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THE INFLUENCE OF TOPOGRAPHIC OBSTACLES ON BASALTIC LAVA FLOW MORPHOLOGIES

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INTRODUCTION

Basaltic lava flows exhibit a spectrum of textures, with smooth pāhoehoe and jagged ‘a‘ā as the end-members. As the ratio between viscosity and shear rate increases, the flow transitions from a smoothly flowing and inflating pāhoehoe to a flow that continually destroys the exterior crust to form rubbly to slabby pāhoehoe and ‘a‘ā (Peterson and Tilling, 1980; Sigurdsson et al, 2000). This change in morphology can reflect an increased mass flux or local changes, such as an increase in slope. However, it is unclear how

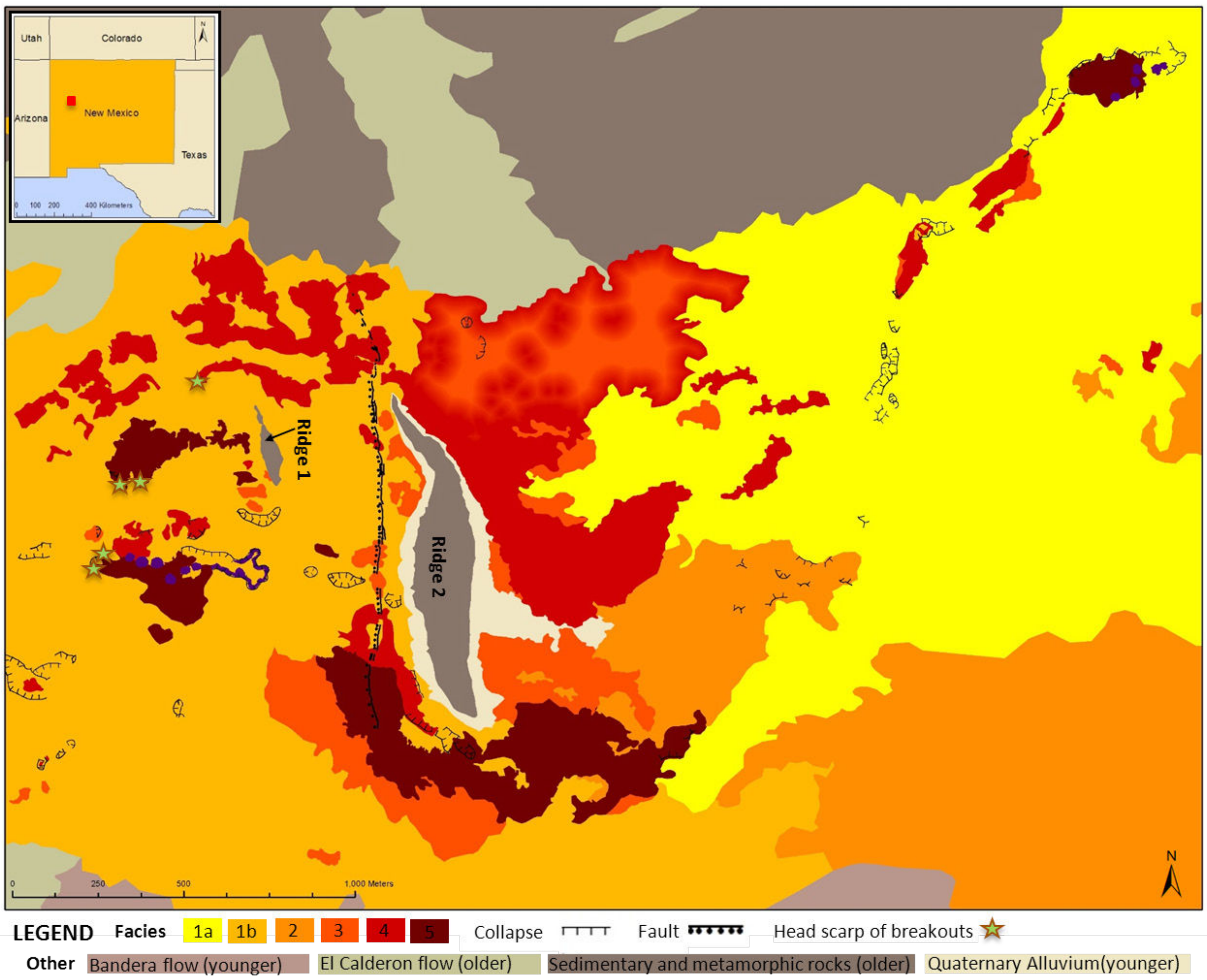

Figure 1. Facies texture map of the field area. The flow direction is west to east. Note the variations in texture upstream and wrapping around the large ridge.

Table 1. Facies descriptions and interpretations for the field area.

