



Natural scoria cone half-section, East Grants Ridge: A test of basalt pyroclastic eruption models

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NATURAL SCORIA CONE HALF-SECTION, EAST GRANTS RIDGE: A TEST OF BASALT PYROCLASTIC ERUPTION MODELS

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ABSTRACT.—The half-sectioned scoria cone exposed on the East Grants Ridge is an exceptional exposure because it preserves the details of the relationship between the near-surface and interior structure of a scoria cone and its surrounding field of basalt. A geometric reconstruction based on observations of the surface geology and exposures within the natural cross-section, together with assumptions based on current knowledge of dynamics of scoria cone formation show that the East Grants Ridge scoria cone was a moderately large, fully-developed scoria cone that developed a deep basaltic lava pond now preserved as a columnar-jointed mass of basalt near the center of the section. The lava pond occupying the center of the section in turn fed a flow, which breached the north rim of the cone and flowed northward and mostly westward and now caps the West Grants Ridge. The concept of a lava pond is a departure from many previous interpretations that consider massive “plugs” to be near-surface reservoirs or widened dikes, or dike sheets. More importantly, many of the observed characteristics within the section agree with predictions of current scoria cone emplacement theory that have otherwise been difficult to test in the absence of a perfectly half-sectioned cone.

INTRODUCTION

This study briefly examines the physical structure of one example of the dissected scoria cones of the Mount Taylor volcanic field, the half-sectioned cone within the East Grants Ridge (EGR) (Fig. 1), also known as “the Plug.” The purpose is to demonstrate the wealth of volcanological information that may be gleaned from a simple examination of these types of exposures and to perform a simple test of predictions made from current theories of scoria cone emplacement processes using geometric reconstructions of cone internal structure.

Scoria cones are the most common type of volcano on Earth (Wood, 1980a, 1980b; Scarth, 1994). Despite their abundance, the internal structure of scoria cones is not well studied and the details of their emplacement and evolution, and details of the general dynamics and internal structural complexity are poorly documented. The volcanic necks and partially dissected volcanoes within the upper drainage basins of the Rio Puerco, Arroyo Chico, and Rio San Jose (Johnson, 1907; Hallett, 1992; Hunt, 1938) surrounding the Mount Taylor volcanic field (Crumpler, 1980, 1982; Hunt, 1938, Lipman and Moench, 1972; Perry et al., 1991) rank as exceptional resources for addressing these questions. Given the abundance of exposures represented by the half-sectioned cones and volcanic necks of the Mount Taylor field, numerous insights into the structure and morphology of small volcanoes are possible based on a combination of relatively basic observations and an appreciation of scoria cone emplacement dynamics.

PREVIOUS STUDIES

Early exploration of the Mount Taylor region noted that the volcanic necks and dissected cones surrounding the field were remarkable examples of eroded small volcanoes (Dutton, 1885; Johnson, 1907; Hunt, 1938). These early reports helped spawn several studies of the magma ascent process related to the formation of volcanic necks in general (McBirney, 1959). The significance of the EGR exposure was first noted in Dutton (1885) where it appeared as one of the figures with a description. Brief discus-

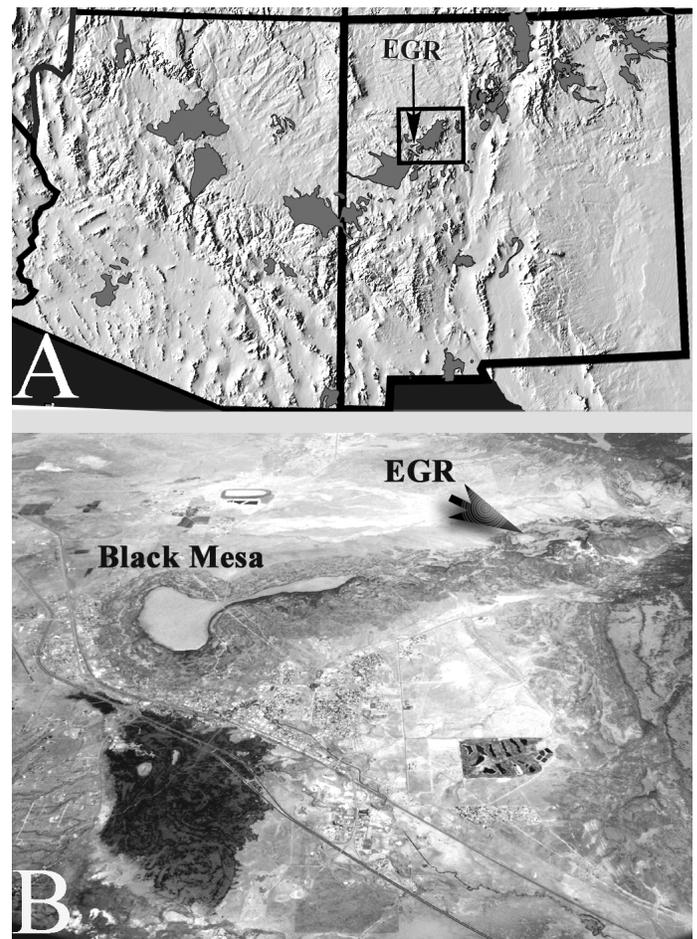


FIGURE 1. A. Location of the East Grants Ridge and the Mount Taylor field with respect to the late Cenozoic volcanic rocks of New Mexico and Arizona. B. Oblique air photo of the east Grants Ridge. The bilateral symmetric plan shape of Black Mesa (also known as the West Grants Ridge) is notable. Dark lava flow in the lower left is the Zuni Canyon flow. North-directed view from approximately 7000 m.

sions of the EGR scoria cone have appeared in several previous studies. The general geology of the EGR was outlined from a master's thesis study (Johnson, 1953) and additional studies examined the petrology and age of the basalts (Basset et al., 1963; Kerr and Wilcox, 1963; Thaden, et al., 1967). More recently, studies have focused on the characteristics of thermal alteration of surrounding rhyolitic tuffs and sediments by the central, columnar-jointed basaltic mass (WoldeGabriel et al., 1999) or the topaz rhyolite (Christiansen et al., 1983) and its surrounding tuffs (Keating and Valentine, 1998). A salient characteristic of these studies is that they have been largely directed towards an assessment of either the overall geology of the EGR, or the underlying rhyolite tuffs and the adjacent topaz rhyolite dome. Oddly, a detailed evaluation of the half-sectioned cone in the light of emerging principals of physical volcanology has not been done.

