

Extensive young silicic volcanism produces large deep submarine lava flows in the NE Lau Basin

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Abstract

New field observations reveal that extensive (up to ~402 km²) aphyric, glassy dacite lavas were erupted at multiple sites in the recent past in the NE Lau basin. This discovery of volumetrically significant and widespread submarine dacite lava flows extends the domain for siliceous effusive volcanism into the deep sea. Although several lava flow fields were discovered on the flank of a large silicic seamount, Niuatahi, two of the largest lava fields and several smaller ones (“northern lava flow fields”) were found well north of the seamount. The most distal portion of the northernmost of these fields is 60 km north of the center of Niuatahi caldera. We estimate that lava flow lengths from probable eruptive vents to the distal ends of flows range from a few km to more than 10 km. Camera tows on the shallower, near-vent areas show complex lava morphology that includes anastomosing tube-like pillow flows and ropey surfaces, endogenous domes and/or ridges, some with “crease-like” extrusion ridges, and inflated lobes with extrusion structures. A 2 x 1.5 km, 30-m deep depression could be an eruption center for one of the lava

flow fields. The Lau lava flow fields appear to have erupted at high effusion rates and possibly reduced viscosity induced by high magmatic water content and/or a high eruption temperature, consistent with both erupted composition and glassy low crystallinity groundmass textures. The large areal extent (166 km²) and relatively small range of compositional variation within the northern lava flow fields imply the existence of large, eruptible batches of differentiated melt in the upper mantle or lower crust of the NE Lau basin. At this site the volcanism could be controlled by deep crustal fractures caused by the long term extension in this rear-arc region. Submarine dacite flows exhibiting similar morphology have been described in ancient sequences from the Archaean through the Miocene and in small batches on seafloor spreading centers.

1.0. Introduction and background

1.1 Geological and tectonic setting

The Tonga intra-oceanic subduction zone (TIOSZ) has the highest subduction and backarc spreading rates on the planet (Zellmer and Taylor 2001). The Lau basin, the backarc region of the TIOSZ, following an initial rifting phase, has been opening along multiple back-arc spreading centers since about ~ 4 Ma (Zellmer and Taylor 2001; Taylor and Martinez 2003) (Fig. 1). The NE Lau basin is defined here as northern section of the backarc region of the Tonga plate (Zellmer and Taylor 2001; Bird 2003) that is bounded on the west, respectively from north to south, by the Northeast Lau Spreading Center, (NELSC) the Mangatolu Triple Junction Spreading Center, and the Fonualei Rift Spreading Center (Fig. 1). The northern boundary of the Tonga Plate is a complex zone marked by the transition from subduction to strike-slip faulting along the Vitiaz lineament marked topographically by the change in strike of the trench from N-S to a more E-W trend (Pelletier et al. 1998; Zellmer and Taylor 2001). An active crustal tear or “STEP” fault (Subduction-Transform-Edge-Propagator (Govers and Wortel 2005) caused by

rollback of the trench, has created a zone of oblique shear that has left a trail of spreading centers and rift basins along this northern boundary (Isacks et al. 1969; Millen and Hamburger 1998; Govers and Wortel 2005). The Tofua Arc defines the eastern boundary of the NE Lau Basin.

The NE Lau basin has the highest upper mantle temperatures (Wiens et al. 2006), has one of Earth's coolest slab thermal parameters (the product of convergence speed and age), and has among the highest slab water fluxes (van Keken et al. 2011) of any intra-oceanic subduction zone. All these factors probably contribute to the region's tectonic and magmatic complexity, including an unusually large number of active volcanic systems in a relatively small area. Unusual lavas such as boninite occur in the extreme north of the region (Falloon et al. 2007; Resing et al. 2011; Rubin and Embley 2012) and at least two historic eruptions have been documented within the NE Lau Basin (Fig. 1): (1) a short-lived 2008 eruption on the NELSC (Baker et al. 2011), and (2) a years-long Strombolian activity on West Mata, a boninite volcano whose historic eruptive episodes have been documented for the 1996-2011 interval (Clague et al. 2011; Resing et al. 2011; Baumberger et al. 2014; Embley et al. 2014). We have concluded that the NE Lau basin is a "magmatically greedy" back arc, perhaps by capture of some of the magmatic flux from the magmatically anemic neighboring northernmost Tofua Arc (Embley et al. 2009a; Rubin et al. 2013; Lupton et al. 2015).

During the 2008 expedition when the two aforementioned ongoing eruptions were discovered, we also mapped extensive areas of seafloor with high acoustic backscatter, most of which we interpret as lava flow fields within the nearby NE Lau "rear arc". We define "rear arc" as the region between the magmatic arc front (Tofua Arc on Fig. 1) and the NELSC (Figs. 1-4). The high backscatter areas include both those on the flanks of Niuatahi seamount (previously known as Volcano "O") and those lying within a 30 km-wide corridor extending northward ~60

km from Niuatahi toward the trench (Figs.1 and 2) (Embley et al. 2009b). Some of the lava flows extend into the southern edge of the Mata rift basin, wherein lie most of the Mata volcanoes (Figs. 2-4), all of which are composed primarily of boninite lava. Nine seafloor dredges and three camera tows were conducted over the high backscatter areas between 2009 and 2011 to determine their morphology, sediment cover, and composition. As reported herein, we establish that they are all dacite lavas, some with unusual morphologies. This was an unexpected result, because extensive submarine dacite flows are rare in modern environments and previously unknown from the deep sea.

Other non-dacite recent lavas contiguous to this northernmost Lau region have a wide range of compositions. The chain of the Mata boninite volcanoes lie to the northeast (Resing et al. 2011; Rubin and Embley 2012; Embley et al. 2014;) and back arc basin basalt (BABB) to basaltic andesite occurs on the NELSC (Fig. 4), including the youngest lavas of NELSC neovolcanic zone (Michael et al. 2009; Clague et al. 2010), with basaltic andesite (Falloon et al. 2007) recovered only about 5 km west of the LL-D lava field (Fig. 4). A small lava knoll (“BoCo” on Fig. 4) has erupted boninite (Rubin et al. 2013). This close geographic continuity of such a range of lava chemistries is intriguing.

1.2 Submarine lava flows

Much is known about the chemical and physical volcanology of effusive submarine basalts produced in a range of eruptive conditions, mostly from studies of mid-ocean ridge basalt (MORB) and analogue modeling. Those that can be chemically mapped as single lava flows are distributed in pillow mounds, lower relief sheet and lobate flows, and dome-like flows along the mid-ocean ridge spreading centers from either point sources or along eruptive fissures (Ballard et al. 1979; Appelgate and Embley 1992; Smith and Cann 1993; Embley and Chadwick 1994;

Fornari et al. 1998; Perfit and Chadwick 1998; White et al. 2000; Sinton et al. 2002; Rubin and Embley 2012; Chadwick et al. 2013; Clague et al. 2013; Deschamps et al. 2014). Larger off-axis mid-ocean ridge basalt eruptions have also been documented in a few studies (Geshi et al. 2007). There have been fewer such studies of back-arc basin basalt (BABB) erupted from back-arc spreading centers (Saunders and Tarney 1979).

Limited quantities of differentiated lavas have been recovered from some mid-ocean ridge and fracture zone environments (Stakes et al. 2006; Wanless et al. 2010; Schmitt et al. 2011; Colman et al. 2012) but, to date, they appear to represent a volumetrically minor portion of lavas sampled along seafloor spreading centers and are usually associated with rift tips, segment ends, graben bounding faults, or other low magma supply regions (Sinton 1983). Petrologically-differentiated magmatic products are somewhat more common on back-arc spreading centers (Lonsdale and Hawkins 1985; Binns and Scott 1993; Taylor et al. 1994; Gribble et al. 1998) and along magmatic arcs, where they are found commonly as lavas, explosive products (from pyroclastic and hydroclastic processes), and endogenous domes (Wright and Gamble 1999; Fiske et al. 2001; Wright et al. 2006; Graham et al. 2008; Stern et al. 2008; Stern et al. 2014).

Despite this body of knowledge, very little is known about the overall distribution of high silica lavas in the ocean basins, their eruptive processes, and their importance in constructing the extrusive ocean crust. In this paper we document the distribution, composition, size and morphology of unusually extensive dacite lava flow fields in a large region where they are the dominant eruptive product, and hypothesize about their eruption conditions, origin, and significance. To our knowledge, this is the first detailed investigation of extensive submarine silicic lava flows in the modern ocean.

2.0. Methods

2.1 Multibeam sonar mapping

The data used here were collected using the R/V *T. G. Thompson* (cruise TN227, November 2008) with a Simrad EM302 multibeam system and the R/V *Kilo Moana* (cruise KM1008, May 2010; KM1024, December 2010; KM1129a, November 2011) with a Kongsberg-Simrad EM122 multibeam sonar mapping system. The data were processed and gridded using [©]MB System and [©]GMT. The 3D images were created using the [©]Fledermaus and ArcMap[©] was used to layer data and to calculate areas of the lava flows. Multibeam data files are available by cruise name (above) through the (NOAA) National Geophysical Data Center.

2.2 Camera tows

The WHOI TowCam system, developed by D. Fornari and others at Woods Hole Oceanographic Institution, was used in this study to visualize the high backscatter lava flow and verify that it was composed of relatively young (lightly sedimented) lava flows. The camera was towed using a 0.322" coaxial cable off the stern of the R/V *Kilo Moana* on cruise KM1008 (28-April to 10-May 2010). In 2010 the camera system used a three megapixel digital still camera, altimeter, a forward looking (obstacle avoidance) sonar, and a Seabird CTD model SBE25 with standard sensors plus a transmissometer to measure water turbidity. Total depth was calculated by adding the depth from the CTD sensor to the altimeter reading at 1 sec intervals. The altimeter and CTD data were available in real time to monitor altitude, bottom temperature and light transmission. The camera system was towed at about 0.25 knots (~0.5 km/hr) to obtain overlapping imagery from the still camera, which was fired at a 10 second interval in synchronicity with a strobe. Details about the operational and instrumentation capabilities of the WHOI TowCam are available at: <http://www.whoi.edu/page.do?pid=17619>

Final navigation files for the camera data were created by a combination of layback calculation (using the CTD depth and wire out) and adjusting the track to minimize calculated offsets of the along-track multibeam depth profile and the depth profile made with the camera pressure and altimeter data. Approximate location errors for the camera tow data presented in this paper are ≤ 50 m. Photographic image names were keyed to time of acquisition (which allowed correlation to other logged parameters such as the sensor data), and auto-processed in ©Adobe Photoshop Elements to obtain maximum contrast and clarity. The mosaics presented in this paper were constructed by cross-matching photos and overlaying them in ©Adobe Photoshop Elements.

2.3 Rock dredging and lava chemistry

Dredge samples were collected from the high backscatter lava flow regions during the KM1024 expedition (December, 2010) and from primary structures associated with the Niuatahi caldera walls, caldera floor, and extra-caldera flows (LL-A1 and LL-A3) on KM1129a expedition (November-December 2011) (Fig. 4; ESM_1). A standard box-mouth chain bag dredge with 10 kg bottom weight was used, along with a wireline-mounted pinger for bottom location. In order to minimize the spatial sampling scale the dredge distance on bottom was usually limited to 0.5-0.7 km, occasionally up to 1.0 km on low relief surfaces. Start and stop locations and seafloor depth of the ship when the dredge hit and left the sea bed are reported in ESM_1, along with persistent sample identifiers (IGSN, registered at www.geosamples.org) and site locations. Dredge rock recoveries were excellent for most deployments (50-150 Kg) and thus representative of the terrains sampled, although two dredges taken on KM1024 recovered much less. The dredge and all work surfaces were thoroughly cleaned after each deployment to limit cross sample contamination. After recovery samples were dried, sorted and placed into visually

distinct groups based on physical, mineralogical, and alteration characteristics, from which 5 to 10 representatives were given specific sample numbers, described, and subsampled on board for shore-based analysis. Several additional samples were recovered when a camera sled touched the seafloor on KM1008 (May 2010). Two of those samples (from “Motutahi”, the young resurgent volcanic cone within Niuatahi caldera) are included here. Representative samples have been examined by petrographic microscopy and analyzed for major element glass composition by Electron Microprobe at the University of Hawaii (see Table 1 notes and ESM_2 for analytical details).

3.0. Dacite flow distribution and character

3.1 Distribution and general characteristics

The dacite lava flows occur in the rear arc, within a roughly triangular corridor between the NELSC on the west (German et al. 2006), the Mata boninite volcanoes to the northeast (Resing et al. 2011; Rubin and Embley 2012), the northernmost Tofua magmatic arc on the east, and Niuatahi Seamount, a large silicic submarine volcanic caldera, on the southern end of the corridor (Figs. 1-4). The volcanoclastic apron of the arc impinges on the area in the SE corner of the corridor. We refer to each geographically distinct site as a “lava flow field” because we cannot, with any certainty, resolve individual lava flows within them. In some places the word “lava flow” will be used in describing a morphologically distinguishable subunit within the lava flow field. The fields are named “Lau Lava” (LL), A, B, C, D from south to north. All three of the northern lava flow fields (LL-B, LL-B1, LL-C, and LL-D), which we will henceforth refer to as the “northern flow fields” when referring to the group, and the two largest Niuatahi flank fields (LL-A1 and LL-A3) have been sampled by dredge (Fig. 4). Only the LL-B and LL-C lava fields have been imaged by the TowCam (in 2010). All of these northern flow fields are

188 associated with the summit or flanks of a feature we call “Niuatahi Ridge”, a diffuse shallow
189 zone extending north from Niuatahi (Figs. 2-4).

190 We determined the extent of these lava flow fields on the basis of (higher) multibeam
191 sonar acoustic backscatter intensity and, in most cases, on seafloor morphology (Figs. 2 and 3).
192 Backscatter intensity is a function of slope, seafloor roughness, and acoustic impedance of the
193 seabed. Most of the lava flow fields have been emplaced onto low regional slopes ($< 5^\circ$), so they
194 can usually be distinguished from scarps that can also generate higher amplitude backscatter
195 patterns. Most of the areas mapped as lava flows (Table 2) in this study also have small-scale
196 topography resolved on the multibeam bathymetry (within a 20 m grid cell size) that is similar to
197 features found in submarine and subaerial lava flow fields, including convoluted flow edges,
198 depressions, pits and channels (Fig. 5) discussed in detail in later sections. Lower amplitude
199 (m's), short wavelength that contributes to the backscatter signal is not resolved with the
200 multibeam bathymetry (see below). One key point in interpreting backscatter is that there is a
201 relationship between sediment cover and surface roughness. For example, sediment is
202 differentially accumulated in pockets on a rough surface and as a blanket on smooth surfaces, so
203 that more sediment accumulation is needed to completely obscure the microtopography in the
204 former case. Thus, an originally smoother lava surface can appear to be “older” (lower
205 backscatter) than a rougher lava surface of the same age. There is some variation in the
206 backscatter intensity over the flow fields. In general, the northern flow fields have higher values
207 versus the southern (Niuatahi fields) with the exception of LL-A3. The volcanoclastic apron of
208 the Tonga arc is clearly defined by low backscatter on the southeast quadrant of the map. The
209 lower backscatter values on the southern lava fields could be due to infiltration of fine
210 volcanoclastic sediment (Figs. 2 and 3).

3.2 Lava samples characteristics and compositions

Most lava samples are sparsely vesicular (<1-3%) with elongate bubbles (1-5 mm in the long direction); samples collected from deeper regions of the lava flow fields (2.6 to 2.8 km water depth) have fewer vesicles than shallower ones (2.0-2.3 km water depth). Samples are sparsely phyrlic (<1%) with plagioclase laths up to 1 mm in length (with rare occurrences of crystals up to 5 mm in length) $\pm$ pyroxene microphenocrysts (<1%). The groundmass varies from entirely glassy to microcrystalline (ESM_3), with unusually thick glass rinds (15-50 cm thick) (Figs. 6a and b). Many samples that preserve the upper lava flow surface have complex striated patterns, including a distinctive lineated texture we referred to at sea as “buffalo head hair”, with subparallel wavy strands of glass forming the outer rind of the sample. We interpret these as local flow extrusion textures, ranging in wavelength from sub cm to several cm, in patches up to 10 cm long on hand samples (e.g., Fig. 6c). Although samples are generally glassy, some have whitish films on exterior surfaces and along internal cracks, although they are otherwise fresh on interior surfaces (Fig. 6).

The TAS (total Alkali and Silica) diagram for all NE Lau silicic lavas (Fig. 7a) shows that all samples of the three largest northern high backscatter lava flows separated from Niuatahi (LL-B, LL-C, and LL-D) are dacite with an $\text{SiO}_2 \approx 65\text{-}68$ wt%. These flows have distinct compositions (warm colored symbols on Fig. 7, Table 1) compared to those associated with the Niuatahi caldera floor, along the ring faults, and on the presumptive youngest Niuatahi lavas on the Motutahi cone near the center of the caldera (cooler colored symbols on Fig. 7). The northern lava flows are also distinct from most of the (poorly sampled) flank lava flows LL-A1 to A5, most of which are also dacite, but with a broader compositional range than the northern flows (described in more detail below). An analysis of one dredge sample from LL-A1 (KM1129-D13-

R02) and one from LL-A3 (KM1008-D03-R01) were distinct from the northern lava trend (Figs. 4 and 7). However, analyses of two subsamples of dredge KM1129a-D15 (Table 1), taken on the shallow area of LL-A3, had compositions within the tight field of the northern lavas.