Facies	Description and Interpretation
1a	**Description:** Smooth-surfaced pāhoehoe lacking inflation clefts, tumuli or any other inflation-related feature. The surface varies from ropy to smooth and is often covered by soil. The crust is at least 20 cm thick with variable vesicularity. Poor exposure prevented precise measurements and characterization of the crust. **Interpretation:** Uninflated or poorly inflated sheet-flow of pāhoehoe.
1b	**Description:** Smooth-surfaced pāhoehoe as described in 1A except with a wider variety of surface roughness features. Prominent features include low relief, often sinuous and positive relief ridges. The ridges are typically 1-1.5 m wide and less than 0.5 m tall. They generally lack clefts or cracks at the ridge axis. However, many of these positive relief regions were caved in, revealing empty void space that sometimes extends back under the flow in the direction of the ridge axis. Areas of broken but in situ place crust are also common and typically grade into Facies 3. Two layers comprise 1b. The bottom-most layer is ≥65 cm, although the base is rarely exposed. Vesicularity increases from 5% (1.5 cm vesicles) at the base to 25% at the top (1 mm – 3 cm vesicles); however several zones of vesiculation were observed throughout the thickness. The top layer of crust is 23-40 cm thick with vesicularity increasing from 10% at the base (1.5-2 cm vesicles) to 15-35% vesicularity at the top (mm-scale vesicles). **Interpretation:** Slightly inflated pāhoehoe formed when lava backed up behind the bluff and began developing pathways beneath the pāhoehoe crust.
2	**Description:** Facies 2 consists of spiny pāhoehoe crust with at least three vesiculated layers above the lava core. The top layer is ~24 cm thick with an average vesicle size~0.2 cm (35-40% vesicularity). The middle layer is ~50 cm thick with average vesicle sizes of ~1-1.15 cm (35-40% vesicularity). The bottom-most exposed layer is ≥ 45 cm thick (the base is rarely exposed) with an average vesicles size of 1-2 mm (15-20% vesicularity). Vesicles up to 1.5 cm were observed (some stretched). Inflation features are abundant, including lava rise pits (2-4 m deep), inflation cracks (1.5 m deep), and evidence for crust uplift & tilt at flow edges. The pāhoehoe crust is often broken into smooth-sided, in situ blocks averaging 10-15 cm in size, although blocks up to 1.7 m (longest dimension) are observed. Large, displaced slabs are commonly found associated with inflation cracks and flow edges. These semi-equant slabs are on average 45- 70 cm across (in longest dimension), with largest slabs up to 2.2 m in the longest dimension. Where exposed, the flow front is 2.5 – 3 m thick. **Interpretation:** Inflated pāhoehoe.
3	**Description:** Facies 3 consists of smooth pāhoehoe crust broken into primarily equant smooth-sided clasts. The clasts range from gravel-size to small blocks with average block sizes around 60 x 50 x 34 cm. Some plates are up to 29 cm in their longest dimension and are 10-35 cm thick. The plates have smooth pāhoehoe to spiny pāhoehoe on the upper side and either smooth bases or bases with evidence for trapped gas bubbles. Facies 3 tends to be oxidized relative to the other facies. **Interpretation:** Pulses of lava beneath the surface of a well-developed crust cause fracturing, breakup and rafting of crust to form rubbly pāhoehoe.
