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PROCESSES DURING SCORIA-CONE COLLAPSE AS RECORDED BY DISPLACEMENT OF CRATER-RIM BLOCKS, STRAWBERRY CRATER, ARIZONA

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ABSTRACT—Strawberry Crater is one of several hundred scoria cones in the San Francisco volcanic field of northern Arizona. The process of scoria-cone formation and deconstruction are not completely understood despite the fact that they are the most common landform on Earth. Strawberry Crater is an unusual cone in that variable magma characteristics caused scoria during late stages of the eruption to become agglutinated upon deposition. This agglutinated scoria broke into large blocks that were displaced as late-stage eruption of lava breached the walls of the cone. Facies analysis shows that many of the blocks represent formerly continuous depositional horizons, which reflect a variance in magma-gas content and magma-rise rate that may have affected the temperature and accumulation rate of pyroclasts, and therefore the degree of agglutination. Faults between blocks are dominantly vertical to subvertical regardless of block size. This suggests that breaching of the cone occurred abruptly as magma pressure exceeded the strength of the cone walls and released the remaining magma trapped in the cone, or that breaching was caused by an increase in magma flux as late-stage lava emanated from the bottom of the cone.

INTRODUCTION

Strawberry Crater, located in the northeast part of the San Francisco volcanic field in northern Arizona (Fig. 1), is an unusual scoria cone in that its upper portion is composed of as much as 11 m of agglutinated scoria layers. These layers were broken and displaced when lava ruptured one of the flanks of the cone (Harwood, 1989), forming various sizes of intact blocks. The resultant exposures provide the opportunity to study the processes that affect scoria cones during their construction and dismantling, including the processes that cause a cone to breach. Research outlined in this paper focuses on the facies of the agglutinated scoria and displacements of agglutinated blocks.

Scoria cones form from the eruption of vesiculated pyroclasts that are deposited around a vent. The size and shape of scoria cones and their clasts are determined largely by the fountain structure of the eruption and the path of the ejected pyroclasts (Head and Wilson, 1989). Pyroclasts that cool and solidify in the air during travel collect in a ring of scoria around the vent and avalanche down the cone flanks (Valentine et al., 2005). Pyroclasts that do not cool completely in the air are called spatter and increase the degree of agglutination, or welding, of the deposited material due to their slightly molten state. Pyroclast trajectories are

