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Abstract

Aden Crater lava field, encompassing 75 km² in south-central New Mexico, offers excellent examples of features of basalt flows associated with a shield volcano. Aerial images and recent field examination allow a re-evaluation of the lava field's surface features. Aden Crater sits atop the summit of the shield (referred to herein as the cone) which is surfaced by channeled lavas merging downslope into lobate lava flows. The cone and its adjacent flow field are divided into five facies. Extending away from the cone are several features associated with inflation and collapse processes, representing early-formed tumuli that did not develop as completely as those farther downslope.

Introduction

The Aden Crater lava field encompassing 75 km² in south-central New Mexico offers excellent examples of features of basalt flows associated with an Icelandic-type shield volcano. In this paper, we present interpretations of some of these features based on recently published work (Walker, 2009), new aerial images, and field examination of the flows conducted in 2012 and 2014. Specifically, we identify four flow facies that formed as a function of the rheology of lava during flow emplacement. We examine the mechanisms of pit formation on the flows, and revisit the relationship of pits to faults in the region.

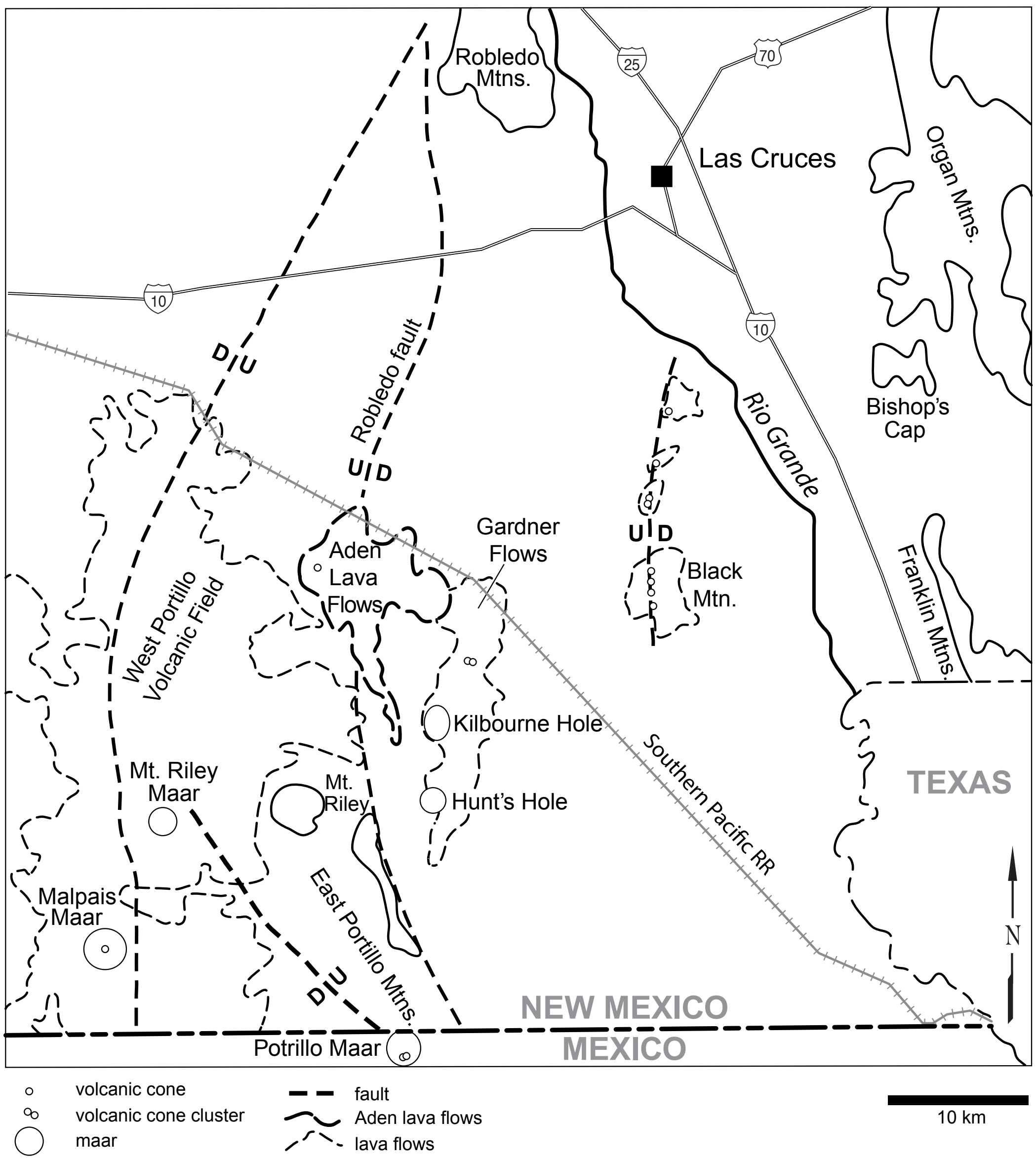

Figure 1. Location of Aden lava flows in south-central New Mexico. Cenozoic basaltic volcanic features in the area include cinder cones, maars, and the Aden shield.

