mechanism (Clague et al., 2009b; Resing et al. 2011) .

Morphologies of angular vitriclasts (Fig. 38) have surface features representative of brittle fragmentation including conchoidal fracturing and step-fractures. Both of these surface features form by MFCI processes during phreatomagmatic eruptions (White, 1996; Buttner et al., 1999; Buttner et al., 2002). Pitted features on fresh vitriclasts (Fig. 38B-3B) are particularly useful in identifying MFCI processes as they are thought to occur due to hydrothermal fluids etching of volcanic glass in the subsurface during ascent (Buttner et al., 2002). Rigid surface features observed in HMT vitriclasts supports brittle fragmentation.

Vesicularity is an important component of vitriclast texture and is controlled by volatile exsolution. High vesicularity is ubiquitous in explosive magmatic eruptions on land where volatile degassing and gas expansion drives explosivity (Sparks et al., 1977). Vesicular vitriclasts are uncommon (<0.2% of total HMT subsamples on average), which is also evident by the “dense” particle populations in SLD vs. CVX plots. MGS results of SLD vs. CVX plots reveal that all subsamples have high *solidity* and *convexity* values therefore corresponding

to low textural and morphological roughness (Liu et al., 2015). These results are consistent with low quantities of vesicular vitriclasts determined in point counts. Lack of vesicular vitriclasts in fine-grained ash is consistent with phreatomagmatic eruptions driven by MFCI (Buttner et al., 2002; White, 1996).

Fragmentation and Eruption Style Conclusions

Convexity distribution curves comparing LPT, TM, and subsamples from West Mata, all of which are inferred to have fragmented during strombolian style eruptions (Resing et al., 2011), have different peak locations compared to HMT, and are distinctly different from Axial Seamount scoop bag subsamples inferred to have fragmented by autoclastic (non-explosive) fragmentation. This implies that the majority of vitriclasts within HMT were not fragmented by magmatic volatile overpressures or autoclastic processes.

HMT is dominated by dense angular / blocky vitriclasts, which represent a fragmented very poorly vesicular melt. Low proportions of fluidal shards in HMT suggest that magma fragmented while in a brittle state and that strombolian eruptions were not the primary eruption style responsible for vitriclasts observed in HMT. Vitriclast surface features including step-fractures and conchoidal fractures, consistent with brittle fragmentation. Surface pitting may be indicative of fresh vitriclasts interacting with hydrothermal fluids in the subsurface consistent with phreatomagmatic eruptions.

The fine-grained nature of HMT (~100 μm peak mode) and abundance of lithics within HMT are consistent with experiments by Wohletz et al. (1986) and

White (1996), and analysis of natural pyroclasts (Deardorff et al., 2011) indicating phreatomagmatic eruptions by MFCI. Chemical heterogeneity of vitriclasts (Portner et al., 2015) support the idea that some vitriclasts are cognate lithics, products of previous eruptions that were incorporated into the erupted plume. Additionally, the presence of accessory lithics (see *non-primary volcaniclast origin - conduit wall-rock*) are indicative of phreatomagmatic eruptions, where conduit walls are stripped and incorporated during magma ascent (Deardorff et al., 2011). Portner et al. (2015) estimated combined lithostatic and hydrostatic pressures on Axial Seamount to be about 29.0 MPa above the melt lens, or 600 mbsf. Based on the provenance of accessory lithics it is estimated that fragmentation by MFCI on Axial Seamount would therefore be limited to a depth of ~600 – 800 mbsf near the critical point of seawater (Fig. 47).

Deep Marine Dispersal

Historically, maximum dispersal of pyroclastic material in submarine volcanic settings has been estimated to be only tens of meters (Head and Wilson, 2003). The intense hydrostatic pressure coupled with the relatively high viscosity of seawater in deep-marine environments relative to subaerial settings, has been thought to limit dispersal of volcaniclastic material (Cashman and Fiske, 1991). However, multiple examples have recently been described where volcaniclastic deposits have been observed several kilometers away from the source in deep-marine settings (e.g. Ferguson et al., 2017; Clague et al., 2009b; Walker et al., 2007).

Figure 47. Conceptual model of mechanisms responsible of HMT formation and deposition. Dikes propagate to and through caldera ring fault system. Seawater infiltrates ring faults and facilitates magma-seawater interaction and MFCI at a depth of 600-800 mbsf (maximum depth is dependent on critical point of seawater). Phreatomagmatic exhalation (large green arrow) strips bedrock and well-rock thus incorporating accessory lithics in conduit, and authigenic minerals from circulating low-temperature hydrothermal fluids (green curved arrows) under reducing conditions. Above the vent, the phreatomagmatic plume entrains authigenic minerals precipitating in the water column under oxidizing conditions. Deposition of HMT is facilitated by bottom currents, plume-collapse gravities, and plume entrainment and fall-out over 3.5 km away from the source. Alteration zones (Alt et al., 1986) shown for reference.

Three primary mechanisms have been proposed for transporting volcanic material in submarine settings and include (1) plume entrainment and subsequent fall-out (Clague et al., 2009b; Barreyre et al., 2011; Verolino et al., 2018), (2) sediment gravity flows (Doronzo and Dellino, 2012; Walker et al., 2019), and (3) bottom current transport of re-worked material (Stow and Lovel, 1979). Dispersal by plume entrainment involves an eruption launching pyroclasts into the water column where they are entrained by warm, buoyant fluids, which eventually fall-out due to gravity (Clague et al., 2009b). Settling velocity experiments by Barreyre et al., 2011 suggest that clast size and shape strongly influence the dispersal distance of particles by plume entrainment and subsequent fall-out and may result in blocky glass shards up to 1 mm being transported up to 1 km, while smaller (~ 0.5 mm) bubble-shards can be transported several kilometers away from the source. Plume entrainment and fall-out therefore preferentially sorts material due to different settling velocities of particles often resulting in normal grading and a decrease in grain-size with increasing distance from the source (Barreyre et al., 2011).

Based on the 100 μm mean grain-size of HMT and extrapolation of settling velocity experiments by Barreyre et al. (2011), average settling velocity of HMT material is approximately 1 cm/s which has the potential to transport material on Axial Seamount more than 3.5 km away from the inferred source (caldera) with a minimum plume height of 1,000 m above the seafloor. Ongoing unpublished work suggests that pyroclasts may have reached the ocean surface, well above 1,000

m above the seafloor, by *megaplume* entrainment (Clague pers. Comm.).

Additional work modeling volcanic plumes in deep-marine settings and vitriclast dispersal is necessary to determine whether Axial Seamount's eruptions could have facilitated plumes capable of dispersing vitriclasts to the extent observed.

Several types of gravity flows exist in submarine volcanic environments including volcanic turbidity currents, (VTC's) caused by slope failure or seismicity, and pyroclastic density currents (PDC's) where the flow is triggered by plume-collapse. Studies by Pritchard and Gladstone (2009) & Brand and Clarke (2012) found that VTC's and PDC's have similar flow dynamics; therefore, for the purposes of this study, we use the term "gravite" (Gani, 2003) to refer to deposits generated by both mechanisms. Volcaniclastic gravites have the ability to transport sediment in excess of 5 kilometers (Brand and Clarke, 2012). Additionally, Walker et al. (2019) discussed the ability of volcaniclastic gravites to detach (liftoff), from the seafloor creating a buoyant plume by that could be transported several kilometers. As with the plume entrainment mechanism, turbulent gravity flows also preferentially sort sediment generally resulting in well-sorted material that is generally normal-graded (Bouma, 1962), but in contrast, may also exhibit reverse-graded bedding in higher density gravity flows over significantly short transport distances (tens of meters) with non-turbulent flow (e.g. grain flow; Fisher, 1971).