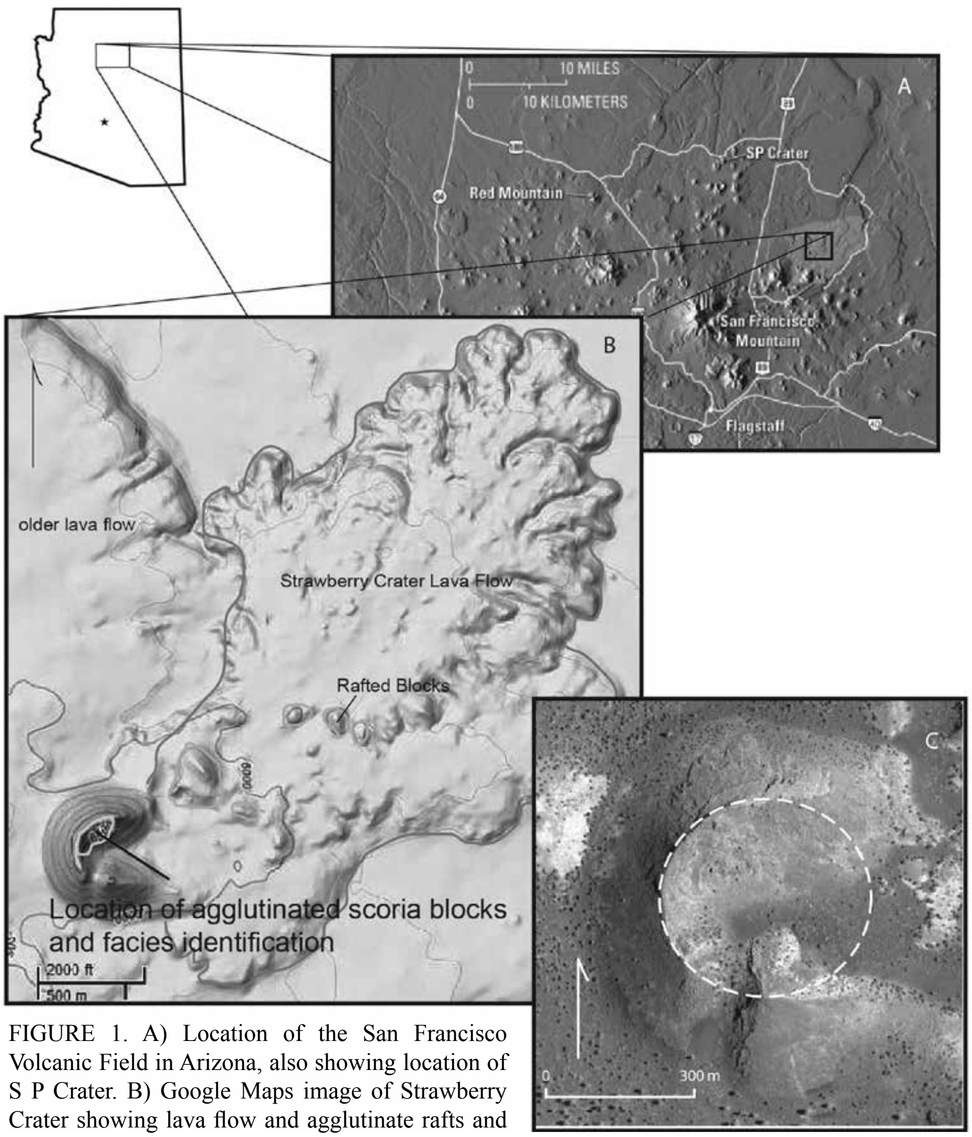

FIGURE 1. A) Location of the San Francisco Volcanic Field in Arizona, also showing location of S P Crater. B) Google Maps image of Strawberry Crater showing lava flow and agglutinate rafts and locations of displaced agglutinated scoria blocks and measured sections. Horse-shoe shape shows the asymmetry typical of scoria cones that breach their sides. C) Google Earth image of Strawberry crater; dashed line is reconstructed crater rim.

largely determined by the gas content of the magma and the rate that magma rises in the conduit (Head and Wilson, 1989). For example, Strombolian eruptions are typically sporadic and violent, caused by slow-moving magma that has high gas content and large, coalesced gas bubbles (Parfitt and Wilson, 1995). As the magma-rise rate increases or gas content decreases, bubbles do not coalesce as readily and lava emerges with a more evenly dispersed gas content, resulting in a more continuous and less violent Hawaiian eruption (Head and Wilson, 1989; Parfitt and Wilson, 1995).

The degree of agglutination during eruption is mostly controlled by pyroclast accumulation rate, but also related to the pyroclast temperature (Fig. 2) (Head and Wilson, 1989). This temperature relates to pyroclast trajectory, as the longer the pyroclast is airborne the cooler it becomes and the more likely it is to break brittlely rather than to agglutinate upon impact. An increase in discharge, accumulation rate and temperature increases the agglutination of eruption spatter, creating agglutinated beds, rootless flows and lava flows or lava ponds (Head and Wilson, 1989). Temperature and accumulation rates are determined by the gas content and volume flux, with hotter pyroclasts and faster accumulation rates related to lower gas contents and higher volume flux (Head and Wilson, 1989). Parfitt and Wilson (1995) attribute this change in eruption style, Strombolian to Hawaiian, to a change in magma-rise rate or, to a lesser extent, to magma-gas content, with very little change due to magma viscosity.

Scoria cones do not always exhibit the same characteristics throughout the eruption. Many scoria cones experience episodes of lava flow that most commonly erupt through the scoria at bottom of the cone. The eruptive cycle of other scoria cones may include a late-stage breaching of one of the flanks of the cone. These cones are easily recognized by their asymmetrical shape that forms as parts of the cone are rafted away during the breaching event (Holm, 1987). This breaching was well documented during the eruption of Kapoho at Kilauea, Hawaii in 1960 (Richter et al., 1970). Gutmann (1979) explained this type of event as the result of pressure on the sides of the cone from lava and upwelling magma that causes its flanks to fail. Strawberry Crater is an example of a scoria cone that may have breached in this fashion.