The samples from the northern flow fields have a tight range of SiO_2 , on average 66.17% with $\sigma = 0.60$ wt% (with σ the population standard deviation). The LL-B field, which has the largest aerial extent and the most dredges (six), has the tightest SiO_2 range with an average of 65.9% and $\sigma = 0.40$ wt% (Fig. 7a and Table 1). Expanded Harker diagrams for Al_2O_3 , MgO and FeO are shown, respectively, in Figs. 7b-d. Pseudo-Harker diagrams for, respectively, TiO_2 and $\text{CaO}/\text{Al}_2\text{O}_3$, versus MgO are shown on Figs. 7e and 7f. The LL-B, LL-C and LL-D lava fields are all very similar and form tight coherent clusters in all diagrams. Niuatahi itself, as well as the LL-A1 and LL-A3 fields on the outer flanks of the volcano, are on trends extending from that tight cluster to more differentiated compositions.

The coherence of the northern flow fields to a single compositional family with a small range is quite evident in all the major element plots shown in Fig. 7. The northernmost dredge sample, on LL-D (KM1024-D24, red diamond) is indistinguishable from the main big flow (LL-B) field (dark orange diamonds). The two dredges on the LL-C field (light orange) are slightly more differentiated but on the same trends. Only one dredge not taken within the northern lava flows, KM1129a-D15 from LL-A3, lies within their compositional field. Interestingly, this is placed within the compositional field of LL-B, whose southwester boundary occurs about 20 km to the northeast. The one dredge from the LL-A1 lava field south of Niuatahi (KM1129a-D13), dredge KM1024-D03 from LL-A3, and both our dredge samples and those samples reported by Park et al. (2015) from the caldera and its walls are all significantly different (i.e., more differentiated) from the northern flow fields.

Flat MgO and FeO trends versus SiO₂ in the northern flow fields (LL-B, C, D) and a positive slope of Al₂O₃ versus SiO₂ in the northern flow fields are distinct from the Niuatahi samples (Figs. 7b-7d). Also of note is the tight TiO₂ vs. MgO (Fig. 7e) vertical trend and very highly clustered CaO/Al₂O₃ vs. MgO (Fig. 7f) of the northern flow fields, both of which are (also) distinct from the Niuatahi samples. It is difficult to make these (LL-B, C, and D) trends and the broad dispersion of the Niuatahi lavas from the same parent melt (see for instance the synthetic differentiation trajectories in ESM_4, which start with West Mata boninite as a parent). In addition, the small but identifiable differentiation trends for the northern flow fields (e.g., positive Al₂O₃ and Total alkalis vs. SiO₂ trajectories and flat MgO and FeO vs. SiO₂ trajectories) contrast with the trend for Niuatahi proper, suggesting different conditions of differentiation and crystallizing assemblage for the northern flow fields compared to Niuatahi. These parent melt and differentiation differences support the notion that the northern flow fields were probably not derived from the Niuatahi magma chamber.

Based on this, although we cannot completely rule out the possibility that the magma that fed the large northern flow fields came from beneath Niuatahi (e.g. the similarity of composition between one dredge from the LL-A3 lava and the LL-B compositional field), the case is not strong. Instead, given the significant differences from Niuatahi on most petrologic diagrams for all but the one LL-A3 dredge, we think that the parent magma for the northern flow fields is distinct from the Niuatahi source.

3.3 Niuatahi and LL-A lavas

Niuatahi seamount is ~21 km in diameter and is characterized by one of the largest submarine calderas (~9 km diameter) discovered to date (Kim et al. 2009). Active hydrothermal venting occurs in several places within the caldera and on the post-caldera Motutahi dacite near

its center (Kim et al. 2009; Resing et al. 2010). Dacite lavas have been recovered from both the caldera floor (~1800 m) and the young cone (Motutahi) (summit at ~1245 m) within the caldera. Rhyolites have been dredged from the ring structures forming the caldera walls (Figs. 4 and 7; Tables 1 and ESM_1) (Falloon et al. 2007; Park et al. 2015) and the present study. The age of the caldera-forming eruption is not known, but the multiple active hydrothermal sites within the caldera (Kim et al. 2009; Resing et al. 2010), very young dacite flows on the young cone (Motutahi) and within the caldera (unpublished data) and the high backscatter over the entire seamount (Fig. 3), imply that Niuatahi is an active volcano.

The LL-A series of high backscatter zones are located on the outward sloping flank of Niuatahi, and do not include obvious ridges or other regions of steep slopes such as the upper flanks of Niuatahi. These flow fields have an estimated area of ~166 km² (Table 2). All of these higher backscatter zones are contiguous to Niuatahi, and appear to have been sourced from the volcano or from structures related to the volcano. Their upper boundaries cannot be mapped in detail because they merge with the steep outer slope of Niuatahi. Only two of the Niuatahi flow fields (LL-A1 and LL-A3) have been sampled by dredge (Fig. 4) and all three dredges were dacite (see section 3.2), so we presume that the others have a similar composition. There is also the possibility that one or more of them (e.g., LL-A2) could be volcanoclastic flows, debris from sector collapse or some hybrid thereof. We surmise that the LL-A deposits were produced either coeval with, or postdate, caldera formation because one or more large paroxysmal eruption(s) would have produced eruptive products covering over the surface of pre-caldera flank lavas, which is not observed. Lavas have also erupted within the caldera of Niuatahi. A camera sled track over the young cone (KM1008 in May 2010) and a submersible dive in 2012 (on cruise RR1211 using the MARUM Quest 4000 ROV) imaged and sampled a dacite flow on the flank

and near the summit of the Motutahi cone in the SE part of the caldera (Fig. 2), as well as copious sulfur-rich emissions and solidified patchy yellow sulfur deposits near the summit.

Field LL-A3 has the highest backscatter of the Niuatahi flows, similar to the values on the northern flow fields (Fig. 3). The multibeam bathymetry (Fig. 8) shows that several lava flow units can be distinguished within the LL-A3 field. The northernmost and largest of the morphologically distinct lava flows (triangular-shaped area that cross-section A-B is centered on in Figure 8) originates from the elbow between Niuatahi and a short (~10 km) north rift zone extending from where the ring structures of Niuatahi have been partially breached (Fig. 2). This flow consists of a series of lobes extending into deeper water to the west. Its upper lobe (<2540 m) is at least 50 m thick and has small (≤ 10 m) domes and ridges on its surface. The deeper portions of the LL-A3a lava flow has a more irregular surface morphology with a series of interconnected lattice-like structures of ~10-15 m relief. The length of the field measures ~6 km from its western toe to its probable source near the summit of the ridge.

Although the LL-A3a unit was not sampled, two dredges further south on the flank of Niuatahi within LL-A3 (KM1004-D03 and KM1129a-D15; Figs. 4 and 8) sampled the upper portion of separate flows emerging from the northern rim of Niuatahi (Fig. 8). These samples are dacite (Table 1) but of measurably different composition (see section 3.2). The chemical similarity between the KM1024-D03 sample and the northern flow field compositional fields could represent a linkage between magma sources but it is difficult to draw a definitive conclusion from one sample location. The small low backscatter area in the middle of LL-A3 field is a kipuka defining the area where the lava flows comprising the LL-A3 field did not quite merge.

The high reflectivity zone on the southern flank of Niuatahi (LL-A1) has a mostly smooth surface on its deeper (SW) portion with higher relief topography on the shallower (closer to the caldera) portion where dredge KM1129-D09 recovered dacite lavas (Fig. 2 and 4). Although there is high backscatter over the entire region (Fig. 3), and some high relief areas that might be flow fronts, much of the deeper (unsampled) zone has low surface relief (~5 m).

We also interpret two other high-backscatter areas on the flanks of Niuatahi as lava flows because of their convoluted lower boundaries (A4, and A5). However, there are no samples from these areas so we can't rule out the possibility that some of these areas could be composed at least partly of slump material or volcanoclastic deposits.

3.4 LL-B lava flow field

The largest LL flow field, designated as LL-B, lies northeast of Niuatahi within the southwest corner of the rift basin that contains most of the Mata volcanoes (Figs. 2-4, and 9). This field has the largest area (~144 km²) of any of the lava fields discussed in this paper (Table 2), is the most densely sampled (KM1024-D06-D11), and has two camera tows on its western (shallower) side (Fig. 9c; CT-01 and CT-02). A much smaller but (apparently) separate lava flow (LL-B1) with an area of ~11 km² lies to the south of LL-B and is unsampled. A series of irregular rounded knolls on the summit of Niuatahi Ridge (Figs. 2 and 9a), upslope of LL-B and LL-B1, are up to ~200 m in height and 4 km in diameter. Several have enclosed deep depressions whereas others have a flat top with steep flanks, which stand out on the slope map (Fig. 9b). They follow an arcuate pattern from NW to SE mirroring the overall shape of the upper limit of LL-B. They have low backscatter values and, where imaged (beginning of CT-02 described below), their surface is smooth sedimented lava. We interpret these (as yet unsampled) features as silicic lava domes and coulees because of their geographic proximity to the silicic

volcano Niuatahi and the dacite lava fields, and their overall morphology and smooth surface. There is also a suggestion that they are part of a zigzag pattern of related hill and ridges extending northeast and then northwest from the eastern flank of Niuatahi (Figs. 2 and 9). To the ENE of the northwest trending “leg” of these hills, the LL-B and LL-B1 lava flow fields extends for ~10 km downslope and ~15 km in a NW-SE direction.

The upper section of the LL-B flow field is defined by a depth range of ~2475-2500 m (level I on Fig. 9c) with a relatively low relief on a local scale with one exception, a 2 x 1.5 km, 30-m deep depression in its northern section (marked “LD” on Fig. 9). The morphology of the LD (size, steep walls, and flat floor; Fig. 10a) is similar to pit craters floored by frozen lava lakes on subaerial shield volcanoes (discussed in the following paragraph). There is also an apparent lava channel on the upper portion of the southern area of Level I (location of “LC” on Fig. 9). The LL-B flow field deepens in a series of steps (levels II-V) into the Mata basin bounded by sinuous (in plan view) high relief (20-80 m) scarps, which we interpret as lava flow fronts (Fig. 9c, profile A-B inset). The flow fronts within LL-B, defined by curvilinear (in plan view) steep slopes, have a lobate pattern that narrow downslope, providing an indication of flow direction at the time of emplacement. Although local flow directions vary, the overall pattern of these lobes suggests multiple sources curving around the southwestern slope of Mata basin. For example the relatively flat surface of the lobe northeast of the lava depression (near “III” on Figs. 9c) appears to have erupted along a SW-NE line and flowed mostly northwest. Also notable is the lining up of the SW-NE edge of this lobe with the long axis of the LD. The northeastern edge of LL-B is marked by a sharp contrast in backscatter within hundreds of meters northeast of the scarps.

Two traverses with the TowCam (Figs. 9c; Figs. 10a and 10b) were made on the upper surface (Level I) of LL-B. The camera tows overlap with dredge tracks so we are confident that

the lava flow images represent flows with a dacite composition. The primary objective of camera tow CT-01 was to traverse the floor and walls of the LD. It began imaging the seafloor about 0.5 km west of the west rim of the LD in a water depth of ~2495 m, descended onto the floor of the LD (~2530 m) and traversed N-NNE along the floor to within about 0.5 km of the northeastern rim (Fig. 10a). The camera contacted the seafloor during the first few minutes of the tow west of LD, apparently having descended into a local 5-10 m steep-walled lava pit or blocky area (Fig. 10a, inset). Photos from this portion of the tow show closely spaced horizontal bands on the wall of the pit (Fig. 11a). Two possible explanations for these lineations are: (1) “bathtub rings” found on drained out lava lakes on the mid-ocean ridge, which record the level of the subsiding lava pond as it drains out (Ballard et al. 1979; Chadwick 2003), and (2) lineations characteristic of crease structures on silicic lava domes and flows formed by progressive cracking and extrusion along a spreading structure (Anderson and Fink 1992). The west rim area of the LD is mostly of rounded pillows and flatter lobate forms with some brecciated ropey flows in places (Fig. 11b). Images of the west wall of the depression show a near-vertical scarp, consistent with both the multibeam and camera tow bathymetry (Fig. 10a, inset). The floor of the LD consists of low relief (~10 m across 2 km) sedimented lava breccia. Most of the lava breccia appears to be flow breccia, probably from broken up ropey flow. However, there are a few areas where large intact ropey lava flow folds were preserved (e.g., Fig. 11c), so the ropey surface is apparently the upper surface of extensive low viscosity lava. The nearly flat floor of the depression is similar in morphology to the floors of drained-out lava lakes on the mid-ocean ridge (Ballard et al. 1979) and lava lakes on subaerial volcanoes. This frozen “lava lake” could have formed directly over the magma conduit as the lava drained through subsurface tubes. Another possibility is that LD is a type of perched lava pond such as have been described from Kilauea eruptions (Wilson and

Parfitt 1993). However, perched lava ponds are rootless features with a maximum of 100s m diameter and a few meters relief, compared to the 2 x 1.5 km diameter of the LL-B depression, so we favor the drained lava lake explanation.

Camera tow CT-02 (Fig. 10b) began on the east side of the sedimented dome on the upper reaches of the northwestern sector of LL-B and traversed downslope and crossed into and then traversed the LL-B field for about 2 km. The first part of the tow (not shown on Fig. 10b, inset) traversed over heavily sedimented terrain with some outcropping substrata that appear to be lavas. The backscatter boundary coincides with an abrupt transition (at ~2590 m) into thinly sedimented lavas displaying a range of morphologies. Many of the images show anastomosing pillow tubes, sometimes flowing down gentle slopes for tens of meters (Fig. 11d), and in some places flowing amidst blocky ridge or dome-like structures (Fig. 11e; ESM_5). The pillow tubes often terminate with ballooning extrusions that can produce a spiny mass (Fig. 11f) or split and extrude into three sections (Fig. 11g). Interspersed within the pillow flows are domes and ridges with 10-100 m scale that show a variety of surface textures and structures. In some places, a series of cracks occur on otherwise smooth lava, presumably formed by extension of the flow surface during eruption (Fig. 11h). There are also fractured structures covered with broken folded ropey flows similar to those seen on CT-01 in the LD (Figs. 11i and j). Many of the ridges have axial fractures that can sometimes occur in a triaxial pattern (Fig. 11k). In some cases, the higher relief structures have smooth surfaces that have probably opened by endogenous growth creating linear features that appear to be extrusion structures resembling the “crease” structures observed in low viscosity subaerial (Anderson and Fink 1992) and some submarine inflated basaltic lava flows (Appelgate and Embley 1992) (Fig. 11l). Some of the inflated/fractured ridges and domes have onlapping pillow lavas suggesting multiple eruptive pulses (Fig. 12a).

3.5 LL-C lava flow field

The LL-C lava field, the third in size of the northern flow fields (total area of ~26 km²), is an inverted v-shaped area of high backscatter centered on the crest of the Niuatahi Ridge and extending to the SW and SE on, respectively, the western and eastern flanks of the ridge (Figs. 2-4). The western flank field is a hummocky terrain aligned within a SW-NE oriented band that separates from the main ridge to the south. The irregular hummocky terrain implies short run out distance, so the flows were probably volume limited (Fig. 10c). Camera tow CT-05 traversed from west to east up and over these hummocky flows. After traversing thickly sedimented, presumptively older, lavas outside of the LL-C backscatter boundaries, the camera passed over the northern terminus of the southern flow (near “SF” Fig. 10c), which consisted of mixed tubular and flatter lobate pillows punctuated (Fig. 11m and 12b) by extrusion structures forming the end of the pillow flow (Fig. 11n; ESM_6). The camera then passed up and over the 40-50 m high northern flow (“NF” on Fig. 10c) (near dredge KM1024-D04) where it imaged more pillows, including some with the peculiar “buffalo head hair” surface texture (Figs. 7 and 11o), which is common on dredged samples of the northern flow fields. The top of the NF has smooth areas, including domes and ridges with large tensional fractures, which are common on inflated lava flow structures. In some cases the underlying massive flow’s columnar jointing was exposed, probably as the lava was domed and fractured by endogenous growth (Fig. 11p).

3.6 LL-D lava flow field

The LL-D lava field abuts the heavily-sedimented (low backscatter) fractured Niuatahi Ridge north of LL-C (Fig. 2). The axis of the NELSC lies to the west. This field has the most uniformly high backscatter of all the northern flow fields and is second in area at 55 km². Without groundtruthing, however, it is not possible to determine whether the higher backscatter

represents a younger (less sedimented) or a less rugose surface. However, this lava flow field is farthest in distance from direct pathways of volcanoclastic sediment transport from the magmatic arc, which is consistent with a thinner sediment cover than the young lava fields that lay to the south. The lava flow surface increases in depth from south to north in a series of steps (I-IV on Fig. 13) whose surfaces have numerous small depressions and ridges. Most of the flow fronts are broad or stubby, but there is one well-defined sinuous lava flow with an along-axis length of ~1.75 km (“a” on Fig. 13) and a relief (thickness?) of 40-60 m. The deeper lava surfaces (II and III) have numerous 5-10 m irregular-shaped pits on them. Some of the depressions, e.g., the ones on surface III (“b” on Fig.13) may have also formed by lava drainout. The scarps defining the outer limits of the various levels of LL-D, which we assume are flow fronts, vary from ~30-60 m, similar to the thickness of the “a” lava flow. A large open channel-like feature one km in width and several km long extends northwest into the valley to the west (“c” on Fig. 13). This channel drops ~300 m into hummocky terrain that could be lava flow fronts. The channel likely formed when the lavas reached a steeper (faulted) slope into the rifted terrain to the west.

