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Emplacement Of Pleistocene Basalt Flows Near Mccoy, Colorado

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EMPLACEMENT OF PLEISTOCENE BASALT FLOWS

NEAR McCOY, COLORADO

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ABSTRACT

Intraflow structures are readily apparent in the Pleistocene basaltic lava flows that erupted from two cinder cones near McCoy, Colorado 0.66 Ma. Intraflow structures are important because each different structure develops by a different cooling mechanism, which are driven by environmental factors into which the lavas are emplaced. These flows are investigated with the modern interpretations of intraflow structures in basalts to describe their emplacement. Particular features that are associated with the McCoy basalts that indicate being at or near the paleosurface were used to map the pre-eruption topography. Upon mapping these features, these lavas are interpreted to have followed the paths of the old fluvial drainage systems of Rock Creek and Egeria Creek. Identifying the direction of the cooling front, which is preserved in plumose structures along columns, is the main tool used to delineate flow events. Results show complex arrangements of one-tiered and two-tiered flows that are interpreted as open channel lava flows that formed a series of stacked lava levees (two-tiered flows) and drained channel bottoms (one-tiered flows) as flow centers proceeded to drain. Subsequent flows spread across the flow tops and developed a series of stacked one-tiered flows after the lava valley completely filled. Entablatures are formed when water penetrates the solidified portions of the flows and increases cooling rates. The lava flows obstructed stream flow of paleo-Rock and Egeria Creeks. Water from these systems eventually breached the lava dams and flooded the flow tops, which is evidenced by the extensive entablatures in the outcrops. Water entered the flow interiors through brecciated flow tops and along fractures between open channel walls and its succeeding flows. A streamflow impoundment analysis of the time required for these streams to flood the basalt

flow tops indicated the flood events possibly occurred within about one week to three months after basalt emplacement. Using Long and Wood's (1986) convective cooling model, the flows at McCoy completely solidified within three years after emplacement. Since emplacement, the fluvial systems have reestablished their flow paths along the western extent of the flows.

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I. INTRODUCTION

This study investigates the morphology of cooling structures within Pleistocene basaltic lava flows in semiarid northwestern Colorado and the importance of the emplacement environment, in particular the prevailing cooling conditions that create the varied jointing structures of these tiered basaltic lava flows. Because of the slow rate of weathering in this region and that the lava flows are relatively young, the cooling structures are still readily apparent and provide an excellent opportunity to delineate the sequence of basalt flows that were erupted and the interaction of particular flows with the local streams.

The four main objectives of this study are to: (1) determine the general topography prior to the eruption and how the basaltic lava flows altered the position of the existing fluvial systems, (2) use cooling structures to define a flow sequence that can be attributed to the volcanic source, (3) investigate the interaction of surface water with the cooling basalt which develops characteristic jointing, and (4) use the lava flows and paleotopography to calculate cooling rates and estimate the time of stream flood events.

i. Significance of Project

Intraflow structures are fractures that develop within a lava flow as a result of cooling. The study of intraflow structures in basaltic lava flows has been an area of active research for almost a century. Early studies recognized complex intraflow structures in basaltic lavas and sought to explain their formation (James, 1920; Tomkieff, 1940; Spry, 1962). The flow of lava across the earth’s surface is governed by the flow behavior of a melt – lava rheology – and the surface conditions present during an eruption, which in turn governs the structures and textures that form within a cooling basaltic lava flow (Griffiths, 2000). The intraflow structures and textures that are developed within a basaltic lava flow preserve patterns that are present in exposures worldwide – including flows of the type exemplified by the Giant's Causeway in northeast Ireland, Columbia River Plateau in northwest United States, and the lavas in southern Iceland – and yield information to a basaltic lava's cooling history (Walker, 1993; Lyle, 2000). Recent workers such as Saemundsson (1970), Long and Wood (1986), and DeGraff and Aydin (1987) use the cooling mechanisms behind the formation of intraflow structures to describe the environment into which basaltic lava is extruded.

Using the methods and conclusions of these and related studies, the current study investigates the emplacement of a set of little-studied Pleistocene basaltic lava flows north of McCoy, Colorado (Fig. 1). Rock Creek, Egeria Creek, and Red Dirt Creek cut the basaltic lava plain, leaving tall and extensive exposures along the western edge of the flows, isolating at one location a small mass of basalt as a flat-top butte (Fig. 2). These outcrops reveal well-developed intraflow structures that were formed during cooling and present an attractive opportunity to interpret their emplacement and cooling histories. Because the manner in which a lava flow cools, solidifies, and fractures largely depends on the eruption environment (Lyle, 2000), analyzing the intraflow structures of the McCoy Pleistocene basalts will yield information to their cooling history.

This investigation provides a more complete interpretation of these basalts than existed before by mapping the pre-eruption topography, mapping and relative age-dating a portion of the flows, and characterizing the interaction of the existing fluvial systems with particular flows. These data will in turn provide an updated analysis and increased understanding of the emplacement mechanisms for the Pleistocene basaltic lavas that erupted near McCoy, Colorado. Results of this study can be incorporated into interpretations of similar tiered basaltic lava flows. Due to the nature of the flow exposures, the study of the intraflow structures is limited to the northern half of the lavas' extent (Fig. 2).

ii. Geologic Setting

Basaltic lavas that erupted during the Quaternary are widespread across the western United States (Wood and Kienle, 1990). The distribution is uneven, with most of them concentrated in well-defined volcanic zones. Basaltic lavas were erupted at four locations in