Regional Volcanism

Strawberry Crater is a scoria cone in the San Francisco volcanic field (SFVF) of northern Arizona (Fig. 1). This volcanic field is home to over 600 scoria cones, as well as several lava domes and stratovolcanoes, all of which are now extinct. Scoria cones in the SFVF tend to young in the northeastern direction with the oldest located near the city of Williams and the youngest at Sunset Crater, approximately 25 km to the northeast of Flagstaff (Tanaka et al., 1986).

Strawberry Crater rises approximately 170 meters from its base. The lower 150 meters of the cone consist of loose lapilli and bomb fragments, while the upper portion and rim of the cone, as much as 23 meters thick, consist of poorly to strongly agglutinated bombs and lapilli and isolated rootless flows. The lava flow

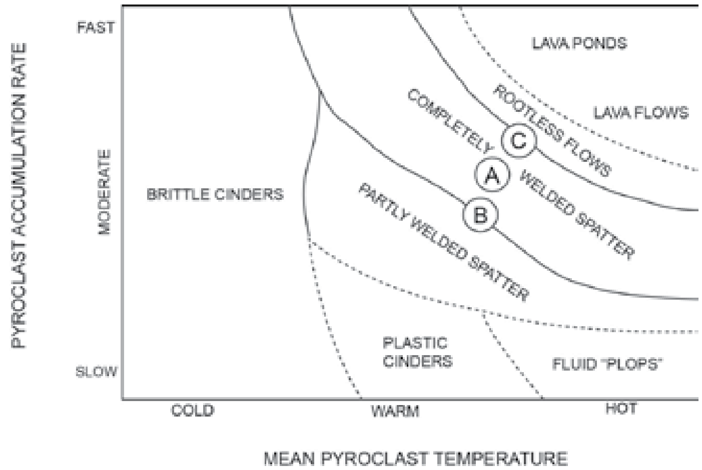

FIGURE 2. Diagram relating pyroclast temperature and accumulation rate and their effect on the degree of agglutination and agglutination of scoria. Strawberry Crater facies are approximately located and identified by letters A-C, from youngest to oldest. Modified from Head and Wilson (1989).

that extends 3.8 km northeast from the cone covers an area of 6.6 km^2 and varies in thickness from 8 meters to almost 40 meters, with the distal reaches typically thicker than the proximal areas (Harwood, 1989).

Displaced agglutinated scoria blocks are the focus of this report because they give some insight into the eruptive history of scoria cone. This study suggests that facies of agglutinated scoria reflect a variable magma volatile content and/or magma-rise speed and displacement of blocks of agglutinated scoria occurred during the breaching event. Without the agglutinated scoria, it would not be possible to study these processes of scoria-cone creation and dismantling, as unconsolidated scoria would not have remained intact during the breaching event. This makes Strawberry Crater a valuable resource for understanding the eruptive history of scoria cones in general.

METHODS

Stratigraphic and structural analyses at Strawberry Crater were conducted in the field from fall 2011 through spring 2012. Stratigraphic analysis included description of three facies of agglutinated scoria, identified as A, B, and C from oldest to youngest (Table 1; Fig. 3), which record the original depositional history and environment of the cone, and construction of stratigraphic sections. Structural analysis involved interpretation of agglutinated scoria-block displacement by correlation of stratigraphic sections and facies blocks with the crater rim. Intact blocks present at the rim of the crater are used as a datum and do not show evidence of displacement.

DATA

Facies Descriptions

Non-agglutinated scoria makes up the basal 150 vertical meters of the cone. Tephra emplaced onto this unconsolidated

TABLE 1. Description of facies of agglutinated scoria.