Relatively gentle slopes on Axial Seamount reduce the chances that VTC's are caused by slope failure (Van Andel and Komar, 1969); however, they could

be triggered by overburden through volcanoclastic accumulation, particularly near vents. They could also be triggered by eruption plume-collapse. Although well-sorted material, well-defined ash laminations and normal grading may be indicative of gravites, the fine-grained nature of HMT coupled with the “reverse-normal graded” structures in proximal and medial cores and diffuse ash laminations in distal cores argue against gravites as being the primary dispersal mechanism. While VTC’s could have occurred in proximal settings, particularly near caldera margins, they do not explain the presence of HMT extending 3.5 km.

Bottom currents on the seafloor have the potential to re-mobilize and disperse sediment resulting in contourite deposits (Stow and Lovell, 1979). Contourite deposits often exhibit normal grading, parallel laminae, and ripples, in fine-grained, well-sorted sediment (Shanmugam et al., 1993; Martín–Chivelet et al., 2008; Rebesco et al., 2014). Although often described in continental slope settings, multiple examples have been described in deep-marine settings (e.g. Stow et al., 2002; Hernández-Molina et al., 2008). Xu and Lavelle (2017) modeled bottom currents on Axial Seamount suggesting the possibility of volcanoclastic dispersal by bottom currents.

The fine-grained, well sorted nature of ash laminations (well-defined and diffuse), and “reverse-normal grading” structures in HMT are all features identified in contourites deposited by bottom currents (Stow et al., 1979; Shanmugam et al., 1993; Martín–Chivelet et al., 2008). Bottom current models by

Xu and Lavelle (2017) show significant bottom current velocities (10 – 11 cm/s) extending more than 200 m above Axial Seamount's summit in a toroidal (anti-cyclonic) pattern. Bottom currents have the potential to transport HMT more than 3.5 km away from the source (Fig. 47).

Although grain-size analysis and visual observations of core structures and depositional / thickness trends allows us to make inferences on dispersal mechanisms, further analysis is required. Multiple mechanisms likely attributed to HMT dispersal. Future work to model plume dynamics and vitriclast dispersal on Axial Seamount is ongoing.

CONCLUSION

Phreatomagmatic eruptions during caldera collapse on Axial Seamount produced a unique volcanoclastic lithology, hydrothermal muddy tuff (HMT) lithofacies, containing fine-grained vitriclasts, and crystalline bedrock and hydrothermal lithics. The uniqueness of this lithofacies, unlike any other lithology on Axial Seamount, is due in part to magma-seawater interaction along ring-faults of the caldera system. The depth in the crust of this interaction is constrained by the formation temperatures of accessory lithics mineralogy in HMT (e.g. greenschist grade fragments) and is close to the critical point of seawater between 600-800 mbsf. Bedrock fragmentation during eruption stripped the conduit walls during ascent and incorporated parts of the basal portion of the upper oceanic crust (pillow basalt section) into the ascending eruption plume. Abundant high temperature clays at the top of HMT in proximal and medial cores

may suggest that deeper crust was stripped during the last phase of phreatomagmatic exhalation.

Magma fragmentation during phreatomagmatic eruption was driven by MFCI. Non-fluidal and poorly to non-vesicular textures indicates that the majority of vitriclasts fragmented while their parent magma was in a brittle state and argues against fragmentation by magmatic volatile degassing alone. Ash morphology trends of HMT compared to deposits of known autoclastic and strombolian-style fragmentation processes suggests that its erupting magma fragmented by a different mechanism. The fine grain-size of HMT (average peak mode 100 μm) implies high fragmentation energy consistent with MFCI (Wohletz et al., 1986; White, 1996). Such high energy interaction would generate the abundance of accidental lithics within HMT, further supporting a phreatomagmatic origin where conduit walls were stripped during by MFCI processes.

Upon eruption through the vent and into the ocean column, the eruption plume precipitated authigenic hydrothermal minerals at low-moderate temperatures (40 – 170 $^{\circ}\text{C}$). This is supported by the notable absence of high-temperature hydrothermal minerals (e.g. siderite, cubanite, chalcopyrite) common in more typical black smoker deposits. Mineral precipitation near the vent is supported by the presence of unique agglutinate particles, which indicates that magma was still molten when it interacted with the hydrothermal mineral precipitates.

The resulting phreatomagmatic eruption plume dispersed HMT over 3.5 km away from the caldera source. Deposition of HMT occurred by different dispersal mechanisms including plume entrainment and fall-out, ocean bottom currents, and, perhaps, localized plume-collapse-induced gravites near caldera margins. Plume fall-out in proximal and medial locations (<2 km), and fluctuating eruption flux or bottom currents created laminations with “reverse-to-normal graded” structures. Lack of well-defined ash laminations in distal cores supports re-working of HMT by ocean bottom currents.

In summary, this study provides insight into how caldera formation can influence deep-marine eruption processes. Lithic provenance data are critical and may be used to distinguish phreatomagmatic vs. other eruptions styles in deep-sea settings. Although work presented here distinguished accessory and accidental lithics, future geochemical work is required to identify juvenile vitriclasts from cognate lithics, which would help confirm models of primary magma fragmentation. The vitriclast morphology datasets from this study is one of the first of its kind and may be used to populate a database with standardized ash morphometric parameters, which would aid future comparison of eruption styles and environments (e.g. subaerial). Such a database will be invaluable in helping future marine volcanologists identify the fingerprints of deep-marine pyroclastic eruptions, a still highly debated topic. Combined with a spatial analysis of the associations between lithofacies to mapped fissures and lava

flows, future workers will better understand the connection between volcaniclast dispersal processes and eruption styles in the deep sea.

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APPENDICES

Appendix A: Core Descriptions

D515-PC74L

Unit	Thickness (cm)	Lithofacies	Description
1	2.0	HMT	Sandy mud – fine-grained ash. Glass is sporadic and mostly appears blocky. Orange Fe oxides are abundant and white mystery mineral is present. Hydrothermal clays present but not green (orange color). No biogenics or volcanic minerals. Contact is gradational with underlying unit (possibly artificial mixing by coring). Color: Light Olive Grey (5Y 5/2).
2	5.0	LPT	Ash – Coarse Ash to fine lapilli containing both fluidal and blocky grains. Additionally, Fe oxides are abundant within ash. Plagioclase and other feldspar crystals are present. Olivine crystals also present. Sample taken from 4 cm depth with oxidized contamination (since removed) from metal pin. Sharp basal contact with below unit.
3	13.0	TM	Ashy mud – Fine grained to medium grained ash that is predominantly blocky. Top 10 cm contains about 15% glass whereas bottom 2 cm is very fine-grained ash mixed with biogenics and similar componentry. Contains abundant orange Fe oxides and biogenic material is present. Feldspars mixed with glass. Possibly some diffuse laminations, but unit has samples removed previously making it difficult to tell. Samples previously taken at 1, 3.5, 5, and 8 cm within unit. The samples at 1 cm and 5 cm had oxidation contamination (since removed). Sharp basal contact with ~5-degree angle. Color: Moderate Brown (10YR 5/4).
4	24.0	HMT	Sandy mud – Fine-grained ash that is mostly blocky and about 10%. Contains orange Fe oxides, green hydrothermal clay particles, and unknown white mineral. Feldspar and olivine crystals appear present within thicker glassy laminations. Diffuse laminations at 2.5 cm and 9.5 cm of about 0.5 cm thickness that is predominantly blocky ash. Thicker pronounced laminations at 18.5 and 24 cm (base of core) of about 1 cm thickness also containing predominantly blocky ash. Laminations Unit is mostly massive with some glassy laminations. Color: Light Olive Grey (5Y 5/2).

