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BASALTIC NEAR-VENT FACIES OF VULCAN CONE, ALBUQUERQUE VOLCANOES, NEW MEXICO

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Abstract—Vulcan cone is the largest and central-most fissure vent among the ~156-ka Albuquerque Volcanoes. The eruptive center consists of a large central cone (~60 m high) with two smaller flanking cones (~10–15-m high) on the south and southwest. Vulcan exhibits complex facies relationships between welded and nonwelded cinder, agglutinated spatter, clastogenic lava flows, pahoehoe flows and a fountain-fed lava pond that are consistent with Hawaiian-style eruptions. The three cones are spatter cones composed mostly of agglutinate and clastogenic lava flows. The central cone is locally armored by thin pahoehoe lava flows that formed from overflow of a late-stage lava pond from its crater. Abundant spatter and cinder were produced by early-stage lava fountaining that was apparently more vigorous at the southwest flank cone. Shortly thereafter, the dominant lava discharge was established at the central cone. A broad platform of shelly pahoehoe flows north of the central cone was likely constructed by discharge from a breach in the north wall of the central cone. This breach was not persistent, however, and permitted formation of a late-stage lava pond that eventually overflowed the west and northwest sides of the cone where the agglutinate rim was lowest because of westerly prevailing wind. Lava flows from all three vents are mostly thin, shelly pahoehoe, which constructed a broad shield adjacent to the north and west sides of the vent complex. Some lava flows that exited the northern breach and spilled over the northwest rim contain small-diameter surface lava tubes. These tubes formed by roofing over of small lava channels or by continual transport of lava through expanding pahoehoe toes of unusual length (roughly 100 m) that initially formed by rapid descent of toes down moderately steep slopes.

INTRODUCTION

Hawaiian-type volcanic eruptions feature continuous fountaining of only slightly fragmented magma to produce steep cones of spatter, clastogenic lava, and cinder at the source vents for far-traveled lava flows (Head and Wilson, 1989). Despite many descriptions of such eruptions (e.g., Swanson et al., 1979; Wolfe, 1988) and general models of cone growth (Head and Wilson, 1989) there are no detailed descriptions of the nature and distribution of pyroclastic and lava-flow facies around these cones.

This paper describes the near-vent facies of Vulcan, a middle Pleistocene cone in the Albuquerque Volcanoes in the western part of the city of Albuquerque, New Mexico, and interprets these facies in terms of descriptions of Hawaiian eruptive activity. Vulcan is well suited for this study because its youth and location in an arid region preserve its morphological elements, whereas excavations on its north and east sides provide insights to its internal stratigraphy (Fig. 1).

The Albuquerque Volcanoes are a 10-km-long chain of at least 15 vents that formed along a north-south fissure near the western margin of the Albuquerque Basin, within the Rio Grande rift (Fig. 1). Flows of olivine tholeiite (Kelley and Kudo, 1978) erupted from these vents to cover approximately 25 km². These flows were emplaced over the Llano de Albuquerque constructional geomorphic surface and advanced eastward 3–5 km over low escarpments toward the Rio Grande, where they now rest on terraces about 25 m above the modern floodplain (Lambert, 1968). Continued dissection has formed a lava-capped escarpment of rift-basin sediment of the Santa Fe Group along most of the eastern edge of the basalt outcrops. Eolian sand and minor alluvium overlie the basalt flows throughout their extent. K-Ar ages of 0.19 ± 0.40 Ma (Bachman and Mehnert, 1978) and 0.155 ± 0.047 Ma (Geissman et al., 1990) have been recently joined by a ^{238}U-^{230}Th age of 0.156 ± 0.029 Ma (Peate et al., 1996). A middle Pleistocene age is consistent with the paleomagnetic orientation of the rocks, which record an excursion, and the degree of soil development in the overlying eolian cover (Geissman et al., 1990).

Vulcan is the largest of the vents comprising the Albuquerque Volcanoes (Fig. 1, lower inset) and consists of a gently sloped 0.25-km² shield surmounted by a steeper central cone. The volcano is also known as the "J Crater" for the letter "J" painted on the east side of the cone (Fig. 2a) by students of the former St. Joseph's University. The central cone rises 60 m above the general lava-flow surface and 20 m above the shield (Figs. 1 and 2b). The central cone is generally symmetrical, although it is higher on its east side and is flanked by a low hill of lava on the north and two small, adventive cones to the south and southwest (Fig. 1). The relationship of the north hill to the central cone has been obliterated by the excavation of a rock quarry between them (Figs. 1, 2a) but this quarry provides otherwise inaccessible exposures of the inner structure of both the cone and the north hill lava flows. A cinder borrow pit (Figs. 1, 2a) has been excavated at the southeast base of the central cone, adjacent to the flank vents and also provides exposure of stratigraphic relationships.

Previous descriptions and interpretations of Vulcan by Lambert (1968) and Kelley and Kudo (1978) have been of reconnaissance nature and have not accurately portrayed the volcanological features of the cone. The senior author has conducted field exercises at Vulcan with University of New Mexico students since 1992, culminating in even more detailed mapping and volcanological observations by students of Earth and Planetary Sciences 450 in the spring of 1998. This report summarizes the results of that class effort. Our research suggests several substantial modifications relative to previously published statements about Vulcan. Although vents of the Albuquerque volcanoes are commonly described as cinder cones (Lambert, 1968; Geissman et al., 1990; Peate et al., 1996), Vulcan is better described as a spatter cone composed almost entirely of spatter and clastogenic lava flows, dipping at angles as steep as 55°. Kelley and Kudo (1978) mistakenly interpreted the central cone as a "plug dome;" i.e., the result of extrusion of viscous lava to produce a domical accumulation above a vent. Kelley and Kudo (1978) also mistook the artificial excavation on the north side of the central cone as a late-stage explosion crater and misidentified lava tubes on the north side of the cone as radial dikes.

NEAR VENT FACIES OF VULCAN

Definition of mappable facies at Vulcan is difficult for several reasons. First, there is a nearly continuous gradation from nonwelded cinder to welded cinder to spatter to clastogenic lava and finally to lava lacking fragmental textures. Second, in some areas these different deposits are so intimately interbedded as to prevent separate mapping, even at the 1:2400 scale used in the field. These different facies are derived from progressively hotter, and more interior, parts of Hawaiian-type fire fountains (Fig. 3; Head and Wilson, 1989) so their intimate association and gradational nature are not surprising. Our map (Fig. 1), therefore, depicts outcrops of interbedded facies as well as single facies. The facies descriptions and interpretations, combined for brevity, emphasize distinctive characteristics while acknowledging the gradational nature of several of the facies.