This study of the EGR scoria cone exposure relates to the broader question of scoria cone emplacement and the details of the eruption processes. Previous research on scoria cones has assessed their morphology (Wood, 1980a) and degradational evolution (Hooper and Sheridan, 1998; Wells et al., 1990), their distribution (Hasenaka and Carmichael, 1985; Connor, 1990), their eruption characteristics (Foshag and Gonzalez, 1956; McGetchin, et al., 1974), and relationship of eruption characteristics to final structure (Gutman, 1979; Head and Wilson, 1989). Direct observations of the shallow vent structure, relationship of cone interiors to cone flank characteristics and lava flows, and general details of their internal complexity (Crumpler and Aubele, 1977; Crumpler et al., 1994, fig. 14) are few. More importantly, several predictions about cone structure have been made from theoretical studies and based on expansion from observed eruption parameters of Hawaiian eruptions and historically active basaltic vents (Head and Wilson, 1989). The EGR section represents an opportunity to directly examine the connection between the vent characteristics and the internal structure of a scoria cone and between observed structure of volcanic necks and the surface structure of scoria cones.

This study picks up where studies during the early part of the 20th century left off, when interest in volcano structure and morphology was high, and when several investigations of volcanic necks were initially made. And it tests some of the concepts of scoria cone formation processes that have developed in the intervening decades.

PLANIMETRIC GEOLOGIC RELATIONS

The EGR has been mapped at several scales and with varying detail in several previous studies of the Grants region (Johnson, 1953; Thaden, et al., 1967). Figure 2 is a simplified planimetric sketch map on a digital shaded relief base that outlines the principal characteristics of the surface geology, which is similar to that associated with individual cones throughout the field. The central cone is denuded to the point where exposures of inward-dipping pyroclastic layers consisting of ash, spatter, and agglomerate are arrayed around the margins of the former crater and underlain on the north by a thick basaltic lava that flowed north and then spread west down the local gradient and partially to the east towards the saddle with the pre-existing EGR rhyolite dome.

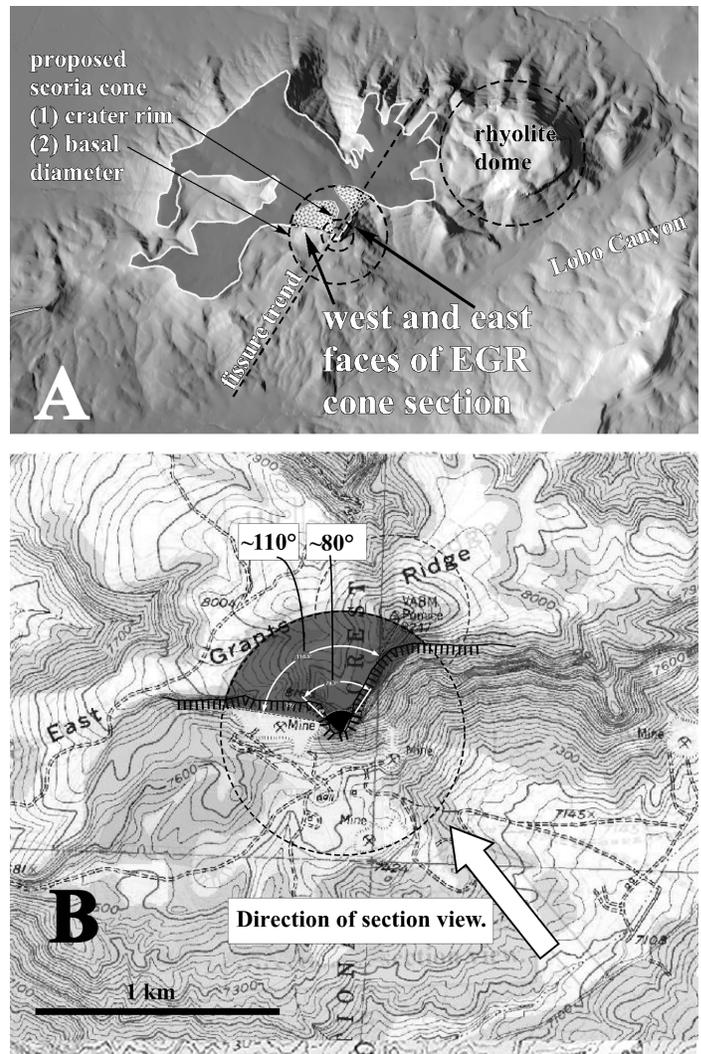


FIGURE 2. Summary sketch maps of the principal geologic relationships in planimetric view, extent of erupted basalts of the East Grants Ridge, the proposed extent of the original scoria cone, and the proposed summit crater dimensions. Approximately three-quarters of the East Grants Ridge half-sectioned scoria cone (gray shaded partial circle) has been removed through back wasting of the mesa margins on the south and northeast flanks of the original cone. The remaining section is distributed over 110° of arc about the vent region and the central columnar basalt mass. A. Sketch geologic map overlay on shaded digital elevation model. B. Contour map of the East Grants Ridge showing the orientation of the geologic section lines and the approximate basal diameter of the mapped scoria cone (shaded area). Additional pyroclastic deposits are associated with a scoria cone to the immediate northeast (dashed circle segment, not shaded).

The flows that spread westward account for the mesa-capping flows constituting the West Grants ridge, or Black Mesa, near the town of Grants. The planimetric symmetry of Black Mesa is distinctive and is one of the more notable landforms visible in satellite images and air photos of the southern Mount Taylor field. At a point 9 km N105°W the flows appear to have fanned out, either as a result of emergence from a confined drainage or

valley, or as a result of an abrupt decrease in gradient existing at the time of eruption, possibly as a result of entering the valley of an ancestral Rio San Jose

Where the flow emerges from the vent and flowed northward a short distance before diverting westward, it is sectioned along the east flank of the half-section line. Many authors have speculated on the precise details of the connection between scoria cones and the associated lava flows. The connection between the flows and the vent are continuously exposed in the EGR.

GEOMETRY OF THE SECTION

The EGR cone is exposed on the margins of a mesa with irregular margins. Therefore the section is not a simple half-section, and the orientations of the bends in section (Fig. 2b) must be taken into account in order to understand the vertical exposures in the context of scoria cone structure. The layered pyroclastic deposits constituting the flanks of the EGR cone are half-sectioned with a "bend in section" of approximately 110° about a point 10 m north of the vent centerline. (Evidence for the vent centerline will be described below.) The two section lines are oriented $N33^\circ E$ and $N81^\circ W$.