Regional setting

Located approximately 40 km southwest of Las Cruces in Doña Ana County, New Mexico, Aden Crater and its associated flows are the youngest volcanic features in a diverse, monogenetic basalt field known as the Potrillo Volcanic Field (Fig. 1). The Potrillo Volcanic Field (PVF) occupies the southernmost part of the Rio Grande rift, where it merges with the New Mexico portion of the Basin and Range Province (Seager and Morgan, 1979). The PVF is included in the Organ Mountain-Desert Peaks National Monument established in 2014 and is accessible by unpaved county roads.

The Aden flows overlie the La Mesa geomorphic surface, with an age of ca. 0.6 Ma, which marks the aggradational top of ancestral Rio Grande deposits of the Camp Rice Formation and is characterized by well-developed aridisol soils with Cca/K horizons approximately 50–200 cm thick (Bulloch and Neher, 1980; Seager et al., 1984; Mack et al. 2006). The region is in the northern Chihuahuan desert and presently has an arid climate with a summer precipitation maximum. The native desert scrub vegetation includes creosote, mesquite and yucca as dominant species. Eolian sand deposits within topographic lows in and around the flows are commonly covered by buffalo gourd.

Dating of the Aden shield and flows is problematic. Seager et al. (1984) reported a K-Ar age from lava-lake basalt inside the Aden crater of 0.53 Ma, whereas ^{3}He surface-exposure dating has yielded ages ranging from 18.3–15.7 ka (Anthony and Poths, 1992) to 22 ka (Williams and Poths, 1994). We consider the younger ages more realistic based qualitatively on the degree of weathering of Aden volcanic features. For example, a spatter cone is present within the crater that retains delicate features and surface textures associated with accumulation of the ejected spatter, which might be expected to be considerably more weathered (both chemically and physically) if exposed to five full glacial episodes and extended periods of significantly cooler and wetter climate (e.g., Betancourt et al., 2001; Barbante et al., 2010).

Volcanic activity in the PVF covers 1,040 km^2 including the 1,800 m high Mt. Riley, which consists of a Tertiary rhyodacite stock, volcaniclastic sedimentary deposits and Quaternary basaltic volcanic rocks (Hoffer, 1976a). The western part of the PVF (West Potrillo Mountains) covers an area of 590 km^2. It includes more than 100 cinder cones averaging 60 to 150 m in height, with surface-exposure ages ranging from 80 to 17 ka (Anthony and Poths, 1992; Thompson et al., 2005). The basalt flows of Aden stand in sharp contrast to the cinder cones of the West Potrillo Mountains or the explosive activity that formed the maar craters to the south of Aden.

There are at least five maar-type craters in the PVF. Kilbourne Hole, Hunt's Hole, and the Potrillo maar lie on the east side of the field (De Hon 1965a, Reeves and De Hon, 1965, Hoffer, 2001, Padovani and Reid, 1989). Riley maar (Bersch, 1977) is located in the interior of the West Potrillo field, and the Malpais maar (Page, 1975), near the south end of the field, is almost completely buried beneath a 75-m-high cone that was built on its floor.

The Gardner craters complex is a cluster of cinder cones to the east-southeast of the Aden flows that is associated with the 80 km^2 Afton lava field that includes Kilbourne and Hunt's Holes and extends 4 km north and 13 km south of the Gardner cinder cones. The Afton basalt is partially obscured by eolian sand cover and low scrub brush. It is best exposed in its northern reaches near the Afton railroad crossing and in vertical sections up to 3 m thick in Kilbourne and Hunt's Holes. The Afton flows, dated at 72–81 Ka by K-Ar (Seager et al. 1984), are overlain by the Aden flows northwest of the Gardner cinder cones.

Additional cinder cones and associated flows are present in a north-south chain 25 km to the east of Aden (Fig. 1). The Santo Tomas-Black Mountain basalts were erupted from four centers. Six lava flows are present at Black Mountain, three at Santo Tomas, and one each at Little Black Mountain and San Miguel. The basalts are in the 69–77 Ka age range by K-Ar dating (Seager et al.,1984).

Structural setting

La Mesa is an aggraded surface of ancestral Rio Grande sediments that accumulated in the Mesilla Basin, one of several fault-bounded basins along the Rio Grande rift (Hawley, 1981). Except for faults related to uplift of the East Potrillo Mountains (Fig. 1), which exhibit visible scarps, faults on the La Mesa surface were originally inferred based in part on an apparent alignment of volcanic features (Kilburn et al., 1988). Fault traces are now documented using well-log analysis and geophysical methods (e.g., Seager et al. 1987). The Robledo—East Potrillo fault exhibits a 100 m down to the east offset and cuts across the La Mesa surface beneath the Aden basalts and extends to the vicinity of Potrillo maar. This range-bounding normal fault on the east side of the East Potrillo Mountains offsets pyroclastic surge deposits associated with the Potrillo maar (Seager and Mack, 1994). Alignment of 12 cinder cones in the Black Mountain-Santo Tomas chain and an 11 km-long series of depressions south of the volcanic chain coincide with a down to the east fault with approximately 170 m of offset in the subsurface (Seager and Mack, 1994). The alignment of various pits on the flanks of the Aden shield were presumed to be formed by venting along the trace of the Robledo fault beneath the flows (De Hon, 1965b: Hoffer, 1976a, b). It was also thought that the Gardner cone complex and Kilbourne and Hunt's Holes were aligned along the hypothetical Fitzgerald fault (De Hon, 1965a; Hoffer, 1976a, b). Subsurface evidence (Seager et al. 1987) and additional observations, developed in following sections in this paper, no longer support the existence of the Fitzgerald fault.