The basalt erupted at Vulcan is everywhere characterized by plagioclase phenocrysts and glomerophenocrysts, 2–5 mm long, and olivine

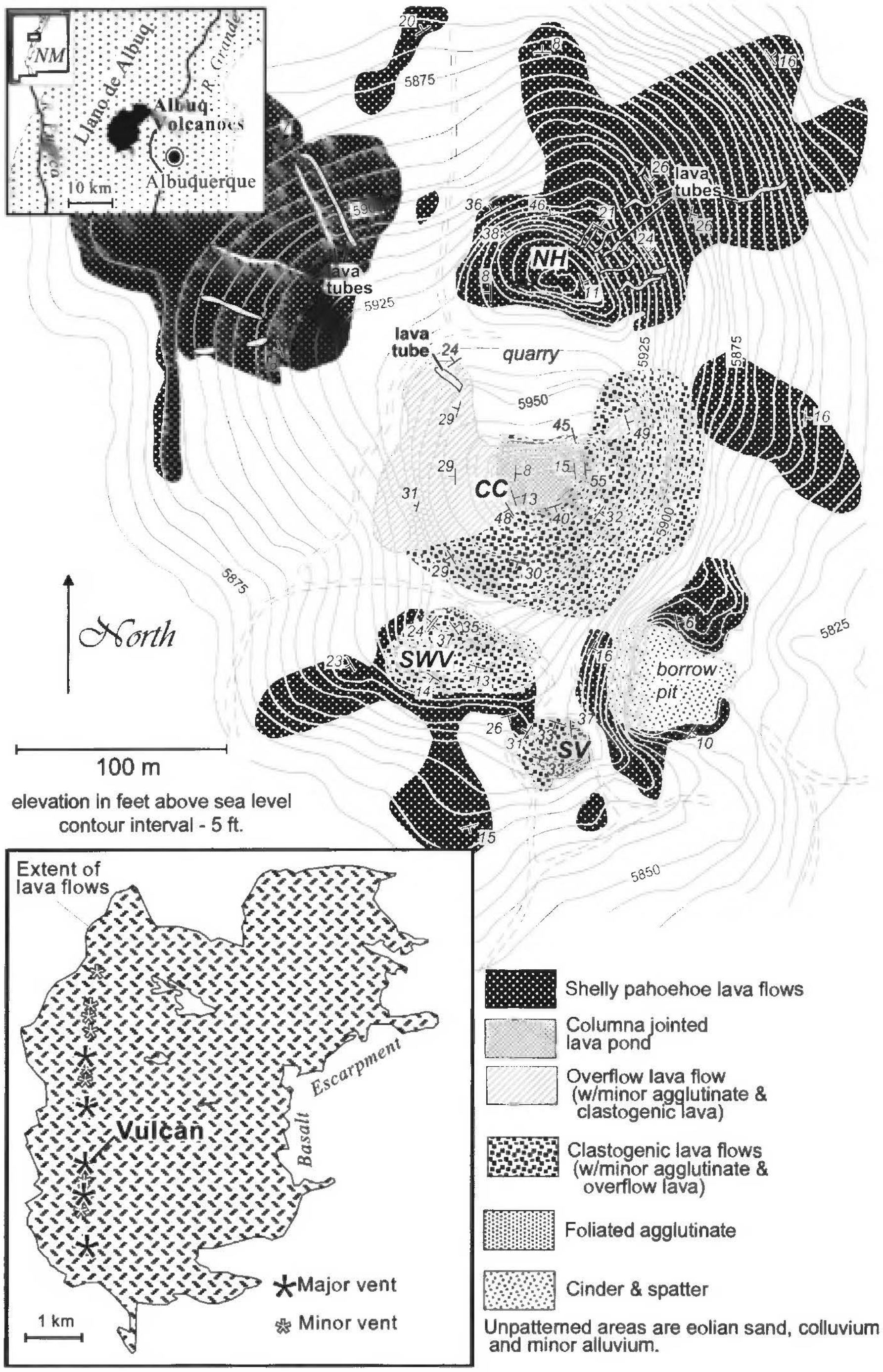


FIGURE 1. Geologic map of Vulcan. Inset maps show location of the study area within the Albuquerque Volcanoes and the extent of basin-fill sediment of the Rio Grande rift (stipple). CC = central cone; SV = south vent; SWV = southwest vent; NH = north hill. Widths of lava tubes are exaggerated. Topographic base from Albuquerque Metropolitan Arroyo Flood Control Authority (1973).

phenocrysts, 0.5–1.0 mm long. Plagioclase abundance varies from <10 vol% to ~30 vol% within adjacent pyroclasts and over distances of decimeters to meters in lava flows, whereas olivine abundance remains fairly uniform at 10–15%. The groundmass varies from hypohyaline to a intergranular mixture of plagioclase microlites, equant augite and opaque phases.

Kelley and Kudo (1978) refer to partially melted sandstone inclusions within the Vulcan ejecta. These are present as highly vesiculated white pumice (~84% SiO_2) near the top of the cinder and agglutinate deposits in the borrow pit southeast of the central cone and as dense, flattened pyroclasts in agglutinate and clastogenic lava flows, especially on the south side of the southwest flank vent. Most of these inclusions were

FIGURE 4. Photographs of pyroclastic deposits. **a,** Loose cinder with a flattened spatter bomb (between arrows) in eastern part of borrow pit. Pencil is 14.5 cm long. **b,** Partly to densely welded agglutinate near the center of the borrow pit. Tip of pencil (14.5 cm long) is at irregular contact between partly welded cinder with obvious fragmental texture and densely welded cinder/spatter (arrows point to flattened pyroclasts), which passes upward to less welded cinder. Such alternations in degree of welding likely relate to fluctuations in accumulation rate and/or fountain height. **c,** Strongly welded and attenuated pyroclasts in agglutinate near east base of the southwest vent. Dark bands in center of view are about 1.5 cm thick.

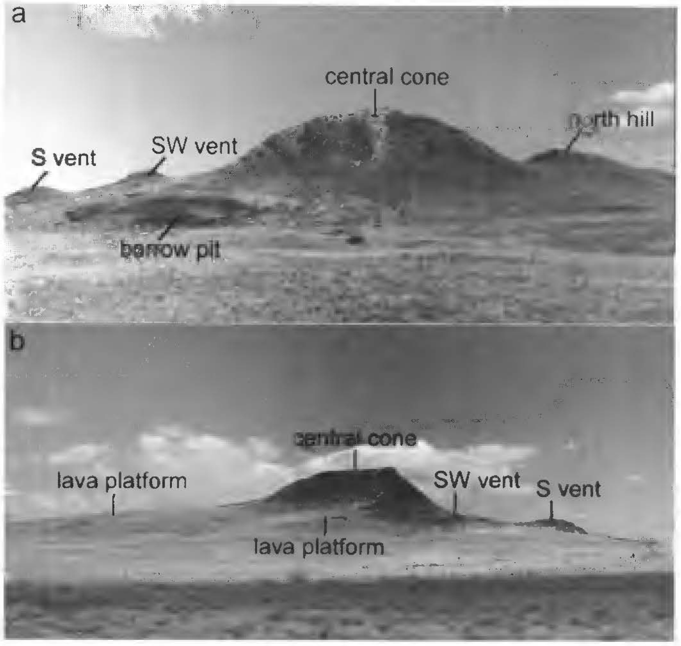


FIGURE 2. Views of Vulcan from the **a,** east and **b,** west. The broad shield form of the eruptive center is apparent in **b,** where lobate platforms of thin lava flows extend westward and northwestward from the vents. A steeper lava platform forms the north hill (a).

mostly molten, and contain <10% quartz grains in glass groundmass. The origin of these unusually thoroughly melted inclusions is currently under further study.