Facies	Degree of agglutination	Color	Thickness (m)	Clasts	Characteristics
C	Strong	Dark Gray	1 – 4.5	Diameter: 1-5 cm Scoria and spatter	Cliff forming Competent Massive Vesicular throughout Contains rootless flows
B	Moderate -Weak	Red-Brown	1.1 - 7.8	Diameter: 1-11 cm Broken lapilli to bombs	More easily eroded than other facies Often undercuts layer above it No rootless flows
A	Strong	Dark Gray	0 - 3.4	Diameter: 1-3 cm Scoria and spatter	Cliff forming Competent Massive Black vesicular clasts at some locations No rootless flows

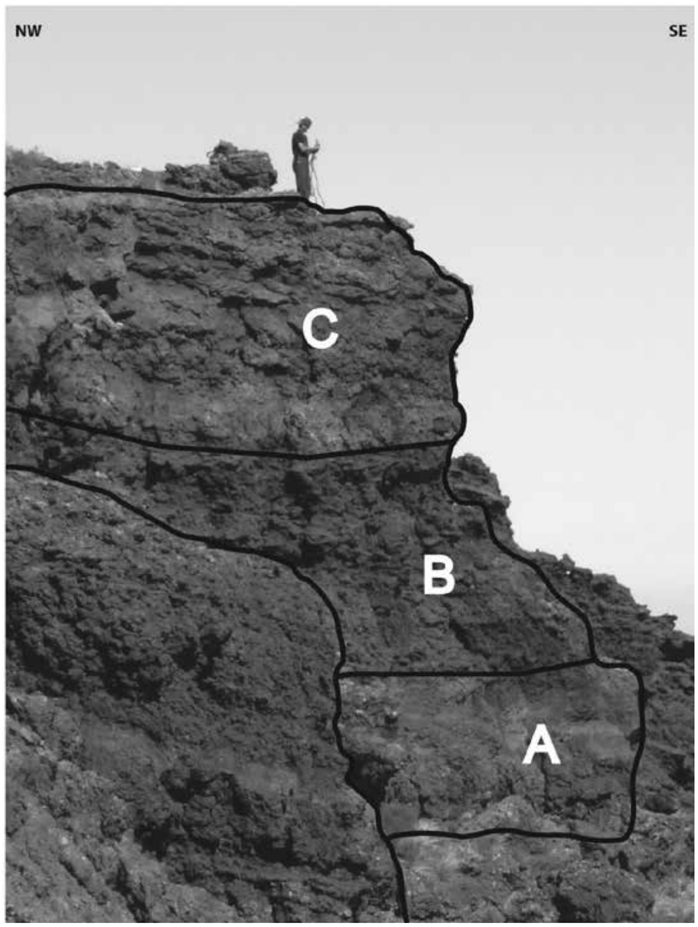

FIGURE 3. Three facies of agglutinated scoria identified at Strawberry Crater. Horizontal lines represent facies boundaries. Person is 1.8 m tall.

scoria during later stages of the eruption is divided into three facies, which are the focus of this study and are described from oldest to youngest (Fig 3).

Facies A: Facies A is a massive, competent layer up to 3.4 m thick that is covered by loose scoria at most locations. Scoria and spatter are dark gray and strongly agglutinated with black vesicular scoria clasts ranging from 1 to 3 cm in diameter.

Facies B: Facies B is a 1.1 to 7.8 meter thick, weakly agglutinated layer of broken vesicular lapilli to bomb fragments. Clasts range from 1-11 cm in diameter, are red in color and contain ~1 mm vesicles. This unit is more easily eroded than other facies and commonly undercuts Facies C above it. Sections of a lighter-red color correlate with the lower degrees of agglutination and higher degrees of erosion.

Facies C: Facies C is a 1.0 to 4.5 meter thick, strongly agglutinated layer that consists of vesicular dark gray scoria and spatter with ropey fragments of lapilli-sized clasts 1-5 cm in diameter and bomb fragments up to 8 cm that forms a massive competent ledge. It is typically difficult to distinguish clasts due to the high degree of agglutination and small clast size. This layer contains xenoliths typically dark gray and fine grained of unknown origin. Isolated rootless flows less than 0.75 m thick are present throughout the layer.

Block Displacement

The original crater is inferred to have been nearly circular, based on the relict part of the rim (Fig. 1), with a diameter of approximately 350 m. This corresponds to crater diameters of other young cones in the San Francisco volcanic field, (e.g. ~475 m for Sunset Crater and ~400 m for S P Crater), which suggests that the relict rim has not been strongly eroded from its original size, and that blocks in the crater were derived from nearby parts of the rim. Facies and thicknesses within blocks correlate with a section measured at the rim (Section 9, Figs. 4, 5) and this study assumes that block displacements can be estimated by correlation of block facies with the facies at the rim.