The eruption source for LL-D is unclear. A large mass of the lavas appear to have flowed north parallel to the regional structure, forming successively deeper levels of the lava surface. However, some of the shallower high-backscatter terrain is contiguous to the faulted structure to the east with some of the lobes deepening to the west. There could be multiple lava sources along the ridge. The LL-D flow field has only one dredged sample set (KM1024-D24 taken within the large channel, Fig. 13), and it is compositionally indistinct from the northern flow fields (LL-B and LL-C).

4.0 Discussion

Although we have presented the setting, morphology and composition of these flows in as much detail as our data sets allow, our interpretations are necessarily limited by the lack of detailed seafloor (optical) imagery, near-bottom high resolution bathymetry, and high density rock sampling, such as is more easily accomplished for terrestrial lava flows. Our sampling is limited and non-uniform so, for instance, we don't know the composition of volcanic products from the intervening areas, between the lava fields. In some ways the level of field study presented here is akin to the early studies of large continental composite volcanoes. In this section we make certain inferences with the present data set and present some hypotheses to be tested in the future.

4.1 Sources of erupted magmas

We divide the dacite lava fields into two main categories, those erupted on the flanks of and/or in proximity to Niuatahi (LL-A1-A5) that are likely erupted from its underlying magma chamber, and those located north of and geographically separated from the volcano. The compositional variation of the northern lava flows is narrowly constrained in major elements whereas the Niuatahi lavas have a wider range, although the latter is poorly sampled (as discussed in section 3.2).

The northern flow fields are of particular interest because of their extent and that they are not clearly related to a major constructional volcanic feature (e.g., spreading center, central volcano). The northern flow fields all occur in a north-south corridor containing some north-south striking structures, including a short (~10 km) rift zone and ridge extending north from Niuatahi. Thus it is tempting to propose that these northern flow fields erupted from dike injections issuing from the magma chamber beneath Niuatahi and extending along the axis of

this region, perhaps associated with caldera-forming paroxysmal event. Along-axis diking events are common at basaltic shield volcanoes such as Kilauea (Epp et al. 1983), Icelandic central volcanoes such as Krafla (Einarsson 1991; Buck et al. 2006), Askja (Sigurdsson and Sparks 1981) and on submarine volcanoes such as Axial seamount (Juan de Fuca Ridge) (Dziak and Fox 1999), and on the mid-ocean ridge (Einarsson 1991; Fox et al. 1995; Embley and Lupton 2004). However, in all these cases mafic magmas were involved. Silicic dikes exist as well (Fink 1985), but their ability to propagate for distances longer than a few kilometers has not been well documented. A lateral dike injection would imply a dike of between 30 and 60 km (from the center of Niuatahi to the southern and northern boundaries of LL-D). Also, the chemistry of the northern flow field lavas is not generally consistent with their being erupted from a dike originating from the Niuatahi magma chamber (see section 3.2).

Alternatively, the dacite lavas could be a differentiate of the boninite magma that erupted in the nearby Mata basin. A differentiated series of Miocene boninitic lava has been well-documented on Chichi-jima (Bonin islands) and within nearby dredged and drilled sections (Bloomer and Hawkins 1987; Taylor et al. 1994) and a similar case has been made for older dredged rocks in the NE Lau basin (Falloon et al. 2007). The very low TiO_2 contents of the dacites reported here (0.60 ± 0.05 wt. %) is consistent with this scenario. There is no trend at all of Fe_2O_3 or TiO_2 vs. SiO_2 in the northern dacites (in fact both don't vary with changes in SiO_2 or with each other) indicating that the low TiO_2 is not due to Fe-Ti-oxide fractionation. Analyses of recently obtained trace element data for the current suite of samples should shed light on this hypothesis (Rubin et al. 2015). However, this scenario requires a location near the locus of boninitic volcanism to store, differentiate and compositionally homogenize magmas before eruption.

If the northern dacite lavas (LL-B, LL-B2, LL-C and LL-D) are differentiated from boninite magmas, and had a magma source separate from Niuatahi, one also has to explain the spatial distribution of the boninite and dacite lavas and apparent lack of inter-fingering. Although the dacites are all centered around and partly on the summit of N-S ridge structures, there are also other regional structures that could influence lava plumbing. Most striking are those along a SW-NE trend, following the trend of rift zone of West Mata and southernmost of the smaller Mata volcanoes (Fig. 2). Similar trending structures appear to control some of the volcanic ridges around Niuatahi (most obvious in the area SW of the caldera) (Fig. 2). An historic eruption occurred along an extension of the southwest rift zone of West Mata (yellow patch with black outline below “West Mata” label on Fig. 9) (Embley et al. 2014) but it has not yet been sampled. There are also apparent SW-NE trends on the LL-B lava, including the elongation of the lava depression and the edges of some of the deeper flows (Fig. 9). The western portion of LL-C is also aligned approximately in the same direction. So it is possible that the northern flow fields are controlled by intersecting N-S and SW-NE crustal fractures.

Overall, the dacite volcanism is apparently restricted to the most rapidly opening part of the NE Lau basin, along tectonic lineaments, in the basins near the northern edge of the region and near the currently subducting slab. The dacite volcanism also approximately coincides with the area near the edge of the active tear fault formed by the northern termination of the Tonga subduction zone at $\sim 15^{\circ}\text{S}$. The eruptibility of melts can be dependent on tectonics as well as buoyancy, which is apparent in subaerial settings such as the Inyo Domes-Mono Craters eruptions in California (Bursik et al. 2003). Tests of these hypotheses await results of future field studies.

The total area of all the silicic flows is $\sim 402 \text{ km}^2$, including $\sim 236 \text{ km}^2$ for the northern flow fields and $\sim 166 \text{ km}^2$ estimated for the southern flows associated with Niuatahi, although the latter might include other types of volcanic flows (Table 2). However, it is not clear that all the areas mapped as lava flow fields around Niuatahi are lavas versus other types of volcanic flow (see section 3.3). Measurement of the volume is problematic, but, at least for the northern flow fields, our estimate is $\sim 2.4\text{--}7.2 \text{ km}^3$ (based on 10–30 m average relief of the flow fronts). With typical eruption rates for dacite lavas in subaerial environments, the NE Lau flows would have taken years to erupt. However, these flows exhibit a wide range of morphology (see next section), which is likely to be at least partly due to variable eruption rates, potentially allowing for a shorter eruption duration.

4.2 Submarine dacite lava regimes

The multibeam data provide a first-order morphology map of the lava flow units, but do not have sufficient resolution to discriminate individual lava flows or small scale morphology (meters to tens of meters). The camera tow images provide some information on small-scale structures, but are very limited in the area they cover, $\sim 0.04 \text{ km}^2$ total area compared to the several hundred square kilometers of the lava flows. The available imaging reveals lava flows with an almost complete overlap of lava regimes found in submarine basaltic lava flows, including ropey, pillow and inflated flows. Different lava regimes often onlap one another.

Both compressional and tensional surface features are observed on subaerial lava fields – this duality apparently modulated by the effusion rate (Blake and Bruno 2000; Lescinsky 2005). Fracture patterns such as the “tri-cracks” (fractures, sometime acting as loci of extrusion, oriented at spacing of $\sim 120^\circ$) are similar to those found on subaerial lavas and submarine lavas formed during endogenous growth are common (Walker 1991; Appelgate and Embley 1992;

Hon et al. 1994). Groups of extensional fractures, such as those found oriented perpendicular to the flow direction on subaerial flows, can also occur as the upper section of the flow stagnates and lower part advances.

Lava pits and depressions found on the surface of LL-B and LL-D suggest high eruption rate, and relatively low viscosity eruptions. The LL-B lava depression has the size and morphological character (e.g., flat floor) of lava lakes formed directly over a primary lava conduit (e.g. Kilauea). The LD is surrounded by a low-relief area extending out for up to ~2.5 km with radial trough dipping in towards the center. To our knowledge such a feature has never been described, neither for subaerial nor for submarine silicic eruptions. The lavas associated with the LD, such as the ropey forms observed on CT-01, are consistent with low viscosity eruptions and high effusion rates, possibly due a higher temperature than usually associated with dacite magma. It is tempting to think of the LD region as a “silicic shield” formed during the eruption of a low viscosity submarine dacite flow that is unlikely to ever form in the subaerial environment. High eruption temperatures, rapid emplacement and subsequent rapid cooling are consistent with the very glassy to mildly microcrystalline groundmass of most lava samples from the dacite flows. High dissolved water contents can lower the viscosity (Spera 2000) of lavas of a given composition. Dacite and rhyolite lava flows in subaerial environments are usually thick and erupted at a high viscosity, generating lavas with short run outs. Yet submarine dacite lavas at these water depths (~2400-2800 m) erupted from magmas with presumptive high dissolved volatile contents high temperatures, and with sparsely phyric texture could, theoretically, be derived from the lowest end of the viscosity scale for melts of their chemistry range, perhaps as low as $\sim 10^{-3}$ - 10^{-4} Pa·s, which is within the range of viscosities for typical andesites (Takeuchi 2011; Takeuchi 2015).

Furthermore, experimental work by Whittington et al. (2009) on hydrous dacitic melts show that, even at typical liquidus temperatures (for the given composition), dacitic melts are only slightly more viscous than andesitic melts (a larger increase is associated with rhyolite composition). The suite of dredged samples from LL-B, LL-C and LL-D show limited vesiculation, even in those samples in the shallower (near-vent?) regions of the LL-B flow field (D06 and D07). Also, they are nearly aphyric, which is consistent with higher temperatures and a lower viscosity.

An important inference from this study is that the morphology of these silicic submarine lava flows almost completely overlap basaltic submarine lavas, which are much better studied. The lava depression on LL-B appears to contain a frozen lava lake of dacite, formed during a high effusion rate episode that ended with the drainout of the lava creating a 30 m deep, 2.0 x 1.5 km depression. Similar depressions are found on LL-D, including a possible breached feature of comparable size to the LL-D depression.

Gregg and Fornari (1998) concluded that submarine basaltic lava flows have the potential for greater flow lengths, mostly due to better insulation from formation of a thick glassy layer not found on subaerial flows. The glass layer for the dacites is about 10 to 100 times as thick as that of a submarine basalt (10s of cm vs. 0.1 to 1 cm), offering an even greater insulation effect. High effusion rates, high liquidus temperatures and high gas retention are the conditions for relatively low viscosity geomorphology of portions of the Lau dacite lava flows. However, a cautionary note is that we have very limited high resolution imagery on these dacite lava fields. Even the existing photographic transects show a wide range of flow regimes, and we have no detailed imaging of the deeper portions of the LL-B (where there are high relief flow fronts), and

none over the entire LL-D flow field. More detailed field work is needed to resolve the range of flow regimes and rheological evolution of a deep submarine dacite eruption.

4.3 Silicic submarine lavas in the ancient record

Knowledge of other submarine silicic lavas is mostly confined to rare ancient sequences exposed on land and to small batches of evolved lavas present within mid-ocean ridge and transform environments, so the NE Lau dacite flows provide the first look at young, aerially extensive, large volume, deep submarine silicic lava flows on Earth. Because of their setting within the world's fastest backarc opening rate intra-oceanic subduction zone and consequent high upper mantle temperatures, the NE Lau basin should potentially provide some new insights into magmatic processes operative in early Earth with its higher heat flow gradients. The production of extensive, geographically contiguous, boninite eruptions is additional evidence for regionally high upper mantle temperature melts here and slab-derived volatile fluxes. The higher upper mantle temperature could yield lavas with higher eruption temperatures for a given magmatic composition, leading to lower than normal viscosities. There are no equivalents in the literature on modern subaqueous dacite lava flows comparable to the observations described here and only a few cases of (apparently deep) submarine dacite lavas have been reported in ancient rock sequences now exposed on land. Extensive pillow like forms of submarine dacite lava reported from the Archaean of Ontario, Canada (Dinel et al. 2008) with at least the run out length of the Lau lavas (~10 km). Dinel et al. (2008) propose that the lava flows erupted in a "superheated" state, consistent with their aphyric nature. They speculate that this superheated state might have resulted from the higher geothermal gradients associated with the Archaean Earth (Langdon and Sleep 1982). Dacite to rhyodacite lavas pillows and tubes from the Ordovician of Wales are also ascribed to high effusion rate, high temperature eruption and

possibly a high slope angle (Bevins and Roach 1979). Cas (1978) reports on extensive andesite to dacite lavas in the Devonian/Carboniferous of New South Wales, Australia and invoked low viscosity resulting from deep water (high pressure) retention of volatiles. Finally, Gibson et al. (1999) emphasize the rarity of such extensive siliceous flows in the geologic record.

Some deep-water dacite lavas from younger subaqueous sequences in island arc settings (exposed on islands and trench walls) are often geochemically associated with boninite lavas (Kuroda et al. 1978; Bloomer and Hawkins 1987; Kuroda et al. 1988; Dobson et al. 2006). Both major and trace element data suggest that the more evolved lavas derive from fractional crystallization of boninite magmas.

5.0 Conclusions

(1) Hundreds of square kilometers of young dacite lavas been mapped and sampled in the NE Lau basin, identifying the largest currently known submarine dacite lava occurrence on Earth. Several fields are flank flows from a silicic volcano (Niuatahi). The remaining three major flow fields (and one smaller field) occur 15-60 km north of Niuatahi within a corridor between the NELSC and the Mata boninite volcanoes and the Tofua arc. The northern flow fields are compositionally indistinguishable from each other, and distinct from the flows nearest Niuatahi.

(2) The northern lava flow fields, which are geographically isolated from the lava fields associated with Niuatahi, cover $\sim 236 \text{ km}^2$ and have thicknesses, at least in places, of $\sim 10\text{-}30 \text{ m}$, yielding a volume of $\sim 2.4\text{-}7.2 \text{ km}^3$.

(3) The geographic magmatic source of the northern flow fields is not clear. Either they erupted from long dikes generated at the silicic Niuatahi seamount to the south, or have tapped separate magma sources and erupted along crustal fractures. Chemical differences with Niuatahi lavas

favor a distinct source scenario, from a large, well-mixed magma body or bodies erupted along crustal fractures in the rear arc north of Niuatahi seamount.

(4) Where imaged by camera, the dacite lavas have similar to indistinguishable range of morphologies compared to MORB lavas, including pillows and ropey flows. Deep submarine dacite lavas can have lower viscosities than subaerial equivalents because of higher volatile retention (due to high confining pressures) and in the Lau case, possibly higher eruption temperatures. The Lau basin, with its high upper mantle temperatures relative to other back arc basins, enhances the eruptibility of large volumes of silicic lavas.

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Figure Captions

- Fig. 1: Map of NE Lau basin (location: see inset map) with major features labeled as: MTJSC- Mangatolu Triple Junction spreading center; FRSC – Fonualei Rift spreading center; NELSC – Northeast Lau spreading center. Dashed blue line is approximate trace of center of neovolcanic zones on spreading centers; dashed red line is approximate trace of topographic low of Tonga Trench. Brown line is 1000 m contour of northern Tofua Arc. Gray arrow labeled 157 mm/yr is vector for relative motion between Tonga and Australian plates (Zellmer and Taylor 2001). Gray lines are 1000 m contours. Box encloses area shown in Figures 2-4.
- Fig. 2: Niuatahi lava corridor multibeam bathymetry with dacite lava flow fields highlighted in grayish overtones bounded by red lines. Boundaries outline areas of higher backscatter and small-scale topography indicative of lava flow morphology such as pits, channels, flow fronts, and lobes. Green dashed line bounding light brown overtone across SE portion of map shows approximate limit of volcanoclastic apron of Tofua Arc. Black dashed line is axis of Northeast Lau spreading center (NELSC). Lava flow fields are named in black letters LL-A (1-5), LL-B, LL-B1, LL-C, and LL-D designate Lau lava flow fields named in text. White patches within lava flow boundaries are kipukas (patches of older seafloor). Niuatahi (*N*), Motutahi (*Mo*), West Mata (*WM*), and BoCo are seamounts or volcanic cones referred to in text. *NR* is older ridge extending north from Niuatahi, and *MB* is Mata Basin, a rifted region containing the Mata seamounts. Grid cell size of bathymetry grid is 20 m. Gray lines are 250 m contours with italicized numbers as contour values.

Fig. 3: Niuatahi lava corridor acoustic backscatter from multibeam surveys (see color table in legend for relative values with minus values highest acoustic return). Letter and line designations are same as Fig. 2.

Fig. 4: Niuatahi lava corridor features with sample and camera tow locations. Numbers in white filled boxes (cruise KM1024) and circles (cruise KM1129a) are dredge numbers (Table 1 and ESM_1) for samples used in this study. Thick black lines (not numbered) are dredges (length defined by begin and end time of dredges on bottom) recovering boninitic composition on cruises KM1024 and KM1129a (unpublished data). Numbered thick yellow and red lines are, respectively, dredges recovering dacite and (one) rhyolite samples. Black filled, yellow filled and red filled triangles are, respectively, boninite dacite and rhyolite dredge samples reported in Falloon et al. (2007). Brown-filled triangle near top left of map is location of back-arc basin basalt dredge sample reported by Falloon et al. (2007). Filled black square on summit of West Mata (*WM*) is location of boninite sample reported in Resing et al. (2011). Thin black lines adjacent or overlapping with dredges 04, 06 and 07 are paths across bottom of camera tows shown in detail in Fig. 10. Rectangular outlines show location of Figures 8 (LL-A3), 9c (LL-B), 10c (LL-C), and 13 (LL-D). Note that lava flow fields outlined in red also mark higher backscatter zones (see Figure 3).

Fig. 5: 3D oblique perspective images created using Fledermaus© supported by QPS Marine and Hydrographic Solutions. White lines show outlines of dacite lava flow fields: (a) View of Lau lavas looking southwest toward Niuatahi seamount; (b) LL-B flow field looking southwest; (c) Zoomed in view of LL-B flow field; LD is Lava Depression; (d) LL-D flow field looking to southeast.