The central columnar-jointed basalt is a rounded, nearly quarter section. The orientation of the section for the columnar basalt differs from that of the cone flanks and is $N33^\circ E$ and $N46^\circ W$. The columnar-jointed basalt therefore protrudes from the cone section plane by at least 10 m. But for purposes of simplification of geometric analysis, in the following a single bend in section of approximately 110° about the vent centerline will be assumed.

The orientation of the sections must also be considered in relation to the orientation of the regional trend of fissure lines within the Mount Taylor field. For example, fissure trends within the adjacent Horace Mesa are $N33^\circ E$, which is typical of the orientations throughout the field (Crumpler, 1980). A fissure line with this orientation passing through the apparent vent centerline is therefore parallel with the section line on the northeast side of the section, implying that the northeast side of the section represents a vertical exposure close to the plane of the initiating fissure.

DESCRIPTION OF THE GEOLOGIC SECTION

Three types of dissected cone morphology may be defined within the Mount Taylor field (Fig. 3): (1) surface dissected, (2) margin back wasted, and (3) denuded. Type 1 includes older cones within the main field that have undergone erosion and stripping of loose scoria, revealing the core and flank structure. Several examples of type 2 occur around the margins of the field, including Mesa Chivato (Crumpler, 1980) north of the Mount Taylor composite volcano (Crumpler, 1982, 1990; Perry et al., 1991; Hunt, 1938; Lipman et al., 1979) where the relationship between the denuded interior, including an exposed interior of columnar-jointed basalt, and the surface characteristic of the cone are exposed on the margins of the plateau. In some examples the cone is almost completely separated from the dense columnar basalt that commonly occupies the interiors, and in others the margins of the cone are only partially back wasted on their distal

margins. Type 3 is the basic volcanic neck where most of the surface cone is removed and the interior residual mass is the only remaining component. Even in the absence of a columnar basalt unit, the relative resistance of the central core is derived from the more indurated interior conduit and proximal vent portions of the original cones, or may represent a central lava lake or dike-indurated vent breccia filling the former crater and vent pathways. There are examples that also represent gradations between two of these three basic types. In addition, many necks consist of exposures of abundant accidental materials and non-juvenile breccias, or mixtures of the two, implying initial phreatomagmatic activity and significant late tuff-breccia crater in-fill development in lieu of columnar-jointed basalt.

The EGR is an example of type 2. Because most of the cones within the field are old enough to have undergone type 1 exposure, type 2 may contain elements all three types, and therefore offers the greatest opportunity to explore the relationship between surface expressions of scoria cones and the near-surface interiors.

The EGR section (Fig. 4) exposes both the flanks of the original cone, the central crater, filled with columnar-jointed basalt, and the underlying tuffs erupted earlier from the EGR rhyolite dome. The nearly horizontal surface of the underlying tuffs conveniently provided a flat surface on which the cone was erupted and yields a geometrically simple base for the reconstruction and analysis that follows. The great contrast in color between the nearly white rhyolite tuff and the overlying black basaltic cinder further provides a convenient, "photogenic", and readily visible and map-

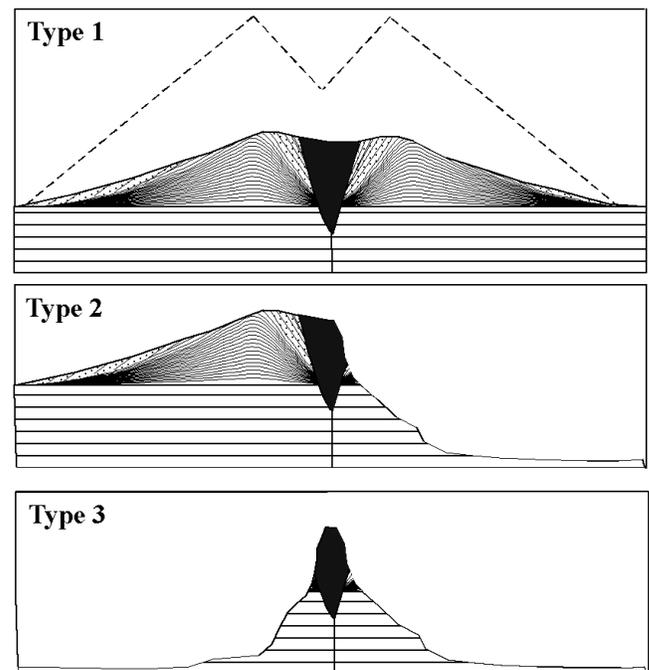


FIGURE 3. The three types of dissected cone morphology outlined in this study: (1) surface dissected, (2) margin back wasted, and (3) denuded. The East Grant Ridge section is an example of type 2 and preserves the relationship between the scoria cone and the shallow interior.