Blocks vary from 2.5 m to 11.1 m in thickness, 1 m to 10 m in width, and 6 m to 75 m in length (Fig. 4). The thickest deposits in the central area of the crater are approximately 6 m thicker than deposits close to the rim of the cone, and in general blocks thicken to the northeast (Fig. 5). All blocks, regardless of size, are bounded by vertical to subvertical fault planes that together strike in a semi-circle around the center of the cone. Displacement ranges from 5 to over 25 meters, with very little displacement along the crater rim where the datum was constructed and

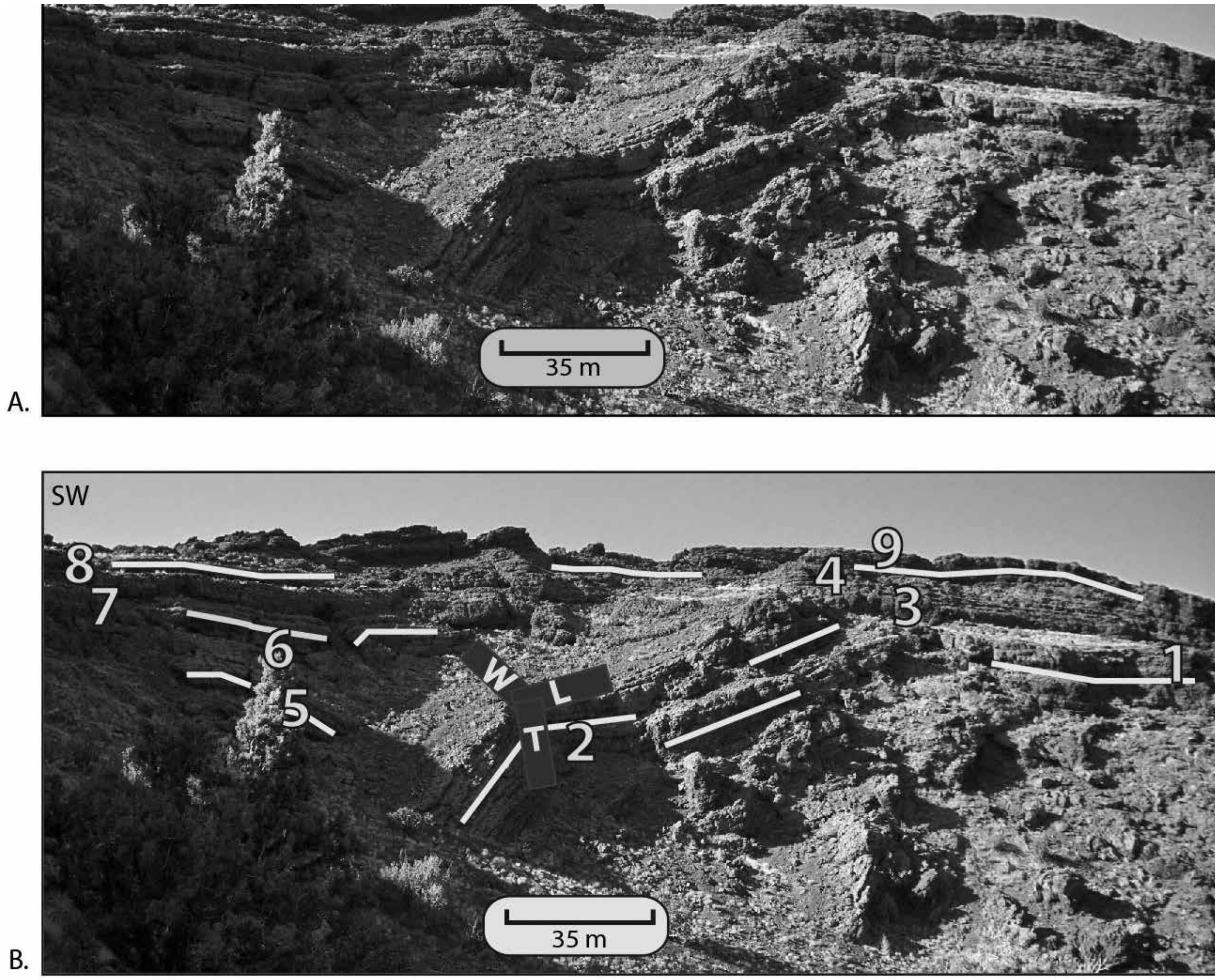

FIGURE 4. Displaced blocks on Strawberry Crater. A) Interior of the crater, showing Facies B which can be located from a distance, by unique shadows of weakly agglutinated and eroded scoria outlined in B. B) Annotated figure showing stratigraphic sections and identifiable horizon in facies B. Numbers correspond to stratigraphic sections in Figure 5. Width, length and thickness are denoted by W, L, and T.

increasing displacement toward the center of the cone (Fig. 5). Blocks experienced little to no lateral displacement.