Cinder and agglutinate

Rocks of unambiguous pyroclastic origin comprise a subsidiary

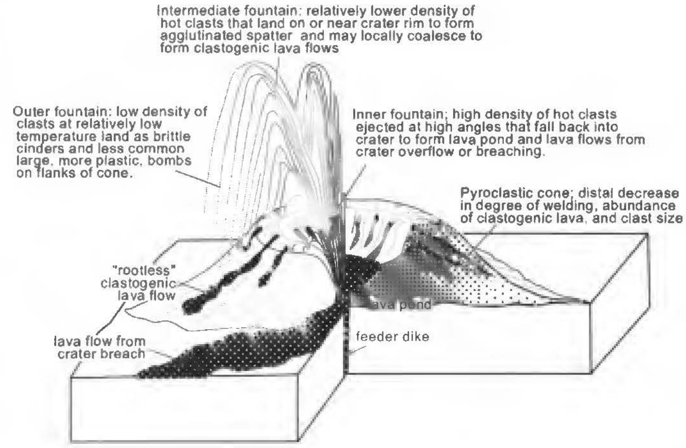
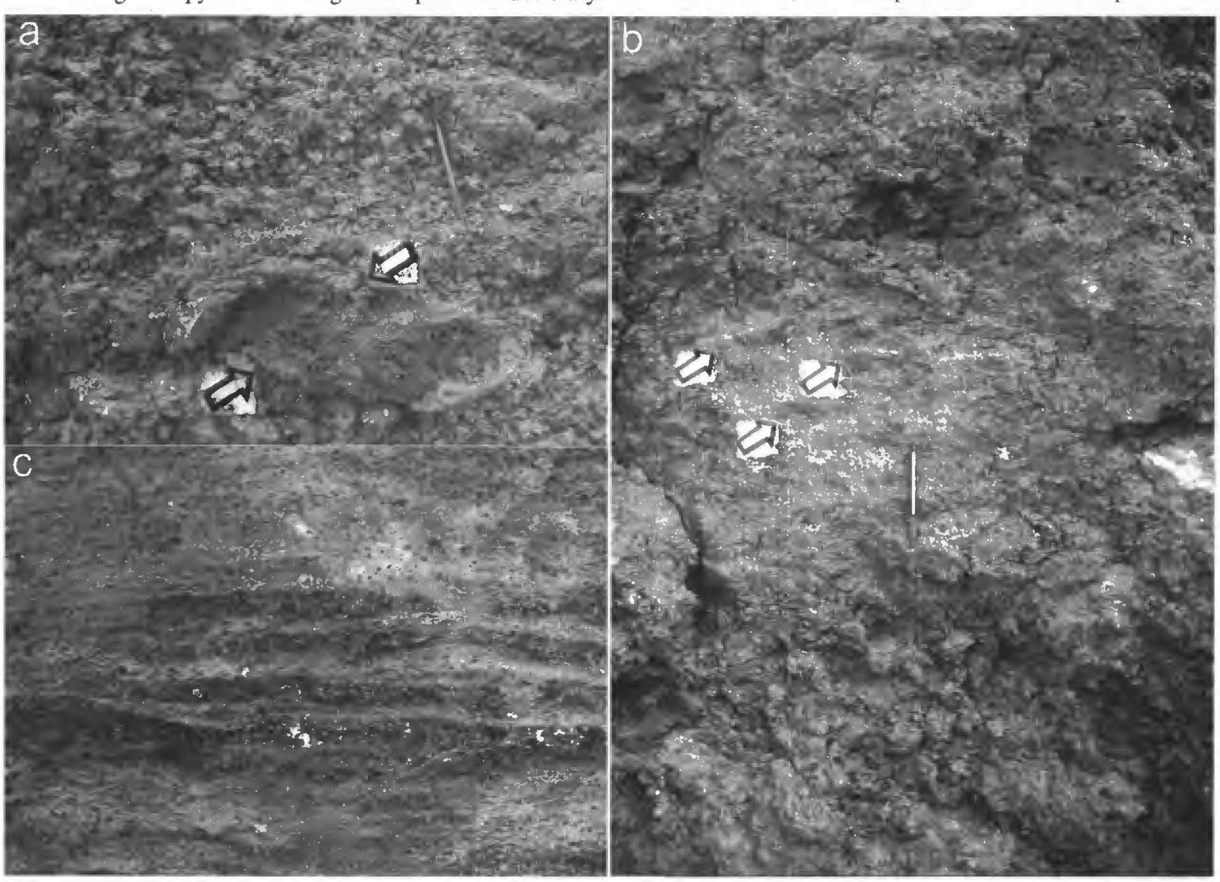


FIGURE 3. Diagram of Hawaiian-style eruptive activity (modified from Head and Wilson, 1989) illustrating the diverse types of lava flows and tephra deposits that can form simultaneously from fire-fountains.

amount of the central cone but are abundant in association with the flank cones to the south and are very well exposed in the borrow pit on the southeast side of the volcano.

The ~70-m east-to-west exposure in the walls of the borrow pit records a westward gradation from completely loose, equant cinder to densely welded cinder with flattening ratios of 4 to 5 (ratio of exposed horizontal to vertical dimensions). Two to eight meters of section are accessible with no exposure of the base of the deposit. The westward welding increase and low northward and southward components to the dip of the ejecta, as indicated by the nature of contact with overlying lava flows (Fig. 1), suggest that most of this pyroclastic material was mainly erupted from the southwest flank vent. In the most distal outcrops, ~180 m from the southwest vent, loose, vesicular cinders, 5–10 cm in diameter, are interspersed with flattened spatter bombs as much