Aden cone

The Aden shield volcano (Figs. 1, 2) is a relatively young feature of the Portillo Volcanic Field. A nontechnical description of the Aden crater was published by Perkins (1949). De Hon (1965b) and Hoffer (1975a, 1990) also described the crater's features, and Kahn (1987) conducted a more extensive study. In this paper Aden "cone" is used refer to the summit area of the shield volcano, which includes Aden crater and the comparatively steep slopes surrounding the crater. The Aden cone is 2.5 km in diameter (Fig. 3) and rises 50 m above the surrounding landscape. Aden crater (unit cr of Fig. 3) is a broad, shallow depression, 350 m in diameter, on top of the cone. The crater rim consists of a steep pile of agglutinate, 2.5 to 3.5 m high, built of spatter from a lava lake that occupied the crater. Open tension fissures ring the crater floor inside the rim. A small 3 m high spatter cone near the center of the crater rises above the lake lavas, and a 120 m diameter, 20 m deep pit is present in the southern part of the crater.

Figure 2. The Aden shield viewed from the north. The gentle slopes lead up to a relatively steep rampart of spatter lava.

Figure 3. Annotated aerial photograph of a portion of the Aden basalt field. The topographically high summit of the shield referred to herein as the Aden cone is built on a basal unit of scabby lava flows (unit sc). The lower flanks of the cone consist of a lobate flow (unit lo), upper channeled flows (unit ch), and the broad, apical crater (unit cr). The early scabby flows were thin fluid flows. Several features are present approximately midway downslope on the scabby flows that represent local tumescence on thin-skinned flow material—including collapse pits (unit cp), rootless shields (unit rs), and blocky rimmed pits (unit br). The bulk of the lava field beyond the cone is shown here as inflated flows (unit if). Inflation pits (unit ip) are present on inflated flows. North is toward the top of the photo; UTM coordinates for the center of the crater are: 305707E, 3549925N, zone 13 (horizontal datum NAD83).

Guano mining from a fumarole on the southeast rim uncovered a well-preserved skeleton of an extinct giant ground sloth, with two associated radiocarbon ages of 9,840 ±160 and 11,080 ±200 BP (Lull, 1929; Simons and Alexander, 1964). The fumarole is approximately 5 ft. (1.5 m) in diameter at the surface and descends vertically for 65 ft. (19.8 m) before becoming an inclined tube extending 80 ft. (24.4 m) to the chamber that contained the guano and sloth remains.

The extent of the lava flows associated with the Aden shield were mapped by Seager et al. (1987). The Aden flows are alkaline olivine basalt and basanite (Kahn 1987; Hoffer, 2001). If the ^{3}He surface-exposure dating of Anthony and Poths (1992) is accurate, the Aden flows at 18.2–15.7 Ka are the youngest in the PVF.

Updated interpretation of flows and features

We have divided the Aden cone and associated proximal flows into three facies (units ch, lo, and sc in Fig. 3) based on surface physiography and mode of emplacement. The cone consists of an upper channeled flow facies (unit ch) that passes downslope into a lobate flow facies (unit lo). The channeled flow facies was formed by lavas spilling over the crater rim from the lava lake; it consists of levied lava channels and lava tubes 0.5–1.5 m wide on slopes of 8 to 15 percent (4.6 to 8.5 degrees). The channels branch in a distributary pattern downslope. The breaching of lava levies to form distributary channels is responsible for the horseshoe-shaped lava ridges, *herradura,* described by Hoffer (1971). Flows emerging from the channels spread as overlapping lobate flows as the slopes decrease to 3–5 percent (1.7–2.9 degrees) at lower elevations. The lobate flows (unit lo) overlie thin flows on the outer flanks that are characterized by a scabby flow facies (unit sc) consisting of intercalated, thin, pahoehoe flows with local micro-relief of 0.5 m that makes up the base of the cone. The scabby flow facies represents the first, very fluid flows that issued from the vent. As lava spread away from the vent, it cooled, viscosity increased, and the flows thickened by inflation. In the distal flow field, individual flows exhibit varying degrees of inflation (unit if in Fig. 3).

Flow field

The thin flows at lower elevations (units sc and if, Fig. 3) are partially obscured by an eolian sand cover, scrub vegetation, and grasses. The higher elevations are generally free of cover and much fresher in appearance. Depressions in the flows and swales between adjacent flow margins are generally floored by sand which supports a hardy growth of buffalo gourd.

Figure 4. Inflation pits (ip) are formed where thin flows surrounded local rises on the pre-flow surface. The flows inflated around the rise leaving a depression. The thickest flows form flat-topped, inflation plateaus (if), which develop peripheral fissures (pf) and steep flow margins. Less inflated flows form pressure ridges and flat-topped plateaus with rounded margins. The surface of the inflated flows have rectilinear joint sets with 5–10 m spacing. North is toward the top of the photo; area shown is located in the distal flow field, 3.5 km east of the center of the crater.