Fig. 6: Photos of dredge samples from NE Lau dredges: (a) Sample KM1024-D24-R04 from lava flow field LL-D showing glassy texture; (b) Sample KM1024-D04-R08 from lava flow field LL-C showing folded glassy layers; (c) Sample KM1024-D08-R02 showing “buffalo head hair” texture common on the dacite flow tops. Black scale bars are 25 cm.

Fig. 7: Major element lava chemistry summary. The general color scheme used is: (1) warm colored triangles for large lava flow fields (LL-B, LL-C, and LL-D); (2) cold colored triangles for samples from Niuatahi caldera, rim, and LL-A lava fields. a) TAS plot of NE Lau lavas, dashed line is the current IUGS definition for the dacite-rhyolite divide; (b) detailed Harker plot Al_2O_3 vs. SiO_2 for LL-A-D fields; (c) detailed Harker plot of MgO vs. SiO_2 for LL-A-D fields; (d) detailed Harker plot of FeO vs. SiO_2 for LL-A-D fields; (e) TiO_2 versus MgO ; (f) $\text{CaO}/\text{Al}_2\text{O}_3$ versus MgO .

Fig. 8: Bathymetry of lava flow field LL-A3 (see Figure 4 for location box). Contours (gray lines) are at 100 m interval. Line A-B locates bathymetry cross-section profile (lower left inset). Southeast corner of map is northwest flank of Niuatahi. Dredges KM-1024-D03 and KM1129a-D15 noted. Lava extent as mapped by backscatter is the red outline and kipukas (older terrain surrounded by lava flow) are brown lines. Dashed lines with arrows indicate possible lava flow directions.

Fig. 9: Details of lava flow field LL-B. Bathymetric dome-like hills discussed in text are labeled “D”, lava depression labeled “LD”, and lava channel labeled “LC”. Backscatter boundary is thick black line and kipukas within the lava flow are outlined in blue. Small yellow patch southwest of West Mata is 2010 eruption as described in Embley et al. (2014). a) Multibeam bathymetry of LL-B lava flow field at 20 m grid-cell size. b) Bathymetric slope of same area as (a) color coded with slope range in degrees as in color bars. (c)

Features of LL-B lava flow field. Orange-shaded areas are possible lava domes on ridge next to lava flows. Lava flow levels marked in italic Roman numerals (*I-IV*) as in inset. Irregular brown lines within LL-B are possible flow fronts. Square boxes with numbers next to thick yellow lines are dredges and circular symbols with numbers next to black lines are camera tows. Arrows represent possible flow directions. Inset shows bathymetric profile (along dashed line A-B on map) showing different levels of lava surface (I-IV).

Fig. 10: Detailed maps of camera tow sites on LL-B and LL-C. On-bottom camera tow tracks are black lines. Thick yellow lines are on-bottom dredge tracks (labeled). Contour interval is 10 m on all maps and thick red line is boundary of high acoustic backscatter zones (except for “a”, which lies completely within high backscatter zone of LL-B). Insets on upper left of each panel is along-track depth profile constructed by adding pressure depth from the camera CTD and the height above bottom from the altimeter mounted on the camera. Small arrows and lower case letters show locations of camera images shown in Figure 11. (a) Close-up map of lava depression (LD) within LL-B lava flow field with track of camera tow CT-01. Location of map on Figure 9c (box over feature labeled “LD”). (b) Close-up map of shallow portion of northwest portion of LL-B lava flow field with track of camera tow CT-02. Location in Figure 9c (box just below inset). Profile on inset starts just east of the backscatter boundary (red line on map), position marked by arrow going from left side of inset. (c) Map of southwest portion of LL-C lava flow field camera tow CT-05 across lava flows within LL-C field. “SF and “NF” are, respectively, north mound and flows. Location on Fig. 4.

Fig. 11: Lava flow gray scale images from camera tows CT-01, CT-02, and CT-05. Locations are noted on insets in Figure 10. All photos were auto-processed in ©Adobe Photoshop Elements to obtain relatively uniform contrast. Approximate long-axis of frames vary between approximately 4 and 9 m. (a) CT-01 photo looking down into depression west of lava depression on LL-B; (b) CT-01 image of broken ropey sheet flow west of lava depression; (c) intact surface of ropey flow (large fold in middle of frame ~ 1.5-2.0 m across) on floor of lava depression, CT-01; (d) pillow tubes on slope (~ 1 m diameter tubes), CT-02; (e) pillows (≥ 1 m diameter each) amidst blocky flows, CT-02; (f) spinose extrusion site ~5 m across, CT-02; (g) Lines of extrusion produced along expanding fractures, CT-02; (h) extensional cracks in lava flow, CT-02; (i) ropey surface (frame ~6 m on long axis), CT-02; (j) ropey surface along CT-02; (k) endogenous ridge with large axial fracture (frame ~8 m across), CT-02; (l) similar to Fig. 11k with possible crease structures as discussed in text (frame ~8 m across), CT-02; (m) anastomosing pillow tubes up to ~2m diameter, CT-05; (n) extrusion at end of pillow tube (~3-4 m across) along tri-crack, CT-05; (o) Pillows, CT-05. Note surface which resembles “buffalo head hair” texture shown on Figure 6c; (p) Looking down into longitudinal fracture of endogenous ridge with columnar jointed lavas, CT-05.

Fig. 12: Mosaics of NE Lau dacite lavas created by overlapping and rescaling photos from Camera Tows CT-02. Scale of each approximately 20-25 m on long axis: (a) overlap of pillow tube lavas edge of lava dome; (b) Anastomosing pillow tubes on slope, CT-05.

Fig. 13: Bathymetry of lava flow filed LL-D. Red line is backscatter boundary; dashed line is path of bathymetric cross section shown below. Roman numerals I-V represent levels of

1066 lava surface, letters A-E are keyed to changes in direction of cross-section, and letters a-c
1067 with arrows point to specific features discussed in text.

1068

1069 **Electronic Supplement Captions:**

1070 ESM_1: Table of named locations, persistence identifiers, and location metadata

1071 ESM_2: Accepted and measured values for STG-56 and VG-2 analyzed for unknowns

1072 ESM_3: Six backscatter electron (BSE) images illustrating the range of groundmass textures in

1073 these submarine dacite lavas. A 100 μm scale bar is present in the lower right corner of

1074 each panel. The images are arranged in order of increasing degree of microcrystallinity.

1075 These groundmass textures develop primarily during lava emplacement, although some

1076 of the larger microphenocrysts (defined as $< 100 \mu\text{m}$ in largest dimension) seen in all

1077 images likely grew in the magma just before eruption. White crystals are pyroxenes, dark

1078 grey are plagioclase, and the bulk of the grey material in each image is glass. Images

1079 were collected in backscatter electron mode on the University of Hawaii microprobe.

1080 ESM_4: Lava compositions reported elsewhere in this paper plotted with three synthetic Liquid

1081 Lines of Descent (LLD) estimated using the MELTS program (adiabat_1ph_2-0) to

1082 investigate parent melt variations and differentiation effects. MELTS is not well

1083 calibrated for the conditions and magma compositions studied here, so these

1084 representative trends are used here only to demonstrate typical differentiation pathways

1085 and slopes. The LLDs are calculated starting from average West Mata boninite

1086 composition for three different conditions: The red colored LLD is for 500 bars pressure,

1087 oxygen fugacity at QFM (quartz-fayalite-magnetite), and 2 weight % water; The green
1088 colored LLD is for 1000 bars pressure, oxygen fugacity at QFM +1, and 3 weight %
1089 water; The Blue colored LLD is for 1500 bars pressure, oxygen fugacity at QFM +1, and
1090 4 weight % water. The trends demonstrate that a boninite parent melt can differentiate to
1091 make dacite magma with compositions similar to those observed in the large lava flow
1092 fields and at Niuatahi. However, a single boninite parent magma cannot make the full
1093 suite of compositions observed in the large lava flows and Niuatahi because some of the
1094 large lava flow compositional trends crosscut the LLD trends in some panels, suggesting
1095 mixing between magmas from different parents.

1096 ESM_5: Movie made from still frames along track of CT-02 (using WHOI TowCam) showing
1097 dacite lava flow morphology within LL-B lava flow field. Camera towed ~5 m above
1098 bottom in 2500-2520 m water depth. Size of view between ~2-5 m across, varying with
1099 altitude. Transect ~200 m.

1100 ESM_6: Movie made from still frames along track of CT-05 (using WHOI TowCam) showing
1101 dacite lava flow morphology within LL-C lava flow field. Camera towed ~5 m above
1102 bottom in 2500-2520 m water depth. Size of view between ~2-5 m across, varying with
1103 altitude. Transect ~200 m.