DISCUSSION

Previous work

Harwood (1989) provided a description of the general eruptive history of Strawberry Crater that is summarized here. The cone was built in a Strombolian-style eruption that occurred through a circular vent. The agglutinated scoria toward the upper portion of the cone is a product of a late-stage decrease in magma volatiles. The existence of a lava lake in the interior is supported by the presence of rafted mounds of the upper sections of the cone at the edges of the lava flow, which also suggests that lava breached the cone from the flanks of the cone rather than from the bottom. Harwood (1989) postulated that the intrusion of a magma body or dike may have inflated the cone, causing pressure on the crater walls and its collapse.

Variations in Magma Characteristics

Parfitt and Wilson (1995) suggested that the rate at which magma rises is the most important influence on whether an eruption displays a Strombolian or Hawaiian style, while gas content of magma and magma viscosity are also factors. These authors explained the transition from Strombolian to Hawaiian eruptions as due to increasing magma-rise rates, coupled with decreased volatile content that may be accompanied by decreased magma viscosity. The change in eruption style at Strawberry Crater may be explained this way. The thick basal unit of non-agglutinated scoria reflects an early Strombolian-style eruption, in which magma-rise rate was likely slow or magma had high effused-gas content, allowing a slug of coalesced bubbles to form (Wilson and Head, 1981). This Strombolian eruption would have sent pyroclasts high in the cooling air with a low accumulation rate to keep the scoria from agglutinating.

The basal scoria is overlain by three unique facies of agglutinated scoria. Pyroclasts during the later stages of eruption retained enough heat and accumulated fast enough to agglutinate upon deposition, but each of the three facies has unique characteristics. Magma-rise rate must have increased, and/or volatile content of magma decreased, enough to keep gas bubbles in the magma from coalescing, creating an eruption closer to Hawaiian style and allowing scoria to agglutinate upon deposition.

Facies A contains the oldest scoria to be agglutinated upon deposition. This scoria is strongly agglutinated and forms a massive, competent layer. The contrast in the degree of agglutination from the basal, non-agglutinated pyroclastic deposits of the cone to this agglutinated layer indicates that eruption characteristics changed suddenly. Magma likely lost significant amounts of volatile content and/or experienced an increased magma-rise rate, shifting the eruption to a more Hawaiian-style and causing a decreased trajectory of pyroclasts, an increased accumulation rate of pyroclasts, and higher degree of agglutination.

Facies B scoria is a weakly agglutinated layer of broken lapilli and bomb fragments that are more easily eroded than the other layers above and below it. Scoria in this layer broke upon impact but is slightly agglutinated, indicating some relict warmth, but this facies is characterized by scoria that was colder than those in the other two agglutinated facies. Pyroclasts likely had moderate trajectories, accumulating less rapidly than the previous layer (Fig. 2), as expected during moderate magma-rising rates and moderate volatile content typical of transitional Strombolian-Hawaiian-style eruptions.

Facies C is a strongly agglutinated, cliff-forming layer of scoria and spatter with isolated rootless flows. These deposits display high degrees of agglutination that may be the result of warm to hot scoria deposition with a moderate to fast accumulation rate of pyroclasts, in contrast to the less agglutinated tephra in Facies B (Fig. 2). Isolated rootless flows suggest that, at times during this period of eruption, pyroclast accumulation rates were fast and mean pyroclast temperature was hot enough to produce secondary melting and allow flowage. Pyroclasts may not have traveled very far from the vent source during this time and retained heat as the cone was beginning to reach its maximum height. This is consistent with Hawaiian-style eruptions, suggesting rapid magma-rise rates or continued decrease in magma-volatile content during this stage of eruption.