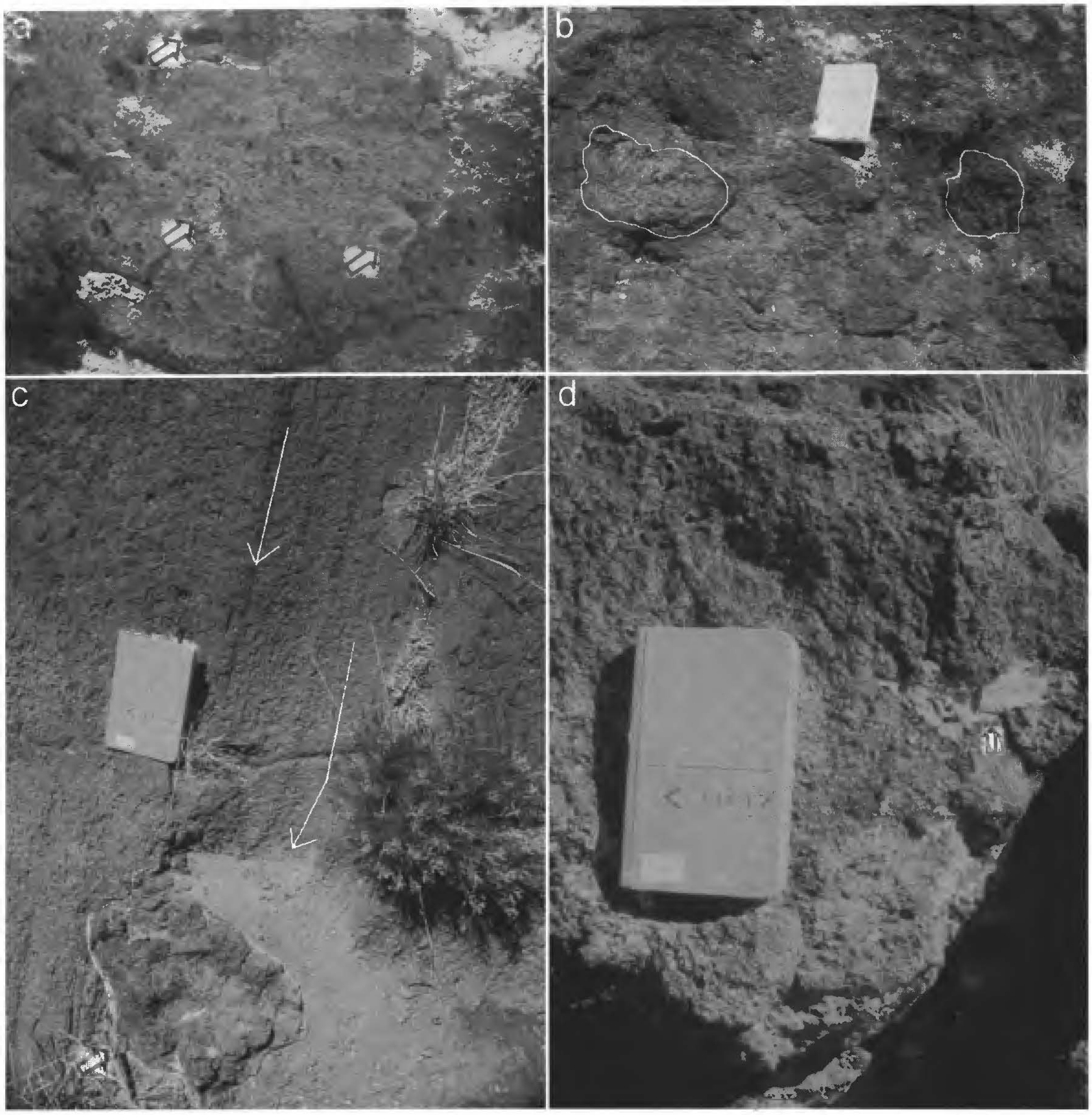


FIGURE 5. Photographs of lava-flow features on the central cone. **a,** Entire thickness of ~ 50-cm-thick clastogenic lava flow on the south flank. Note extremely heterogeneous distribution of vesicles. Arrows point to deformed, partially remelted(?) spatter within the lava. **b,** Top of clastogenic lava flow on the south flank showing irregular flow surface with embedded bombs (outlined). Notebook is 19-cm high. **c,** Steeply inclined, lineated (thin arrows) flow surface in clastogenic lava flow on south flank. Thick arrow points to rotated bomb at termination of curved lineations. **d,** Cross-section of entire thickness of ~50-cm-thick overflow lava flow on the south rim; note more uniform texture compared to clastogenic flow illustrated in (a). Arrow points to melted sandstone inclusion within the flow.

as 40 cm long (Fig. 4a). Preferential flattening of larger fragments is consistent with greater heat retention in larger clasts during airborne transit from the vent (Sumner, 1998). The deposit is oxidized red at the base of exposure and grades to black at the top. Slight welding lithification, without significant flattening, is present in this deposit at a depth of 1.4 m. At 160 m from the principal source vent, 2.4 m of ejecta are largely nonwelded, except for an interval between 0.8 and 1.2 m from the top that might correlate with the slight welding observed more distally. Within another 20 m toward the SW vent this same stratigraphic interval is completely lithified by welding with an upward increase in flattening of cinder lapilli and spatter bombs, the latter as long as 75 cm (Fig. 4b). Some layers here, and farther west in the quarry exposures, more closely resemble agglutinate than welded cinder, although the distinction of the two deposit types is difficult where flattening is extreme. The abruptness of the change in degree of welding suggests abrupt lateral changes in accumulation of ejecta from fire fountains (Fig. 3; Head and Wilson, 1989).

Strikingly banded, densely welded, foliated agglutinate (Figs. 1 and 4c) is present on both flank cones and, at the southwest vent, locally grades upward from deposits described above. Bands are defined by subtle variations in degree of reddening, abundance of plagioclase phenocrysts, and vesicularity. The bands are lenticular with dimensions on the order of 0.5–2 cm thick and 20–50 cm long. We interpret this facies as highly welded spatter, although the attenuation of interpreted pyroclasts (i.e., individual bands) would also be consistent with rheomorphic flow of reconstituted spatter. The foliated agglutinate is texturally distinct from what we have mapped as clastogenic lava flows although, in terms of process, these facies may be gradational from one to another.

Cinder is notably rare on the central cone itself although spatter is present. Layers of porous spatter 25–40 cm thick are present between lava flows comprising the cone and are especially conspicuous on the east and south sides, probably reflecting distribution controlled by prevailing winds. These pyroclastic layers are composed of deformed spatter bombs, generally 15–50 cm in longest dimension, that are firmly welded together at clast contacts but not densely compacted to agglutinate so that irregular pore spaces of centimeter to decimeter scale remain.

Clastogenic lava flows

Most of the eastern and southern flanks of the central cone, and the well-exposed parts of the adventive cones, are composed of thin (10–65 cm), texturally heterogeneous gray basalt interpreted to be flows of coalesced spatter in close proximity to fire fountains where accumulation rates and emplacement temperature of ejecta were highest (Fig. 3). These layers dip both inward, toward the vents, and outward to comprise a substantial part of the outer cone flanks. Textural heterogeneity is imparted mostly by abrupt lateral and vertical variations in vesicle size and abundance, in some cases subtly marked by the glassy selvedge of a spatter bomb (Fig. 5a). The upper surfaces of these flows commonly preserve the partly remelted shapes of large bombs (Fig. 5b). We interpret the heterogeneity in vesicularity, therefore, to result from the varying vesicularity of component spatter fragments whose margins are obscured by coalescence but whose internal heterogeneities, because of limited transport distance, have not been homogenized by flow (cf., Sumner, 1998).