D516-PC61XL

Unit	Thickness (cm)	Lithofacies	Description
1	11.0	TM	Ashy mud – Ash is mixed with both fluidal and angular, medium lapilli and approximately 40 – 50% modality. Components: Orange Fe oxides are present, biogenics are sparse, hydrothermal clays are absent. Plagioclase is present, no other volcanic material was observed. Unit has several pulses of ash throughout unit where ash is concentrated, but no laminations. Top of unit contains slightly more ash and larger sized particles and thins out near the bottom, reversely graded. Sharp contact with underlying unit. Color: Moderate Yellowish Brown (10YR 5/4).
2	4.5	HMT	Sandy mud – Ash style appears angular, but is very fine-grained and sparse, fine-grained ash with about 25% modality. Components: Orange Fe oxides are present, hydrothermal clays are present (more yellow colored), biogenics are absent, volcanic material and plagioclase appears absent, but may be sparse within mud. Unit contains a lamination at very top, ~1 cm thick that is more yellowish grey in color than the overall unit and only about 1% modality of ash. Gradational contact with underlying HMT unit. Color: Pale Yellowish Brown (10YR 6/2).
3	13.5	HMT	Sandy mud – Ash is predominantly blocky/angular, but does contain some fluidal ash, fine-grained ash approximately 50% modality. Components: Orange Fe oxides are present, hydrothermal clays are present, altered zeolite minerals are abundant, plagioclase is present, no sulfides or biogenics observed. Unit contains one ash lamination approximately 11 cm depth and about 1 cm thick, contains mostly thin, platy fluidal ash with some blocky material that is fine lapilli. Plagioclase and crystalline basalt is also present in lamination Sharp contact with underlying ash unit. Color: Light Olive Grey (5Y 5/2).
4	18.5	LPT	Ash – Predominantly blocky/angular, with some fluidal vitriclasts present. Grain size is medium lapilli. Contains a wide variety of ash morphologies. Contains abundant feldspars including plagioclase both as single crystals and that appear attached to glass. Crystalline basalt fragments are present. Olivine appears sparse. Orange Fe oxides are absent, other than contamination from metal pushpins. No other material is present. Lamination at approximately 1 cm depth and about 1 cm thick that is muddier, but still ~ 70% ash modality. Lamination is mixed with hydrothermal material and components similar to above unit (HMT). Unit is normally graded with a sharp contact with underlying unit.

Notes:

Samples previously taken at the following depths (cm):

0.0; 5.0; 9.0; 13.5; 17.5; 21.5; 27.0; 29.5; 30.5; 32.5; 44.0 . . . All metal pushpins were removed, heavy oxidation contamination was present and was removed as best as possible.

Used to describe thickness of units near rim of caldera, do not sample as already heavily sampled.

D522-PPC1

Unit	Thickness (cm)	Lithofacies	Description
1	8.5	TM	Ashy mud – Ash is predominantly blocky but also contains some fluidal shards. Grain size is coarse ash and modal percent is about 30 – 35% ash. Contains abundant orange Fe oxides – Unit appears heavily oxidized – Plagioclase and crystalline basalt fragments appear sparse. Hydrothermal lithics also appear sparse, but some are present near bottom of unit, likely mixed in from underlying HMT. Unit is structureless. Gradational contact with underlying unit. Color: Moderate Brown (10YR 5/4).
2	10.5	HMT	Sandy mud – Ash is a mixture of fluidal and angular, fine-grained ash. Modal percent is about 25% ash. Components: Orange Fe oxides are present, hydrothermal lithics are abundant. Plagioclase is present. Crystalline basalt appears sparse. Biogenics are absent. Unit contains a lamination at very top of unit, about 1.0 cm thick that is the distinct yellow/green/grey color and contains fewer ash modality. Second lamination at ~3.0 depth and about ½ cm thickness containing “stacked” platy vitriclasts that appear heavily oxidized. Two diffuse laminations of more ash at 7.0 and 8.5 cm depth. Contact is sharp with underlying unit and at ~15-degree angle. Color: Light Olive Grey (5Y 5/2).
3	2.5	LPT	Ash, Predominantly blocky/Angular with some fluidal vitriclasts present. Ash is medium lapilli. Contains abundant feldspar crystals, crystalline basalt is present. Sparse olivine crystals. Orange Fe oxides are present. Some clay material mixed with very top of unit, likely from overlying HMT. Overall unit is normally graded. Contact is sharp at ~15-degree angle.
4	8.0 – 10.0	HMT	Sandy mud – Overall unit is very similar in terms of ash size and style and components as unit #2 (HMT). Ash is a mixture of fluidal and angular, fine-grained ash. Modal percent ~35% ash. Components: Orange Fe oxides are present, hydrothermal lithics are abundant. Plagioclase is present. Crystalline basalt appears sparse. Biogenics are absent. No laminations; however, there is a weird-shaped bulge of ash at ~6cm depth within unit that is 3 cm thick on sides of core and pinches out near the middle of the core. Weird shape could be artificial coring artifact? Ash within bulb is a mix of angular and fluidal and contains plagioclase, abundant crystalline basalt – medium to coarse lapilli. Basal contact of unit is sharp at no angle. Color of overall unit: Light Olive Grey (5Y 5/2).
5	3.0	LPT	Ash – Predominantly blocky / angular. Grain size is coarse lapilli. Contains abundant plagioclase, abundant crystalline basalt lithics, orange Fe oxides are present mostly as a fine surficial coating on vitriclasts. No hydrothermal clay lithics or other components. Lamination at 1.0 cm depth of approximately ½ cm thickness of highly oxidized volcanic glass.

D522-PC62L

Unit	Thickness (cm)	Lithofacies	Description
1	9.0	TM	Ashy mud – Ash is predominantly blocky but does contain some fluidal vitriclasts. Ash grain size is medium lapilli. Modal percent is 35 – 40% ash. Contains orange Fe oxides present, plagioclase is sparse, crystalline basalt is sparse, biogenics are also sparse. Hydrothermal lithics are absent. Unit is intermixed with fine mud and coarser ash without true laminations. Gradational contact with underlying unit. Color: Moderate Yellowish Brown (10YR 5/4).
2	21.0	HMT	Sandy mud – Ash style appears to contain both blocky and fluidal ash and varies within unit. Ash is fine-grained ash and is approximately 5 – 30% modal percent. Contains orange Fe oxides are present, hydrothermal lithics are abundant. Plagioclase and crystalline basalt is present. Unit contains a lamination at very top of unit that is ~ ½ cm thick and more yellowish, greenish grey color. The top 16 cm of the unit is relatively ash-poor and finer-grained hydrothermal clays whereas the bottom 5 cm of the unit is more ash-rich (~30% ash modality) and coarser-grained ash containing predominantly fluidal ash. Overall unit is normally graded, particularly the bottom 5 cm. Color: Light Olive Grey (5Y 5/2).
3	3.0	LPT	Ash – Predominantly angular/blocky ash with some fluidal shards present. Grain size is medium lapilli. Contains abundant feldspars including plagioclase. Crystalline basalt fragments are also present. Olivine appears sparse. Orange Fe oxides are absent. Some hydrothermal clays are mixed into top of unit likely from overlying HMT. Overall unit is normally graded. Contact is sharp and at ~ 15-degree angle.
4	16.0	HMT	Sandy mud – Ash appears predominantly fluidal, fine-grained ash and approximately 5% modality. Contains orange Fe oxides are present, hydrothermal clays and lithics are abundant. Plagioclase is present. Sulfides may be sparse. Unit contains several diffuse laminations at ~ 15-degree angles. First lamination is at 5.0 cm, another at 7.0 cm, and a third at 12.0 cm. All of these diffuse laminations are normally graded. Sharp contact with underlying unit at ~10-degree angle. Color: Light Olive Grey (5Y 5/2).
5	2.5	LPT	Ash – Predominantly blocky / angular. Grain size is medium lapilli. Contains abundant plagioclase, olivine is present. Orange Fe oxides are absent. Hydrothermal lithics and other components are also absent. Unit is normally graded.