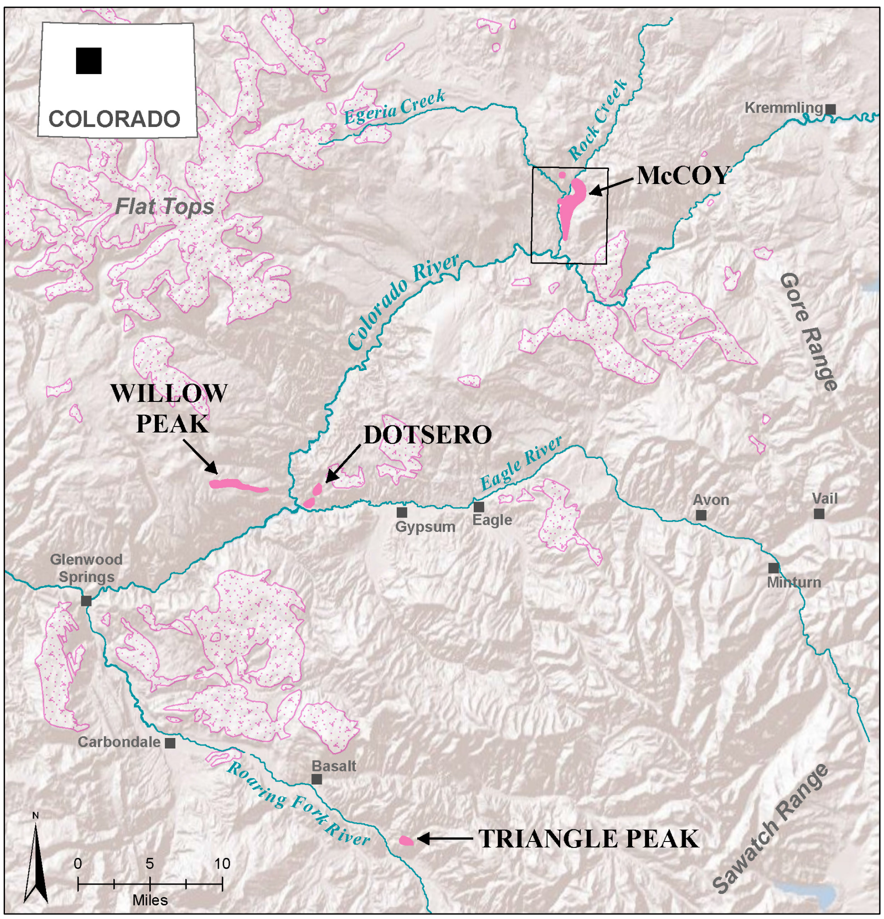


Figure 1. Map of part of northwest Colorado showing locations of the Quaternary basalt flows (pink) at McCoy, Willow Peak, Dotsero, and Triangle Peak and Miocene basalt flows (stipple). Location of volcanic outcrops modified from Leat et al. (1989). Main towns shown by squares. Figure 2 outlined by rectangle.

northwest Colorado during the Quaternary, far from any volcanic zone (Fig. 1). According to Leat et al. (1989), the total volume of erupted lava probably did not exceed 0.3 km^3. In contrast, the area experienced voluminous basaltic volcanism during the Miocene (Fig. 1), with approximately 500 km^3 of erupted lava (Leat et al., 1989). Northwest Colorado experienced crustal extension in the Late Oligocene to Late Miocene. The resulting rifting and extensive volcanism are thought to be related to the development of the early Rio Grande rift to the south.

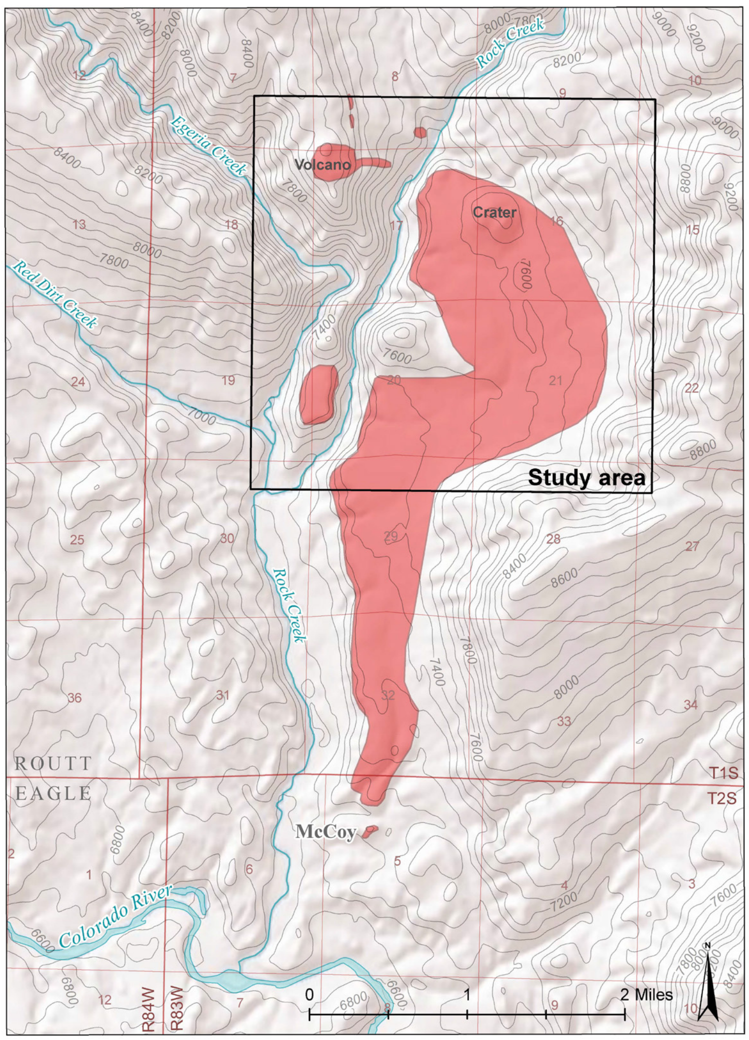


Figure 2. Topographic map of the McCoy area with Pleistocene basalt flow extent. Pleistocene basalt flow extent (pink) is modified from Donner (1949). Study area outlined by rectangle. Contour interval is 100 feet.

Contrary to the origin of the Miocene lavas, there is no strong evidence that the Quaternary lavas are associated with crustal extension and renewed graben formation (Leat et al., 1989).

The Quaternary lavas of northwest Colorado were erupted at four locations (Fig. 1): Dotsero, Willow Peak, McCoy, and Triangle Peak (Leat et al., 1989). The Pleistocene basalts at McCoy are the focus of this project (Fig. 2). The McCoy area encompasses southern Routt County and northern Eagle County, Colorado and lies in the transition zone between the ancestral Front Range Highland and the Central Colorado Basin. The area is a hilly region near the northwest border of the Southern Rocky Mountain physiographic province that has experienced faulting and folding and has been dissected considerably by drainages. Located in the McCoy 7 ½ - minute Quadrangle is a mass of Pleistocene basaltic lava, and its flow extent is preserved in the topography as a raised flat-top plateau roughly in the shape of a question mark. From a point about a half-mile east of the town of McCoy, basalt extends roughly 4 miles to the north and gradually widens to nearly a mile (Fig. 2). It ranges from approximately 15 feet thick at the south end to at least 250 feet thick at the north end. At the north end are two cinder cones, Crater and Volcano (Fig. 2), each roughly a quarter-mile in diameter, and it is believed that both centers contributed lava (Donner, 1949).

The oldest rocks in the study area are Precambrian granites, gneisses, and schists that are well exposed in Rock Creek and Egeria Creek canyons. Cambrian clastic rocks of the Sawatch Quartzite rest unconformably upon the Precambrian crystallines. These rocks are light-gray to white quartz conglomerates with interbedded sandstones that were deposited by the shallow Cambrian sea (Soule, 1992). Ordovician, Silurian, and Devonian sedimentary units are missing, and the Mississippian Leadville Limestone unconformably overlies the Sawatch Quartzite. The Leadville is a fine-grained, bluish-gray limestone that was deposited by the Mississippian sea

(Armstrong et al., 1992). An unconformable surface occurs between the limestone and the less-resistant Minturn Formation of Pennsylvanian age. The Minturn Formation includes as much as 6,300 feet of gray to salmon-colored coarse arkosic sandstones and conglomerates formed from the eroding Ancestral Rocky Mountains with interbedded limestones and micaceous shales formed from an oscillating shoreline in the Central Colorado Basin (Houck, 1991).