On the steepest (~50°) eastern and southeastern slopes of the central cone, flow-unit tops are strongly lineated (Fig. 5c). The lineated zones are as much as 50 cm wide and at least 1–2 m long. In some cases, spatter bombs are found at the distal end of the lineated zone, demonstrating that the lineations are drag marks resulting from downslope sliding of large masses of spatter on the plastic, solidifying crust of the clastogenic lava. Local areas of deformed layering likely represent wholesale slumping of reconstituted ejecta on the steep flanks of the cone.

Lava-pond basalt

Massive gray basalt with crude columnar jointing forms an 8-m high cliff along the north face of the central cone, which has been modified by quarrying. Vesicles are generally more abundant and larger upward to within 20 cm of the top of this thick layer. Local heterogeneity, which is nowhere as pervasive as in the clastogenic lava flows, defines minor accumulations of largely remelted spatter and cinder within the lava. Vesicle cylinders are also present. The abundance of plagioclase phenocrysts appears to increase upward. This thick lava can be continuously traced around the west side of the cone to a lateral pinchout near the southwest corner. It is overlain, in the center of the crater, by texturally similar, but much thinner (20–50 cm) lava flows that are interlayered with red spatter layers of comparable thickness. These thin layers dip inward at low angles toward the center of the crater (Fig. 1) and are continuous across it, resembling a stack of saucers with upward decreasing diameter at the top of the cone.

We interpret the thick basalt as lava that was ponded at a high level in the vent. The time interval of accumulation and solidification was sufficiently long to permit vesicles and relatively low-density plagioclase phenocrysts to rise in the denser melt. The overlying thinner lavas are interpreted as additional accumulations within the crater as the eruption drew to a close. The continuity of these thin layers across the entire width of the crater suggests that the crater was filled to, or near, its top by lava and spatter. Late stage eruptions did not excavate a vent through the crater floor nor was there drainage back into the vent to leave an open crater.

Overflow lava

Relatively thin, 20–80 cm, gray lava flows comprise most of the west slope of the central cone and are interlayered with spatter and clastogenic lava flows on the south and east flanks. These lava flows are distinct from clastogenic lava by (a) absence or near absence of recognizable pyroclasts, (b) greater textural homogeneity with laterally uniform and continuous upward increase in vesicle size and abundance beneath a 4–8 cm thick crust of fewer and smaller vesicles (Fig. 5d), and (c) local development of ropy pahoehoe surfaces. Vesicle zonation is consistent with degassing and solidification of simple, thin flows (Aubele et al., 1988). These thin flows are texturally similar to thin lava-pond layers but, in contrast, were emplaced on outer cone flanks. We interpret these thin pahoehoe flows to represent overflows from the lava pond.

Shelly pahoehoe flows

Shelly pahoehoe (Wentworth and Macdonald, 1953) comprises most of the north hill (Fig. 6a) and all of the lower outer flanks of Vulcan where exposures are adequate for study (Fig. 1). Flow units are mostly 10–30 cm thick with cavernous vesiculation in the center and less vesicular upper and lower margins (Fig. 6b). Glassy selvedges, generally <1 cm thick, are well preserved at the smooth or ropy flow tops. Pahoehoe toes, approximately 10–25 cm across, are readily apparent in both plan view and in cross-sections provided by the quarry walls on the south side of the north hill (Fig. 6b). The pahoehoe flows are also associated with surface tubes, likely more than 100 m long and as much as 2 m wide, which are discussed separately below.

Pahoehoe flows comprising the upper part of the north hill pinch out to both east and west and coalesce into thicker lava in the central part of the hill (Fig. 6a). The thicker basalt clearly formed by amalgamation of thinner flows such that flow-unit boundaries are indistinct. This phenomenon may have resulted from greater northward flux of lava through a narrow zone now represented by the central part of the north hill exposure.

The north side of the north hill is veneered by shelly pahoehoe flows that parallel the 20–45° slopes. These steep slopes may have resulted

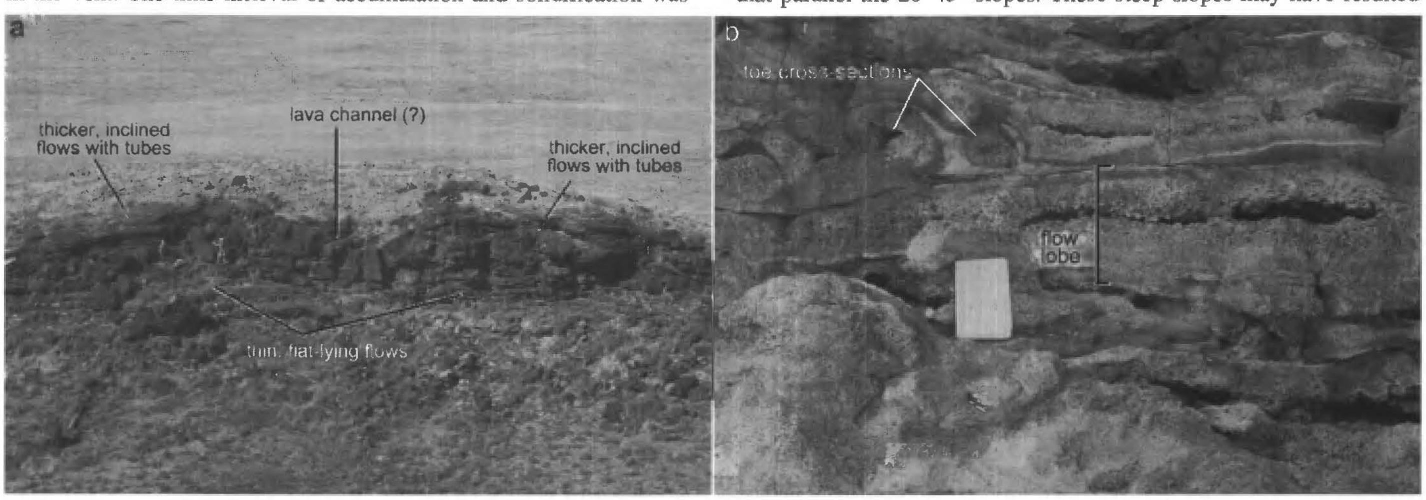


FIGURE 6. **a,** View of the south side of the north hill from the central cone. Thin, flat-lying shelly pahoehoe flows at base of quarry exposure are followed by thicker, semiradially inclined flows that contain toe tubes (not visible). The thicker lava in the center is an amalgamation of thinner flow units, possibly marking a channel. **b,** Close view of shelly pahoehoe flows on the south side of the north hill, showing thin, sharp topped flow lobes with highly vesicular interiors and small pahoehoe toes.