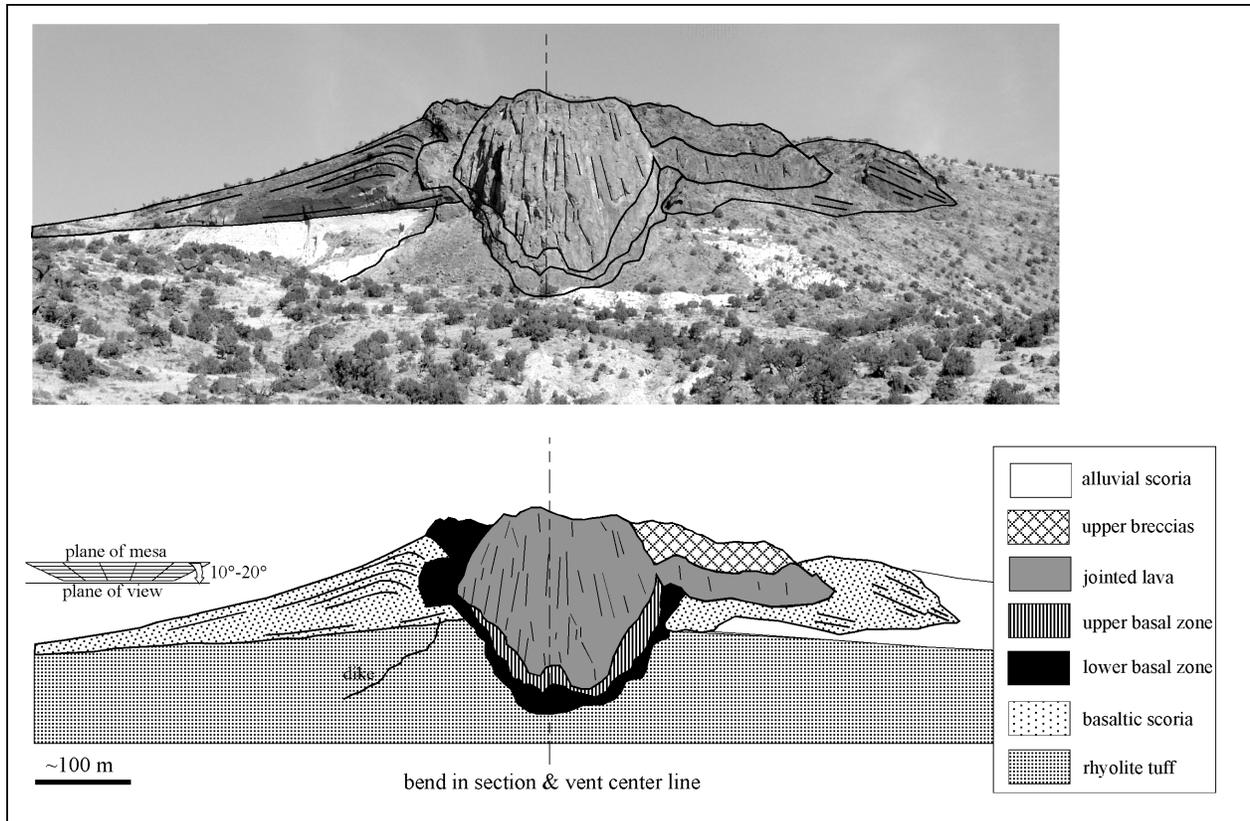


FIGURE 4. Geologic sketch map of the half-section. The central “plug” of columnar basalt narrows to less than 2 meters in width near the base of the section. Most of the scoria cone layering on the south (left) side is consistent with ballistically emplaced pyroclasts. A thick mass of basalt on the right connects the plug to surrounding lava flows that lie outside of the section plane behind the section.

pable demarcation. The section may be discussed in terms of the cone flanks, the structure of the columnar-jointed basalt, and the underlying tuffs.

The western half of the exposed section is a “textbook” exposure of the accumulation profile for near-vent scoria in a cone. This half of the exposed section also preserves a section of the cone flanks from distal margins, where it is overlain by late-erupted basalt, to the interior of the cone where it abuts the central columnar-jointed basalt and preserves the crater structure. Pyroclasts are dominantly within the size range of ash, cinder, and lapilli throughout most of the cone section. The pyroclastic bedding planes within the distal cone, delineated by variations in pyroclast size distribution and local calcareous deposits along bedding planes, dip uniformly outward, gradually steepening and thickening toward the vent to a rounded hump approximately 100 m thick. Bedding planes then roll over to inward-dipping orientations within the last 120 m of the vent centerline. A few bombs, many bipolar fusiform, and local rootless flows or spatter layers may be distinguished on the outward-dipping bedding planes, but are more frequent within the proximal cone section, particularly in the upper sections where bedding planes dip inward toward the vent region.

A small section of the proximal and distal flanks is present on the distal northeastern section where scoria bedding planes dip uniformly northeastward away from the vent centerline. Near the vent region, the cone section is interrupted by unconformable

contact with a thick mass of basalt. The basalt continues uninterrupted to its connection with the central columnar-jointed basalt. This section is interpreted to preserve the path of a basalt flow where it emerged from the vent and flowed northward over pre-existing lower portions of the cone, most likely in a deep breach or channel on the north flank of the cone.

Immediately adjacent to the central columnar-jointed basalt mass, and at the base of the thick proximal basalt section where it connects with the central columnar-jointed basalt (Fig. 5), there is a small section of outward-dipping scoria that is interpreted to represent the lower section of the near-vent crater rim. Pyroclasts in this proximal area, which represent the earliest phases of cone-construction, are dominantly ash, cinder, and lapilli-size materials, similar to that seen in the western half of the distal flanks, and there is a relative paucity of bombs, blocks, and spatter. The inward-dipping portion of the cone section, that is well preserved on the western part of the cone section, here appears to have been replaced as the crater was breached during extrusion of the overlying basalt.

The central columnar-jointed basalt preserves some of the more unusual exposures and relations with the cone. From a distance the central columnar-jointed basalt appears to be a uniform mass that descends vertically into the underlying tuff. Examination of the base of the columnar-jointed basalt shows that the contact is visible and that the columnar basalt rests on a surface that is excavated into the underlying tuffs to a depth of as much as 80 meters

below the base of the cone. A nearly complete view of the geometry of the contact may be seen from the south side of the columnar-jointed basalt (Fig. 5). Here the contact between the columnar-jointed basalt descends from a contact with the crater wall within the scoria of the cone, and into the underlying substrate rhyolite tuffs. The contact decreases in dip along a cone-shaped or parabolic curve from nearly 60° within the cone to less than 10 degrees near the base of the columnar-jointed basalt. This is interpreted as an exposure of the crater floor in which the contact between the base of the columnar-jointed basalt and the underlying substrate closely follows the top of the talus slope, undulates in and out of cover, but is otherwise completely traceable around the base of the columnar-jointed basalt. At the lowest elevation of the columnar-jointed basalt exposure, the horizontal separation between exposures of the substrate is less than 2 m, implying that the feeding conduit for the volcano is less than two meters wide at this point or that the actual feeder lies further south and is covered by the surrounding talus. A two-meter or less width for a feeding conduit is entirely within the range predicted by various studies (e.g., Head and Wilson, 1987) for dikes feeding individual vents and is in agreement with observations regarding the width of dikes beneath volcanic necks in general (e.g., Hallett et al., 1999).

Within 2 to 3 m of the contact with the substrate the outcrop texture and jointing differs from that within the rest of the columnar-jointed basalt and may be mapped as a relatively uniform unit. In detail the basalt within the contact unit appears poorly jointed and relatively “knobby” or lumpy. Where the columnar-jointed basalt contacts the crater walls within the scoria cone, the basalt zone is a uniform thickness upturned slab. Locally a few large rounded blocks of scoria may be identified within the mass of the enclosing basalt. But considering the proximity to base of the basalt mass and location in a near-vent environment, particularly if this represents the crater floor, there is relatively little in the way of accidental material, including fragments of the surrounding tuff. Rather than being a breccia, the basal zone appears to be a boundary layer across which the columnar-jointed basalt is texturally. Immediately overlying this basalt contact zone, there is another zone of similar thickness that appears less convoluted in texture, yet does not preserve the same massive jointing evident throughout the rest of the columnar-jointed basalt. Many columnar joints terminate at the top of this layer, which appears to represent a transition from the contorted characteristic of the basal zone and the more massive, jointed characteristics of the main mass of the basalt. The nature of these basal zones is unclear, but could represent either a thermal boundary layer decoupled from the central mass of the columnar-jointed basalt by mixing within an original lava pond, inflow of cooler lava or crater wall debris from the surface of the pond down the crater walls and along the crater floor, or an accretion zone where basalt was cooled during emplacement and thermally detached from the main mass of the columnar-jointed basalt.