The McCoy area was folded and faulted during the Laramide Orogeny. Donner (1949) describes folds trending north-northwest and asymmetrical with the steep limb of the anticline on the northeast side. The largest fold in the McCoy area is exposed in the study area. Over 200 feet high, it is an asymmetrical fold that is slightly overturned along the west wall of Rock Creek valley between Crater and Volcano. The mosaicked faults in the area are mainly high-angle and are interpreted as resulting from vertical forces, like those of the Laramide Orogeny, rather than horizontal forces (Donner, 1949). The position of the two cinder cones relative to the faults mapped by Donner (1949) suggests that the faults influenced the position of Crater and Volcano.

iii. Previous Studies of the McCoy Area

Donner (1949) was the first to describe the Pleistocene basalts in a regional study of the McCoy area, where he described the geology and created a geologic map that covers an area of about 70 square miles. Included in the study was a brief description and analysis of the youngest volcanics that cover roughly 4 square miles of his study area. He described these as a porphyritic olivine basalt. The groundmass, constituting approximately 90 percent of the rock, is composed of feldspar, augite, and magnetite. Approximately 10 percent of the rock is subhedral to euhedral olivine phenocrysts that range from 0.1 to 2 mm in diameter. Near the top of the flows, Donner (1949) noted the rocks contain spherical to elongate vesicles, and near the middle of the flows the rocks contain approximately 15 percent glass. Donner (1949) also described the rocks at

Crater and Volcano as being composed almost entirely of scoria with bombs ranging up to 3 feet in diameter.

Donner (1949) suggested the lavas to have followed the course of the old drainage system of Rock Creek. This drainage was east of the present Rock Creek drainage and was approximately 200 feet above the current elevation of Rock Creek in the north and approximately 300 feet above it in the south. The present Rock Creek drainage has cut its valley along the western edge of the lavas to a depth of 450 to 500 feet below the top of the lava plain, forming steep cliffs that reveal the intraflow structures developed during cooling. Donner (1949) noted areas along these cliffs that show columnar jointing structures and other areas where jointing was rather erratic. Straddling sections 19 and 20, T1S, R83W is a flat-top butte where intraflow structures are well exposed along the east, south, and west walls (Fig. 2). Donner (1949) described the features along the south wall as a "very peculiar structure", noting zones of columnar jointing and erratic jointing. He speculated the formation of these structures as a series of stacked lava flows poured over older lava levees that developed as its center continued to flow. Donner (1949) concluded that within each flow event was an overlying zone of columnar jointing and an underlying zone of erratic jointing.

Since Donner's (1949) work, there has been numerous publications on the nearby Miocene basalts in northwest Colorado (i.e., Larson et al., 1975; Lipman and Mehnert, 1975; Leat et al., 1988, Budahn et al., 2002) but little has been studied of McCoy's younger basalts. Kucera (1962) conducted a regional geologic study of the Yampa district – an area of northwest Colorado spanning 600 square miles in Routt, Rio Blanco, and Garfield counties – which included a brief description of these basalts and Crater and Volcano. Based on the freshness of olivine, presence of glass, and undissected appearance of Crater and Volcano, he suggested the basalts be of Pleistocene age rather than of Pliocene as suggested by Donner (1949). Kucera (1962) also suggested Volcano did not contribute lava to the basalts that filled the valley of pre-eruption Rock Creek, based on the absence of massive basalt proximal to Volcano and because the base of Volcano is approximately 300 feet higher than the top of the basalt flows that are exposed across Rock Creek valley.

The basalts were first age-dated by Larson et al. (1975) using whole-rock K-Ar analysis as 0.64 ± 0.2 Ma, which was later recalculated by Wallace (1995) as 0.66 ± 0.2 Ma. Leat et al. (1989) conducted petrographic and geochemical studies of the Quaternary lavas in northwest Colorado to determine the role of the lithosphere and asthenosphere in the genesis of their magma. During their study of the McCoy lavas, Leat et al. (1989) noted the basalts are chemically similar to ocean island basalts. They proposed a model in which the Quaternary mafic magmas have been derived by hybridization of three magma end-member compositions from three distinct mantle sources (Leat et al., 1989). Leat et al. (1989) also stated that the McCoy lavas are a product of one flow event rather than multiple flow events as concluded by Donner (1949) and Kucera (1962).

Rates of stream incision since emplacement of the McCoy basalt flows were calculated by Larson et al. (1975) to support findings of increased incision rates for the Colorado River since 3 Ma. Larson et al. (1975) reported an average rate of 9.4 in./k.y. for Rock Creek during the past 0.6 m.y. Reports of river incision rates for the Colorado River measured in Glenwood Canyon estimate 6.6 in./k.y. for the past 0.64 m.y. (Lidke et al., 2002) and average 9.4 in/k.y. for the past 3 m.y. (Kirkham and Scott, 2002). These rates have increased an order of magnitude during the last 3 m.y. where rates measured in the Glenwood Canyon averaged 0.94 in./k.y. between 7.8 and 3.0 Ma (Kirkham and Scott, 2002). In addition to the rates calculated for Rock

Creek, Larson et al. (1975) calculated a rate on another tributary to the Colorado River that supports the increased incision rate for the Colorado River. They reported a rate of 10.2 in./k.y. for the past 1.5 m.y. at a site along the Roaring Fork River (Fig. 1).

II. CHARACTERISTICS OF BASALTIC LAVA FLOWS

i. Eruptions and Eruption Products

Basalt is chiefly composed of calcium-rich plagioclase feldspars, pyroxenes, and olivine, all of which indicate a high-temperature magma source (Manson, 1967). Because melts are more fluid with increasing temperature, the high-temperature magma source produces less viscous basaltic lavas. The lack of abundant silica in a basaltic melt, however, plays an even greater role on its viscosity. Silicon, the most abundant cation in a melt, and oxygen, the most abundant anion in a melt, generate electrically charged silicon-oxygen tetrahedra that are attracted to and bond with other Si-O tetrahedra. This bonding results in polymerization of the liquid that increases the "internal friction" of the melt. Thus, the silica-poor basaltic melts exhibit lesser degrees of polymerization and have lower viscosities than melts with high-silica content (Decker and Decker, 1998).

The low viscosity of basaltic melts greatly controls the explosivity of eruptions and the volume of lava expelled. An eruption is more explosive with increased gas content of the melt. Basaltic melts have relatively low gas contents because the lesser degree of polymerization of the liquid allows escaping gases to rise rapidly and unimpeded through the melt. The gas bubbles migrate to the earth's surface without significant build-up of gas pressure and result in relatively calm, often non-explosive eruptions. Once the melt is expelled onto the surface, the low viscosity of basaltic lavas permit flowage to great distances, often producing flows of considerable volume and low aspect ratios where the aspect ratio is defined as the height divided by the width (Decker and Decker, 1998).

Basaltic eruptions on dry land form two distinctive morphologic types of lava, pahoehoe and aa, which are distinguished by their surface structural differences (Rowland and Walker, 1990). Pahoehoe lava has a smooth surface with many internal flow units and lava tubes, whereas aa lava has a rough surface consisting of rubble and loose clinker with underlying coherent basalt that averages 60 percent of its total flow thickness (Walker, 1993). Whether lava becomes pahoehoe or aa upon exiting a vent is not the result of chemical differences or eruptive temperatures. Rather, it is dependent on the volumetric flow rate that is usually, but not always, determined by the eruptive discharge from the vent (Rowland and Walker, 1990).