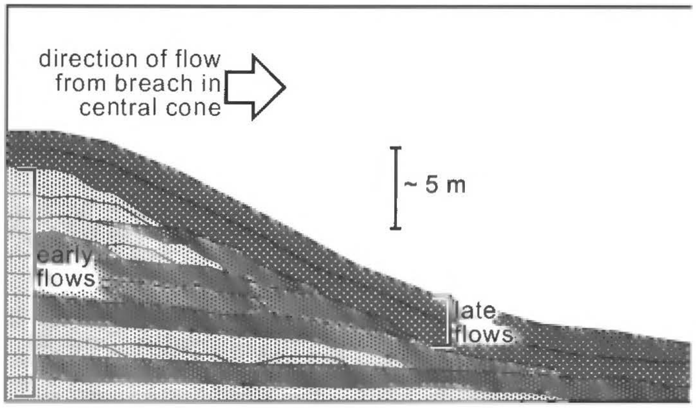


FIGURE 7. Schematic diagram illustrating explanation for geometry of lava flows comprising the north hill. Early, nearly flat-lying flows (exposed in the quarry (Fig. 6a)) formed a sharply outward tapering wedge that was later veneered by lava flows now seen to have descended semiradial steep slopes of the hill.

from northward termination of successive thin, near-horizontal flows. Later flows then advanced over the resulting constructional escarpment (Fig. 7).

Lava tubes

Lava transport from the central cone was apparently accomplished in large part by flow through features that have characteristics both of lava tubes and pahoehoe toes. These structures are roughly cylindrical in shape, mostly 20–50 cm wide and laterally traceable along variably sinuous paths for distances approaching 100 m (Figs. 1 and 8a). The tubes exhibit upward tapering triangular or teardrop shapes in transverse section (Figs. 8b and 8d). Concentric layering is defined by alternations in degree of vesiculation and tubes are either completely filled with lava (Fig. 8a) or exhibit triangular-shaped voids above flat-topped lava fill. (Fig. 8b)

Lava tubes are found in two semi-radial groupings on the east side of the north hill and near the northwest base of the central cone (Fig. 1). Tubes in the latter area converge upslope into an area of eolian cover at the downslope projection of an unusually large tube preserved on the flank of the central cone (Fig. 8c). This tube is approximately 1.5 m wide toward its base with the characteristic upward-tapering triangular cross-section. At least 10 concentric rings of variable vesicularity comprise the rim of the feature, which is partly hollow (Fig. 8d). Some of outermost rings have slumped or folded over where dips exceed 75° near the upper edges of the tube (Fig. 8d). In cross-section, tubes resemble smaller pahoehoe toes observed in the shelly pahoehoe flows. The larger size and concentric vesicle zonation, suggest multiple injections of lava, unlike pahoehoe toes, which form by short distance, halting advance of small-volume pulses of lava. Walker (1989) suggested late flowage of lava through interconnected toes, without an increase in the cross-sectional area of the toes, could generate concentric zones of variable vesicularity in pahoehoe toes. The locally sinuous courses of the tubes and slumping of outer layers indicates that they were free flowing at the surface, rather than as interconnected toes within the interior of lava flows and the slumping suggests inflation of the tube roof. Tubes are observed to diverge downslope into two or more tubes of nearly comparable size and the distribution of tubes below the northwest slope of the central cone (Fig. 1) suggest a distributary system of smaller tubes linked to a principal upslope feeder.

We are unaware of previous published descriptions of such lava tubes. S. Rowland (written communication, 1998) suggests a comparison to small roofed-over channels in Hawaiian pahoehoe flows. Narrow channels form steep marginal levees so that lava accretes upward and inward until a continuous cover is formed, analogous to features described in a'a at Mount Etna, Italy (Sparks et al., 1976). The triangular cross-sections and concentric layering of tubes at Vulcan may be explained by this mechanism.

We hypothesize that the tubes at Vulcan are also compatible with formation by continued influx of lava into unusually long pahoehoe toes that rapidly descended moderately steep slopes (20–25°). Initially, a highly elongate toe descended the slope. Once emplaced, the toe became a preferential pathway for additional influx of lava. In such a fashion, the original toe was expanded and served as an insulating tube to convey additional lava downslope.

Critical slope angles may be required for the formation of these small tubes. On the north side of the north hill tubes are prominent in the northeast sector (slopes of 20–25°) and absent from the northwest sector (slopes of 35–45°). This suggests that pahoehoe descending a steep slope advanced rapidly as a nearly continuous sheet. On low slopes (<20°), pahoehoe also advanced as thin sheets but by the slow, discontinuous process of budding, spreading and halting of individual toes. On the intermediate slopes, some thin, but elongate, pahoehoe toes advanced relatively rapidly to the base of the slope thus spawning the formation of tubes.

GROWTH OF THE VULCAN ERUPTIVE CENTER

Although the Vulcan eruptive center covers a very small area, it is composed of a rich diversity of volcanic facies. The various types of deposits need not, however, be correlated to discrete phases of a reconstructed eruption history. The dynamics of fire fountains (Fig. 3) to simultaneously produce spatter, cinder, and clastogenic lava flows while also feeding lava ponds that, in turn, are sources for far-traveled lava flows can account for simultaneous emplacement of all described facies. In fact, such contemporaneity is clearly required at Vulcan in order to explain the intercalation and gradation exhibited between most defined facies.

Field relationships suggest, but do not conclusively prove, that the most energetic fire-fountain activity preceded construction of most of the central cone (Fig. 9a). The borrow pit excavations illustrate that the pyroclastic deposits are overlain by, but not intercalated with, lava flows. We cannot discount the possibility that later erupted cinder and spatter were rafted away on moving flows or have subsequently been removed by erosion. Preservation of ropy flow surfaces east of the volcano suggests, however, that erosion has been minimal, at least in some areas. As noted above, the distribution of cinder and agglutinate exposed in the borrow pit suggest derivation principally from the southwest flank vent rather than from the central cone. Lava flows from the central cone onlap and bury the northern margin of the gently east-sloping pyroclastic deposit. North of these lava flows the east slope of the central cone is very steep (below the "J" in Figure 2a) and there is no geomorphic expression of the northward continuation of the buried pyroclastic apron exposed in the pit. This suggests that the central cone grew adjacent to the pyroclastic deposits largely derived from the southwest flank vent. We do not exclude the presence of fire fountains at the central cone, which consists to a great extent of spatter and clastogenic lava flows that were produced by such phenomena. The field relationships suggest, however, that fire fountains forming the central cone were not very high and did not produce a significant downwind accumulation of cinder.

The relative order of eruption at the three vents comprising Vulcan is unclear and eruptions at the three vents were likely contemporaneous (Fig. 9a). Although lava flows from the central cone overlie cinder and agglutinate largely derived from the southwest flank vent, this relationship does not preclude at least partial contemporaneity of eruptions from these vents. There are no deep exposures on the south side of the central cone to elucidate stratigraphic relationships between proximal deposits of all three vents.