The Aden flow field consists of relatively thick, flat-surfaced flows intermingled with thinner flows. The thicker flows form by the process of inflation as described by Walker (1991, 2009) in Hawaii. Inflation occurs when fluid lavas begin to develop a brittle crust underlain by a ductile core. Once the crust becomes thick enough at the flow front to impede the flow, the fluid interior begins to exert pressure, which lifts the upper surface to produce tumuli and inflation plateaus (Walker, 1991, 2009; Hon et al., 1994). Partially inflated flows with rounded margins are 1 to 3 m thick. As the crust strengthens further, flows form well-developed, flat-topped inflation plateaus with the greatest height and prominent peripheral fissures (Fig. 4).

Flat-surfaced uplifts formed by injection of lava under a surface crust have been termed "lava rises" by Walker (1991); inflated sheet lobes (Hon et al., 1994; Self et al., 1998); pressure plateaus (Wentworth and Macdonald, 1953): and inflation plateaus (Keszthelyi et al., 2004; Zimbelman et al., 2011). Fully formed inflation plateaus in the Aden field range from 100 to 300 m in width and 300 to 1,200 m in length, and reach a thickness of 4 to 5 m. The upper surfaces of the plateaus are level and cut by intersecting extension joints. The flow margin is steep, often blocky, and the edges of the inflation plateaus are marked by deep fissures. The bulk of the Aden flow field consists of the inflated flow facies (unit if in Fig. 3) which consists of overlapping flows displaying different degrees of inflation.

Pits

Various depressions associated with the Aden flows have been misinterpreted by earlier investigators (De Hon, 1965b; Hoffer, 1975b). Large, deep pits on the inflation plateaus were thought to be collapse depressions formed by withdrawal of underlying lava, and pits surrounded by raised blocky rims were thought to be explosion craters. Walker's (2009 and 1991) analysis of flow structures in Hawaii have provided analogs for the pits observed at Aden. Our re-examination of the pits on the Aden flow field recognizes four types—lava rise pits (Walker, 1991), also termed inflation pits (Scheidt et al., 2014) on the inflated plateaus, shallow collapse depressions, pits on rootless shields, and blocky rimmed depressions.

Inflated flows are pocked with large depressions ranging from 20 to 150 m across and 4 to 5 m deep. These *inflation pits* (unit ip on Figs. 3 and 4) formed in areas in which small rises in the underlying land