1104

Figure 1

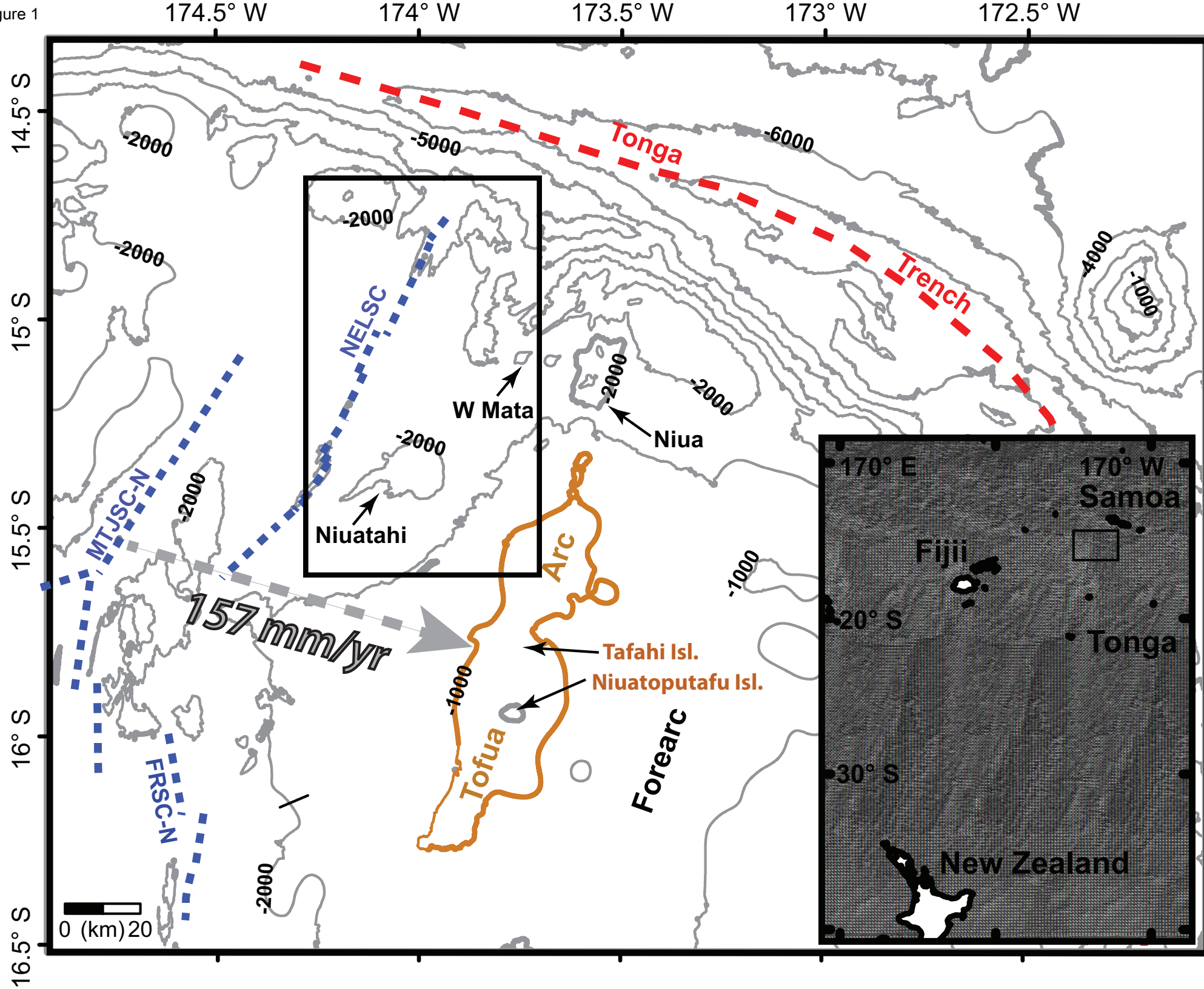


Figure 2

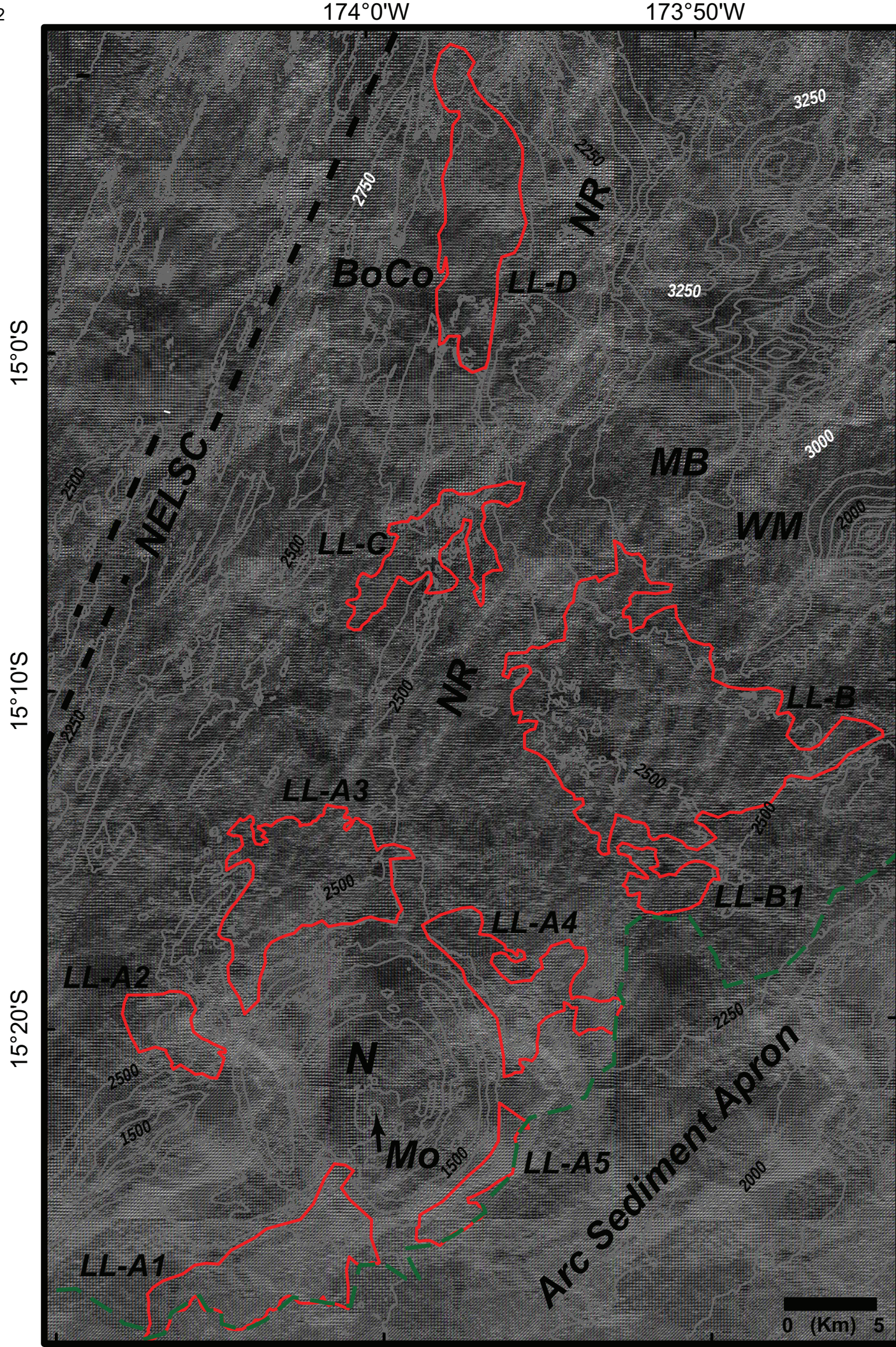


Figure 3

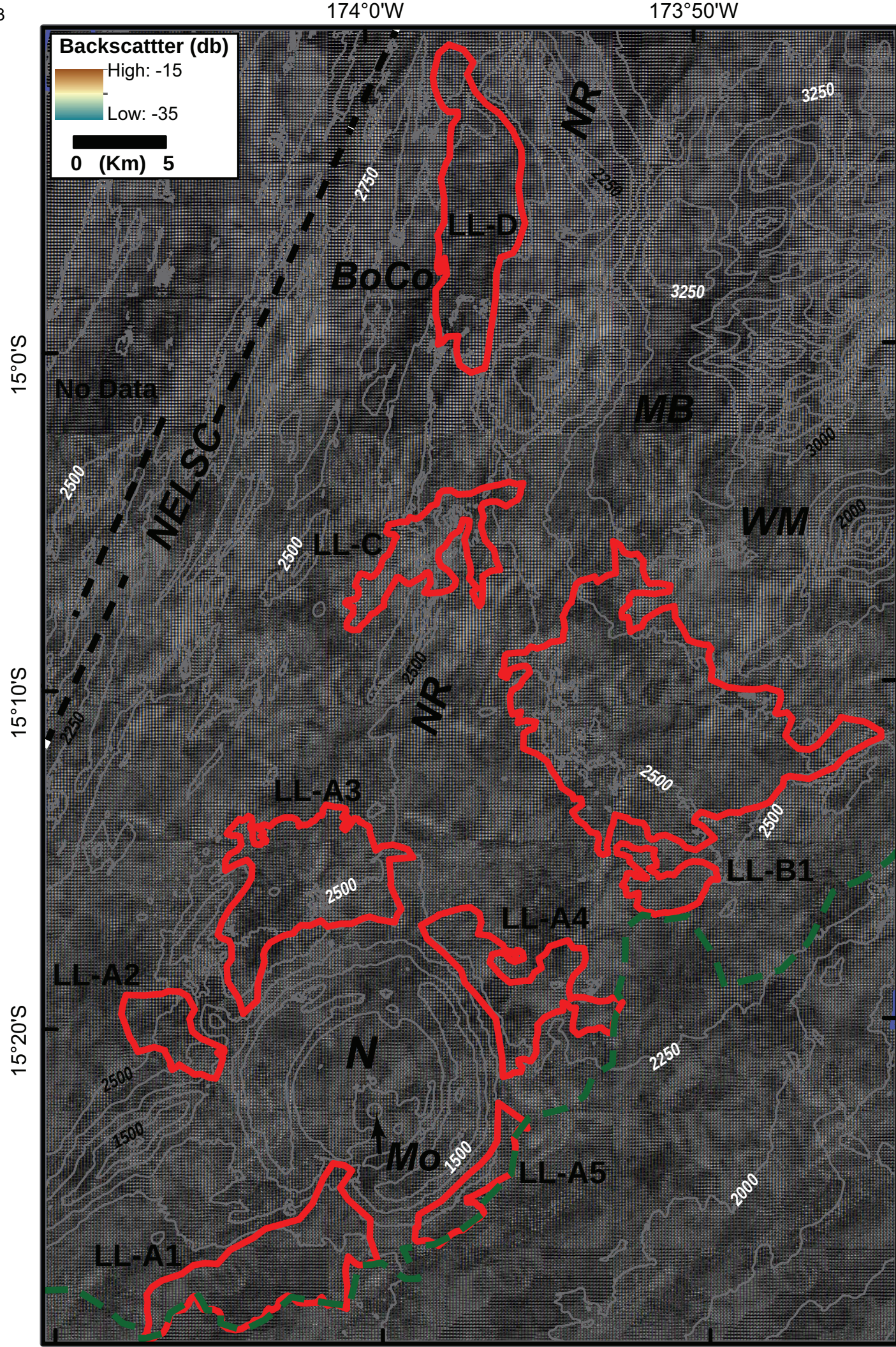
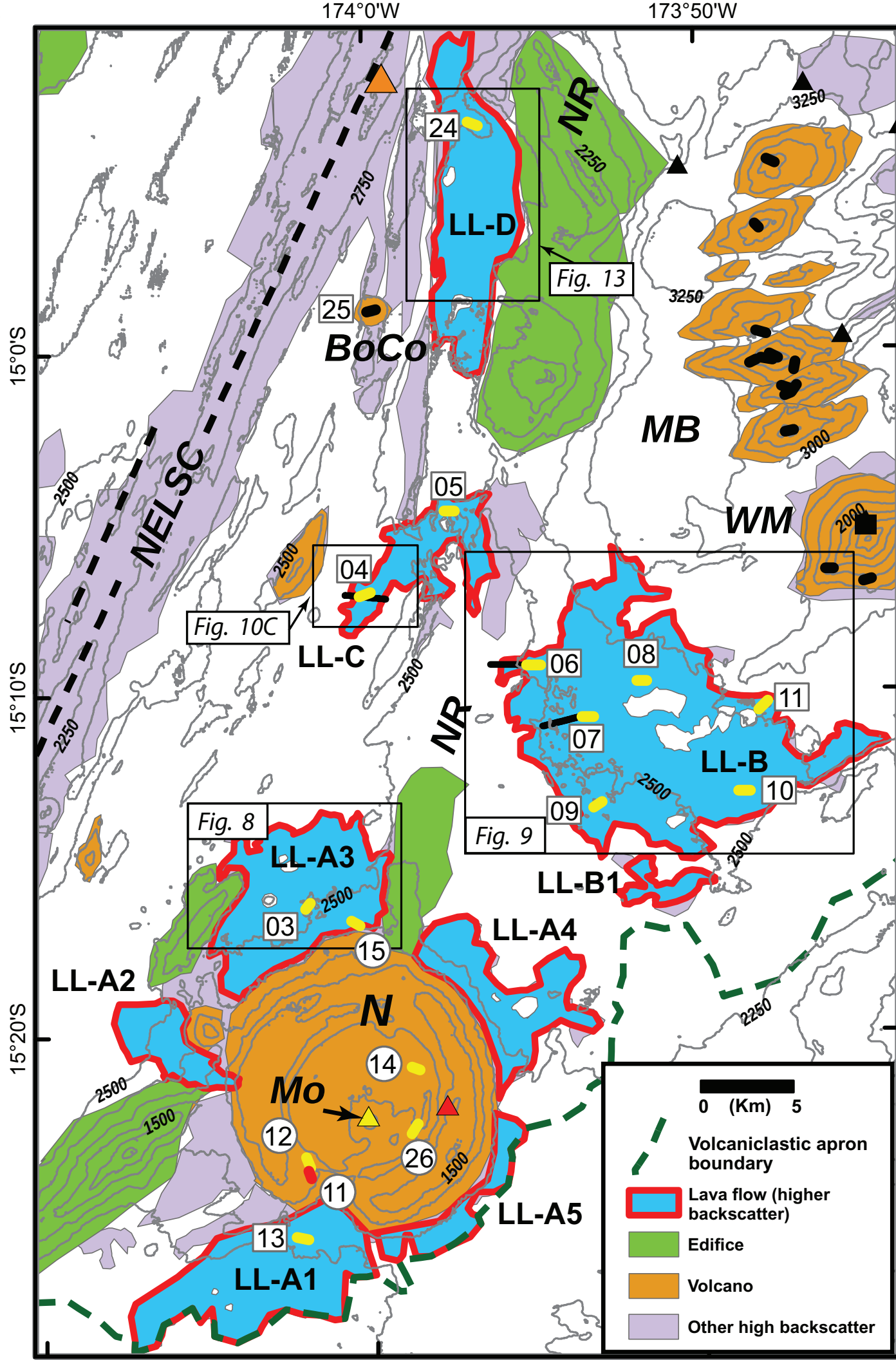


Figure 4



Figure

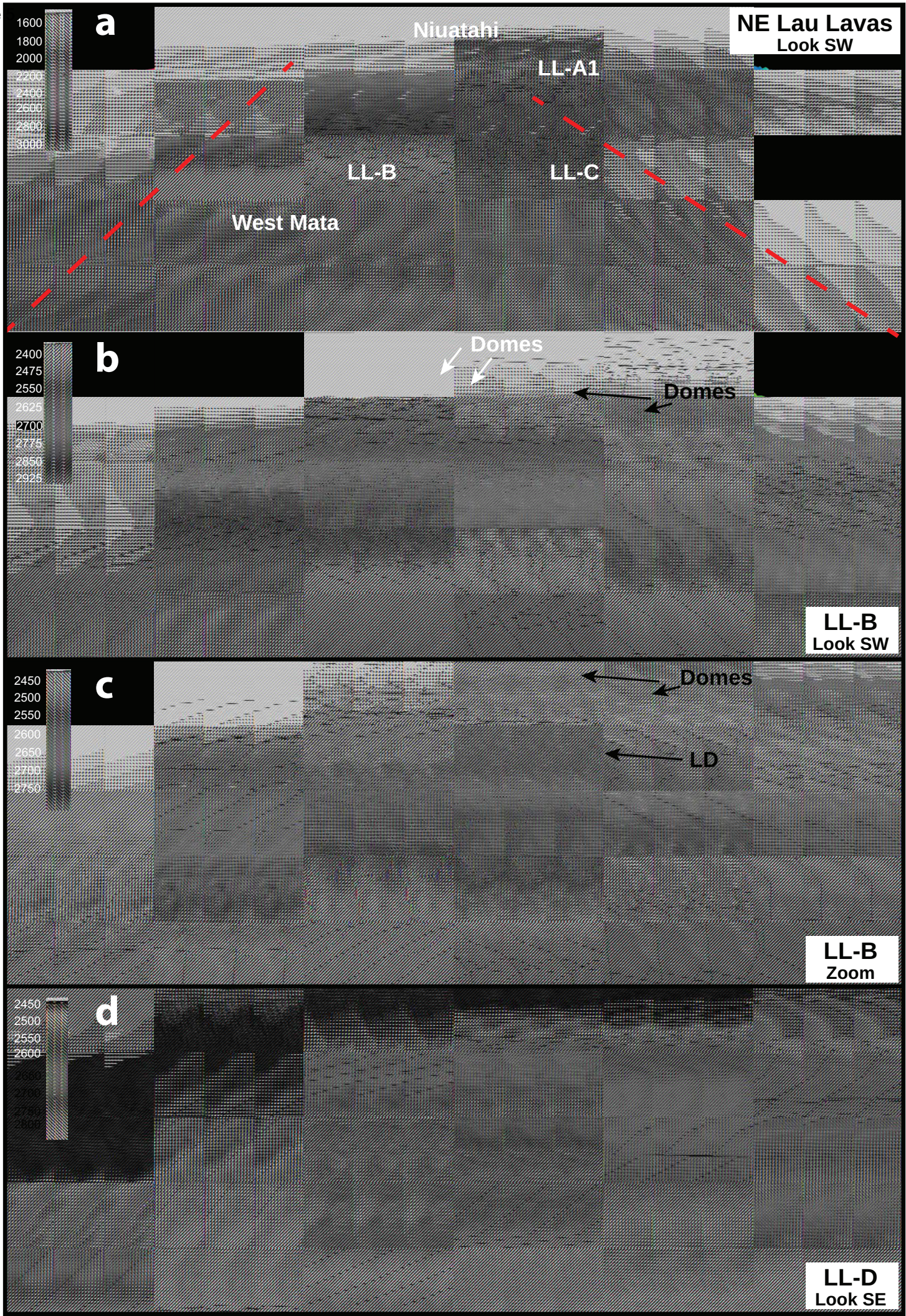
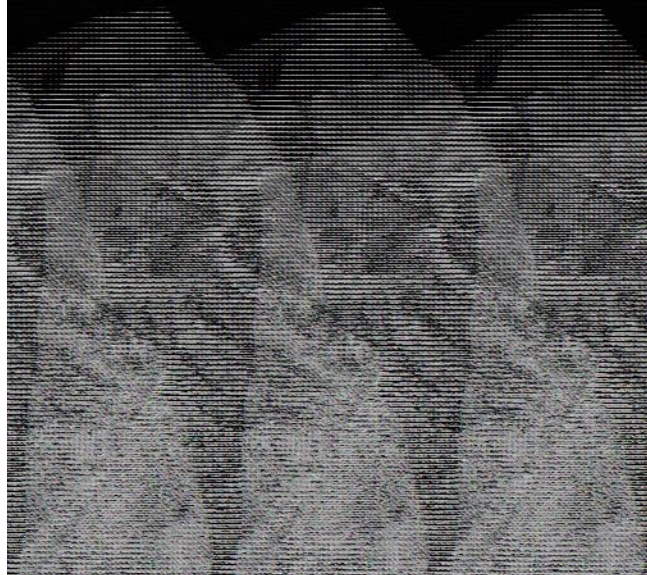