Topography suggests that most far-traveled lava flows fed by Vulcan exited the near-vent complex to the northeast and northwest. Lobate topography to the northeast and northwest are associated with tube complexes radiating from the north hill and northwest flank of the central cone, respectively (Fig 1).

The relationship of the north hill to the central cone is obscured by the removal of intervening rock in the quarry. Exposures in the north wall of the excavation, however, demonstrate that the north hill is not anoth-

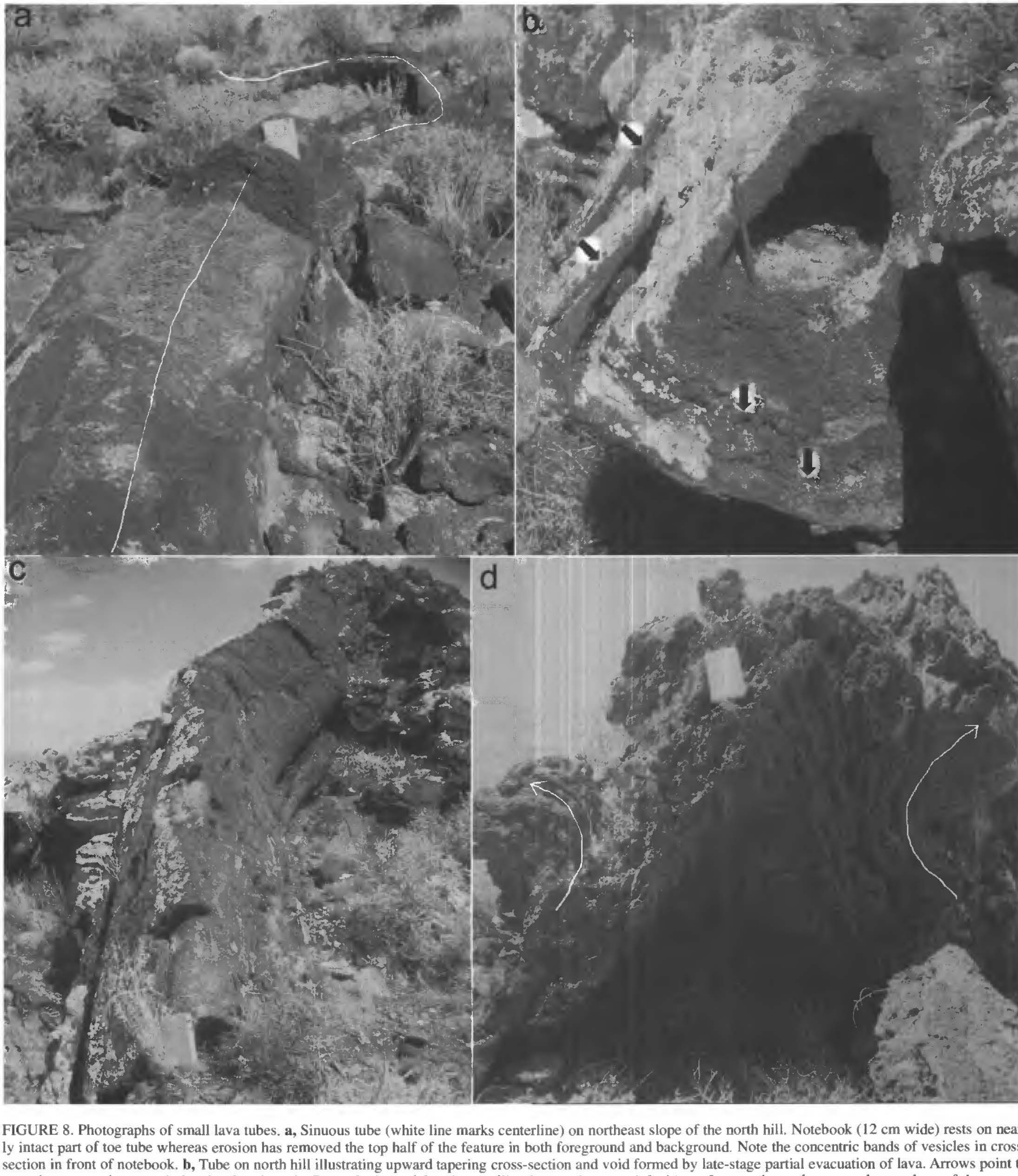


FIGURE 8. Photographs of small lava tubes. **a,** Sinuous tube (white line marks centerline) on northeast slope of the north hill. Notebook (12 cm wide) rests on nearly intact part of toe tube whereas erosion has removed the top half of the feature in both foreground and background. Note the concentric bands of vesicles in cross-section in front of notebook. **b,** Tube on north hill illustrating upward tapering cross-section and void formed by late-stage partial evacuation of lava. Arrows point to conspicuous semiconcentric bands of vesicles in floor of tube and forming spalling layers along the left side. **c,** Large tube on lower northwest slope of the central cone (notebook is 19 cm high). **d,** Transverse section through upslope end of large tube shown in (c). Tumbleweeds partly fill the triangular void formed by evacuation of lava. Note the many concentric bands of vesicles, the outermost of which (arrows) are overturned or appear to be partially spalled off of the outer surface of the tube, perhaps as it expanded at the surface of the flow.