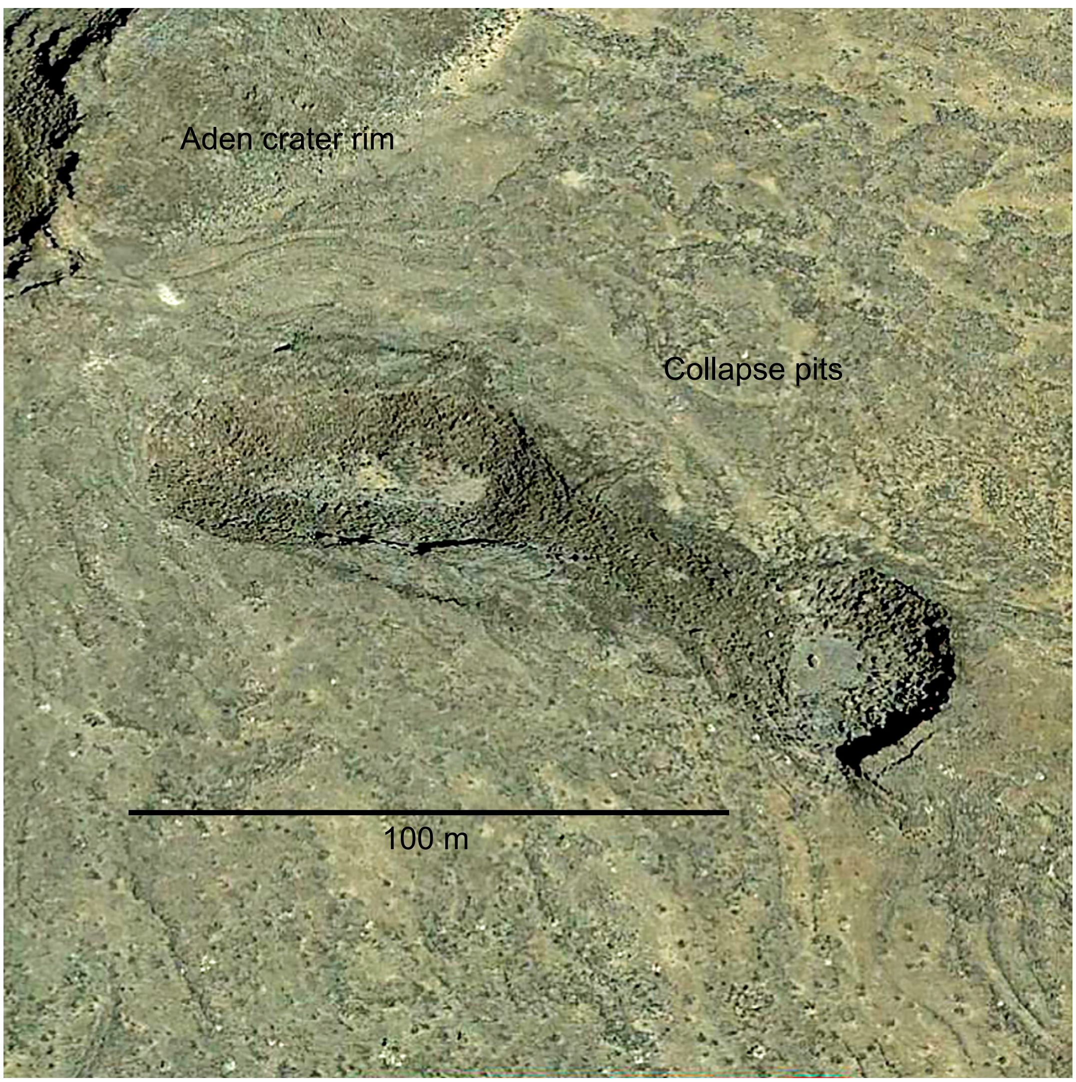

Figure 5. Collapse pits on SE flank of the Aden cone (see Fig. 3), formed by removal of lava from beneath a weak surface crust. The resulting pits are rimless and have blocky interiors.

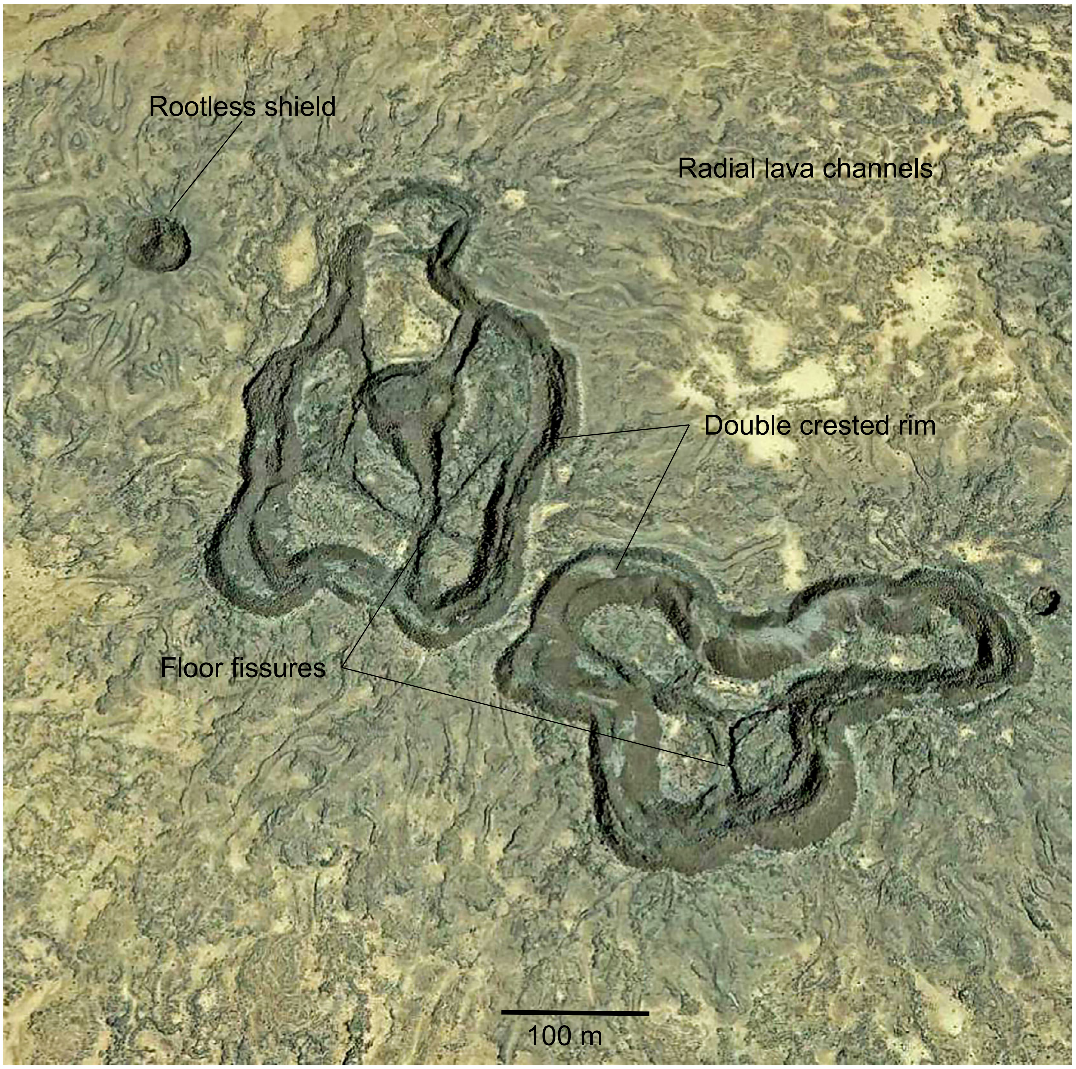

Figure 6. The scabby flow facies contains several morphologies that represent failed attempts to inflate, including rootless shields and blocky rimmed pits. Blocky rimmed depressions are irregular in plan view and represent collapsed inflation plateaus. The raised double-crested rims are split by a medial trough, and the interior "floor" is crossed by large fissures. Lava channels radiate away from the failed plateau. North is toward the top of the photo; area shown is one km southeast of the crater in Fig. 3.

surface were not covered by active flows. After a flow stopped advancing, it inflated around these patches, creating depressions on the inflated flow surface that are as deep as the flow is thick. The depressions are floored with either pre-basalt Camp Rice Formation, or thin earlier flows.