Columnar joints (Fig. 5) are oriented similarly to that seen in many of the freestanding volcanic necks elsewhere within the field. The longest and most vertical columns characterize the central face of the exposure of columnar-jointed basalt. Near the upper sides of the columnar-jointed basalt, the joints are shorter and generally oriented at angles that are oblique with

respect to the horizontal. This pattern has been noted before in many of the more massive volcanic necks (Johnson, 1907; Hunt, 1938) and has been interpreted by Williams (1936), and more recently in studies of columnar jointing in general, as reflecting the orientation of conductive thermal flux lines in relation to the contacts with country rock (DeGraff et al., 1989). The rotation of columnar joint orientations from vertical to nearly horizontal was proposed to reflect the shape of the confining walls of a shallow reservoir (McBirney, 1959; Williams, 1936). In many of these studies the presence of a thick mass of basalt is generally interpreted as a shallow reservoir beneath the edifice. The significance of the observations of columnar joint orientations at EGR is that the crater wall is directly visible and the principal thermal loss directions can be determined from observation directly and compared with the orientation of joints.

There are several small details that demonstrate that other related processes must have occurred during the emplacement of the columnar-jointed basalt. For example, a thin (0.5 m), horizontal layer of basalt extends outward into the layering within the scoria from the margins of the thin upturned slab within the crater wall portion of the scoria cone (Fig. 6a). Two possible interpretations of this unusual relationship include (1) it represents an early spatter flow that was annealed and resorbed along its contact with the central lava pond; and (2) it represents a sill-like offshoot from the lava pond into the layered lower structure of the cone. Another anomaly is present in the contact between a vertical dike that traverses the face of the underlying exposure of rhyolite tuff (Fig. 6b). The dike strikes east-west out of the plane of the regional fissure trend, probably oriented in parallel with

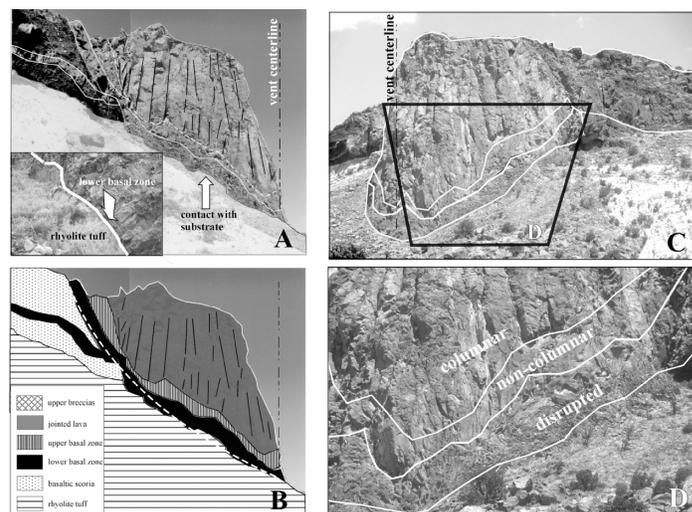


FIGURE 5. View of the south and northeast sides of the columnar basaltic mass near the center of the section showing that it rests on a floor of substrate and is bounded by the interior of the cone along angular unconformities, interpreted as a crater floor and walls. The contacts dip steeply in the upper section and shallowly near the lower part of the section. Inset shows steeply dipping contact between substrate rhyolite tuff and the main mass of the basalt. A zone of disrupted jointing and partial brecciation separates the columnar-jointed interior from the crater walls.