Figure 6

a



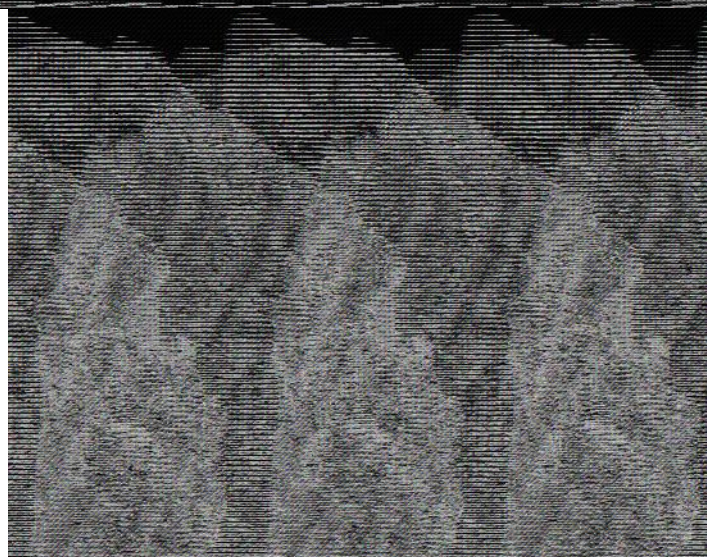
KM1024-D24-R04

b



KM1024-D04-R08

c



KM1024-D08-R02

Figure 7

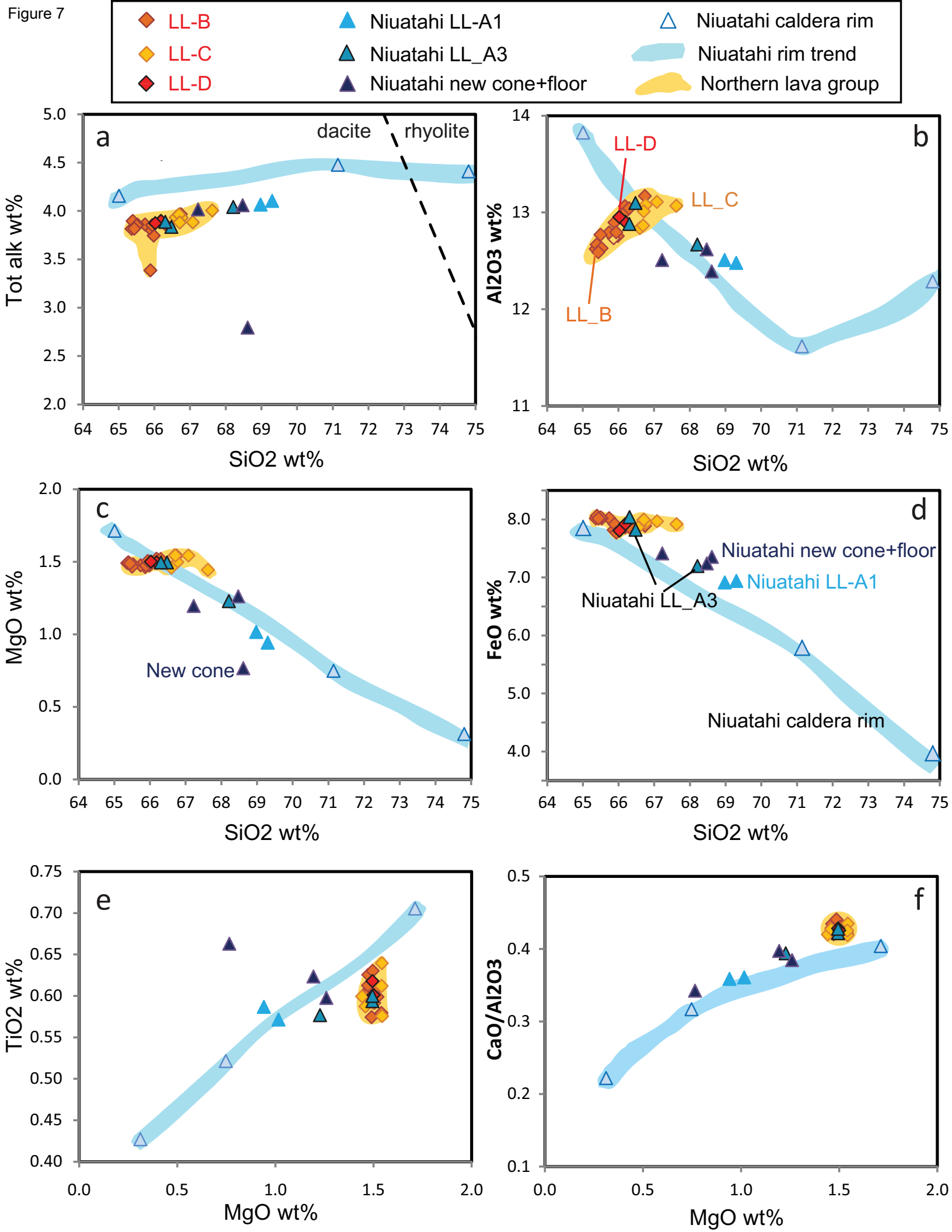


Figure 8

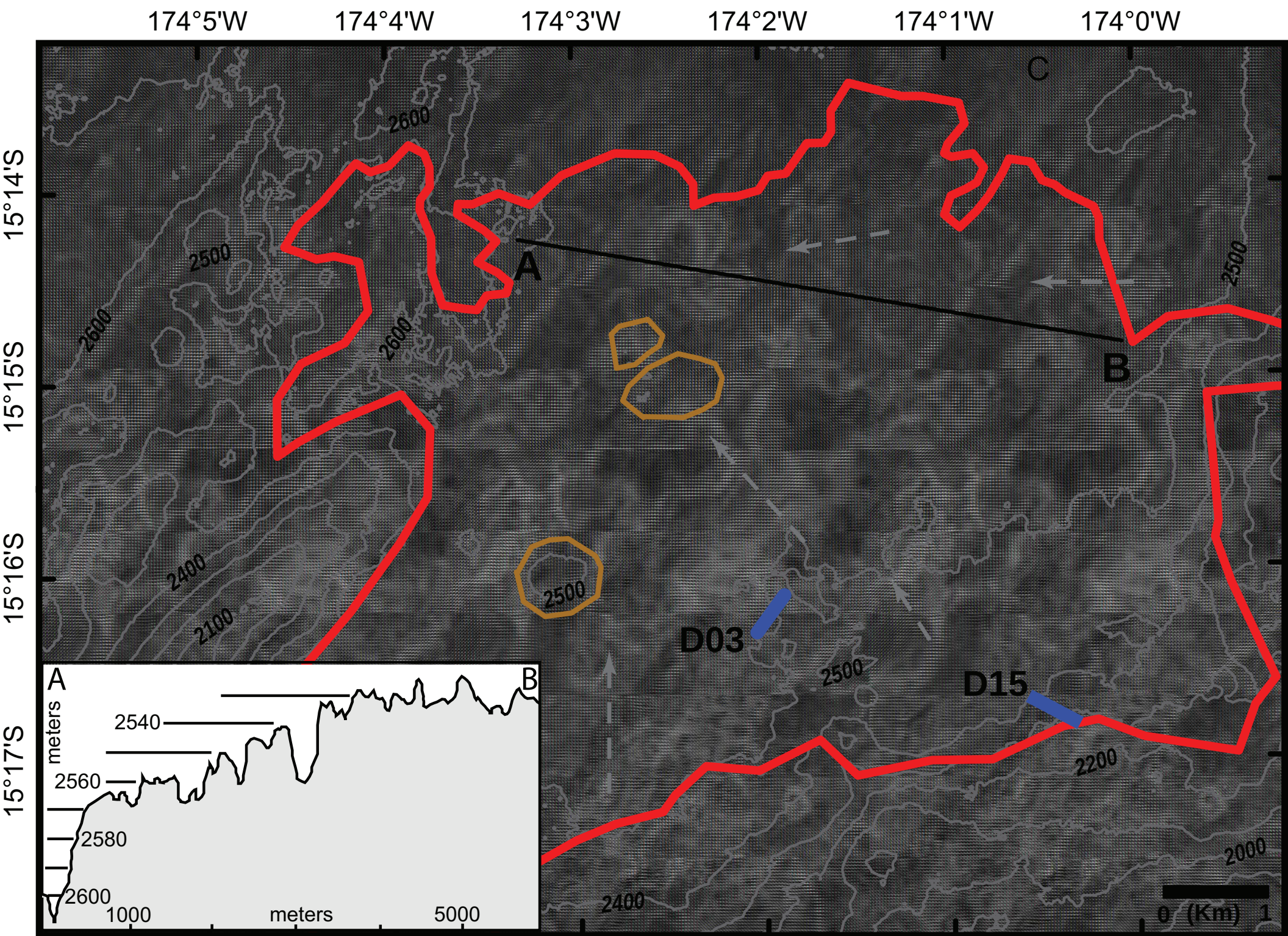


Figure 9_a-b

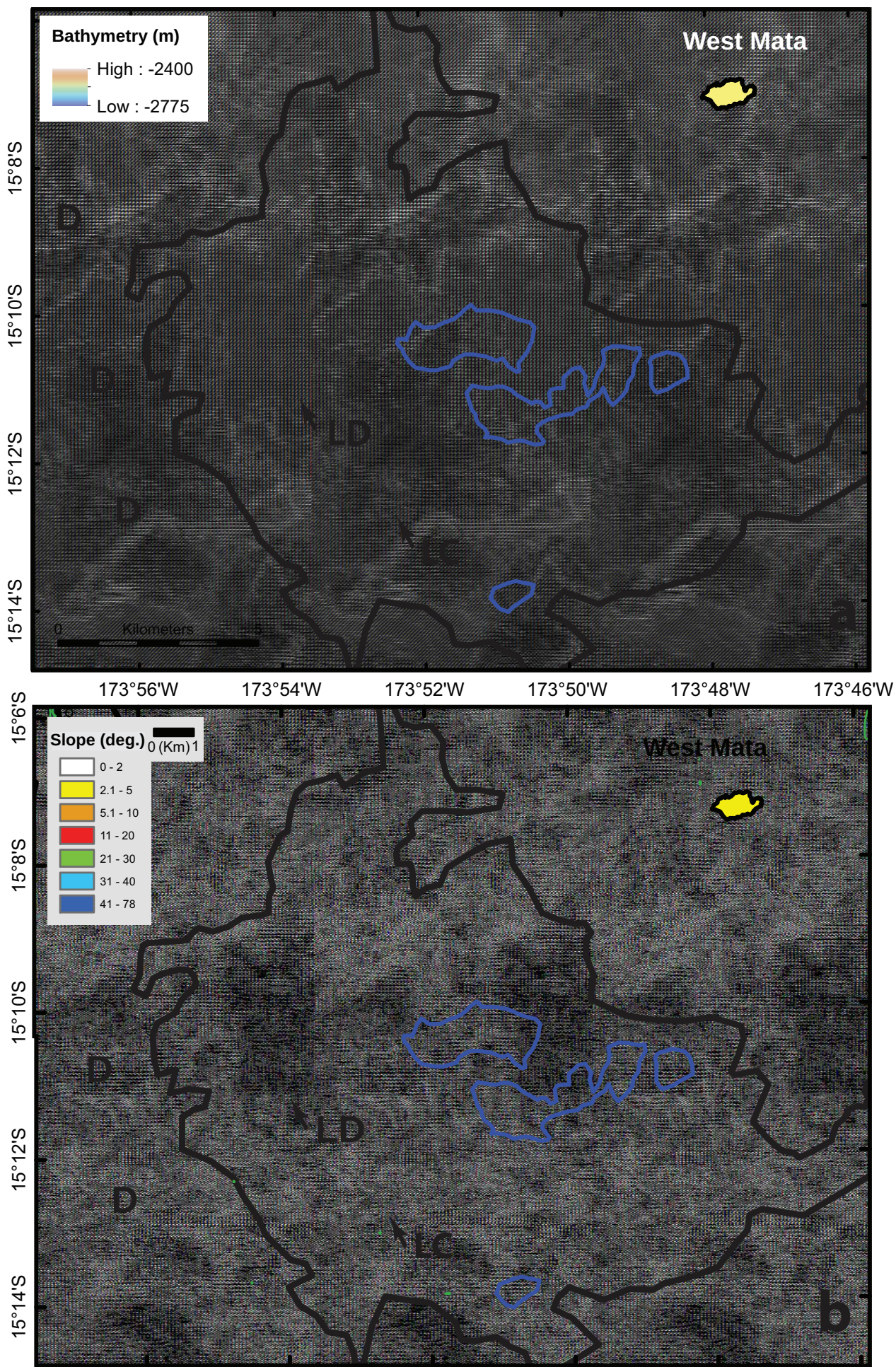


Figure 9_c

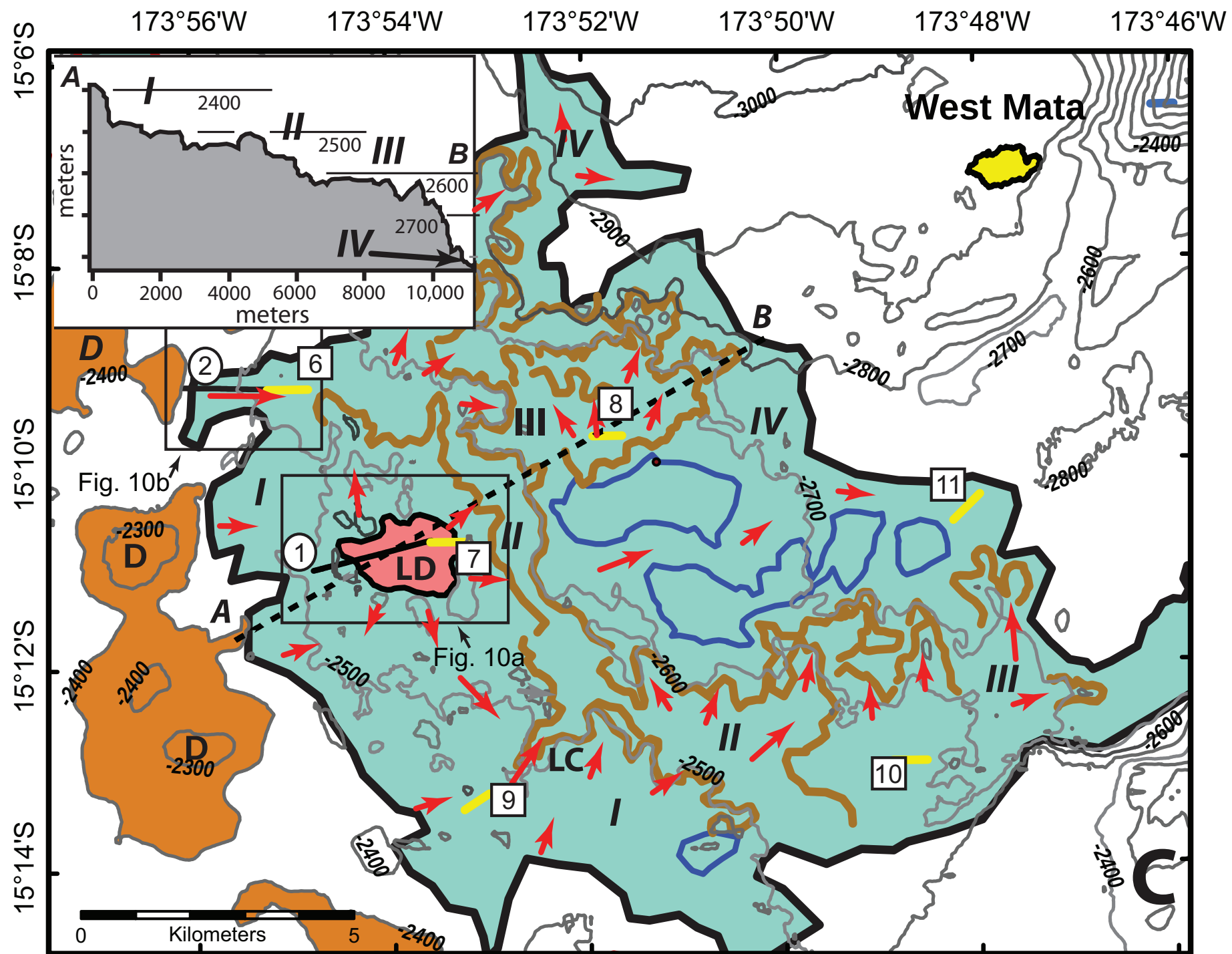


Figure 10

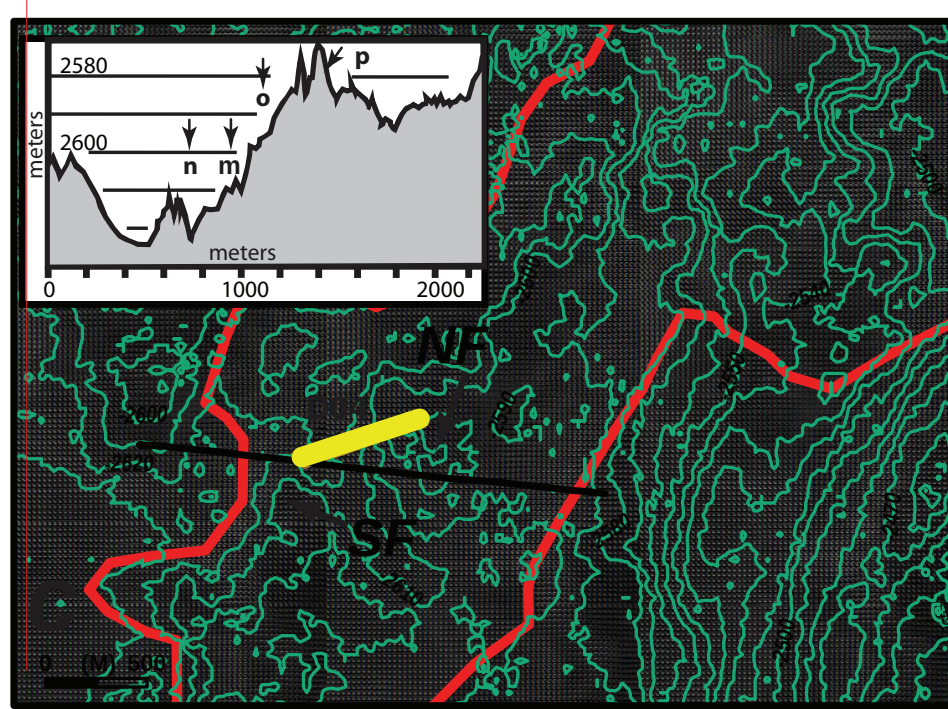
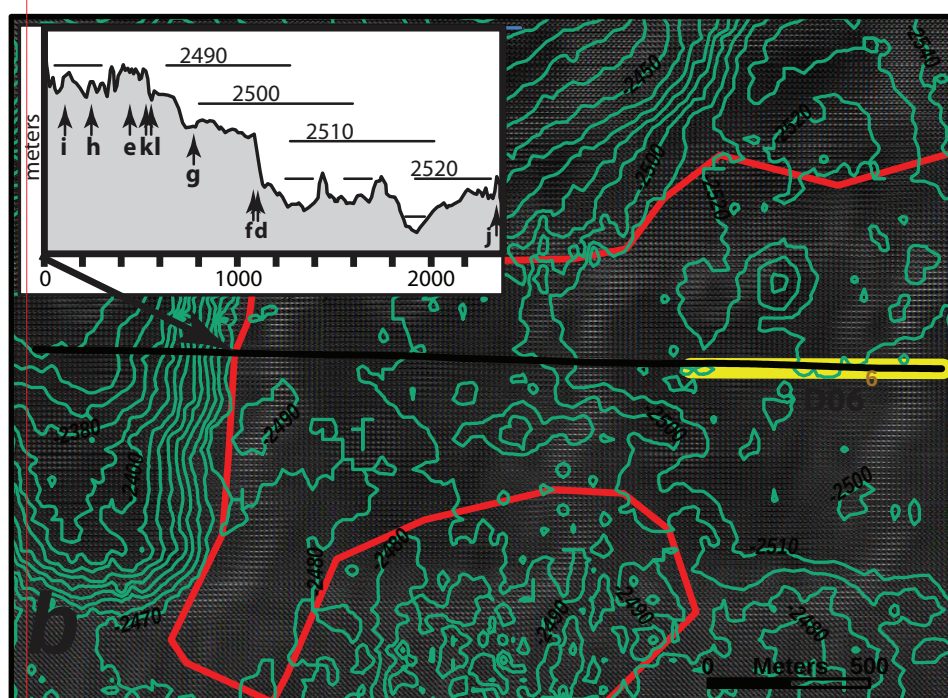
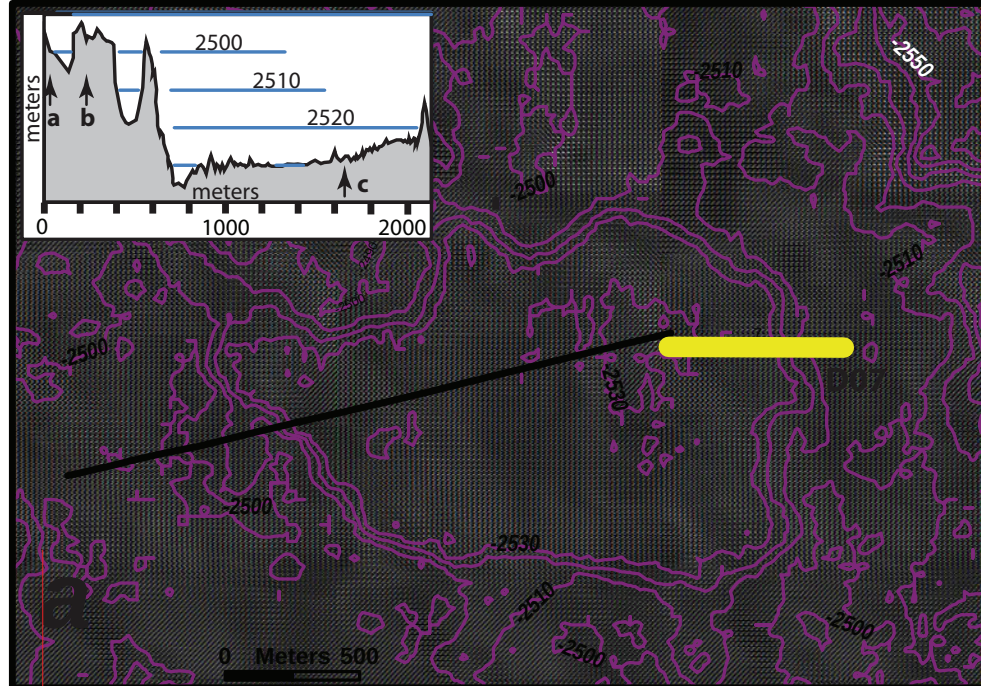