Simple *collapse pits* (unit cp on Fig. 3) result from removal of lava beneath a thin, solidified crust. The crust was too thin to support itself once the mobile interior flowed away, and collapsed, forming the depression. The resulting collapse pit is lined with broken fragments of lava crust. Two collapse depressions occur on the upper flanks of the cone (Figs. 3 and 5). One is an oval measuring 70 by 30 m, and the other is circular and 35 m in diameter. A 10 m wide and 45 m long shallow trough connects the two depressions.

Two hundred and thirty meters downslope from the collapse pits is a well-defined *rootless shield* (unit rs on Fig. 3; also see Fig. 6). As observed in lava flows in Hawaii, a rootless shield is formed by a tumulus on the flow surface that lifts the semi-hardened crust into a dome that rises above the surrounding flow (Patrick and Orr, 2012). Fractures in the domed crust allows interior lava to escape and flow away in all directions forming a radial pattern of lava channels. Rootless shields at Aden rise a few meters above the surface. Their central pits range from 3 to 10 meters in diameter and 1 to 3 m deep. Rootless shields are found at several places in the scabby flow facies (Fig. 3).

Six *blocky rimmed pits* are the largest of the pits on the flanks of the cone (unit br on Fig. 3). They generally range from 60 m to 250 m across, and the largest is elongate and 330 by 60 m across (Fig. 7). All blocky rimmed pits are located on the scabby flow unit. They are irregularly shaped in plan view and are surrounded by a raised rim of broken, blocky basalt (Fig. 6). The floor material on the interior is relatively smooth, and cut by large, intersecting fractures. The floor is approximately the same elevation as the flow surface outside the rims. The broken blocky rims exhibit a double crest with an intervening trough that occupies a similar position as the peripheral fractures observed on typical inflation plateaus (Fig. 4). Blocky rim materials overlie both smooth floor material and floor fractures (Fig. 8).

In much the same pattern as the rootless shields, lava channels are found draining away from the pit margins. Previously interpreted as explosion pits based on the presence of blocky raised rims (De Hon, 1965b; Hoffer, 1975b), these irregularly shaped pits are reinterpreted here as collapsed lava-rise tumuli (small inflation plateaus), which spilled lava to the surface at breakouts along their margins. Thus, the inflated flow surface of the plateau sank back to near-previous flow-surface level as lava spilled out of the interior. The blocky raised rims are simply fractured remnants of lava crust at the margins of the feature that could not support the incipient plateau after removal of the underlying lava (Fig. 9). It is also noted that the irregular shape of the rims of these features in plan view (Figs. 6 and 7) is inconsistent with the interpretation that they formed as explosion craters.

A blocky rimmed pit in an early stage of development is preserved near the terminus of the scabby flows (Fig. 7). Here, a partially collapsed inflation plateau displays a typical, steep, inflated flow front on its northwestern flank, but has collapsed on its southeastern margin. Hence, the originally horizontal, raised plateau surface is tilted and slopes to the southeast to terminate at a double-crested, blocky rim.

Discussion and conclusions

We identify five volcanic facies (Fig. 3, units cr, ch, lo, sc and if) on the Aden shield volcano based on surface physiography. The crater facies (unit cr) consist of several physiographic features including the spatter rim, lava lake basalts, rim fissures, spatter cone, inner crater, and fumaroles. The conical summit of the shield consists of channeled and lobate flow facies (units ch and lo), which are built on antecedent, thin, scabby lavas (unit sc). The flow field beyond the cone consists of thin scabby flows and thicker, inflated basalt flows (unit if). Age relations between the flow facies beyond the cone are not always clear, but in general, the scabby flows are the oldest flows on which the cone is built. The scabby flows near the cone exhibit failed attempts at inflation while the lava crust was still weak. This phase is marked by the rootless shields and blocky rimmed depressions. As the crust thickened tumuli and inflation plateaus developed in the distal flow field.

Pits on the flanks of the Aden cone are a continuum of landforms generated by similar processes as governed by the rheology of the lavas. Simple collapse pits form by collapse of thin, weak lava crust over voids created by removal of lava beneath the crust. Rootless shields