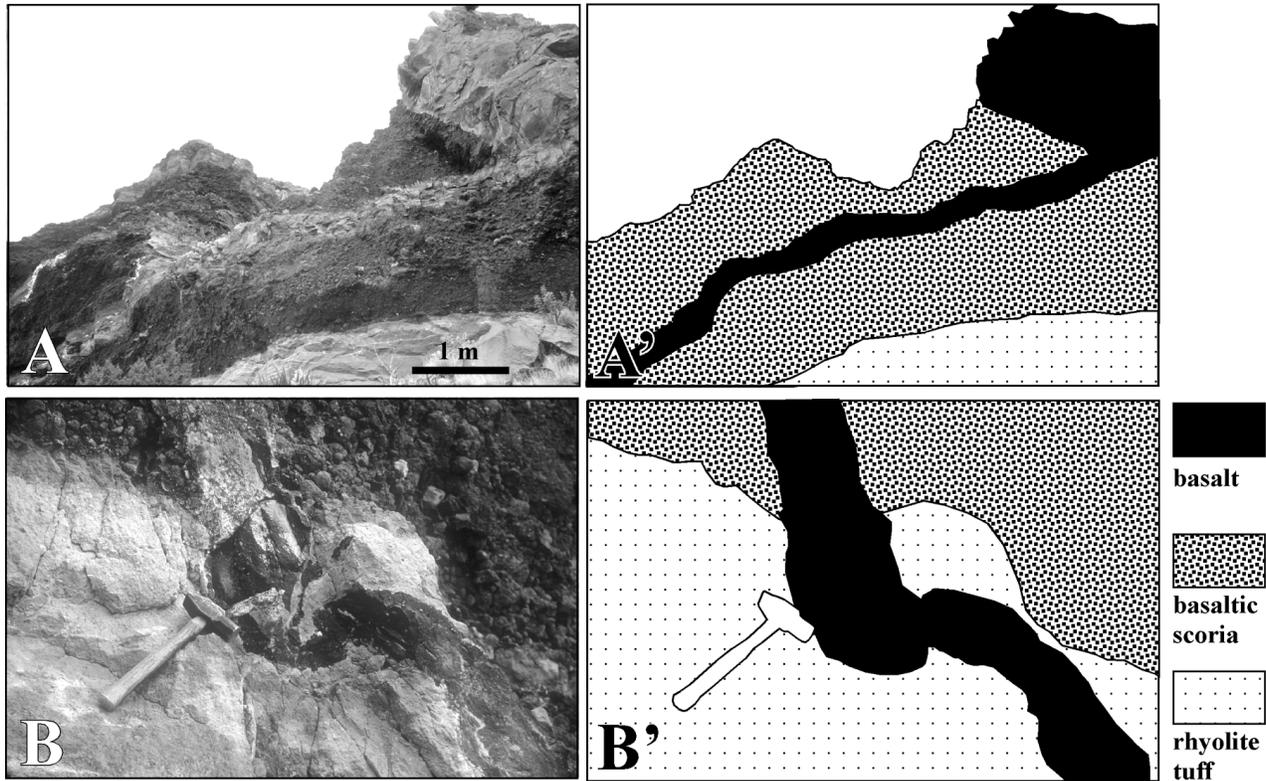


FIGURE 6. A. Horizontal basaltic layer within the scoria cone layering merges uniformly with the steeply-dipping margins of the central crater-filling basalt mass. B. “S”-shaped curve in late-stage basaltic dike suggests deformation during and immediately following emplacement. View also shows the abrupt contact between the base of the cone and the underlying rhyolite tuff.

faults identified (Thaden et al., 1967) on the West Grants Ridge, and connects to the upper slab. The dike undergoes a short S-curve in the vertical section where it enters the scoria at the base of the cone. This abrupt departure from its planar form elsewhere may imply deformation at the time of emplacement or shortly thereafter. Both the sill-like layer and this deformed dike may be evidence for small deformations within the upper cone section during emplacement of the main body of the columnar-jointed basalt. That intruding masses of basalt are capable of displacing the flanks of cones is well documented in many scoria cones (e.g., Holm, 1987), so the type of deformation suggested by these examples is reasonable for the dynamic conditions that must have existed during emplacement of the columnar-jointed basalt.

The pattern of columnar jointing in the EGR section, in which centrally located columns are vertical and those near the upper surface and margins of the crater are more horizontal, is similar to that postulated for thermal flux line-controlled column orientations developed within a thick, enclosed cooling volume of basalt. Because the relationships between the cone and the central columnar basalt may be directly observed in the EGR section, the central columnar basalt is more consistent with the interpretation that the columnar-jointed basalt represents a large pond or semi-endogenous volume of basalt within an original crater extending tens of meters into the substrate. This is essentially the model presented by Head and Wilson (1989) in which an interior, crater-filling lava pond is fed by fire fountains and upwelling within the crater.

Scoria cone craters in mature cones that extend into the substrate are not commonly considered in current models of scoria cone development. In the case of the EGR cone, an early vent enlarged and deepened a crater during the later stages of the eruption. Further support for the concept of a shallow lava pond is the fact that the central basalt connects directly to an extruded lava flow that emerged on the north side of the vent. This means that the central columnar basalt was at least as shallow as the surrounding surface basaltic flows, if not higher. Because the exact geometric arrangement between scoria cones and hosted lava flows is often obscured in the surface by subsequent covering from either later rebuilding of the cone flanks over the exit region of the flows or by later slumping and weathering of the upper cone flanks, the EGR section represents one of the clearest examples of the connection between a scoria cone and its surrounding field of basalt.

The position of the rim profile rollover visible in the section is also relevant to estimating the conditions of eruption during the initial cone-building phase. Most of the erupted pyroclasts accumulate within a well-defined range of the vent centerline (McGetchin et al., 1974; Head and Wilson, 1989) because the distribution of ejecta vectors within strombolian eruptions is nearly vertical to within 15° . This range is defined principally by the ejection velocity, which in turn is controlled largely by volatile content of the erupting mass. Assuming volatile contents between 0.15 and 0.25 wt percent (water) during the initial cone-building phase of the eruption, within the range observed for modern

strombolian eruptions (Head and Wilson, 1987), ejection velocities between 50 to 100 m/sec and mass eruption rates of 10^4 to 10^8 kg/sec may be estimated. Expected pyroclast ejection heights of 100 to 300 m will result in 90 percent falling within the range of 40–110 m (McGetchin et al., 1974). The apparent distance of the rollover from the vent centerline is 120 m. From this dimension one may estimate that volatile contents driving the eruption were probably within the upper range of that observed in modern strombolian eruptions (Wilson and Head, 1981). Another potential cause for the relatively large distance from the vent centerline to the rollover is a greater ejection spread angle, as, for example, might arise from slow ascent rates of magma within the conduit, shallow accumulation of large bubbles, and correspondingly shallow fragmentation. The presence of bipolar fusiform bombs throughout the deposits and relative paucity of thick spatter layers and rootless flows within the section imply that fire fountaining was less significant than strong strombolian explosions.

Exposure of this section and the geometry of the observed pyroclastic deposits, particularly the rounded, or humped, thickening of the section near the vent, are significant for several reasons. First, the location of the rollover from ventward dipping and flank dipping layers within the cone section reliably documents the approximate location of the initial crater rim during early cone construction. Second, the distal extent from the vent center established the approximate diameter of the original cone. Third, assuming a mature cone was built and that the angle of repose was characteristically 30–33 degrees typical of scoria cones throughout the world (Wood, 1980b), then the distal extent of the pyroclastic section enables the original cone profile to be reconstructed, along with the corresponding cone height and the disposition of bedding planes throughout the upper section of the original cone (Fig. 7). These characteristics may be compared with the observed arrangements of bedding planes and locations of pyroclastic deposits observed

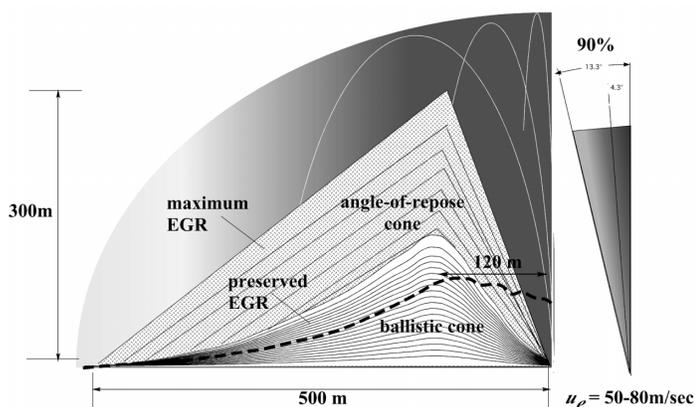


FIGURE 7. Model pyroclastic structure of scoria cones based on current model of scoria ballistic transport and deposition (McGetchin et al, 1973; Head and Wilson, 1989). Most pyroclasts are ejected from a typical strombolian vent at angles of 15° or less from the vertical with velocities less than 100 m s^{-1} . The accumulation is controlled initially by the ballistic range, followed by redistribution once the growing pile exceeds the angle of repose of loose scoria. Dashed line indicates approximate dissection level of EGR cone.

within the section in order to test whether the reconstruction is a reasonable approximation of the original cone.