D522-PC66

Unit	Thickness (cm)	Lithofacies	Description
1	7.0	TM	Ashy mud – Ash is primarily fluidal with some small blocky particles, coarse ash and about 40% modality. Components: Biogenics are sparse, orange Fe oxides present. No plagioclase crystals visible. Clay aggregates are sparse. Slight color variation and mottling within overall unit. Lamination at 6.5cm depth of a muddy, olive-grey color about 2 – 3mm thickness. Sharp basal contact at bottom of glass lamination with next unit. Color: Dark Yellowish Orange (10YR 6/6).
2	4.0	HMT	Ashy mud – Ash fine-grained ash and about 30% modality. Components: Orange Fe oxides are present. Sulfide minerals are present. Near top of unit, small amount of ash settled from overlying unit. Biogenics are absent. Clay particles are present. At 2 cm depth, 3 mm thick glassy lamination composed of fluidal ash and also containing plagioclase. At 3.5 cm depth, 5mm thick ash lamination containing both fluidal and blocky ash, plagioclase crystals and crystalline basalt present. Sharp contact with underlying unit marked by glassy lamination. Color: Light Olive Grey (5Y 5/2).
3	6.0	HMT	Sandy mud – Ash contains both fluidal and blocky fine-grained ash. Ash modality is approximately 10–15%. Components: Biogenics are sparse. Orange Fe oxides are present, green hydrothermal clay particles are abundant. Sulfides also present. Plagioclase crystals are absent. Overall unit is structureless. Sharp contact based on ash content. Color: Light Olive Grey (5Y 5/2).
4	3.0	HMT	Ashy mud – Ash contains both fluidal and blocky fine-grained ash with approximately 30% ash. Components: Biogenic material is present, orange Fe oxides are present, green clay material is present, sparse plagioclase crystals, very sparse crystalline basalt fragments. Possibly some sulfides near top of unit. Very diffuse lamination at top of unit ~2 mm thick which includes more fluidal and stacked platy vitriclasts and includes more plagioclase within the lamination. Color: Light Olive Grey (5Y 5/2).

D524-PC47XL

Unit	Thickness (cm)	Lithofacies	Description
1	1.0	Artificial	Sandy mud/silt – Mix of glass and hydrothermal fragments. Massive (no structures). Edges taper down ~3 cm and mostly sand. Layer is likely artificial from coring process. Color: Moderate Yellowish Brown (10 YR 5/4).
2	1.0 – 4.0	Artificial	Muddy ash – mostly glass particles mixed with mud brought up from underlying unit. Irregular orientation as it is pulled down the sides of the core. Layer is likely artificial from coring process. Color: Mostly ash (Black).
3	6.5	TM	Ashy mud – Ash is fine ash to fine lapilli with blocky and angular ash particles. Few fluidal vitriclasts present. Ash is evenly distributed. Mud is mottled slightly with areas of lighter/darker mud. Biogenic material is present. Orange Fe-oxides area also present. Layer is structureless (no laminations). Sharp basal contact Sample previously pulled at 5.0 cm within unit. Color: Light Brown (5YR 5/6).
4	10.0	TM	Ashy mud – Ashy laminations. Ash is very coarse ash – fine lapilli and is mostly blocky with few fluidal shards. Laminations ~0.5 – 1.5 cm thick with alternating mud/ash laminations. Ash laminations are diffuse (not obvious). Mud within laminations is similar to mud above laminations. No volcanic crystals observed. Biogenic chunks present. Mottling within unit is present. Sharp basal contact at ~10-degree angle. Color: Pale Yellow-Brown (10YR 5/2).
5	7.0	HMT	Sandy mud. Ash is fine-grained ash, but coarser than surrounding sandy material. Contains orange Fe-oxides and green hydrothermal clay material with white mystery mineral. At ~2cm depth, a much lighter color horizon (whitish -pale yellow) with a lack of ash. No biogenics observed. Some mottling within unit. Gradational basal contact with increasing sand & ash. Color: Moderately Yellowish Brown (10YR 5/4).
6	3.5	HMT	Muddy sand (similar to above unit) – Ash is fine grained ash in top of unit and medium ash near bottom. Componentry is same as above includes Fe-oxides and green hydrothermal clay material with white mystery mineral. Increase in percent of sand and ash. No biogenics or visible volcanic minerals within mud. Unit is normally graded (coarser near bottom fining upward). Sample taken from 1.0 cm depth within sample. Color: Olive Grey (5Y 3/2).
7	5.0	LPT	Ash – Medium to coarse grained lapilli. Fluidal shards concentrated near top and blocky shards near bottom. Contains plagioclase crystals, and some olivine. Notable proportion of feldspar. Crystalline basalt fragments also present. Morphology and grainsize are crudely graded. Sharp basal contact with below.
8	5.0	LPT	Muddy Ash - Medium to coarse grained lapilli with mostly blocky ash. Mud present in rip-ups the entire width of the core. Crystalline basalt and feldspars are present. Similar to overlying unit with slightly more mud from rip-ups. Orange

			oxidation is artificial from metal thumbtack left in unit. Gradational contact with underlying unit.
9	11.0	LPT	Ash – Coarse grained lapilli. Ash is mostly blocky/angular with a few fluidal shards that are thick. Some have “primary surfaces (stepped fragment pattern – brittle, smooth – ductile). Plagioclase crystals present, no good orientation on glassy blocks. Plagioclase crystals appear part of phenocrysts (larger crystals).

D525-PPC2

Unit	Thickness (cm)	Lithofacies	Description
1	16.5	TM	Ashy Mud – Medium-grained ash that is mostly fluidal. Approximate ash modality is about 30%. Contains orange Fe oxides present, green hydrothermal clays are sparse, and biogenics are also sparse. Several laminations within unit: At 6.0 cm below base, lamination of ½ cm containing both fluidal and angular ash that is fine-medium ash. Second lamination at 14 cm that is diffuse (not obvious) and about 0.2 cm thick containing ash that is fluidal/platy appearing stacked together, or on top of each other. Finer lamination at base of unit about 0.5 cm thick that contains a lighter/pale yellow/green color, is sandy mud with lack of ash and includes Fe-oxides. Samples taken at 6.5 cm, 12.5 cm below the base. Color: Light Brown (5YR 5/6).
2	13.5	HMT	Sandy mud – Coarse to fine-grained ash. Contains abundant orange Fe oxides and white mystery minerals, and hydrothermal clays are present. Plagioclase and olivine crystals relatively abundant. Several laminations: at 5 cm depth, fine-grained ashy lamination about 1 cm thick that contains about 7% ash. Second lamination angled at about 25 degrees at 11 cm, that is about 1 cm thick containing medium-grained fluidal ash and few blocky grains and also contains orange Fe oxides, white mineral and green hydrothermal material. Sample taken from 5.5 cm and 11.0 cm. Mottling of color within mud of this unit. Gradational structure with increasing ash towards bottom of unit. Contact with underlying unit is sharp and angled at ~30 degrees. Color: Moderate Yellowish Brown (10YR 5/4).
3	3 – 4	LPT	Ash – Fine to medium-grained lapilli that contains both fluidal and blocky vitriclasts. Contains plagioclase that is abundant, and olivine crystals are present. Sample previously taken at 0.5 cm depth of unit with artificial oxidation (now removed) from metal pin.