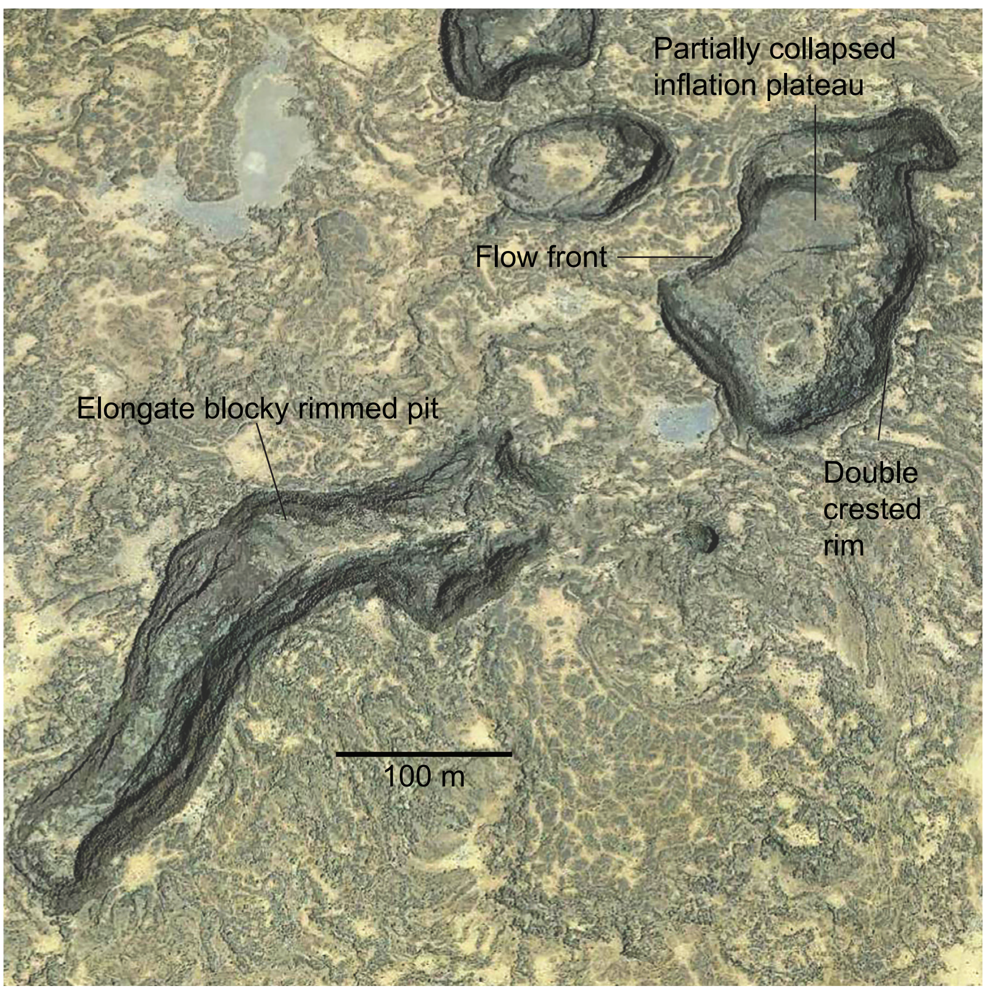

Figure 7. Aerial photograph of an elongate blocky rimmed pit and a partially collapsed inflation plateau (approximately 2 km E-NE of the Aden crater in Fig. 3) near the northern end of the scabby flow facies. The partially collapsed plateau exhibits features of both inflation plateaus and blocky rimmed pits. It is flanked on the west by a steep, blocky flow front, and on the east by a double-crested blocky rim. The interior is a comparatively smooth surface that slopes from the raised flow front to the raised blocky rim.

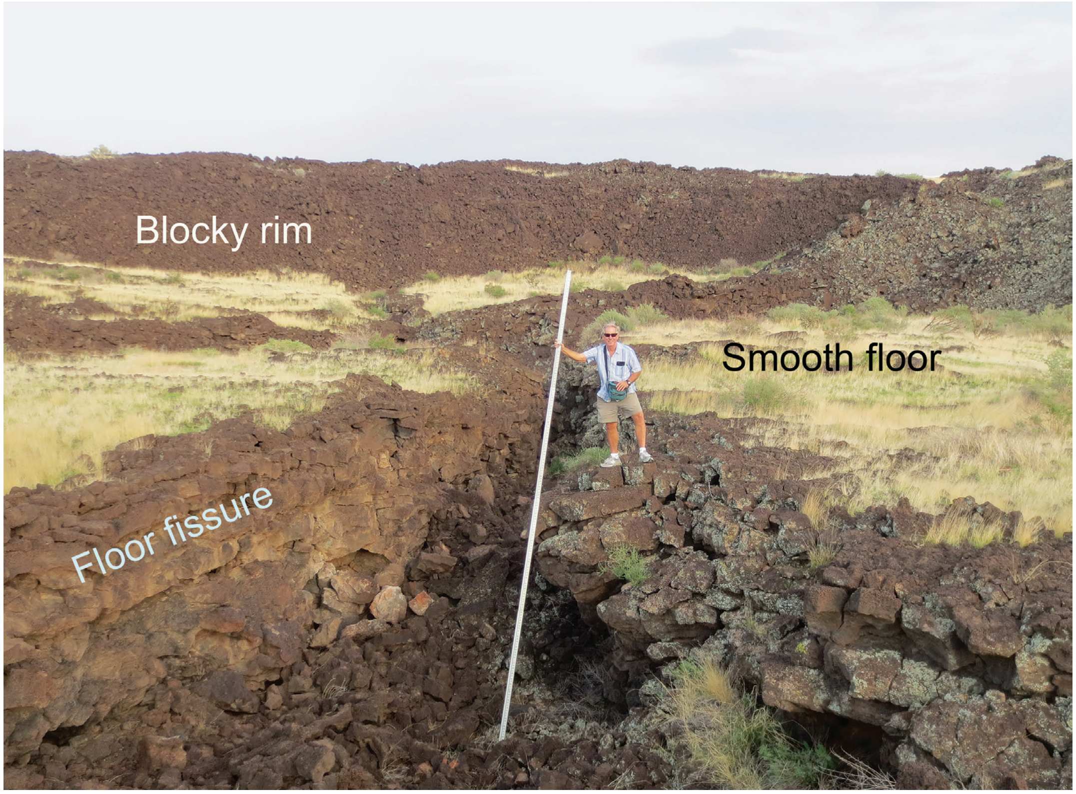

Figure 8. Photograph of a fissure on the floor of a blocky rimmed pit. The blocky rim material in the background overlies both the floor and the fissure. The blocky rim formed as solidified crust was stretched and broken during collapse of the incipient plateau surface.