RECONSTRUCTION AND TESTS

In the following the geometry of the cone structure is reconstructed on the basis of the parameters outlined for the geometry of the section and the geologic details mapped in the exposures. The purpose here is to construct a schematic section that outlines the principal geometry of the cone, the arrangement of the internal structural details in the light of what is known about the general geometry scoria cone structure, to summarize the relationships that may be seen in the EGR section, and to relate the section to the original cone morphology prior to erosion. The results provide a summary of the relationship between general scoria cone structure and the detailed characteristics of the EGR section.

Assumptions made in the reconstruction are as follows: (1) The centerline of the vent is represented by the base of the columnar-jointed basalt where it narrows to less than 2 m width; (2) the cone diameter is approximately 1 km as determined from the most distal exposures of outward-dipping scoria and from mapping on the surface of EGR; (3) the mature cone was circularly symmetric such that a revolution of the original cone profile about the vent centerline adequately represents the shape of the original cone; (4) the limiting angle of repose (AOR) of scoria in a mature cone is 33 degrees and that the cone flanks may be projected upward from the distal edges along a profile with this angle; (5) the central crater into which the columnar-jointed basalt was emplaced represents a crater formed within the mature cone near the end of the main cone-building stage; thus the upper section of the cone within the proximal region of the vent was truncated along steeply-sloping walls that may have attained, temporarily, angles of as much as 60 degrees; (6) the top of the columnar-jointed basalt immediately following emplacement, and upper surface of the associated flow, was close to the current level exposed.

Assumption (1) is reasonable given that the distance from the lowest and narrowest exposure of the columnar-jointed basalt to the roll over point on the early cone section is well within the maximum range of scoria from typical strombolian eruptions. A small complication is the presence of what appears to be a satellite cone on the distal eastern edge of the section, possibly representing another center of eruption along the original fissure. Mapping on the surface of the mesa shows that inward dipping spatter, ash, and agglomerate layers overlie the main cone but appear to underlie the thick extruded basalt on the far eastern edge of the section.

Assumption (2) is based on direct observations of the section and is consistent with the median dimension of scoria cones throughout the world (Wood, 1979, 1980b; Hasenaka and Carmichael, 1985; Scott and Trask, 1971; Porter, 1972) and is largely established from the interaction of the maximum ejection velocity, height, and range of scoria associated with typical strombolian style explosions (McGetchin et al., 1974; Head and Wilson, 1989) and the limiting angle of repose of loose scoria. Assumption (3) is consistent with the mapped extent of the cone flanks on the surface of the EGR. Most mature cones tend toward circular symmetry in the absence of prolonged development of a

fissure. In performing the revolution about the vent centerline, the current strike of the section halves are assumed, in other words, 110 degrees of rotation. The angle is assumed for both the central columnar-jointed basalt and the cone. Although the columnar-jointed basalt protrudes somewhat with respect to the section line, the results are sufficient for comparison. Many cones within the Mount Taylor field are elongate along presumed fissures, which are relatively uncommon in the Southwest, but most are circular. In addition the mapped extent of the structural crater on the surface of the EGR appears to agree with the assumption of overall circularity of the vent region.

Assumption (4) follows from the range of uneroded cone slopes that lie between 25 and 34 degrees (Wood, 1980b; McGetchin et al., 1974). The actual value is not critical to the comparative analysis, but serves only to establish the maximum height of the cone given that the basal diameter is well-constrained. The height estimated from this range for the original EGR would thus be between 260 to 330 meters, although values in excess of 250 m are relatively uncommon in all but the largest recent cones.

Assumption (5) simply reflects the fact that the observed contact of the columnar-jointed basalt mass with the proximal cone section is steeply dipping. Steep angles, up to 60 degrees, are frequently present within many scoria cone craters and are probably supported by a combination of greater induration as a result of proximal spatter and welding of scoria and truncation of the layered structure by crater-excavating explosions.

Assumption (6) is not critical to the reconstruction, but agrees somewhat with the presence of a few preserved ropey structures and the angular and confused-appearing basaltic outcrops near the upper section suggestive of near-surface deformation within a moving lava flow.

The results are shown in Figure 8 as compared with the view from the highway in Lobo Canyon. The view is directed N50°W at an angle between 10 and 20 degrees below the horizontal surface of the contact between the cone and the relatively flat-lying upper between the cone and the relatively flat-lying upper surface of the underlying rhyolite tuff. This reconstruction supports the assumption of circular symmetry based on the good agreement between predicted locations of the contacts between the central columnar-jointed basalt and the cone on both section halves, and based on the agreement between the predicted and observed disposition of scoria layering in the distal flanks on the northeast. The otherwise detached-appearing outward dipping layers of scoria on the far northeast end of the section, predicted from this circular rotation of the apparent cone about the vent centerline, are predicted to represent the most distal northeastern margins of the original AOR cone. The assumption of a 33-degree slope for the loose scoria is somewhat greater by only a few degrees than that actual observed within the section at that point. The result is also in good agreement between the predicted location of the base of the cone and the observed, implying that the view from the roadside in Lobo Canyon is slightly upward and underneath the basal surface of the cone. Finally, although the base of the cone is largely hidden beneath alluvium and talus along the base of the eastern section, examination of the sparse outcrops there show that the contact between the rhyolite tuff and scoria is approxi-

mately where the geometric reconstruction predicts that it should occur. As a further note, small outcrops of outward dipping scoria in this area of the mesa flanks that were originally interpreted as small slump blocks of the cone displaced downward over the rhyolite tuff, are implied from the reconstruction to be in place. This interpretation was reexamined subsequent to the above analysis and found to be in agreement with additional small outcrops that may be traced throughout this part of the mesa slopes.