4a	**Description:** Facies 4 consists of a high proportion of rubble with displaced and crustal plates. The matrix ranges from gravel-sized clasts to irregularly-shaped, vesiculated block-sized clasts. Semi-equant blocks with curved sides are present but less common. Block-sized clasts (both irregular and semi-equant) generally range from 12 – 21 cm in their longest dimension, 7.5 – 11 cm in their second dimension, and 5-7 cm in their third dimension. The matrix blocks have variable vesicularity (average ~10%) with round vesicles from 0.1 – 1 cm in size (average size ~0.1 cm). Some plates are semi-equant in their longest dimensions (average ~68 cm by 68 cm) with thicknesses of 17-20 cm thick. The plates are comprised of overturned crust with up to three distinct layers. The top layer is generally 3-12 cm thick with round vesicles on average ~1-2 mm (~10% vesiculated). The top of the first layer varies between smooth, ropey, and spiny pāhoehoe. The base has a sharp contact with the second layer and is sometimes spiky with lava dribbles. The second layer varies greatly in thickness and often has a gradational contact with the underlying the third layer. When distinct the second layer is on average ~5.5 cm thick with round vesicles on average ~1-2 mm in diameter (~30% vesiculated). The surface of the second layer is often ropy to spiny pāhoehoe. The base of the second layer varies from distinct with small lava spikes (lava dribbles) to gradational into the third layer. Rare scour marks can also be found at the base of the second layer. The third layer is highly irregular in thickness and texture and is not found as a distinct layer. It contains round, ~0.1-0.2 cm-sized vesicles (~35-40% vesiculated). The average thickness is ~6-11 cm; however, within the same plate the thickness can vary greatly (up to 25 cm thick). Scour marks and agglutinate balls are common at the base of layer three, which marks the base of the plates. Lava balls are common between plates and matrix rubble. They average 50 x 52 x 38 cm. A cross section through Facies 4 was found in a normal fault running across the field area. The fault exposed a rubbly cap ~0.8-0.9 m thick overlying a 0.-9 – 1 m thick non-vesiculated, aphanitic core. A poorly exposed rubbly base appears to be ~0.3 m thick, although the base is not exposed. **Interpretation:** Voluminous (relative to Facies 3) pulses of lava beneath the surface of a thin crust (<20 cm) caused fracturing, breakup and rafting of crust. Continued pulses resulted in extrusion of lava to form lava balls and agglutinate) and continued to shatter and disrupt the slightly older, more established crust. This is interpreted to be a mix between heavily disrupted pāhoehoe and ‘a‘ā.
4b	**Description:** Same as Facies 4A except with a greater percentage of plates. Often the rubble is piled into ridges <2 m high. Plates often oriented with their longest axis in the direction of flow except at flow margins or toes, where orientation is more irregular. **Interpretation:** Same as Facies 4b. Compression ridges common at the terminal end of a flow.
5	**Description:** Facies 5 consists of irregular, sharp, spikey rubble with few to no crustal plates. The rubble averages 6.5 x 4.5 x 4.5 cm with vesicles on the mm scale (10% vesiculated). The rubble often forms ridges or piles 1.5 – 2 m tall. Some large, somewhat round agglutinate balls are found in this facies. The few crustal-like plates have two layers. The first is a 5.5 crust layer with mm-scale vesicles, and the second is a layer with an irregular texture and thickness, and vesicles approximately 1 cm. The plates are frequently found in conjunction with agglutinated masses or bases marked with scour marks. Higher concentrations of plates were found at the distal margin of the flow. **Interpretation:** Agglutinate masses, evidence for viscous tearing and clinker indicate an ‘a‘ā flow.

topographic obstacles influence the formation of different lava textures, and what inferences can be made about the flow conditions from an analysis of the textures. The objective of this study is to assess the influence of topographic obstacles on flow behavior and the resulting lava textures through field and aerial mapping of a lava flow around an obstacle.