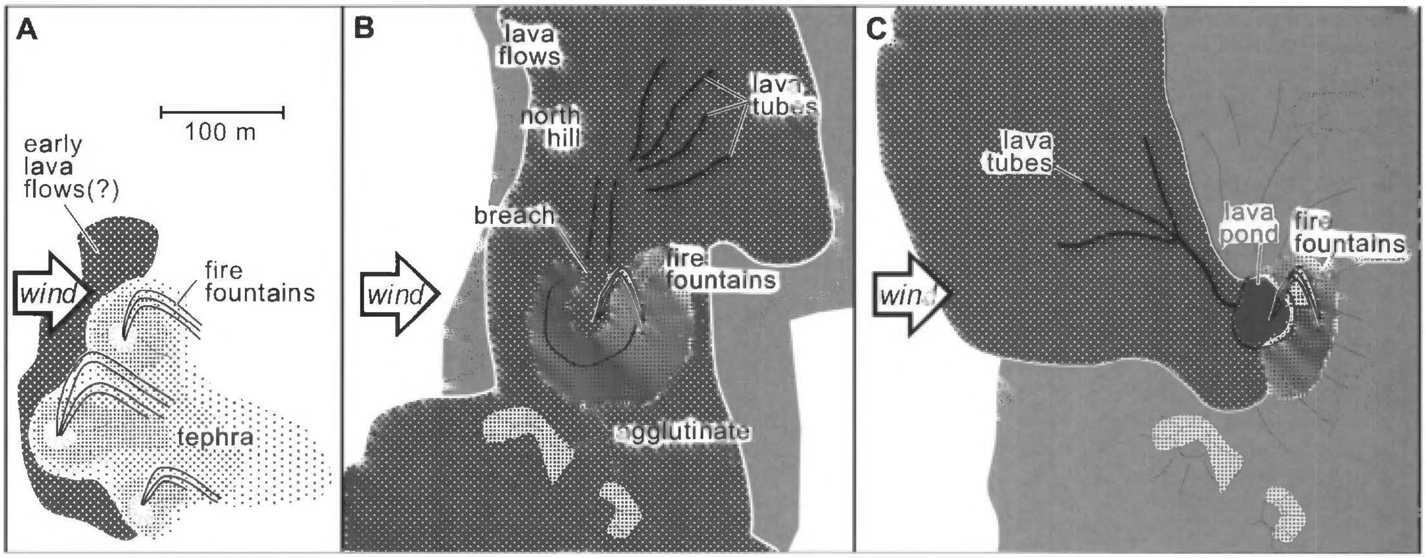


FIGURE 9 Schematic diagrams illustrating hypothesized development of Vulcan. **A,** Early, and likely simultaneous, fire fountaining from all three vents with the resulting tephra apron of variably welded pyroclasts extending farthest from the site of most vigorous fountaining at what was to become the southwest flank vent. **B,** Dominant, low fountaining constructs the central cone of agglutinate and clastogenic lava; lava flows from breach in north wall of crater to form north hill lava platform and, eventually, a semiradial system of toe tubes on the northeast slope. Lava was likely also extruded from the flank vents at this time, possibly accompanied by minor fountaining. **C,** Following closure of north breach, lava ponds in crater and spills over westward and northwestward crater rim, while low fountains built up higher rim of agglutinate on east side. Most overflow occurred through a distributary tube system to build a lava platform toward the northwest, adjacent to previously emplaced north hill flows.

er flank vent but represents a constructional landform at the proximal end of the lava-distribution system. A breach in the north side of the central cone may have caused preferential outflow of lava to the north (Fig. 9b).

We interpret the north hill as a lava platform produced by three stages of fountain-fed-lava drainage through a breach in the central cone. First, thin, shelly pahoehoe sheets, visible at the base of the excavation (Fig. 6a), formed a broad, low relief bench extending toward the north and northeast and, to a lesser extent, toward the east. In the second stage, perhaps associated with diminished discharge through the breach, lava was more generally focused in a single thread of flow, now represented by the thick lava in the center of the excavation. Lateral spreading of flows from this central part built most of the uppermost 8–10 m of the north hill (Fig. 6a). Because individual flow lobes did not extend very far, they built a platform with relatively steep distal slopes (Figs. 6a and 7). In the final stage, further outflows veneered the northwest flank of the hill and fed tubes that descended the regional gradient to the northeast and east (Figs. 7 and 9b).

We hypothesize that the lava pond in the central cone formed after closure of the breach that fed lava toward the north hill (Fig. 9c). The approximately located base of the ponded lava on the north side of the central cone is at the same elevation as the top of the north hill. Because the lava pond has a top surface at an elevation nearly 10 m higher than the north hill, a barrier along the north side of the central cone is required, evidence for which has perhaps been subsequently removed by quarrying. The coincidence in elevation between the base of the lava pond and the top of the north hill is consistent with a connection between the central cone and the north hill prior to the formation of the lava pond. The breach may have been closed by accumulation of spatter during a time of limited lava-flow transport through the gap, slumping of agglutinate from adjacent sectors of the cone, or blockage by lava-flow crust.

Following the closure of the north breach, lava ponded in the crater and overflow occurred principally toward the west and northwest (Fig. 9c). Formation of the lava pond was accompanied by low fountaining, with downwind dispersal of spatter principally to the south and east where agglutinate and clastogenic lava are interbedded with thin overflow lava. Most overflow, therefore, was more prevalent along the lower western rim, which had not been as substantially raised by accumulating spatter. Overflow was particularly focused at the northwestern part of the crater rim and formed a distributary tube system (Figs. 1 and 9c). This tube system is associated with a fan-shaped lava platform that continues northwestward as a 4–5-m-high ridge of lava extending more than 1.5 km from the base of the central cone (Figs. 1 and 2b). That this lava did not flow eastward toward the Rio Grande valley probably indicates that the north hill lava platform had already been constructed and prevented flow in that direction (Fig. 9c).

The broad shield form of the lower slope of Vulcan, apparent on all but the east side of the vent complex, represents the growth of lava platforms contemporaneously with the spatter and lava cones rather than being a feature upon which the cones were constructed. The shield form is mostly composed of the north hill lava platform and the lava platform and ridge extending northwestward from the central cone. Additional, smaller accumulations of lava produced a trilobate shield form adjacent to the southwest and south flank vents. Because the low-relief lava platforms and flow lobes comprising the broader shield are clearly traceable to the surfaces of the three vents, it is clear that the shield form evolved with the cones and did not form before them.

CONCLUSIONS

Field study of Vulcan reveals that small, monogenetic cones produced by Hawaiian-style eruptions can be characterized by remarkably diverse volcanic facies with complex inter-relationships. The dynamics of fire fountains (Head and Wilson, 1989) can account for simultaneous emplacement of diverse pyroclastic facies (including short-distance gradations from cinder, to spatter, to clastogenic lava) and accumulation of transient or long-lived lava ponds, which feed far-traveled lava flows either by overflowing the crater rim or exiting through breaches of the crater wall.

Facies distributions can be further complicated by the activity of more than one vent. Although the flank vents might as first be deemed inconsequential, because of their lower elevation and smaller diameter compared to the central cone, it is likely that the most energetic fire fountain activity accompanying the formation of the Vulcan center came not from the higher central cone but rather from the southwest flank vent.

The general shield shape of the lower slopes of Vulcan does not reflect a shield-volcano substructure but rather the formation of lava platforms and lobes adjacent to the vents. The most prominent part of the lava shield is a broad ridge extending northwestward from the central cone and which was clearly formed by overflow lava, partly fed by tubes, late in the history of the cone. The steeper north hill lava platform forms another segment of the shield and lobate flows from the flank vents form the southern part of the shield. The lack of a shield form on the east side of the vent complex is probably related to preferential flow in other directions because of higher rims of agglutinate on the eastern, downwind sides of the cones. That the flows on the surface of the shield can be traced to surface features at the vents clearly demonstrates that the shield and near-vent cones formed simultaneously.

The relationship between near-vent facies at Vulcan and the extensive inflated sheet flows that surround it, especially to the east, is not explicitly clear. The thin shelly pahoehoe flows surrounding the vents obscure this relationship. No classic lava-tube systems are apparent in the surrounding sheet flows, although tumuli are prominent northeast of the small tubes on north. Tubes may exist and not be visible, or the sheet flows may largely have been derived from other vents along the fissure north and south of Vulcan.

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Wolf Elston, Stu Northrop, Vin Kelley, and Ken Larsen take a break alongside the car caravan in the Sandia Mountains on Day 1 of the first Albuquerque country field conference in 1961 (photograph courtesy of Florence Wengerd).