Figure 11 pt1

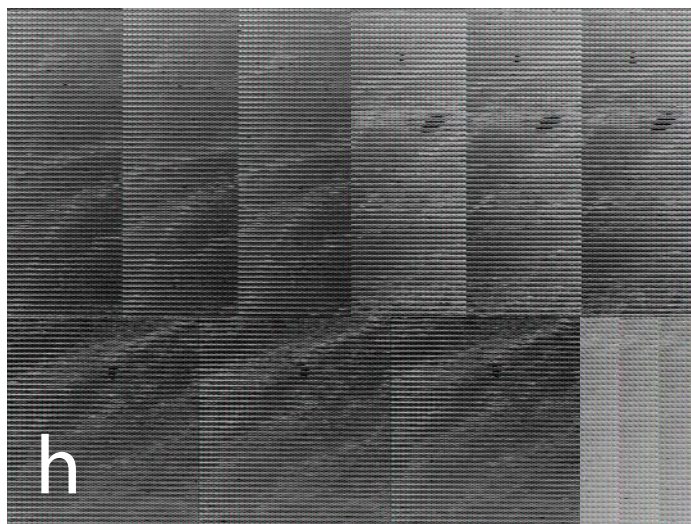
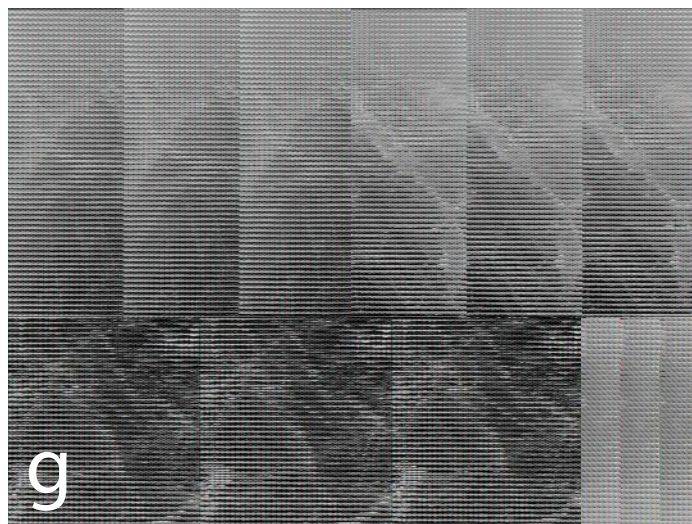
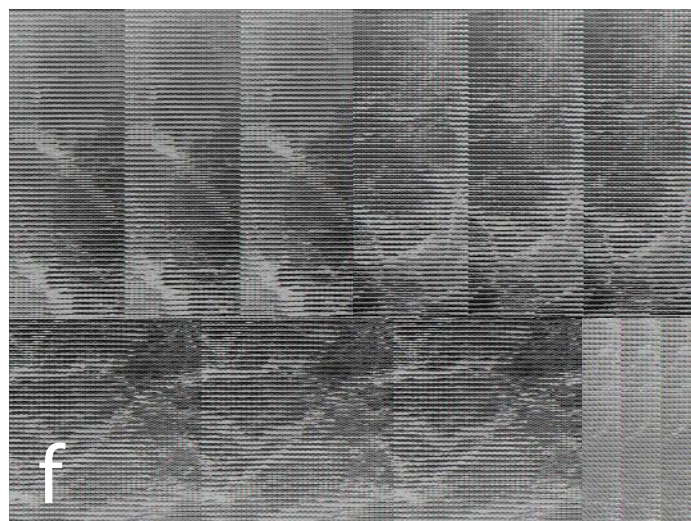
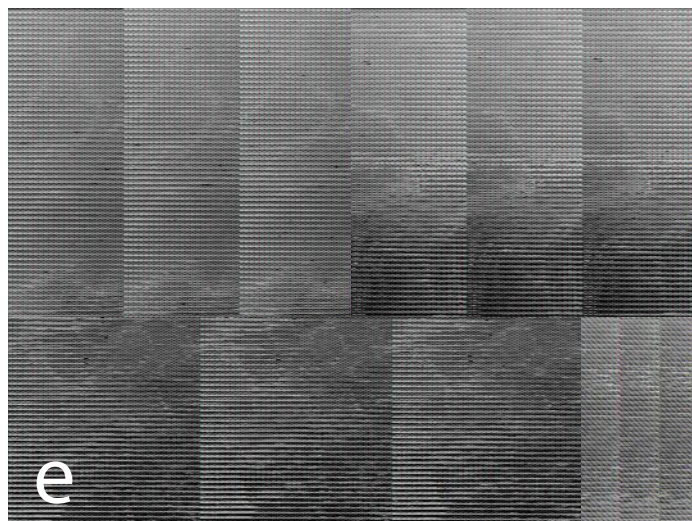
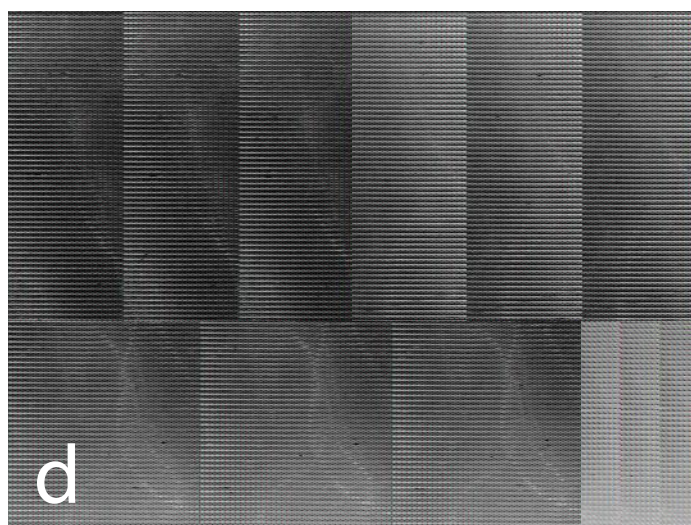
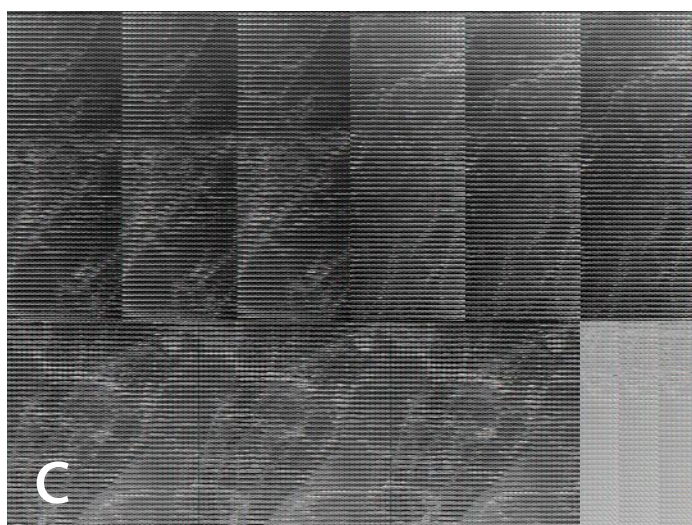
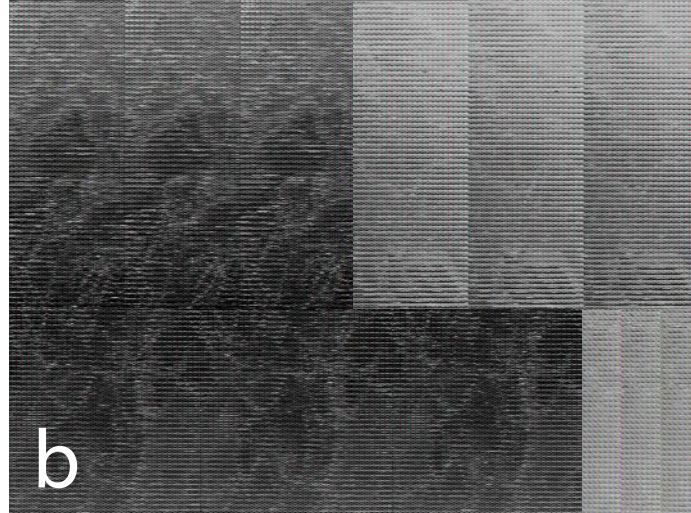
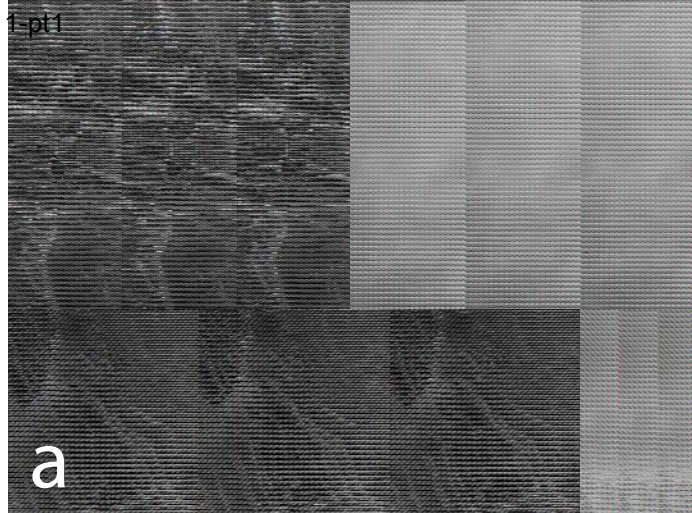


Figure 11-pt2

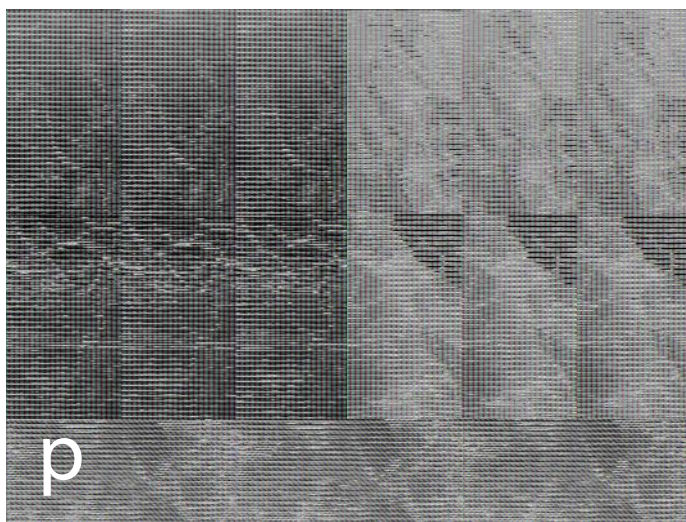
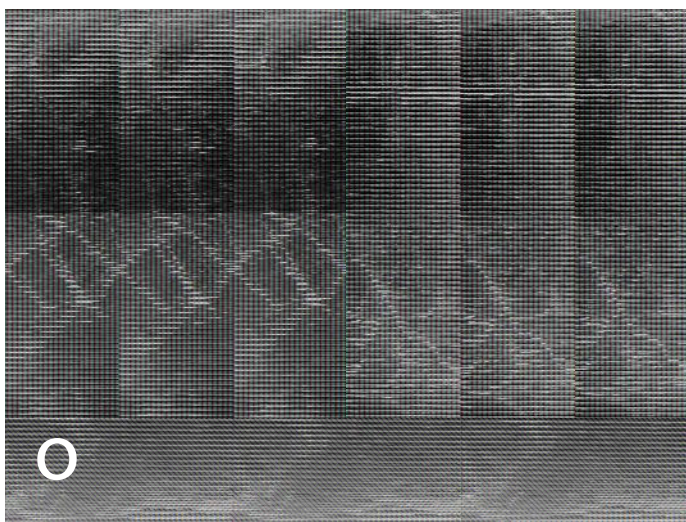
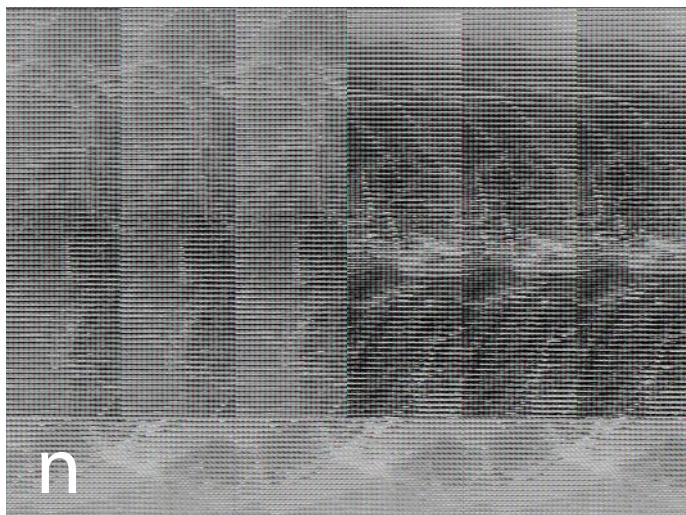
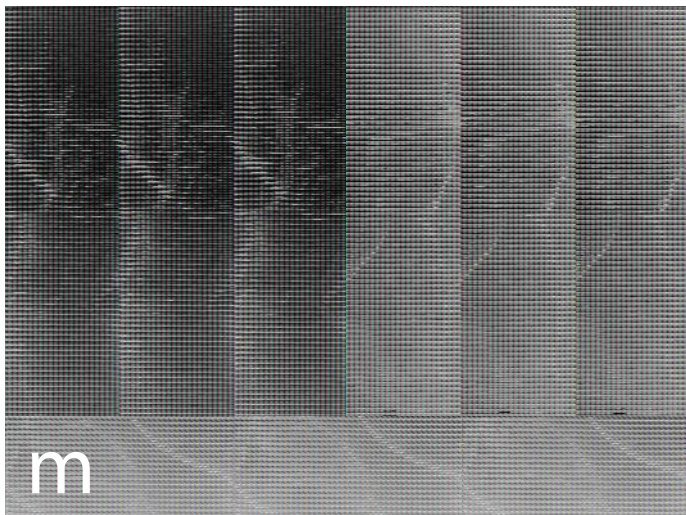
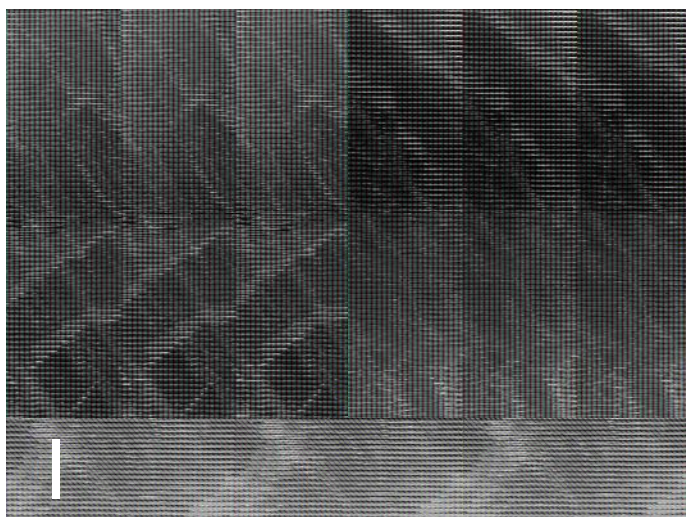
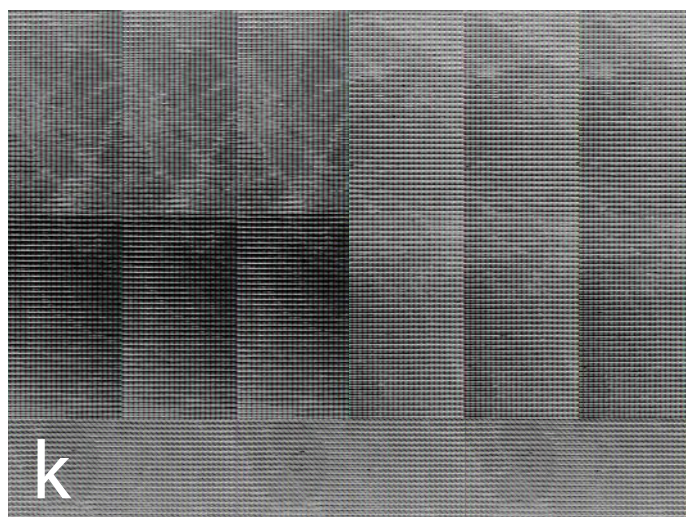
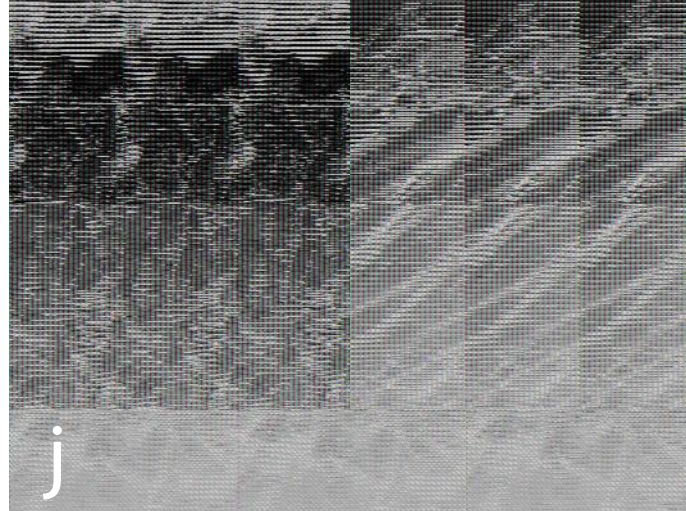
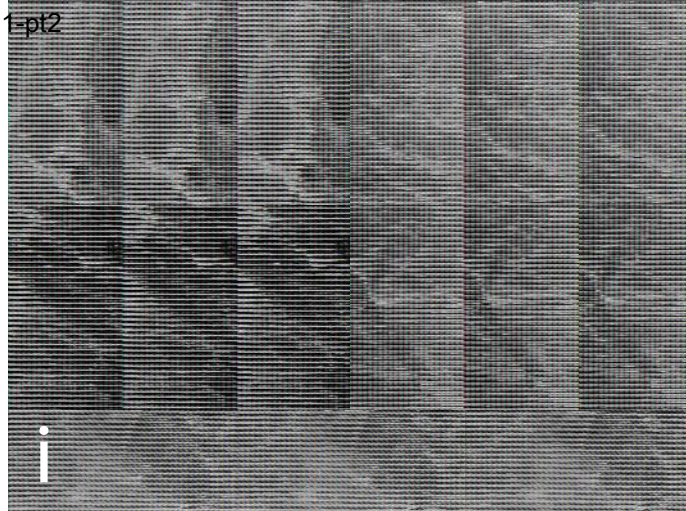