FIELD AREA AND METHODS

The Twin Craters basaltic lava flow (18.0 ± 1.0 ka, Dunbar and Phillips, 2004), part of the Zuni Bandera Volcanic Field and largely located in El Malpais National Monument, is between 0.2 – 3.8 km in width and nearly 20 km in length. The portion of the

Figure 2. Features upstream of the ridges, including Facies 5 and the Facies 3 depressions east of the small ridge. (a) Depression interpreted as the source for the Facies 5 breakout. Note that Facies 1b is dipping up away from the contact with Facies 5. Person is 1.68 m for scale. (b) One of the upturned crustal plates of Facies 5, surrounded by small rubble fragments. Person is 1.68 m for scale. (c) A depression floored with Facies 3, < 100 m east of the small ridge. Note the gradational contact with Facies 1b. Person is 1.5 m for scale. (d) A large depression floored with Facies 1b. Person is 1.5 m for scale. Note: the depressions in (c) and (d) were not visible in the aerial imagery.

field considered in this study is located 11.5 km from the source and includes two limestone ridges, both oriented with their longest axis perpendicular to the lava flow direction (Figure 1). The larger ridge is 1100 m long and 250 m wide, and the smaller is 250 m long and 45 m wide. The flow field in this location is 2 km wide (north to south) and the flow direction is west to east (Figure 1). A combination of mapping using aerial imagery (ESRI, 2013) and field characterization of lava textures, contacts and other features was completed.

RESULTS

Five facies were identified based on the characteristics of surfaces and clasts, as well as crustal plates (if present). Definitive characteristics included layer thickness, vesicularity and textures. Figure 1 is a map of these facies; descriptions and interpretations are provided in Table 1. Note that many boundaries between facies are gradational, as illustrated by the orange-red mottled colors for gradational Facies 3 and 4.

The flow field is primarily comprised of Facies 1. Upstream from the ridges Facies 1 is characterized by smooth pāhoehoe crust with a low relief, slightly hummocky surface due to a number of positive relief sinuous ridges ~0.5 m high and 1-1.5 m in width (hereafter referred to as Facies 1b). Downstream from the large ridge Facies 1 is characterized by a flat, smooth surface with no obvious mounds or inflation cracks (hereafter referred to as Facies 1a).

A set of collapse features delineate a lava tube that extends from the west (upflow), wraps around the south side of the large ridge, and continues to the east (downflow). Facies 5 is commonly found along and extending out from the lava tube (Figure 1). Areas of textural variations (i.e. textures rougher than smooth pāhoehoe) occur upstream from both ridges and wrap around the largest ridge to the east. The latter texture variations are the focus of this short contribution.

Figure 3. Images of Facies 4 found upstream or wrapping around the large ridge. (a) One of several depressions interpreted as the source for the Facies 4 breakouts to the northwest of the large ridge. Note the plates of Facies 1b dipping up away from the contact with Facies 4. (b) Crustal plates found in Facies 4 oriented with their longest axis parallel to the direction of flow. (c) The contact between Facies 4 and Facies 2 located to the southeast of the ridge. Note that Facies 2 is dipping up away from the contact. Person is 1.68 m for scale in all photos.

NORTHWEST OF LARGE RIDGE

Facies 1b dominates the flow field upstream (west) of the large ridge. However, patches of Facies 3, which grade into Facies 1b, are found throughout this area (Figure 1). The most prominent feature both from the field and aerial remote sensing is the large patch of Facies 5, located 300-400 m directly west of the small ridge. The start of this feature, designated by the stars in Figure 1, is characterized by a series of minor depressions (<2 m in depth; Figure 2a). Facies 5 is topographically lower than Facies 1b, and consists of jagged rubble, found either as irregular clasts averaging 6.5 cm in diameter or as agglutinated clumps (Figure 2b). The few crustal plates found in Facies 5 have a 2 cm thick crust of spiny pāhoehoe with agglutinated material on one side (Figure 2a, b). This rubble is found piled into 1.5 – 2 m tall ridges oriented perpendicular to flow, with taller ridges and a higher concentration of large crustal plates found near the distal margins of the facies.