D528-PPC72

Unit	Thickness (cm)	Lithofacies	Description
1	11.5	TM	Ashy mud – Medium to fine-grained ash with some medium-grained ash. Ash is angular/blocky. Contains Fe oxides present, minute amount of plagioclase, no visible hydrothermal clays or biogenics. Lamination of muddy glass at 2.5 cm depth. Mostly massive. Glass is homogenous. Samples previously collected at 2.5 & 10 cm depths. Color: Moderate Brown (10 YR 5/4)
2	7.5	HMT	Sandy Mud – Ash is fine-grained ash. Glass is homogenous. Mud and sand is very fine-grained. Large abundance of plagioclase, orange Fe-oxides and hydrothermal clays also abundant. Samples previously taken from 1.0 & 7.0 cm depth. Some possible glass contamination from underlying unit. Contact is gradational with underlying LPT layer at ~ 15 degrees. Color: Moderate Yellowish Brown (10YR 5/4).
3	2.5	LPT	Ash – medium lapilli contains both blocky and fluidal ash. Orange Fe-oxides and green hydrothermal material present in top portion of the unit and is likely fall-out from above unit. Small amounts of plagioclase crystals. Sample previously taken from 1.0 cm depth and contains artificial oxidation from metal pushpin. Sharp basal contact.
4	8.0	TO	Ashy mud – Ash is both angular and fluidal and is medium-grained ash. Ash modality is approximate 15%. Top 3 cm of unit is muddy ash with about 50% ash and abundant biogenics. Overall unit contains abundant biogenics with a sparse amount of ash. No other minerals or crystals observed within unit. Two samples collected at 0.5 & 2.0 cm depth in unit with heavy artificial oxidation contamination (removed) from metal pins. Basal contact not well defined (gradational) but marked by change in color. Color: Greyish Orange (10YR 7/4).
5	12.5	TO	Ashy Mud – Coarse-grained ash that is poorly sorted with some larger vitriclasts. Ash is mostly blocky and approximately 5-7 modal percent. No Fe oxides, hydrothermal material or volcanic crystals. Abundant biogenic material. Samples collected at 6 cm and 9.5 cm depth within unit and contained heavy artificial oxidation from metal pins (since removed). Bottom 4.0 cm of core is only ~3% glass. Section contains more ash percent at top and less near bottom. Color: Greyish Orange (10YR 7/4).

D655-PPC43

Unit	Thickness (cm)	Lithofacies	Description
1	6.5	TM	Ashy mud – Predominantly blocky, fine lapilli with approximately 30 – 40% modality. Components: Orange Fe oxides are present, feldspars are present, hydrothermal material is absent, biogenics are absent, sulfides also absent. Unit is reversely graded containing finer ash near bottom and coarser ash near top. Gradational contact with next unit. Color: Moderate Yellowish Brown (10YR 5/4).
2	12.5	HMT	Sandy mud – Ash is mostly fluidal that is fine-grained ash and approximately 10% modality. Components: Orange Fe oxides are present, green hydrothermal clays are abundant, sparse plagioclase, sulfides present, biogenics are absent. Two diffuse laminations of ash: First is about 1cm from the top and ~ ½ cm thick. Second is at about 2.5 cm depth and ~ ½ cm thick. Large lamination of ash at 6.5 cm depth and about ~1 cm thick, predominantly block medium lapilli, feldspars are abundant, other volcanic material is also abundant. Entire unit is normally graded and has a sharp contact with underlying unit. Color: Light Olive Grey (5Y 5/2).
3	9.0	LPT	Ash – Ash is mixed with both blocky and fluidal, medium lapilli. Components: Abundant plagioclase, olivine is present, oxidized glass shards may be due to exposure ex situ. Wide range of glass morphologies. Lamination at ~ 2.5 cm depth that is about 1.5 cm thick that is ashy mud, containing blocky, fine-grained ash containing orange Fe oxides and plagioclase, no clays or biogenics (similar to TM unit with a Moderate Yellowish Brown color 10YR 5/4 within the lamination).

D655-PPC49

Unit	Thickness (cm)	Lithofacies	Description
1	11	TM	Muddy ash – Predominantly blocky, with some fluidal shards, size is coarse ash with approximately 30 – 40% modality. Components: Orange Fe oxides are present, feldspars are present, hydrothermal material is absent, biogenics are absent, sulfides also absent. Unit is structureless. Sharp contact with next unit. Color: Moderate Yellowish Brown (10YR 5/4).
2	2.5	TM	Sandy mud – mostly angular ash fragments. Grain size is fine-grained ash with ~10% modality. Components: abundant orange Fe-oxides, plagioclase is absent, hydrothermal lithics are sparse, biogenics are absent. Unit is structureless but some orange color mottling is present. Sharp contact with underlying unit (although some disturbance due to settling). Color: Light brown (5YR 5/6).
3	4.5	HMT	Sandy Mud – Fluidal, medium ash fragments with ~15% ash modality. Components: Sparse orange Fe-oxides, green hydrothermal lithics present. Sulfides are present, plagioclase present in areas with higher ash modality. Biogenics are absent. Lamination near top of unit about ½ cm thick, noted for yellow-pale grey color and contains very fine-grained ash with ~1-5 ash modality, abundant orange Fe-oxides and green lithics while volcanic lithics are absent from lamination. Diffuse lamination of increased ash at ~3cm depth. Color: Light olive grey (5Y 5/2).

D655-PPC67

Unit	Thickness (cm)	Lithofacies	Description
1	4.5	TM	Muddy ash – Ash is mostly fluidal that is fine lapilli. Modality of ash is approximately 40%. Components: Orange Fe oxides are present, sparse biogenics, plagioclase is present, hydrothermal clay material is sparse, although more clays appear near the bottom of the unit. Entire unit is structureless. Gradational contact with ~10-degree angle. Color: Greyish Brown (5YR 3/2).
2	1.0 – 3.0	TM	Sandy mud – Ash is mostly fluidal with grain size being medium ash and modal percent is about 15%. Components: Abundant orange Fe oxides, biogenics are present, hydrothermal clays are present. Plagioclase is present. Entire unit is structureless. Sharp contact with underlying unit. Color: Light Brown (5YR 5/6).
3	8.0	HMT	Sandy mud – Predominantly fluidal ash with fine-grained ash and approximately 35% ash modality. Components: Orange Fe oxides are present. Green hydrothermal clay aggregates are abundant. Plagioclase is sparse, white zeolite mineral is present. Biogenics are absent, Sulfides appear abundant. Entire unit is normally graded with coarse ash near bottom and fining upwards. Lamination at top of the unit defines the upper contact. Lamination is ~ 1 cm thick, volcanic ash-rich containing fluidal medium-grained ash containing orange Fe oxides present, abundant plagioclase and volcanic material, clays and biogenics appear absent. Color of entire unit: Light Olive Grey (5Y 5/2).

Notes:

Entire core is dried out making colors appear different than other cores

D655-PPC79

Unit	Thickness (cm)	Lithofacies	Description
1	0.5 – 2.5	Artificial	Artificial – Disturbed layer, drags along the edges of the core. Contains ash, hydrothermal material, biogenics all likely brought up & disturbed from coring process.
2	9.5	TM	Ashy mud – Predominantly fluidal, fine lapilli that appears platy. Modal percent of ash is approximately 35%. Components: Orange Fe oxides present, biogenic material is present. Plagioclase is present and olivine absent. Crystalline basalt is present. Entire unit is structureless. Gradational contact marked by a reduction of ash modality and grain size. Color: Light Brown (5YR 5/6).
3	5.0 – 6.0	HMT	Sandy mud – Mostly blocky ash that is medium-grained ash and approximately 15% modality. Components: Abundant orange Fe oxides and abundant clay aggregates. Sparse biogenics, possible presence of sulfides, sparse plagioclase. Unit is structureless. Contains a variation of color/mottling with an orange hue. Sharp contact at ~20-degree angle. Color: Light Brown (5Y 5/6).
4	12.0 – 13.5	HMT	Muddy Ash – mix of angular and fluidal ash with slightly more fluidal shards. Grain size is fine-grained ash and approximately 40% modal percent. Components: Sparse orange Fe oxides, abundant green hydrothermal clay aggregates, sulfides are sparse, crystalline basalt fragments sparse, plagioclase is present and biogenics are absent. Top of unit contains a lamination about ½ cm thick that has pale-yellowish grey color. Within the lamination, there is approximately 10% modality of ash that is fine-grained, abundant orange Fe oxides, sulfides present, clays present, plagioclase and crystalline basalt is absent, biogenics also absent. Second lamination at ~2 cm depth that is 1 cm thick ashy lamination containing mostly fluidal, coarse ash with abundant plagioclase, sparse clays and sparse Fe oxides and no biogenics. A third lamination at ~5 cm depth and thickness of about 1 cm containing predominantly fluidal, coarse-grained ash and composed of similar material to entire unit (highly variable) with Fe oxides present, clays present, clays present, biogenics absent, sulfides present, and plagioclase sparse. Fourth lamination at ~8-9 cm that is 1 cm thick that is an ashy lamination containing fluidal and angular, fine lapilli vitriclasts with Fe oxides, sparse clays, abundant plagioclase and absent biogenics. Color of entire unit: Light Olive Grey (5Y 5/2).