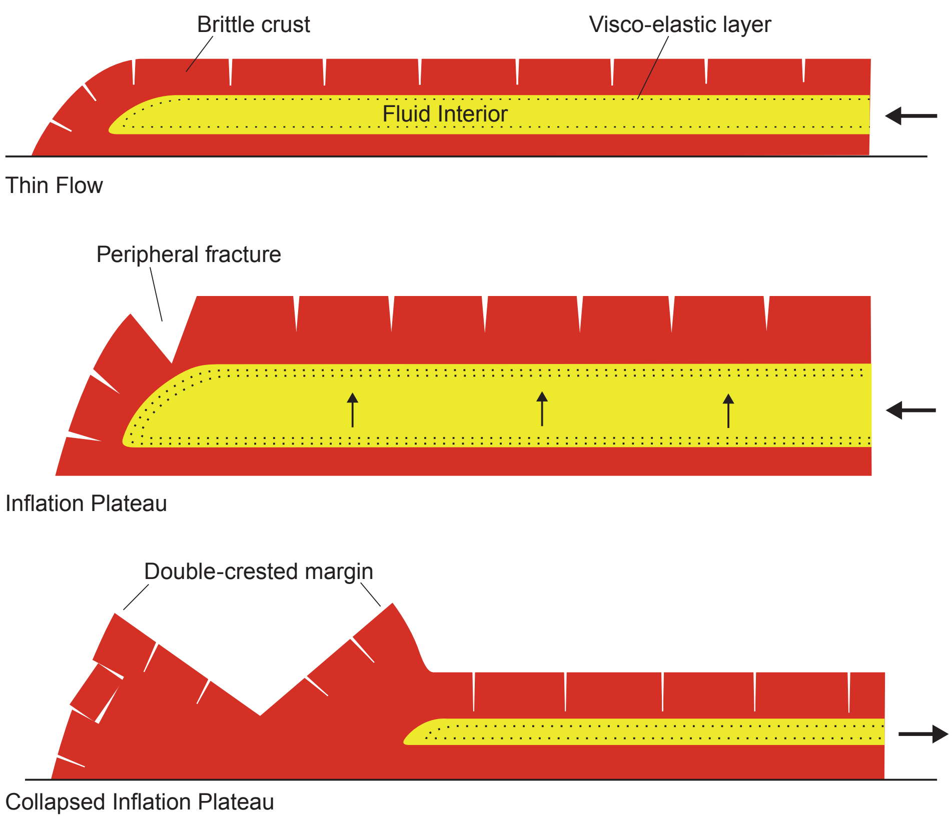

Figure 9. Cartoon of the formation of blocky rimmed pits. *Thin Flows* have a thin crust, an intermediate ductile layer, and a fluid interior. *Inflation Plateaus* form as the crust thickens, spreading is impeded, and internal pressure lifts the crust. Inflation plateaus exhibit deep fissures outlining the outer edge, and extensional jointing in the stretched upper surface. *Collapsed Plateaus* form when breakouts along the flow margins remove internal fluid lavas, allowing the plateau surface to sag back to pre-inflation levels. Brecciated lava crust forms a double-crested, blocky rim around the sunken interior.

form as crust strengthens and is pushed up into small tumuli on the surface of the flow. Breakouts of lava from the tumuli form radial lava channels. As stronger crusts develop, tumuli form small, flat-topped inflation plateaus. At some early formed plateaus, lava breakouts around the periphery cause the plateau to deflate and form blocky-rimmed depressions. Finally, lava crusts develop sufficient strength to retain lava infusions and to inflate to form large, high-standing lava plateaus. Inflation pits formed where lava inflated around subjacent rises in the pre-flow surface.

The alignment of pits on the south flank of the cone were previously assumed to be evidence of the trace of faults beneath the lava flows that served as conduits for eruptions to the surface (De Hon, 1965b; Hoffer, 1975b). The southeast trend of the pits was thought to be evidence of venting along the hypothetical Aden fault (Hoffer, 1976a). East of the cone, an apparent northeast trend of pits was thought to be evidence of venting along the Robledo fault trend. Our current analysis does not require active volcanic venting at the sites of the pits. Indeed, the pits are explained by processes that commonly occur within actively flowing lava.

The earliest flows from the Aden vent were controlled by existing topography, and spread eastward and in a narrow stream southward. As the flows spread away from the source their surface crust thickened, breached tumuli formed rootless shields and failed inflation plateaus (blocky-rimmed depressions). As these flows developed a more resistant surface crust they were able to build increasingly more substantial inflation plateaus, and ultimately accumulations of slightly more viscous lavas built the Aden cone.

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