Several additional depressions occur toward the small ridge, each seemingly the 'head' of a Facies 5 occurrence (stars in Figure 1). Slabs of Facies 1b are tilted upward away from Facies 5 to the level of the relatively flat surrounding terrain. Both Facies 5 and Facies 1b appear buckled at the distal contact, closest to the small ridge. Closer to the small ridge (within 100 m) Facies 1b grades repeatedly back and forth into Facies 3. The thickness of Facies 3 in this location is ≤ 40 cm, and it is comprised of oxidized and broken pāhoehoe crust that forms mounds ~2 m tall.

A series of more distinct pits characterize the area within 100 m southwest of the small ridge (Figure

2c). The depressions generally have a gradational contact with the surrounding Facies 1b, but the pits themselves are characterized by broken pāhoehoe blocks of Facies 3 (Figure 2c). The exception is the large pit <100 m south-southwest of the small ridge (Figure 2d), which is ~ 50 m x 100 m in size and ~4.5 m deep. The walls of the pit have fractured but intact pāhoehoe plates dipping toward the center. The pāhoehoe plates have primary flow features such as ropes that are not consistent with the inward dip of the slabs. Facies 1b covers the floor of the pit.

Within the 1100 m northwest of the large ridge, and wrapping around the northern end of the small ridge, there are two semi-parallel, discontinuous regions of Facies 4. Subtle (unrecognizable with aerial imagery) ≤1 m depressions are found at the start of Facies 4 (stars in Figure 1; Figure 3a). Facies 4 consists of jagged pieces of rubble <5 cm along their longest axis. Crustal plates ≤ 13.5 cm thick were found dominantly oriented parallel to the flow axis (Figure 3b). This rubble is found in mounds < 2 m tall, although an area with mounds up to 10 m high is also seen. Facies 4 is generally topographically lower than the surrounding Facies 1b; however, the contact often appears gradational and is characterized by up to 2 m wide slabs of pāhoehoe that slope up and away from Facies 4, often with long, semi-continuous cracks at their upper axis before leveling out across the flow field.

NORTHEAST TO EAST OF LARGE RIDGE

Facies 4 wraps around the north side of the ridge and forms a much larger textural variation that extends to the east. The southern contact with the limestone alluvium is sharp and characterized by 2.3 – 3 m thick lobes of Facies 4. The lobes are characterized by large (0.5 – 0.78 meter-sized), upturned and near-vertical plates of smooth pāhoehoe (vesiculated crust averaging ~11-26 cm thick). Toward the axis of the flow, the margin of the texture variation abruptly grades into rubbly blocks of Facies 3 and then into Facies 4a less than 4 m to the north. The axis of Facies 4 contains several 0.3-1.6 m size plates (longest dimension). The longest dimension of the plates is generally oriented in line parallel with the axis of the texture variation. The textures grade back and forth from Facies 4a and 4b without a recognizable pattern. Lava balls ~50 cm in diameter are more common in Facies 4b.

To the northeast of the large ridge, the textural variation grades into Facies 3 and has several lobes that extend over Facies 1a (sharp contact). The gradational facies change from 4 to 3 occurs several times across the entire flow field (orange-red gradations in Figure 1), with lobate features at the facies boundary. These lobes are 3.5 m thick and generally overlie (or are in contact with) Facies 1a.

Along the southeast side of this textural variation Facies 4 has a sharp contact with Facies 2. The rubble of Facies 4 is topographically lower than the smoother surface of Facies 2 (Figure 3c). Facies 2 tilts upward away from Facies 4 at the contact and displays abundant inflation clefts, tumuli and pits. The textural variation of Facies 4 extends to the east and then bends to the northeast at the distal end. This distal end of Facies 4 is characterized by Facies 4b; however, the plates are oriented perpendicular to the flow direction and along ~1.5 m thick ridges. The flow front has a sharp contact and appears to overlie Facies 1a.