D875-PC75

Unit	Thickness (cm)	Lithofacies	Description
1	6.0	TM	Sandy mud – Ash is very hard to determine shape. Ash grain size is very fine-grained ash and modality is approximately 1%. Contains very sparse orange Fe oxides (<1%). No other volcanic material is present. Biogenics are absent – sparse. Most of the unit is just mud. Sharp contact based on color. Unit is structureless. Color: Moderate Brown (5YR 5/6).
2	18.0	TO	Sandy mud – Ash shape hard to determine. Ash grain size is very fine-fine grained ash and modality is approximately <1% (nearly absent). Contains abundant biogenic material (forams) and that is it. No structures in unit, but color variation & mottling is present, includes darker brown (similar to above unit color) with lighter brown of this unit. Darker brown material has slightly more ash and may be distal fall-out from previous eruptions. Color: Greyish Orange (10YR 7/4).

Notes:

Off Ridge, Very far south (furthest south of all cores) ~149 km

D876-PC66

Unit	Thickness (cm)	Lithofacies	Description
1	7.5	TM	Ashy mud – Contains both blocky and fluidal ash that is medium lapilli and approximately 40% modality. Components: Orange Fe oxides abundant, biogenics are present, plagioclase crystals are present, hydrothermal clay aggregates are absent. Lamination near bottom of the unit at ~6 cm depth and about 1 cm thick containing more ash than surrounding unit with similar composition and ash morphology. Gradational contact. Color: Moderate Yellowish Brown (10YR 5/4).
2	3.5	TM	Sandy mud – Ash is a mix of both blocky and fluidal, medium-grained ash that is approximately 30% modality. Components: Abundant orange Fe oxides, hydrothermal clays are present and more yellow in color. Biogenics are sparse and fragmented near top of the unit. Plagioclase is present. Diffuse lamination at ~2 cm depth approximately ½ cm thick that is more ashy, fine-grained fluidal and blocky with similar composition with surrounding unit but ~40% ash modality. Gradational contact. Color: Light Brown (5YR 5/6).
3	10.0	HMT	Sandy mud – Ash is predominantly fluidal, fine-grained ash that is approximately 15% modality. Components: Orange Fe oxides are present, hydrothermal clays are present, sparse plagioclase. Lamination at ~1.5 cm depth that is yellowish grey in color and ~2 mm thick, similar composition but with finer ash than surrounding unit (~10% ash modality). Sharp contact with underlying unit. Color: Light Olive Grey (5YR 5/2).
4	2.5	LPT	Ash – Mostly fluidal vitriclasts but also contains some blocky particles and is medium lapilli. Components: Plagioclase is abundant, olivine and crystalline basalt is present. Wide range of glass morphologies. Normally graded and sharp contact with underlying unit.
5	1.0	TO	Sandy mud – Predominantly blocky, fine-grained ash with about 10% modality. Overall unit contains abundant biogenics with a sparse amount of ash. No other minerals or crystals observed within unit. Color: Greyish Orange (10YR 7/4).

D876-PC75

Unit	Thickness (cm)	Lithofacies	Description
1	7.5	TM	Ashy mud – Ash is fluidal, medium lapilli with approximately 30% modality. Components: Orange Fe oxides are abundant, biogenics are present, hydrothermal clays are absent. Feldspars are present. Some pulses of ash throughout unit but no laminations. Gradational contact with underlying unit. Color: Moderate Yellowish Brown (10YR 5/4).
2	8.0	TM	Ashy mud – Ash is a mix of angular and fluidal, fine-grained ash with about 10% modality. Components: Abundant orange Fe oxides, abundant hydrothermal clays (more yellow colored), sulfides present, biogenics are absent, white altered zeolite minerals are present, plagioclase is sparse. Unit is structureless. Gradational contact. Color: Dark Yellowish Orange (10YR 6/6).
3	4.0	HMT	Sandy mud – Mostly fluidal, fine-grained ash with approximately 15% modal percent. Components: Orange Fe oxides are present, hydrothermal clays are present, plagioclase is sparse, white altered zeolite minerals are present, biogenics are absent. Unit is structureless. Sharp contact with underlying unit. Color: Light Olive Grey (5Y 5/2).
4	2.5	LPT	Ash – Mostly fluidal with some blocky, medium lapilli sized vitriclasts. Contains a wide variety of ash morphologies. Plagioclase and feldspars are abundant, orange Fe oxides are present. Crystalline basalt fragments are present. Unit is normally graded with a sharp contact with underlying unit.
5	1.0	HMT	Sandy mud – Ash is predominantly fluidal, fine-grained ash with approximately 30% modality. Components: Orange Fe oxides are present, hydrothermal clays are present, feldspars are present, biogenic material is absent. Unit is structureless. Color: Light Olive Grey (5Y 5/2).

D878-PC44

Unit	Thickness (cm)	Lithofacies	Description
1	10.0 – 12.5	TM	Muddy ash – Ash is predominantly fluidal ash that appears platy and is coarse-grained ash with modal percent approximately 40%. Components: Biogenic material is present. Orange Fe oxides are sparse. Hydrothermal clay aggregates absent. Two fine ashy laminations at about 3 and 5 cm below top of the unit. Both laminations are about 2mm thick. Sharp basal contact at approximately 25 – 30-degree angle. Color: Moderate Yellowish Brown (10YR 5/4).
2	4.5 – 5.0	TM	Sandy mud – Gradational ash near top of unit (grades from more ash near top of unit into less ash within unit). Ash is mostly blocky and fine-grained ash and approximately 1% modality. Components: Biogenics are sparse, orange Fe oxides are abundant, green hydrothermal clays are abundant. Overall unit is structureless. Basal contact is at approximately 25 – 30-degree angle and is gradational in color. Color: Light Brown (5YR 5/6).
3	3.5 – 5.0	HMT	Sandy mud – Ash is mostly fluidal, but some blocky particles are present and is fine-grained ash. Modality of ash is approximately 1%. Components: Sparse white zeolite minerals, green hydrothermal clays are abundant, biogenics are very sparse, orange Fe oxides are present. Unit is structureless. Color: Light Olive Grey (5Y 5/2).