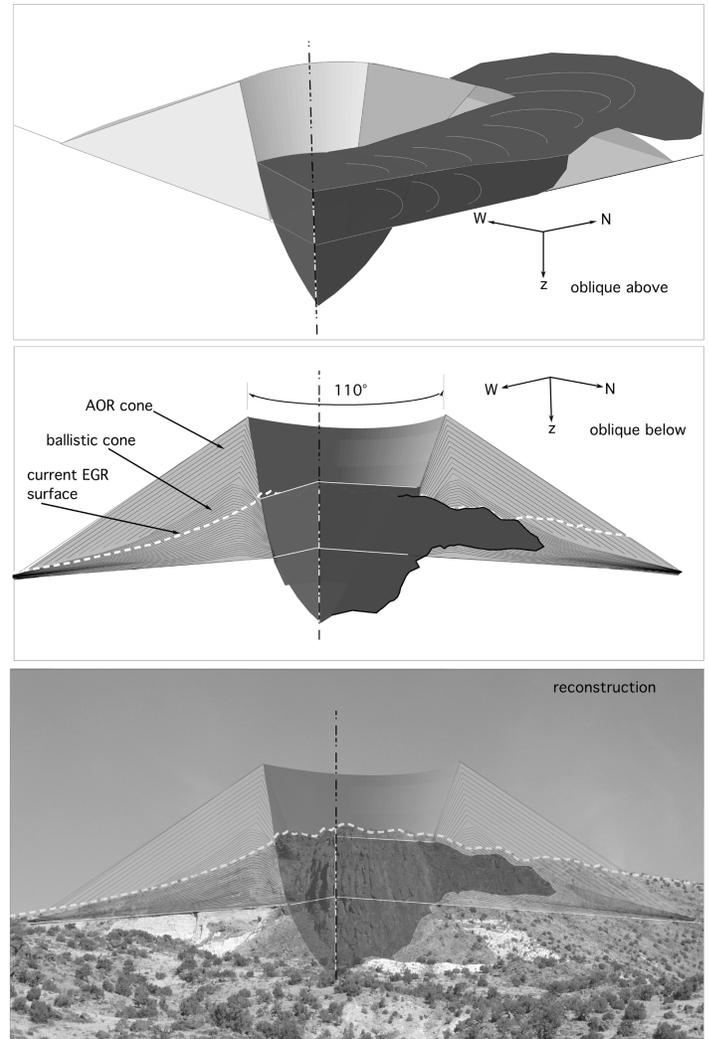


FIGURE 8. Geometric and geologic reconstruction of the East Grants Ridge scoria cone following application of the assumptions discussed in the text. A. Oblique view of reconstructed cone from above. B. Same reconstruction, but from angle of section view as seen in Lobo Canyon. C. Reconstruction superimposed on image of section. Bedding planes within the ballistic cone (left, proximal cone) and angle-of-repose (AOR) cone (right, distal margins) are consistent with the predictions of the reconstruction. The original cone is estimated to have been 1 km in basal diameter and 250 m in relief. The upper one-half of the cone flanks, consisting essentially of the AOR cone, have been removed by surface erosion.

SUMMARY OBSERVATIONS AND RECONSTRUCTED GEOLOGIC HISTORY

Several observations and deductions may be made from the above reconstruction. First, the rather large size of cone is impressive compared with the current level of its current level of preservation. The height of approximately 250 m in the reconstruction implies that between one-half and two-thirds of the original vertical relief has been removed by subsequent erosion during intervening the 2.6 Ma (Basset et al., 1963). Second, this study supports the concept that the central basaltic masses common to the volcanic necks of the Mount Taylor field are best interpreted as lava ponds occupying central craters rather than near-surface reservoirs, widened feeder dikes, or intrusive sheets. The sheer mass of the original lava pond that developed columnar-jointed basalt is impressive, given that the perimeter of the current exposure represents less than one-third of the originally circular crater-filling basalt volume. The reconstruction offers some further insight into the actual geometry of volcanic necks elsewhere within the Mount Taylor field with respect to their original cones. It is easy to envision that complete back wasting of the surrounding basalts and cone would lead to a free-standing, otherwise uneroded massive columnar-jointed basalt much like those throughout the Rio Puerco valley. And finally, this brief study shows that additional insights into the nature of scoria cones can be gained through some simple geometric reconstructions. This follows in part from the more or less regular structure of scoria cones in general and the corresponding ability to make predictions based on current theory of scoria cone physical processes. These predictions may be tested through direct observation of exposures.

Based on observations of the surface geology and the natural cross-section, together with the reconstruction, the East Grants Ridge scoria cone appears to have followed an evolutionary path typical of many scoria cones. Initial eruption likely took place from a short fissure, which subsequently built a surrounding cone of ballistically emplaced scoria. Continued strombolian activity built a mature cone in which, once the rim height exceeded approximately 150 m, the angle of repose of loose scoria controlled further flank development. At this point the cone was well on its way to developing a mature profile. Local welded spatter layers and possible rootless flows imply some alternation between strombolian activity and less explosive hawaiian style eruptions. Upper-gradation in the proximal cone to more bomb-rich and agglomeratic layers implies strong explosive activity later in cone building, possibly including short excursions into more vulcanian activity. Some evidence for the latter is the fact that at or near the maximum development of the mature cone, a pronounced central crater developed either as a result of late, stronger strombolian or vulcanian explosions. An alternative is that upwelling of large volumes of basalt within the vent widened the vent through direct traction with the conduit effectively excavating large blocks of the substrate during emplacement. Considering the large volumes of basalt that appear to have been erupted, and that now cap the West Grants ridge (Black Mesa), the later interpretation is an interesting possibility, if not currently demonstrated or otherwise documented in existing studies of volcano near-surface conduits.

During emplacement of the lava flows, the north flank of the cone was breached, possibly through rafting of large segments of the cone flank through inflation of the proximal lava and outward expansion of the flow. Part of the pathway for this basalt is exposed in the northeast half of the section. Radially-directed static pressures were likely at a maximum at this point in time, leading not only to failure of the northern cone flanks, but also possibly to internal deformation and local injections of lava within the cone. These are preserved as thin layers within the cone directly connected with the central basalt mass. It is envisioned that the resulting geometry with respect to the main cone was analogous to that at Capulin Volcano (Sayre et al., 1995) and Paricutin Volcano (Foshag and Gonzalez, 1956) where late stage bocas developed into thick inflated lava masses protruding from the lower flanks of the cone feeding surrounding fields of basalt.

The great diversity of scoria cone structure and eruption details throughout the world suggests that there are many variations on the basic theme of scoria cones in general, ranging from entirely constructional evolutionary paths to complex arrangements involving building and subsequent destruction, overlapping vents, bilaterally - rather than circularly - symmetric fissure cones, significant early or late stage phreatomagmatic modifications, and so on. The EGR cone appears to be relatively "text book-like" in that many of the constructional features are preserved and late events only partially modified the original cone. The EGR geologic section offers a more generalized view of scoria cones that may be applicable to understanding the general process of scoria cone formation.

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