DISCUSSION

The similarity in crust texture between Facies 1a and 1b suggest these two facies are closely related. Facies 1a is ~20 cm thick, and the top crust of Facies 1b was found to be 20 – 40 cm thick. This suggests that a sheet flow initially covered the field area. The multiple crusts and sinuous mounds observed in Facies 1b suggest much of lava became trapped behind the large ridge and began to create pathways beneath the pāhoehoe crust.

The transition from Facies 1b to Facies 3 behind the ridge suggests that the cooled crust of Facies 1b was locally disrupted and remobilized. Plates of this crust are 10-30 cm thick, implying a cooling period of 2 - 15 hours before disruption (according to the cooling model of Hon et al, 1994). The gradational transition between these two facies and the discontinuous series of disrupted areas suggests that localized areas of disruption occurred, rather than disruption across the entire flow.

The crustal plates with primary pāhoehoe layers 10 – 20 cm thick and agglutinate layers <43 cm thick in Facies 4 suggest an earlier pāhoehoe crust that was progressively broken. As this occurred, fresh lava was exposed and sheared into textures consistent with ‘a‘ā, creating the irregular, jagged clasts and lava balls. Conversely, Facies 5 exhibits few crustal plates, suggesting the flow broke through the previous crust and traveled as a true ‘a‘ā flow. Plates oriented parallel to the flow axis are indicative of flow direction. Mounds of material oriented perpendicular to flow, most commonly found at the distal flow margins, are interpreted as compression ridges.

The depressions on the upstream edge of Facies 4 and 5 (stars in Figure 1) are interpreted to be the source for the breakouts. While confined within Facies 1b, the lava was likely insulated from convective cooling and developed a significant hydrostatic head. Breakouts or crust remobilization occurred when the hydrostatic pressure exceeded the lithostatic pressure. These features are similar to those described for rubbly pāhoehoe flows that formed via a combination of inflation and disruption at Laki (Keszthelyi et al, 2004; Guilbaud et al, 2005).

The lack of phenocrysts or microlites in Facies 4 and 5 implies that these textures are not the result of increased crystallinity and viscosity, but rather an increase in shear, likely due to high local flux rates and high flow velocities (e.g., Rowland and Walker, 1990). Similar fast-moving ‘a‘ā flows that broke out from tubes were described by Patrick and Orr (2012). The fact that Facies 4 and 5 are typically topographically lower than Facies 1b suggests that Facies 1b continued to inflate after breakouts occurred.

The prominent area of Facies 4 to the northeast of the large ridge appears to be another breakout from Facies 1b. Both its narrow origin and disrupted texture suggest that it was extruded at a high rate. A significantly higher number of plates are found at the margins of this area, suggesting that the flow pushed previous crust in front of it as it flowed. The surrounding Facies 1a is not inflated, suggesting the backup of lava behind the ridge prevented further inflation to the northwest. Thus, in this case, textures recorded in the lava flow reflect local topographic influence.

CONCLUSIONS

The presence of numerous isolated breakouts, as well as the low relief inflation features of Facies 1b, suggests that lava was backing up beneath the pāhoehoe crust behind the ridge. Pressurization beneath the thermally insulating crust resulted in numerous breakouts of low-viscosity lava upstream and around the large ridge. These results indicate that topography can have a significant influence on lava flow dynamics and the ultimate textures produced.

Constraining the relationship between local topography and potential lava flow paths is critical for hazard analysis. In addition, being able to distinguish the impact of topography from the influence of vent conditions can help constrain eruption parameters for flows within the existing geologic record, both on Earth and on other planets.

Finally, while a significant amount of textural information could be found in the aerial imagery, fine details were not visible. These include the distinction between Facies 1a and 1b, the distinction between Facies 4a and 4b, the depressions at the upstream ends of the northwest area of Facies 4, and several other large depression features found upstream of the ridges. While higher resolution imagery could remedy that discrepancy, ground-truthing remote observations significantly improves our ability to interpret morphological changes in lava flows.

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