At a low volumetric flow rate a chilled crust is rapidly created and becomes static before cooling significantly (Walker, 1993). The slow moving lava quickly heals any disruptions of its crust and thus preserves a smooth pahoehoe surface (Rowland and Walker, 1990). Pahoehoe lava migrates beneath its static crust, and where thickening of the chilling crust may restrict flow, the lava may subdivide into smaller flow units and establish new flow paths (Nichols, 1936). As flow units are fed through a system of lava tubes, lava is able to flow freely and without significant heat loss, and pahoehoe lavas are therefore able to travel great distances despite its slow advance (Walker, 1993).

Contrary to pahoehoe, lava destined to become aa leaves a vent at a high volumetric flow rate and often produces a fast-flowing, large-volume flow. Any cooling roof that develops on the flow is likely to be torn away. Aa lava thus favors flow in an open channel rather than in tubes. Heat loss is much higher in an open channel. Consequently, the channelized lava cools significantly, and its viscosity increases correspondingly (Rowland and Walker, 1990). The high volumetric flow rate enables the aa lava to flow even after significant cooling and increased viscosity, but it eventually reaches a critical stage where viscosity is too high to repair any surface disruptions by flowage of the underlying lava. It is at this stage the lava forms the rubbly surface layer that is well-recognized in aa lava (Walker, 1993).

Vesicle shape is another distinctive feature of pahoehoe and aa lavas. Pahoehoe lavas tend to preserve spheroidal to ellipsoidal shaped vesicles, a product of its slow moving advance. To the contrary, fast-flowing aa lavas commonly have irregular-shaped vesicles with many sharp angles and projections (MacDonald, 1967).

Static marginal levees between which a central channel of lava continues to flow are common features in aa flows (Hulme, 1974). The mechanism for levee development was explained by Hulme (1974) with both theoretical and experimental results. A stage is eventually reached as lateral movement of flowing lava diminishes where the lateral boundary basal shear stress equals the yield stress. Here, lateral motion ceases, and a stationary body of fluid forms at the margins of the flow (Hulme, 1974). Levee development and morphology has been observed and described in many active basaltic aa lava flows including the Mauna Loa, Hawaii eruption of 1984, Mt. Etna, Sicily eruptions of 1974 and 2001, and Krafla, Iceland eruption of 1984 (Sparks

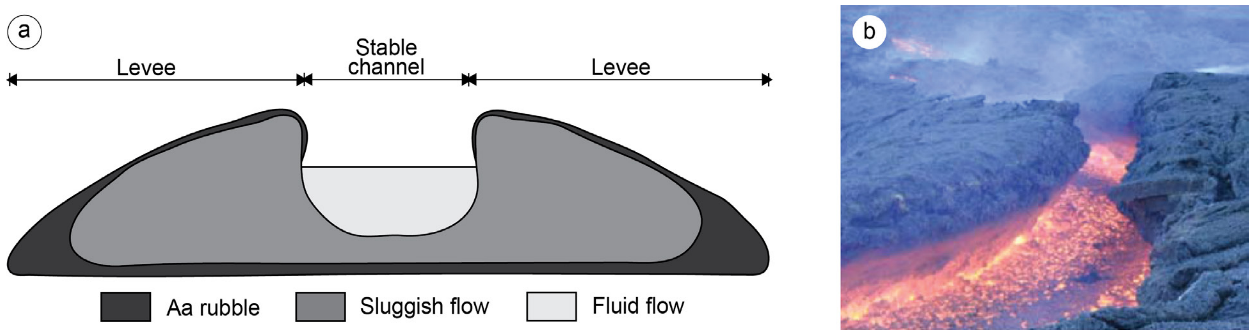


Figure 3. Profile through typical aa channelized flow zone. a. Profile modified from Lipman and Banks (1987) and Bailey et al. (2006). b. Channelized flow zone of an aa lava flow observed at Mt. Etna on May 30, 2001 (Bailey et al., 2006).

et al., 1976; Lipman and Banks, 1987; Rossi, 1997; Bailey et al., 2006). Levees are wedge-shaped, stagnant, cooling bodies of lava (Fig. 3a). Their thickness increases from the flow margins towards the active channel (Rossi, 1997). The inner-channel levee walls are approximately vertical and may become overhanging by accretion to the inner walls during overflow events (Fig 3b) (Bailey et al., 2006). The dimensions of channel and levee development depend on a variety of factors, including topography and lava rheology (Hulme, 1974). Bailey et al. (2006) observed a relatively narrow active channel (~10 feet wide) in the 2001 Mt. Etna eruption, while Rossi (1997) observed an active channel up to 1,800 feet wide in the 1984 Krafla eruption. Favalli et al. (2010) observed an active channel flowing over a previous channel. The active channel was 3.2 miles long, 180 to 345 feet wide, and bounded by 50- to 80-foot high levees (Favalli et al., 2010).

When lava is erupted underwater, or when a flow front enters a body of water, pillow basalt and palagonite breccias may form as a result of extremely rapid cooling from aqueous chilling (Saemundsson, 1970). Pillow lava flows have an appearance like that of a pile of sandbags in cross-section. They are composed of small, subdivided flow units called pillows that have glassy exteriors and are interconnected by narrow tubes (Walker, 1993). The palagonite breccias known as hyaloclastite lavas are chiefly composed of glassy, angular fragments and yellow-brown palagonite. Palagonite is an earthy or clay-like substance formed by the hydration of volcanic glass. Hyaloclastites may be confused with tuffs of explosive origin. However, the quenching and granulation of hot lava in water creates their fragmented rocks. Pillow fragments are commonly found in hyaloclastites, and pillow basalts may be found adjacent to hyaloclastites in a flow (MacDonald, 1967).

ii. Petrographic Textures

The textures that develop in a crystallizing melt largely depend on the temperature of the initial melt and the rate of cooling. In general, as the rate of cooling increases the glass content increases, crystal size decreases, and crystal shape becomes more complex (DeGraff et al., 1989). Crystals are able to grow to larger sizes if fewer nuclei form, and nuclei formation increases with increasing cooling rates (Lofgren, 1974). Relatively equant and euhedral crystals form at low cooling rates, elongate and needle-shaped crystals form at moderate cooling rates, and spherulitic and dendritic crystals form at high cooling rates. Nucleation and crystal growth cease at extremely high cooling rates, and most of the melt solidifies as glass (DeGraff et al., 1989). The increasingly complex crystal forms that are associated with accelerating cooling rates represent increasingly large departures from equilibrium crystal growth (Lofgren, 1974). Both phenocrysts and the groundmass of a basaltic rock may show a textural pattern due to flowing lava, but it is not a common feature of true basalts (MacDonald, 1967). Basalts that do show megascopic flow texture may exhibit a marked alignment of platy minerals, commonly those of plagioclase feldspar. This parallelism, named a trachytic texture, is caused by shearing during flowage of lava and creates a foliation along which the rock may readily break into platy fragments (Walker, 1993).

iii. Intraflow Structures

The complex intraflow structures in the McCoy area's Pleistocene lavas that were first recognized by Donner (1949) have yet to be interpreted using the studies of later workers such as Spry (1962), Saemundsson (1970), Long and Wood (1986), and DeGraff and Aydin (1987). Their studies recognized complex intraflow structures in basaltic lavas in a variety of localities around the world and sought to describe the development of these cooling structures. They concluded that the manner in which a basaltic lava flow cools, solidifies, and fractures largely depends on the environment into which it is extruded. Thus, the structures described in their studies provided information to a basaltic lava's flow and cooling mechanisms and the eruption environment (Spry, 1962; Saemundsson, 1970; Long and Wood, 1986; DeGraff and Aydin, 1987).