Volcanic History of Strawberry Crater

We propose here a history of the Strawberry Crater eruptive episode that complements and expands on that proposed by Harwood (1989). Magma volatile content was irregular and variable throughout the eruption of Strawberry Crater and this variability in gas content and magma flux, including the rate of rising magma, contributed to the change in the degree of scoria agglutination upon deposition. During early stages of cone eruption, lava exhibited a low magma-rise rate and/or a low volatile content that caused a high bubble coalescence rate,

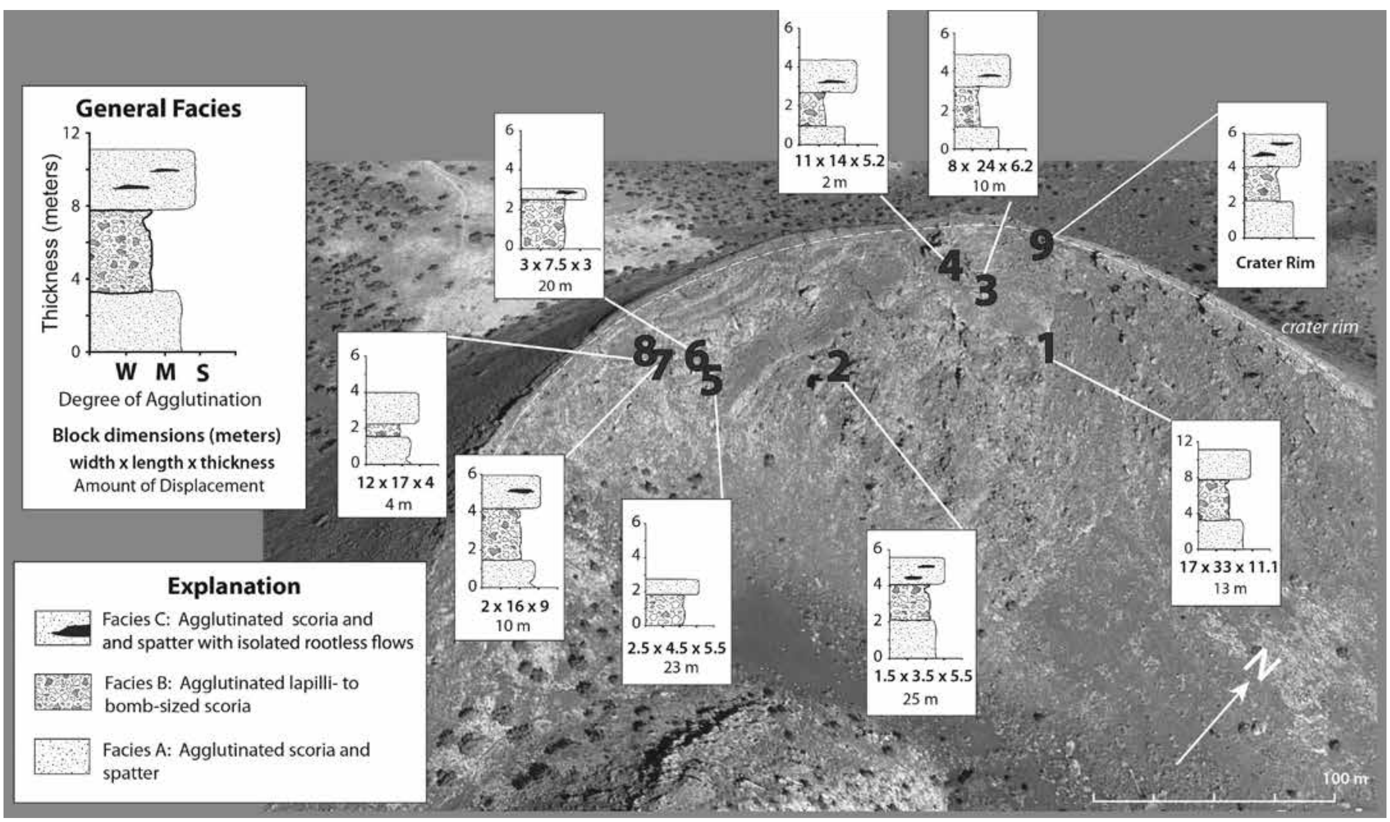

FIGURE 5. Oblique GoogleEarth image of Strawberry Crater showing stratigraphic sections. Locations are numbered according to estimated increasing distance from center of crater before breaching, to crater rim. Degree of agglutination denoted as W (weak), M (moderate), and S (strong). Vertical scale is reduced in section 1 to show thickness. Note the variability of agglutinated-scoria-block thickness with location, with scoria deposits increasing from central crater to rim, as well as generally increasing to the northeast.