D878-PC53

Unit	Thickness (cm)	Lithofacies	Description
1	8.0	TM	Ashy mud – Ash contains both fluidal and blocky coarse-grained ash with a modality of approximately 30%. Components: Plagioclase crystals are present, biogenics are present, orange Fe oxides are present, green hydrothermal clays are sparse. Lamination of light mud, about 1 cm thick, separating an upper ashy layer from a muddy layer. Basal contact is gradational based on change of ash content. Color: Moderate Brown (5YR 4/4).
2	4.0	HMT	Sandy Mud – Ash is mostly fluidal, fine-grained ash with a modality of approximately 1%. Components: Orange Fe oxides are present, biogenics are sparse. Bulbous clay particles present to abundant. Composition changes from orange oxides to more greenish clays with increasing depth. Plagioclase crystals sparse. Overall unit is structureless. Gradational contact marked by modal abundance of ash and no angle. Overall color: Light Olive Grey (5Y 5/2).
3	8.0	HMT	Ashy Mud – Ash contains both fluidal and blocky but with higher proportion of blocky vitriclasts. Grain size of ash is medium ash and modal percent is approximately 25%. Components: Biogenics are sparse, plagioclase crystals sparse, crystalline basalt fragments are present, orange Fe oxides abundant. Clay particles are abundant, sulfides are present. At ~3 cm depth, lamination of lighter mud of about 1 mm thickness with abundant Fe oxides and overall less ash. Color: Dark Yellowish Brown (10YR 4/2).

D878-PC58

Unit	Thickness (cm)	Lithofacies	Description
1	5.5	TM	Ashy mud – Ash is mostly fluidal, coarse-grained ash with modal percent approximately 5 – 7%. Components: Biogenics are present, orange Fe oxides are sparse, plagioclase crystals and clay particles both absent. Laminated overall with glass laminations starting at ~2 cm depth, very fine at about 1 mm thickness. Basal contact is gradational and difficult to differentiate with underlying unit. Color: Moderate Yellowish Brown (10YR 5/4).
2	2.5	TM	Sandy mud – Predominantly fluidal, fine-grained ash with about 1% modality. Components: Orange Fe oxides are present, biogenics are sparse, Hydrothermal clays are present. Plagioclase is absent, sulfides also present. Overall unit is structureless with a 1 cm-thick “lamination” near base of the unit which appears artificial due to core splitting process. Unit contains some mottling of red/brown colors. Basal contact is sharp. Color: Light Brown (5YR 5/6).
3	1.5	TM	Ashy mud – predominantly fluidal, fine-grained ash with about 10% modality. Components: Biogenics are present, orange Fe oxides are sparse, plagioclase is absent. Clay aggregates are found near top of the unit which may be from overlying HMT unit. Overall unit is structureless – but so thin it is difficult to see much else. Color: Dark Yellowish Brown (10YR 5/2).

D878-PC62

Unit	Thickness (cm)	Lithofacies	Description
1	4.0	TM	Ashy mud – Ash is mostly blocky (with some fluidal) medium-grained ash with a modal percent of approximately 30 – 40%. Components: White biogenic material is present. Crystalline basalt fragments are present. Plagioclase crystals are abundant. Orange Fe oxides are present. Clay minerals are absent. Inter-fingering of mud and ash without true laminations. Basal contact is gradational and marked by disappearance of ash. Color: Moderate Brown (5YR – 3/4).
2	13.0	TM	Ashy mud – Ash is predominantly fluidal fine-grained ash with a modality of about 1 – 2%. Components: Orange Fe oxides are abundant. Plagioclase crystals present, biogenics are present, clay hydrothermal material is sparse. At approximately 9 cm fine lamination about 2mm thick, pale-grey color but similar to overall unit in composition, may be bioturbation. At approximately 10 cm depth, a second lamination about 5mm thick consisting of fine-grained orange material that contains less ash (fluidal), plagioclase absent, orange Fe oxides abundant, sparse clay particles (looks similar to above lamination). Below orange lamination is another lamination approximately 1 cm thick of ashy mud consisting of fluidal and platy ash, possibly stacked and includes crystalline basalt, biogenics, and plagioclase. Remaining layer similar to upper portion of unit. Color: Light Brown (5YR 5/6).
3	4.0	TM	Ashy mud – Ash contains both blocky and fluidal ash and is fine-grained ash of approximately 30% modal percent. Components: Plagioclase crystals present, sparse crystalline basalt fragments. Orange Fe oxide particles are present. Clay particles are absent. Biogenic material is sparse. Entire unit is normally graded with coarser ash near the base fining upwards. Color: Moderate Brown (5YR 3/4).

Notes:

Furthest core from caldera in the 878 transect.

D878-PC63

Unit	Thickness (cm)	Lithofacies	Description
1	6.5	TM	Muddy ash – Mostly fluidal ash containing approximately 30-40% ash modality & fine -medium lapilli ash size. Contains orange Fe oxides, biogenic material present, plagioclase crystals present within ash. At approximately 2cm depth, lamination of ~1cm thickness where reduced ash content (~15%). Color: Dark Yellowish Brown (10YR 4/2).
2	5.0	TM	Sandy mud – Ash is predominantly blocky and is fine ash size. Modal percent ash is approximately 1% with gradational ash content near the top. Contains orange Fe oxides are abundant, hydrothermal clay material is present, biogenic material are sparse. No other visible volcanic material. Unit is structureless. Basal contact is at ~25-degree angle and is gradational into unit below. Color: Light Brown (5YR 5/6).
3	2.0 – 4.0	HMT	Sandy mud – Ash is predominantly fluidal and fine-grained ash with some blocky and approximately 1-2% modality. Contains orange Fe oxides present, white altered mineral are sparse, hydrothermal aggregates are abundant, biogenics are very sparse. Unit is structureless. Color: Dark Yellowish Brown (10YR 4/2).

D878-PC66

Unit	Thickness (cm)	Lithofacies	Description
1	2.0 – 3.5	TM	Ashy mud- Predominantly block ash with coarse ash to fine lapilli size with average modality of ~40%. Contains abundant biogenic material, abundant orange Fe oxides, sparse hydrothermal clays. Entire unit is structureless. Basal contact is gradational and dependent on decrease of ash modality. Contact is also at an angle of about 25-30 degrees. Color: Dark Yellowish Brown (10YR 4/2).
2	2.5 – 3.0	TM	Ashy mud – Ash is predominantly fluidal with medium grained ash and approximately 3-5% modality. Unit contains abundant orange Fe oxides, biogenics are present, sparse hydrothermal clay material. Basal contact is marked by a ½ cm thick lamination containing 30-40% modality ash at ~25-30-degree angle. Overall unit is more orange than overlying unit. Within bottom lamination contains feldspar crystals mixed with ash, Fe oxides present, hydrothermal material also present. Color: Moderate Brown (5YR 4/4).
3	2.5 – 3.5	TM	Sandy mud – Ash is mostly fluidal and fine-grained ash with approximately 1-2 modal percent ash. Contains orange Fe oxides present, biogenic material is present, hydrothermal clay aggregates are present. Two 3-5mm circular zones or bulbs containing ~30% ash, likely bioturbation related. Orange mottling near basal contact is present. Gradational contact into the next unit with about a 20-degree angle and marked by abundance of ash but not sharply delineated. Color: Moderate Yellowish Brown (10YR 4/2).
4	2.0 – 3.5	HMT	Ashy mud – Ash is mostly fluidal and fine-grained ash with approximately 20-25% ash. Contains abundant orange Fe oxides, biogenic material is present, green hydrothermal clays are present. Unit is structureless although there is some color variation and mottling near top of unit similar to unit #3 above. Color: Dark Yellowish Brown (10YR 4/2).