The internal structures and textures that form in cooling basaltic lavas create persistent patterns that exist in preserved basaltic lava flows worldwide. The patterns structurally divide basaltic lava flows into tiers, which is a term that refers to a set of columnar joints between two relatively horizontal levels in a flow (DeGraff and Aydin, 1987). Tiered basalt flows commonly show the following intraflow cooling structures, which may vary greatly in thickness, repeat

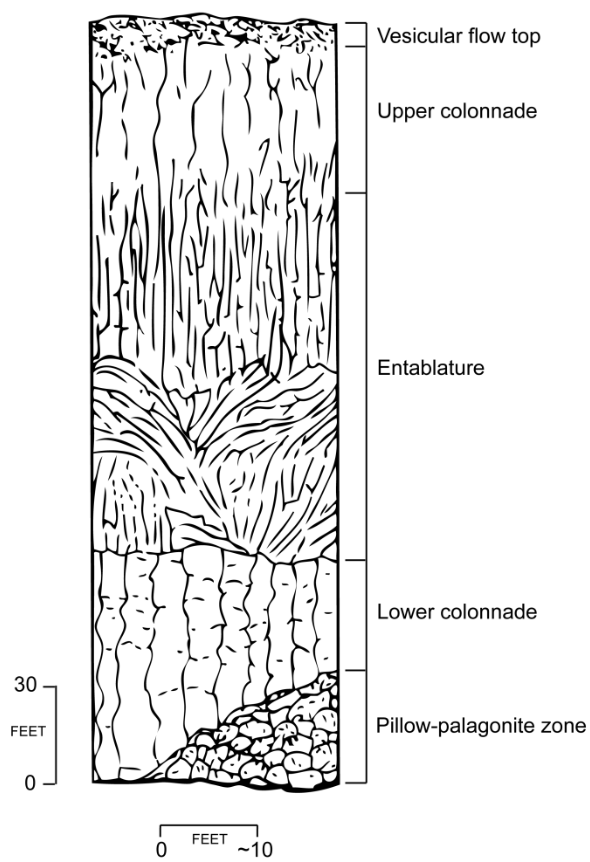


Figure 4. Schematic columnar section through a typical tiered basaltic lava flow in the Columbia River Basalt flows. Diagram modified from Long and Wood (1986).

within a single flow, or be absent entirely (Fig. 4): a brecciated flow top; an upper colonnade with relatively large, wavy columns; an entablature with relatively small, hackly-to-regular columns; a lower colonnade with large, well-formed-to-wavy columns; and a basal zone that may be highly fractured, vesicular, or pillowed with hyaloclastite (Long and Wood, 1986).

Tiered basalt flows are classified into three general types: one-tiered flows, two-tiered flows, and multi-tiered flows (DeGraff and Aydin, 1987). One-tiered flows are relatively thin flows. They consist primarily of a lower colonnade of regular or irregular-shaped columnar joints at the flow base and an overlying vesicular-to-brecciated flow-top. Two-tiered and multi-tiered flows are significantly thicker than one-tiered flows. Two-tiered flows primarily consist of a relatively thin lower colonnade, overlain by a relatively thick entablature that typically occupies the interior one-third to one-half of the flow, and a vesicular-to-brecciated flow-top. A crude upper colonnade may exist above the entablature in two-tiered flows but is not always present. Figure 4 is an example of a two-tiered flow. Multi-tiered flows primarily consist of a relatively thin lower colonnade, overlain by a significantly thicker series of repeated colonnade and entablature tiers, and a vesicular-to-brecciated flow-top. Each tier represents a different cooling mechanism that has acted upon a cooling basaltic lava flow and yields information to the eruption environment as a result (Long and Wood, 1986).

When a basaltic melt cools from magmatic to atmospheric temperatures it experiences a thermally induced tensile stress and a volume contraction by several percent (Walker, 1993). The result is a series of mode-I fractures that form normal to the surfaces of equal tensile stress. These stress surfaces are parallel to surfaces of equal temperature, or isotherms. Isotherms are parallel to the cooling surfaces, so fractures will thus form normal to the cooling surfaces (DeGraff and Aydin, 1987). In an isotropic cooling regime, a flow cools by thermal conduction and a set of master joints initiate at the cooling surfaces. Upon further cooling, master joints further subdivide into a polygonal network of mega-columns, commonly 15 feet across, and individual columns, commonly one foot across. Individual columns are linked at triple junctions and have high aspect ratios. In some flows fracturing may cease at mega-columns leaving very stout columns, and in other flows mega-columns and master joints may be totally absent (Spry, 1962).

Columns often have discontinuous band-like markings on their surfaces that are typically around a few inches thick and arranged normal to the column axes. Contrary to the columns, they have low aspect ratios. These bands are plumose structures that represent incremental fracture-propagation and growth of a column. When a fracture is initiated from a cooling surface, it will penetrate into warmer rock until the accumulated thermal stress is insufficient to cause rupture. Further cooling and shrinkage reestablishes a build-up of tension, which is followed by a release of stress when rupture occurs, thus forming a new band (Spry, 1962).

Fractures originate at edges of older fractures at points of inhomogeneity or distortion where stress is concentrated. A fracture propagates away from its origin and reaches its shorter extent soon after leaving due to the slow moving cooling front, but it continues to propagate laterally along the cooling front. As a fracture propagates, it remains nearly coplanar with or diverges from the upper edge of the old fracture (Fig. 5). Coplanar fractures form a half plume if they originate at the intersection of two column faces and form two half plumes if they originate in the middle of a column face. Noncoplanar fractures form two-sided, asymmetric plumes that diverge from and overlap the upper edge of the old fracture. This forms a curved “overhang” or “ledge” in the overlap zone of the new fracture that grows larger as the separation between the new and old fracture increases (Fig. 5c). The old fracture is not curved in the overlap region, which suggests that it formed before the new fracture. The upper termination of the old fracture is thus preserved as a blind crack front when the new fracture is noncoplanar. Despite that a noncoplanar fracture diverges from the old fracture, the plume axis remains near parallel to, and is asymmetrically situated toward, the upper edge of the old fracture (Ryan and Sammis, 1978; DeGraff and Aydin, 1987).