Figure 12

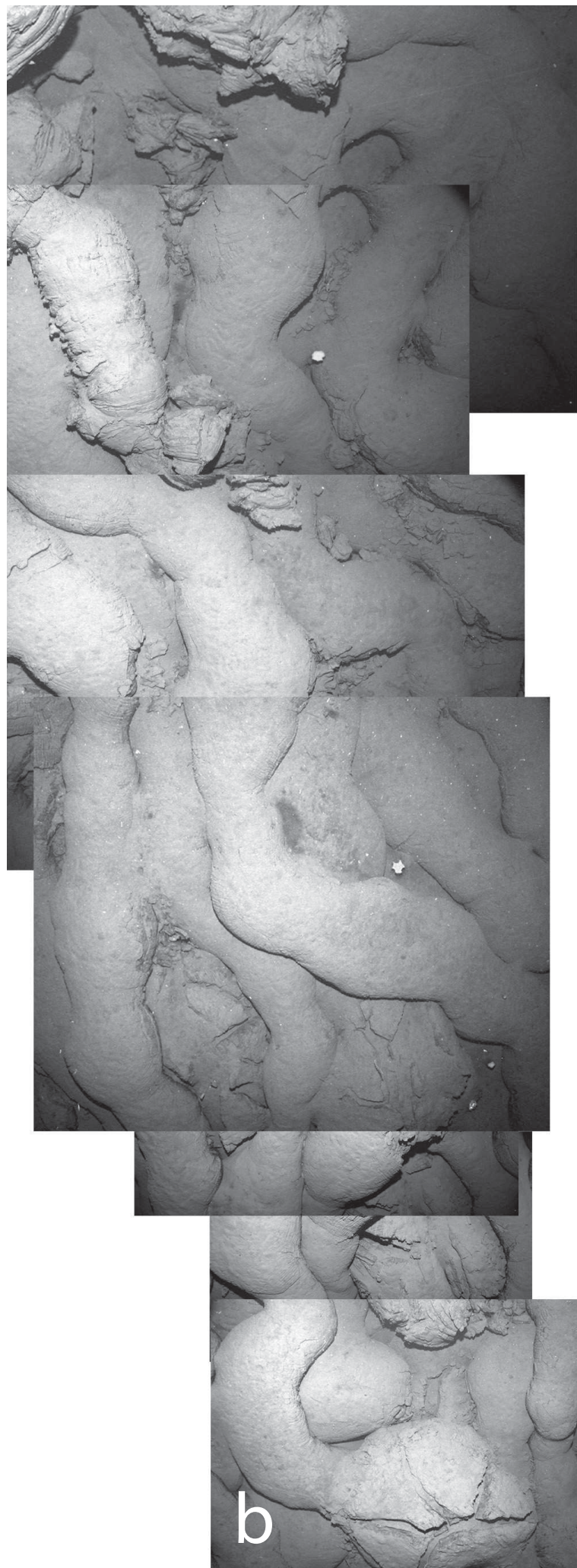
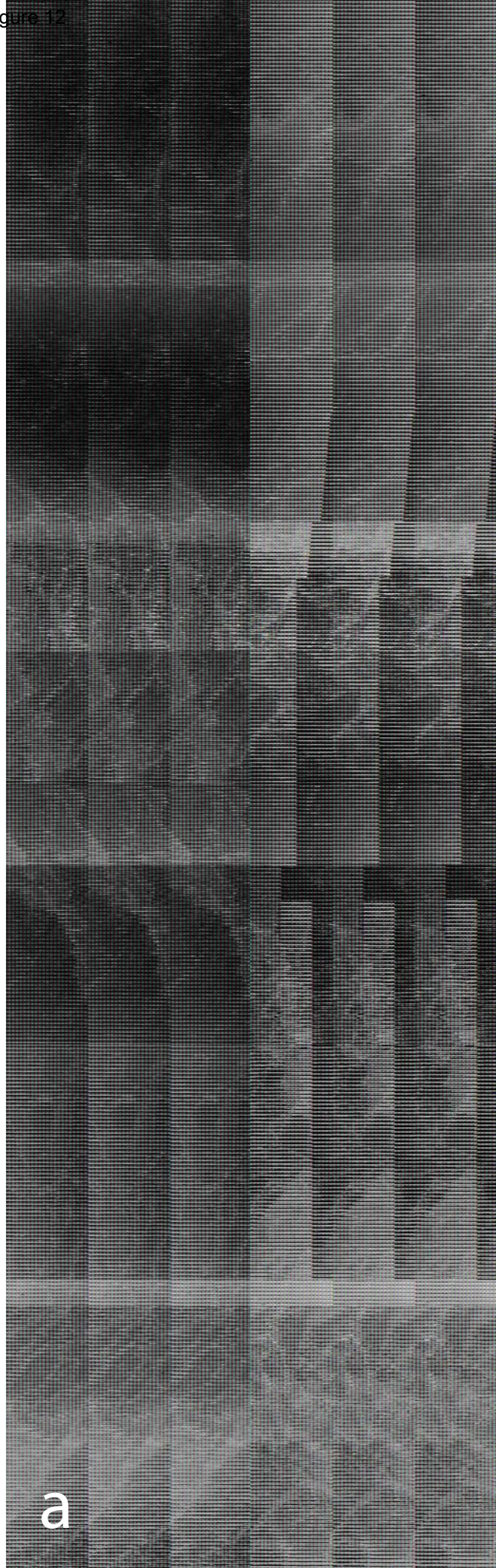


Figure 13

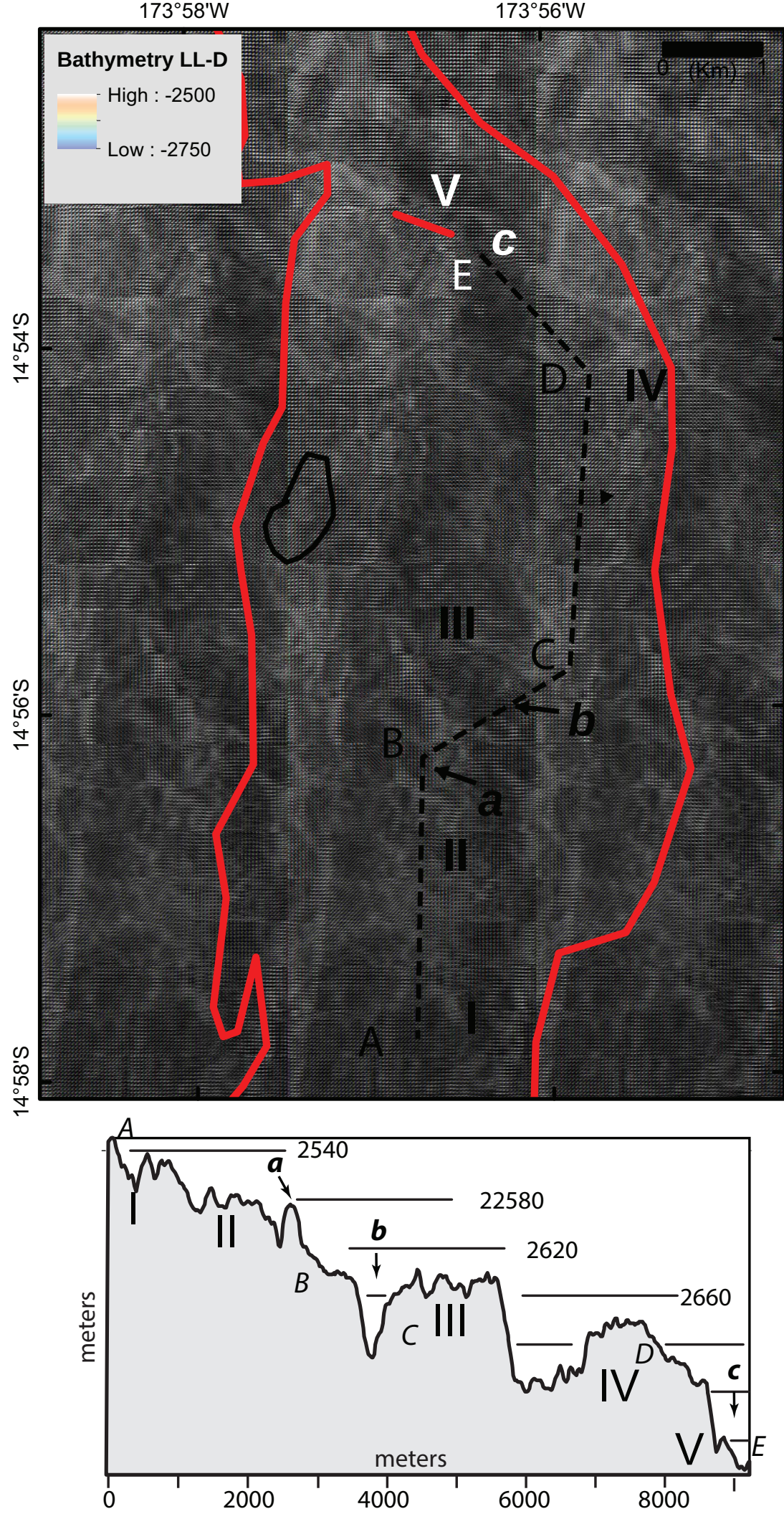


Table 1

Table 1. Volcanic Glass Composition by Electron Microprobe

Locaton	Sample Name	Site Description	IGSN	SiO ₂ wt %	TiO ₂ wt %	Al ₂ O ₃ wt %	FeO wt %	MnO wt %	MgO wt %	CaO wt %	Na ₂ O wt %	K ₂ O wt %	P ₂ O ₅ wt %	Sum %	Total Alk	CaO Al ₂ O ₃
Niuatahi	KM1008-CT08-1	Mohutahi Cone	KHR000026	68.62	0.66	12.39	7.35	0.12	0.77	4.24	1.66	1.13	0.22	97.60	2.79	0.34
	KM1008-CT08-2	Mohutahi Cone	KHR000027	67.23	0.62	12.51	7.41	0.13	1.19	4.97	2.92	1.10	0.22	98.68	4.02	0.40
	KM1129a D14-R02	NE caldera floor	KHR000186	68.47	0.60	12.62	7.24	0.14	1.26	4.85	3.01	1.05	0.20	99.88	4.06	0.38
	KM1129a D11-R01 †	SW flank	KHR000170	74.81	0.43	12.29	3.97	0.09	0.31	2.72	2.61	1.80	0.06	99.47	4.41	0.22
	KM1129a D26-R01	SE side	KHR000223	71.15	0.52	11.61	5.79	0.12	0.75	3.68	2.85	1.62	0.19	98.61	4.48	0.32
	KM1129a D12-R03 †	SW flank knoll	KHR00017a	65.01	0.71	13.82	7.85	0.15	1.71	5.58	2.84	1.32	0.19	99.53	4.16	0.40
Flows outside Niuatahi caldera	KM1129a D13-R02	LL_A1	KHR000181	69.31	0.59	12.48	6.94	0.14	0.94	4.47	2.91	1.19	0.20	99.53	4.10	0.36
	KM1129a D13-R03	LL_A1	KHR000182	68.98	0.57	12.51	6.91	0.14	1.02	4.51	2.87	1.19	0.18	99.23	4.06	0.36
	KM1024 D03-R01	LL_A3	KHR00002L	68.21	0.58	12.67	7.19	0.15	1.23	4.99	2.89	1.15	0.19	99.58	4.04	0.39
	KM1129a D15-R01	LL_A3	KHR000189	66.48	0.59	13.10	7.82	0.16	1.50	5.52	2.77	1.06	0.16	99.49	3.84	0.42
	KM1129a D15-R06	LL_A3	KHR00018e	66.31	0.60	12.88	8.04	0.16	1.50	5.51	2.81	1.08	0.20	99.41	3.89	0.43
Large lava flow fields	KM1024 D07-R01	LL_B	KHR00003A	65.99	0.63	12.76	7.83	0.16	1.47	5.52	2.67	1.08	0.18	98.58	3.74	0.43
	KM1024 D06-R06	LL_B	KHR000035	65.87	0.60	12.73	7.82	0.16	1.46	5.46	2.74	1.08	0.18	98.43	3.82	0.43
	KM1024 D06-R06	LL_B	KHR000035	65.37	0.57	12.62	8.02	0.15	1.49	5.54	2.74	1.07	0.20	98.11	3.81	0.44
	KM1024 D08-R02	LL_B	KHR00003N	65.74	0.61	12.79	8.02	0.16	1.47	5.55	2.79	1.07	0.19	98.70	3.86	0.43
	KM1024 D08-R08	LL_B	KHR00003T	65.39	0.63	12.67	8.06	0.15	1.50	5.54	2.83	1.06	0.19	98.35	3.90	0.44
	KM1024 D08-R10	LL_B	KHR00003V	65.53	0.60	12.63	8.02	0.15	1.48	5.54	2.80	1.06	0.19	98.33	3.86	0.44
	KM1024 D09-R03	LL_B	KHR000041	65.50	0.60	12.77	8.03	0.16	1.47	5.55	2.78	1.06	0.19	98.46	3.85	0.43
	KM1024 D09-R05	LL_B	KHR000043	65.44	0.61	12.59	8.02	0.15	1.49	5.54	2.76	1.05	0.20	98.19	3.82	0.44
	KM1024 D09-R06	LL_B	KHR000044	66.19	0.60	13.07	7.86	0.16	1.52	5.51	2.83	1.07	0.15	99.27	3.90	0.42
	KM1024 D10-R01	LL_B	KHR000046	66.18	0.61	13.00	7.89	0.15	1.49	5.52	2.83	1.06	0.18	99.24	3.89	0.42
	KM1024 D10-R03	LL_B	KHR000048	66.75	0.58	13.17	7.89	0.16	1.54	5.54	2.91	1.06	0.18	100.07	3.97	0.42
	KM1024 D10-R06	LL_B	KHR00004B	66.30	0.61	13.04	7.87	0.14	1.52	5.53	2.79	1.07	0.18	99.39	3.86	0.42
	KM1024 D11-R03	LL_B	KHR00004E	65.89	0.61	12.90	7.92	0.15	1.47	5.42	2.39	1.00	0.17	98.24	3.39	0.42
	KM1024 D11-R04	LL_B	KHR00004F	65.94	0.59	12.79	7.77	0.15	1.50	5.50	2.80	1.06	0.17	98.61	3.85	0.43
	KM1024 D04-R01	LL_C	KHR00002M	67.63	0.60	13.07	7.92	0.16	1.44	5.48	2.90	1.11	0.17	100.80	4.01	0.42
	KM1024 D04-R04	LL_C	KHR00002P	66.77	0.59	13.08	7.94	0.16	1.50	5.55	2.86	1.07	0.17	100.01	3.93	0.42
	KM1024 D04-R09	LL_C	KHR00002U	66.60	0.59	12.84	7.90	0.15	1.46	5.48	2.86	1.07	0.16	99.44	3.93	0.43
	KM1024 D05-R01	LL_C	KHR00002V	66.69	0.58	12.86	7.99	0.15	1.54	5.59	2.86	1.10	0.17	99.86	3.96	0.43
	KM1024 D05-R02	LL_C	KHR00002W	67.08	0.64	13.11	7.96	0.15	1.54	5.49	2.82	1.06	0.18	100.35	3.88	0.42
	KM1024 D05-R03	LL_C	KHR00002X	66.71	0.61	13.01	7.99	0.16	1.54	5.53	2.80	1.08	0.18	99.93	3.88	0.42
	KM1024 D24-R03	LL_D	KHR00006C	66.18	0.62	12.90	7.91	0.16	1.50	5.52	2.82	1.07	0.18	99.20	3.90	0.43
	KM1024 D24-R04	LL_D	KHR00006D	66.03	0.60	12.95	7.81	0.17	1.50	5.51	2.82	1.05	0.16	98.93	3.87	0.43

Notes:

Analyses were conducted using the University of Hawai'i JEOL JXA-8500F five-spectrometer electron microprobe (3 points per sample). All samples analyzed at 15 keV accelerating voltage, 10 nA beam current, and 10 micron beam diameter, except two microcrystalline samples † (5 micron beam diameter). Count times (seconds) and spectrometer crystal were SiO₂ (50, TAP), TiO₂ (40, LIFH), Al₂O₃ (60, TAP) FeO (30, LIFH), MnO (40, LIFH), CaO (30, PETH), Na₂O (30, TAP), K₂O (40, PETJ), P₂O₅, (30, PETH). Three points on two different standards, VG-2 and STG-56 were measured as unknowns before and after every three samples (Supporting Information Table S2).

Table 2. NE Lau Dacite Lava Flow Statistics

Lava Flow	Area (km ²)	No. Samples
<u>Niuatahi Lava Fields</u>		
LL-A1	49	1
LL-A2	15	0
LL-A3	55	2
LL-A4	34	0
<u>LL-A5</u>	<u>13</u>	<u>0</u>
<i>Subtotal</i>	<i>166*</i>	<i>3</i>
<u>Northern Lava Fields</u>		
LL-B	144	6
LL-B1	11	0
LL-C	26	2
<u>LL-D</u>	<u>55</u>	<u>1</u>
<i>Subtotal</i>	<i>236</i>	<i>9</i>
Total	402	12

* Probably overestimate - some fields are likely mixtures of volcanic products