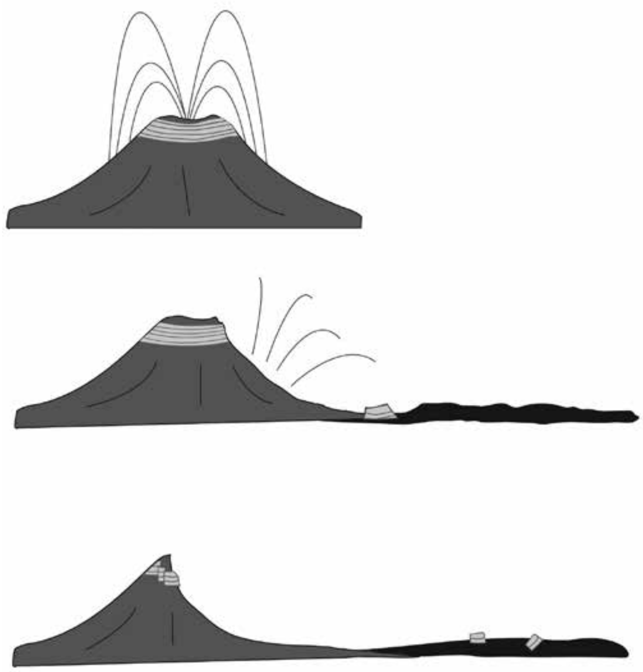

FIGURE 6. Eruptive history of Strawberry Crater. Illustrated sequence of breaching as the northeast flank of the cone failed during the breaching event, creating the amphitheater shape and displacing the agglutinated blocks (represented in light color) of scoria.

producing a Strombolian-style eruption. The trajectories of pyroclasts were great enough to allow the pyroclasts to fully cool before deposition when rising magma reached the surface. These cooled clasts make up the basal 150 meters of unconsolidated scoria of the cone. Variations in magma-rise rate and/or volatile content are responsible for three facies of agglutinated scoria found on the upper portion of the Strawberry Crater. During the final stage of eruption, pressure from within the cone became too great for the walls of the cone to support, or magma flux from the vent increased enough to destabilize the bottom of the cone, causing the lava flow and breaching in the last stage of eruption.

The three agglutinated scoria facies were significantly displaced as blocks during breaching of the cone as the eastern flank of the cone collapsed (Fig 6). This final stage of eruption dismantled the cone, rafting eastern segments of the agglutinated scoria on the lava flow. The agglutinated western scoria blocks fell nearly vertically into the center of the cone with the sudden removal of the eastern portion of the cone, with the central cone segments experiencing the greatest displacement, up to 25 meters. Harwood (1989) suggested that magma intruded into the cone, citing evidence in the over-steepened beds of the crater rim.

No horizontal displacement of the blocks was found during this study, and block facies remained locally intact upon displacement. Consistent vertical faulting with variable offset, regardless of block size, implies the breaching and extrusion of lava flow was a short-lived event that removed the support for the large agglutinated blocks that had formed on the cone rim.

CONCLUSION

Strawberry Crater has three distinct facies of scoria that are strongly agglutinated and faulted. Displaced agglutinated scoria blocks fell vertically into the cone upon displacement, regardless of size of agglutinated material and agglutinated blocks, which suggests that agglutinated spatter and scoria were cooled prior to breaching. These facies show variation in the speed of magma rise and magma volatile content. A lava lake may have existed in the crater and as magma pressure increased, the integrity of the eastern flank of the cone was overcome, or magma flux may have increased dramatically at the vent, tearing away the eastern portion of the cone from the bottom. Breaching of the cone was probably a sudden event as agglutinated scoria blocks show little response to lateral migration of lava, as opposed to horizontal drag that may accompany lava movement during a slower breaching event.

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