Fractures may terminate laterally within a column face or at a column triple junction. Lateral termination of a fracture within a column face is marked by a curved arrest line where plumose hackle are everywhere normal to the curved line. More than one fracture may exist within a column face at a certain level, and fractures may laterally terminate when a new fracture

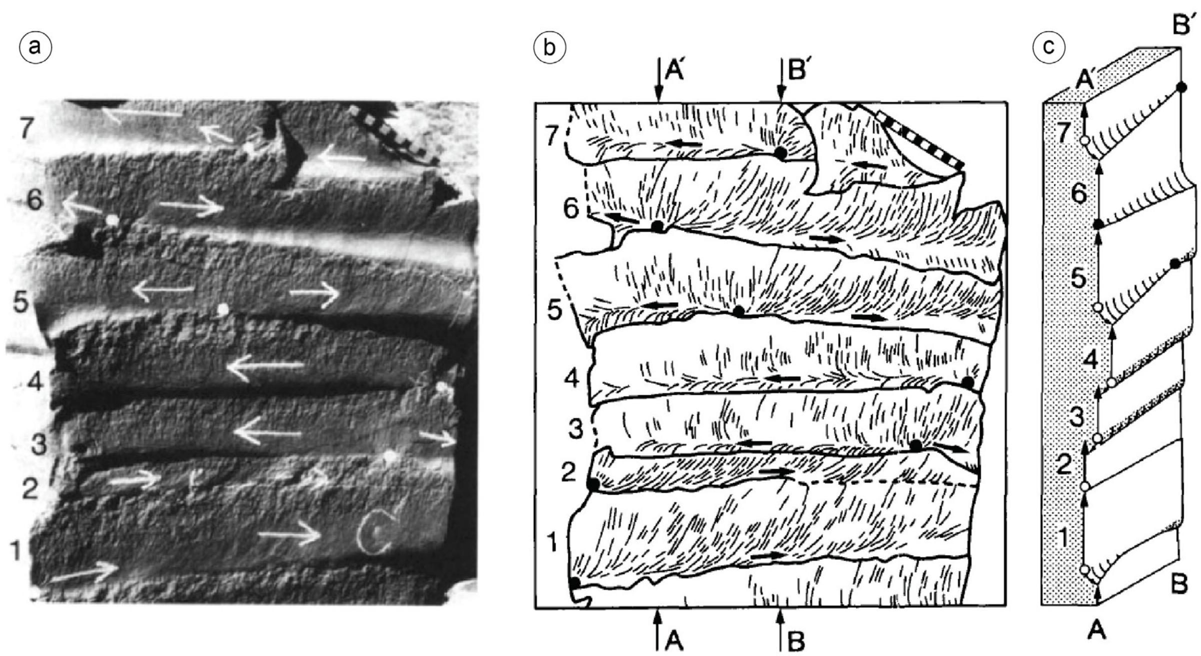


Figure 5. Interpretation of incremental fracture-propagation along a column face near the bottom of a flow. a. Each band-like marking is a plumose structure on a column face and represents an individual fracture formed during a discrete fracture event. b. Dots show crack origins, short thin lines show hackle, continuous thick lines show crack terminations, arrows on plume axes show local propagation directions, and numbers give fracture formation sequence. c. Oblique view of column face between A-A’and B’-B. Parallel curved lines show overhangs and ledges, open circles show plume axes, and vertical arrows show vertical direction of crack propagation (DeGraff and Aydin, 1987).

forms on or near the lateral terminus of an older fracture or when a new fracture propagates toward an older fracture. Although columns are linked at triple junctions, fractures do not necessarily laterally terminate there. Fractures may laterally terminate, propagate away from, or propagate toward, through, and away from triple junctions. No two fractures form simultaneously at triple junctions, and fractures arrive at or depart from triple junctions in a definite order. Although each fracture has a local lateral propagation direction, the addition of new fractures to the terminus of old fractures produces a net vertical growth of columnar joints (DeGraff and Aydin, 1987).

Because a lava flow cools inward from the outer surfaces, most commonly the upper and lower surfaces, fracture-forming tensile stresses also proceed inward (Walker, 1993). Thus, the formation of columnar joints initiates at both the top and bottom of a flow and propagates inward, normal to the isotherms, resulting in a colonnade structure and an irregular jointing pattern where the two colonnades meet. When a lava flow is cooled solely by thermal conduction, heat loss at the top is only slightly greater than at the bottom, and the two solid-liquid interfaces meet between 50 and 60 percent of the way down from the top (Long and Wood, 1986; DeGraff et al., 1989). Many basaltic lava flows, however, exhibit zones of irregular, curvicolumnar jointing known as entablatures that are found adjacent to colonnades (Fig. 4). Entablatures, when present, make up as much as 80 percent of a flow's thickness and are usually found above or between smaller colonnade sections (Long and Wood, 1986).

An entablature's irregularly shaped columns imply some form of change in the stress regime and cooling mechanism such that thermal conduction is not the only process of heat-transfer that is operating during cooling of a flow (Long and Wood, 1986). Aqueous chilling is the most widely accepted explanation for the formation of an entablature (Saemundsson, 1970).

Long and Wood (1986) developed a one-dimensional thermal model that illustrates undisturbed conductive cooling as well as convective removal of heat by water through quenching the lava flow to ambient conditions. Their model shows that water circulation induces relatively high cooling rates, approximately 10 times greater than conductively cooled lava flows (Long and Wood, 1986).

When the lava is quenched, near horizontal isotherms become modified by rapid heat transfer, and curved columns may begin to form as a result (Lyle, 2000). The quenching interface follows the solidus down through the lava flow, quenching the melt to freezing temperature as it continues to cool and pass through the solidus. The Long and Wood (1986) thermal model shows a rapidly quenched zone comprising 50 percent of the flow interpreted as an entablature, two rapidly cooled zones interpreted as a flow top and flow bottom, and a slowly cooled zone interpreted as a lower colonnade. The contact between the entablature and lower colonnade represents the position where the upper solidus meets the lower solidus and solidification of a flow is complete. This will typically be 70 to 80 percent of the way down from the top of the cooling flow (Long and Wood, 1986).

iv. Applications to Flow Stratigraphy

Cooling structures in a lava flow commonly show patterns based on the direction and rate in which a solid-liquid interface moves. Because a flow cools inward from its upper and lower surfaces, these directional patterns reveal many relationships that may allow for determination of the relative intraflow position of an isolated, incomplete exposure of a lava flow. The patterns developed during incremental fracture growth along a column face are arranged based on the direction of the moving solidus. The arrangement of these patterns functions as criteria for determining the overall growth direction of columnar joints that may prove useful in applications to flow stratigraphy when columnar joints are present (DeGraff and Aydin, 1987).

Exposures that show any or all combinations of plumose structures originating at the upper edges of older plumose structures, plume axes situated towards the lower end of its plume, and straight blind fronts at the plume-tops indicate upward growth of columnar joints. Similarly, downward growth of columnar joints may be inferred in exposures that show any or all combinations of plumose structures originating at the lower edges of older plumose structures, plume axes situated towards the upper end of its plume, and straight blind fronts at the plume-bottoms. These relationships are particularly useful when applied to complicated flow sequences of multiple tiers. Additionally, using the directional criteria may resolve a flow sequence into separate flows if not already separated by interbedded sediments. Separate flows may be marked by two joint sets that grow away from each other rather than towards each other as a single flow would show (DeGraff and Aydin, 1987).

v. Implications for the Eruption Environment

The presence of an entablature represents a fundamental difference between the eruption environment and cooling histories of two and multi-tiered flows and one-tiered flows. It is evidence of an interaction between solidifying lava and water. Entablatures have a number of intraflow cooling textures and structures that demonstrate an interaction with water. The entablatures of tiered flows show distinctive petrographic textures evident in thin sections. Henderson (1970) used the term mesostasis to apply to the last interstitial material to crystallize within a melt. The large abundance and very fine crystal size of mesostasis and the large abundance and dendritic morphology of opaque grains are all products of an accelerated cooling rate (Saemundsson, 1970; Long and Wood, 1986; DeGraff et al., 1989). The morphology of tiered flows agrees with Long and Wood's (1986) thermal model of cooling through water ingress. The model's results show a significant portion of the melt affected by quenching, while the top and bottom flow margins show slow cooling and retain a smaller thickness. This is commonly seen in tiered flows where an entablature makes up a significant portion of a flow relative to the lower colonnade and other structures. A basic assumption in the model is that water penetrates the solidified part of the flow, so the model also explains common structures of curved columns within the entablature (Long and Wood, 1986). The large, early-formed master joints may act as conduits for water movement into the cooling lava, and the transfer of heat by water convection may modify isotherms to where the master joints become secondary cooling surfaces. Columnar joints may grow radial to the master joints to form fan-like columns, thus explaining some of the complex patterns seen in entablatures (DeGraff and Aydin, 1987). Master joints, however, are not the only means for water movement into a lava flow. Columns may radiate from dimples beneath a permeable flow-top breccia, permitting water to preferentially cool the flow at this point (Long and Wood, 1986).