D878-PC75

Unit	Thickness (cm)	Lithofacies	Description
1	6.0	TM	Ashy mud – Contains both angular and fluidal, coarse-grained ash with approximately 30% modality. Components: Orange FE oxides are present, biogenics are present, hydrothermal material is absent, plagioclase is sparse. Unit is structureless with a gradational contact with underlying unit. Color: Moderate Yellowish Brown (10YR 5/4).
2	7.0	TM	Sandy mud – Predominantly fluidal, medium-grained ash with approximately 10% modal percent ash. Components: Orange Fe oxides are present, hydrothermal clays are present and appear more yellow in color. Plagioclase is sparse, biogenic material is sparse and fragmented, sulfides appear to be present. Unit is structureless. Sharp contact with underlying unit. Color: Dark Yellowish Orange (10YR 6/6).
3	3.0 – 4.0	HMT	Sandy mud – Predominantly angular, fine-grained ash with approximately 10% modal percent ash. Components: Orange Fe oxides are present, green hydrothermal clay aggregates are abundant, white zeolite minerals present, sulfides are absent (none observed). Plagioclase is present near bottom of unit; biogenic material is absent. Unit is normally graded with sharp contact at ~10-degree angle. Color: Light Olive Grey (5YR 5/2).
4	2.0	LPT	Ash – Predominantly fluidal, medium lapilli sized vitriclasts. Contains: Abundant plagioclase, crystalline basalt fragments are present, wide range of glass morphologies. Unit is normally graded. Sharp contact with underlying unit.
5	5.0	TO	Ashy mud – Mix of both angular and fluidal, coarse-grained ash with approximately 40% modality. Components: Biogenic material is abundant. Plagioclase is sparse and only in glass-rich areas. Other components are absent. Unit is entirely ash and biogenic material. Color: Yellowish Grey (5Y 7/2).

D878-PC76

Unit	Thickness (cm)	Lithofacies	Description
1	8.0	TM	Ashy mud – Ash is mostly blocky but also contains some fluidal shards. Ash is coarse ash – fine lapilli size and approximately 20-25% modality of ash. Contains orange Fe oxides present, abundant biogenic material, green hydrothermal aggregates are sparse. Small amounts of layering without defined laminations or structures. Sharp contact with underlying unit. Color: Yellowish Brown (5YR 5/6).
2	2.0	TM	Sandy mud – Ash is predominantly blocky and is sub-millimeter (medium ash) and approximately 3% modality. Contains abundant orange Fe oxides, biogenics are present, yellowish hydrothermal material is also present. Overall unit is structureless. Color grades from darker orange (top) to yellow-orange (bottom). Sharp basal contact with unit below. Color: Light Brown (5YR 5/6).
3	1.5	HMT	Ashy mud – Ash is both blocky and fluidal (platy) with blocky being the predominant shape. Ash is fine-grained ash and approximately 15% modality. Contains orange Fe oxides present, abundant green hydrothermal material, feldspar crystals present among vitriclasts. Overall unit is structureless. Sharp contact with underlying unit with ~5-degree angle. Color: Yellowish Grey (5YR 7/2).
4	2.0	LPT	Ash – Ash is mostly fluidal with largest ash Medium lapilli near bottom & coarse ash near top. Feldspar crystals are present among ash. Tachylite crystals sparse. Normally graded with finer ash near top & coarser ash near bottom. Sharp contact with basal unit at ~5-degree angle and parallel with contact above.
5	1.5	TO	Ashy mud – Ash is mostly fluidal and medium-grained ash with a modal percent ash of approximately 50%. Orange Fe oxides are sparse, absent hydrothermal material. Biogenic material is abundant (~90%). Lamination at ½ cm depth that is about ½ cm thick containing slightly more ash. Color: Greyish Orange (10YR 7/4).

D878 PC78

Unit	Thickness (cm)	Lithofacies	Description
1	6.5	TM	Ashy mud – Ash is predominantly fluidal and grain size is medium to coarse ash and modal percent is approximately 15%. Edges of core in this unit are likely contaminated with more ash as there is a bulge along the sides (40% ash near edges). Contains orange Fe oxides present. Biogenic material is present. Hydrothermal material is sparse-absent. No other volcanic material (feldspars) observed. Mottling of yellow and orange colors but no distinct laminations. Sharp basal contact with below unit. Color: Light Brown (5YR 5/6).
2	7.5	HMT	Sandy mud – Very small amounts of ash and too difficult to determine ash shape. Very fine-fine grained ash with ~1% modal percent. Contains no biogenic material, abundant hydrothermal material, no orange Fe oxides present, no other volcanic material present. Two laminations present: First is about ½ cm below base approximately 2-3 cm thick. Second lamination is approximately 1.5 cm below base and ~2-3 mm. Both laminations contain slightly higher ash content that is fine-grained, fluidal ash. Color: Yellowish Grey (5YR 7/2).

D881-PC72L

Unit	Thickness (cm)	Lithofacies	Description
1	7.0	TM	Ashy mud – Ash is both angular and fluidal. Largest particle is ~1/2 cm (medium lapilli). Ash modality is approximately 40% ash surrounded by orange/brown mud. Contains orange Fe oxides sparse (~1%), plagioclase is present. Hydrothermal clays & altered minerals absent. Biogenics sparse-present. Top of unit is structureless. Reverse-graded (more ash near the top and ash thins out near bottom of unit). Mottling of color with underlying unit. Gradational contact. Color: Moderate Brown (5YR 5/6).
2	5.0	TM	Ashy mud – Ash is mostly blocky/angular. Largest particle ~3mm (fine lapilli). Modal percent ash is approximately 10%. Contains orange Fe oxides very sparse – absent. Plagioclase & volcanic minerals absent. Biogenics are present to abundant. Hydrothermal clays absent. Layer is structureless but noticeable variation where mix of TO & TM. This unit is more of a gradational transition layer from underlying ooze and overlying mud units. Gradational contact. Color: Greyish orange (10YR 7/4).
3	44.0	TO	Sandy mud – Ash is blocky and fine-grained ash and is <1% modality. Contains only <1% ash and the rest is biogenic material. Unit is very fine-grained. Entire unit is structureless. Very slight color variation but mostly massive. Color: Yellowish Grey (5Y 7/2).

Notes:

Core is ~47 km south of caldera

3 previous samples taken from core @ 13.0, 31.0, & 61.0 (very bottom of core) cm.

Appendix B: Core Logs

The following core logs were compiled primarily based off of core descriptions (Appendix A). Core images have been enhanced for better contrast. Lithofacies boundaries, structures, color, modal ash percent, and grain size represent visual observations and not quantitative measurements (e.g. PSA). Color is based on the Munsell color system. Location of subsamples used for analysis in this study are indicated. Geophysical characteristics including *P-wave velocity*, *bulk density*, and *magnetic susceptibility*, which were measured at USGS in Santa Cruz, are also included. The D655 series of cores were not measured for geophysics. For information regarding symbols, see the *core log key* below:

Core Log Key		
Material:	Structures:	Contacts:
Ash	Massive (structureless)	Sharp Contact
Muddy Ash	Muddy Laminations	Gradational Contact
Ashy Mud	Ashy Mud Lamination	Undulose Contact
Sandy Mud	Ash Lamination	Subsamples:
Muddy Sand	Normal grading	PSA (Granulometry)
Artificial	Reverse grading	XRD (Bulk Mineralogy)
	Color Motteling	XRD (Bulk & Clay Mineralogy)
		Point Counts
		MGs

A vertical cross-section of a tree trunk, showing various layers of wood and bark. The top layer is dark, followed by a lighter, textured layer, then a thick, dark, and highly textured layer, and finally a lighter, smoother layer at the bottom.

D516-PC61XL

D522-PPC1

D522-PC62L

D522-PC66

D524-PC47XL

D525-PPC2

D528-PPC72

D655-PPC43

D655-PPC49

D655-PPC67

D655-PPC79

D875-PC75

D876-PC66

D876-PC75

D878-PC44

D878-PC53

D878-PC58

PC878-PC62

D878-PC63

D878-PC66

A vertical section of a rock sample. The lower portion is dark, almost black, with a crystalline texture. Above this is a lighter, yellowish-brown layer with a more granular or crystalline texture. The boundary between the two is somewhat irregular.

D878-PC76

D881-PC72L