A general consensus has been established that the creation of an entablature is the result of inundation of a lava flow surface by water (Saemundsson, 1970; DeGraff and Aydin, 1987; Long and Wood, 1986). Presumably, the source of this water must have been present prior to an eruption (Lyle, 2000). In his study of the cooling history of tiered flows of the interglacial lava flows of southern Iceland, Saemundsson (1970) suggested that river drainages displaced by an intruding lava flow might be a viable source of the inundating water. He suggests that lavas may flood river valleys and cause rivers to temporarily dam. If the dam is breached or overtopped by the impounding water, water may inundate the solidifying flow surface (Saemundsson, 1970). The thickness of the upper and lower colonnades is dependent on how long the flow is allowed to cool before its surface is flooded with water. Thick colonnades relative to its adjacent entablature indicate that inundation must have occurred late in the cooling history of the flow, whereas thin colonnades, or an absence of the upper colonnade, indicate a rather early inundation of the flow surface.

The alternating colonnade and entablature tiers seen in multi-tiered flows may be explained by multiple flooding events with intervening dry periods, given that the structural differences between the colonnades and entablatures reflect different cooling rates (Long and Wood, 1986). This hypothesis is supported by the observations of DeGraff and Aydin (1987), where they used criteria developed for features seen in plumose structures along column faces to determine the overall growth direction of columnar joints in a flow. They concluded that multi-tiered flows show a single upward-propagating joint set that represents the lower colonnade and a downward-propagating joint set that is represented by all other tiers, and the two joint sets meet at a level well below the middle of the flows. Thus, if multiple flooding and drying events occur on a flow surface, the joint set will experience changes in cooling rates as it continues to propagate downward, and the joint features preserved will show evidence of downward growth across the alternating tiers (DeGraff and Aydin, 1987).

Aside from the presence of an entablature, other features may be associated with tiered lava flows that support evidence of a displaced drainage from an impeding lava flow. Hyaloclastites and pillow lavas are commonly found at the base of tiered basaltic lava flows. Because they are formed through extreme cooling by contact of lava with water, their presence at the base of a lava flow indicates that a flow must have invaded a water body (Lyle, 2000). Additionally, gravel beds may be found beneath these flow foot breccias, providing direct evidence of a displaced drainage (Saemundsson, 1970). Frequently linked with hyaloclastites are interbasaltic lacustrine and fluviatile sediments that are interpreted as shallow lakes formed on the surfaces of lava flows that mark periods of stagnation between flow events (Lyle, 2000).

Lavas that flood river valleys may pond as they become restricted by valley walls. This explains the great thickness of two and multi-tiered flows relative to one-tiered flows, and suggests that one-tiered flows erupt onto a relatively flat surface, or they flood a river valley but are of insufficient volume to pond. Unponded lava is more prone to movement that can disrupt uniform tensile stresses, which may contribute to the irregular character of columns seen in one-tiered flows (Long and Wood, 1986). Presumably, if lava is erupted onto a relatively flat surface as with one-tiered flows, columns will grow everywhere normal to the ground surface and form relatively vertical columns. This also means that ponded flows, like two-tiered and multi-tiered flows, may develop a tilted lower colonnade as it cools and solidifies along a valley wall (Saemundsson, 1970).

III. PALEOTOPOGRAPHY

Because the manner in which lavas cool, solidify, and fracture largely depend on the environment into which they are extruded (Griffiths, 2000), the eruption environment largely controlled the complex features that are preserved in the McCoy basalt flows. Thus, these features yield information about the eruption environment at McCoy and were used to reconstruct the pre-eruption topography bordering Rock Creek. Distinct characteristics that occur in the McCoy basalt flows are consistent with the observations and conclusions of Saemundsson (1970): the McCoy basalt flows show a relatively narrow width in plan view and relatively thick exposures occur along the canyon walls adjacent to the present drainages, which suggests that the lavas were pooled as flowage was confined by valley walls of an old fluvial drainage system. Based on spatial and topographic relationships, the McCoy lavas erupted from Crater and Volcano and followed the path of Rock Creek's pre-eruption drainage system southward (Fig. 2), and thus the paleochannel of Rock Creek still exists beneath the flat-topped basalt flow.

Particular features are associated with the McCoy basalts that indicate being near or at the paleosurface. Observed features include hyaloclastites composed of basalt and bedrock fragments, basalt in direct contact with in-place bedrock and gravel-filled paleochannels, and bedrock – in-place or float – and stream-rounded gravel float occurring near basalt occurrences. The presence of such features, shown in Figure 6, is the most reliable indication of the pre-eruption paleotopography.

Hyaloclastites composed of basalt and bedrock fragments are present at various locations along the base of particular outcrops (Fig. 7a). These zones typically range between 1 and 3 feet thick. Formed by extremely rapid cooling caused by the contact of hot lava with a comparatively cold, moisture-laden surface (Rittmann, 1962), these palagonite breccias mark locations of the paleosurface. At a few of the outcrops where the hyaloclastites occur, basalt was found in direct contact with bedrock (Fig. 7b), which clearly demonstrates the original edge of the lava flow. A small zone of bulbous basalt textures resembling pillow lavas is adjacent to a hyaloclastite zone along the base of the east wall of the butte (Fig. 7c), evidence that the lavas invaded a body of water (MacDonald, 1967). Although bedrock fragments were absent in the particular hyaloclastites shown in Figure 7c, this occurrence appears to be formed at or near the paleosurface and possibly from lavas invading the pool of a meandering paleostream.

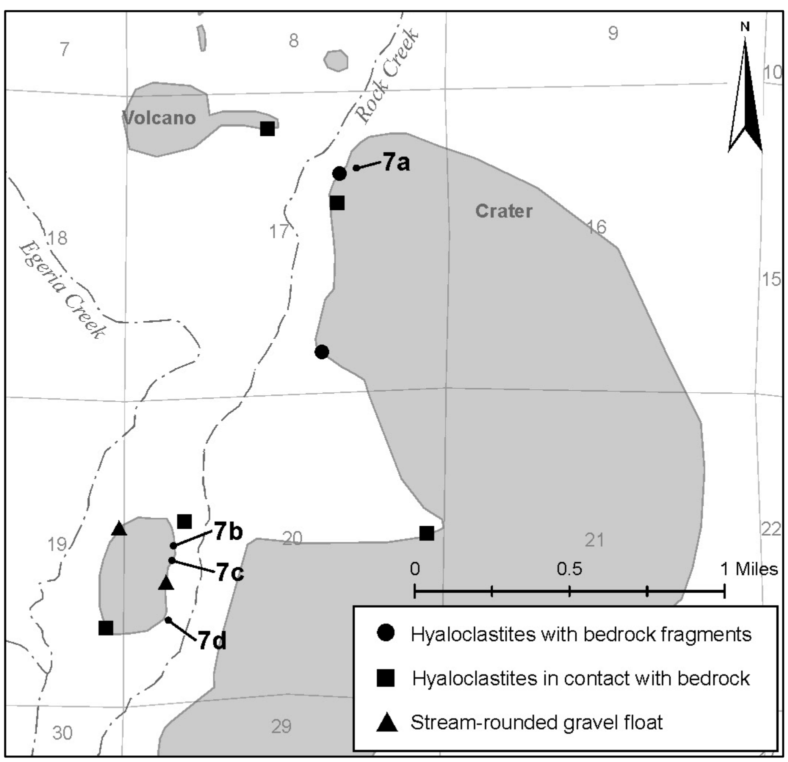


Figure 6. Location map of paleotopography indicators shown for the study area of the McCoy basalt flows. Locations for figures are identified by their figure number.

Basal hyaloclastite in contact with a paleochannel is exposed at the southeast corner of the butte that borders section 19 and 20 of T1S R83W, and this feature occurs nearly 250 feet above Rock Creek's present drainage to the east (Fig. 6, 7d). The paleochannel is a lens-shaped assemblage of rounded cobbles and boulders of igneous and metamorphic compositions and ranges up to 6 feet thick. The exposure extends about 15 feet on the south wall of the butte and wraps around the east wall continuing an additional 20 feet. Weak imbrication of some gravel pieces suggests a southeastward flow direction for this old fluvial system. The overlying hyaloclastites are up to 3 feet thick and are overlain by thick exposures of columnar basalts. The paleochannel gravels provides direct evidence that lavas did impede a major fluvial system.

Rounded cobbles and boulders of similar size and composition occur locally as float directly below basalt outcrop in two areas along the butte (Fig. 6) – about 220 feet above Egeria Creek's present elevation along the northwest side of the butte and nearly 250 feet above Rock Creek's present elevation along the east side of the butte. The present drainage basins of both Egeria Creek and Rock Creek contain Precambrian igneous and metamorphic units to the north and northwest of the butte, but Red Dirt Creek, to the west of the butte (Fig. 2), appears to drain only Paleozoic sedimentary formations. The cobbles found along both sides of the butte appear to represent the pre-eruption channels of Egeria Creek and/or Rock Creek. The close proximity of these gravel float occurrences to the presumed pre-eruption location of Egeria Creek as it likely joined Rock Creek implies that these gravels belong to paleo-Egeria Creek, and the lavas probably backed up into Egeria Creek while making a turn to flow due south down Rock Creek (Fig. 6). Sedimentary outcrops and float occurring alongside but not in direct contact with basalt were interpreted as locations near the paleosurface. In some places bedrock was exposed at elevations much higher than its neighboring basalts and represents a paleo-high in the pre-


a


b

Figure 7. Photos of paleosurface indicators in the McCoy basaltic lava flows. Dashed lines mark boundaries between different textural features. Photo locations shown in Fig. 6. 7a. Hyaloclastite with bedrock fragments. 7b. Hyaloclastite in contact with in-place Minturn Formation bedrock. Colonnade overlies hyaloclastite zone in upper left corner. 7c. Pillow basalts beneath hyaloclastites. 7d. Hyaloclastite in contact with paleochannel. Colonnade overlies hyaloclastite zone. Largest boulders in gravel approximately 2 feet in diameter.

eruption topography, which was never overtopped by the lava. Bedrock in the local area was mapped to identify structural and topographic trends, which were later utilized to project into the now-covered paleosurface where appropriate.

In order to model the paleotopography of Rock Creek valley, the gradient of the stream needs to be determined as it encounters the various pre-eruption bedrock types. Using the existing Rock Creek fluvial system as a guide, the channel shows three different gradients, which correspond to the changing resistance to erosion exhibited by bedrock exposed in this area. The Minturn Formation is exposed along Rock Creek from the town of McCoy northward to where Egeria Creek joints Rock Creek, a horizontal distance along the channel of about 12,700 feet. A 120-foot elevation change indicates that Rock Creek has an average gradient of about 10 feet per 1,000 feet while it is flowing through the relatively unresistive Minturn Formation. When Rock Creek encounters the Sawatch Quartzite and Leadville Limestone, which it does through much of section 17 T1S R83W, the gradient increases to about 25 feet per 1,000 feet. The Precambrian igneous and metamorphic rocks appear to be the most resistive to erosion, as Rock Creek assumes the even higher gradient of 52 feet per 1,000 feet of channel length as it has in sections 8 and 9 T1S R83W and northward from there. Using these gradients with the elevations of the gravels exposed immediately beneath the basalt flows in section 20 T1S R83W allows one to estimate the bottom elevation of the basalt along the length of the flow, from the north end to the south end. In the NW ¼ of section 5 T2S R83W, near the south end of the flows (Fig. 2), the calculated elevation of the basalt-bedrock contact is 7020 feet, which is within about 20 feet vertically of what is exposed in the field. Similar close elevations between calculated and observed paleochannel positions are present on the north end in section 17 T1S R83W.

The slopes of the valley walls along the ancestral Rock Creek need to be estimated since the basalt flows likely filled the lower parts of the valley from wall to wall, particularly at the north end. The positions of the now-buried valley walls were estimated by projecting the established slopes for bedrock exposed in the higher parts of the bordering valley walls to the depth of the paleochannel elevation as described above. In some cases, such as in the center of section 16 T1S R83W, this slope amounts to the regional dip of the bedrock, which is the Leadville Limestone in this particular example. Establishing the ancestral west valley wall for Rock Creek prior to the eruption is problematic since it has been completely removed by later Rock Creek erosion. It is assumed that this west valley wall was probably positioned very close to the current limit of exposures along the west side of the basalt plateau. This assumption is based on the observation that the basalt appears to be quite resistant to erosion by the fluvial systems of this area. The steepest slopes for any of the lithologies exposed along the canyon walls of Rock Creek are those composed of basalt; in several cases these are truly vertical for a height of nearly 100 feet or more. Of the 5.1-mile-length of Rock Creek where it flows with basalt cropping out in the canyon walls (from the northern boundary of section 17 T1S R83W to the NE ¼ of section 5 T2S R83W as shown in Figure 2), only about 2,000 feet (7%) of this total length has basalt on both sides of the canyon, where Rock Creek had to cut through the basalt flows themselves. As Rock Creek was reestablishing its channel after the emplacement of the lava flows, it appears this fluvial system preferentially located to the western edge of the basalts, finding it easier to erode either Precambrian rocks or the Paleozoic sedimentary rocks than these recently-emplaced volcanics.

The paleotopography along Rock Creek that existed prior to volcanism is modeled on a topographic map (Fig. 8a) based on locations of the aforementioned features (Fig. 6) and the

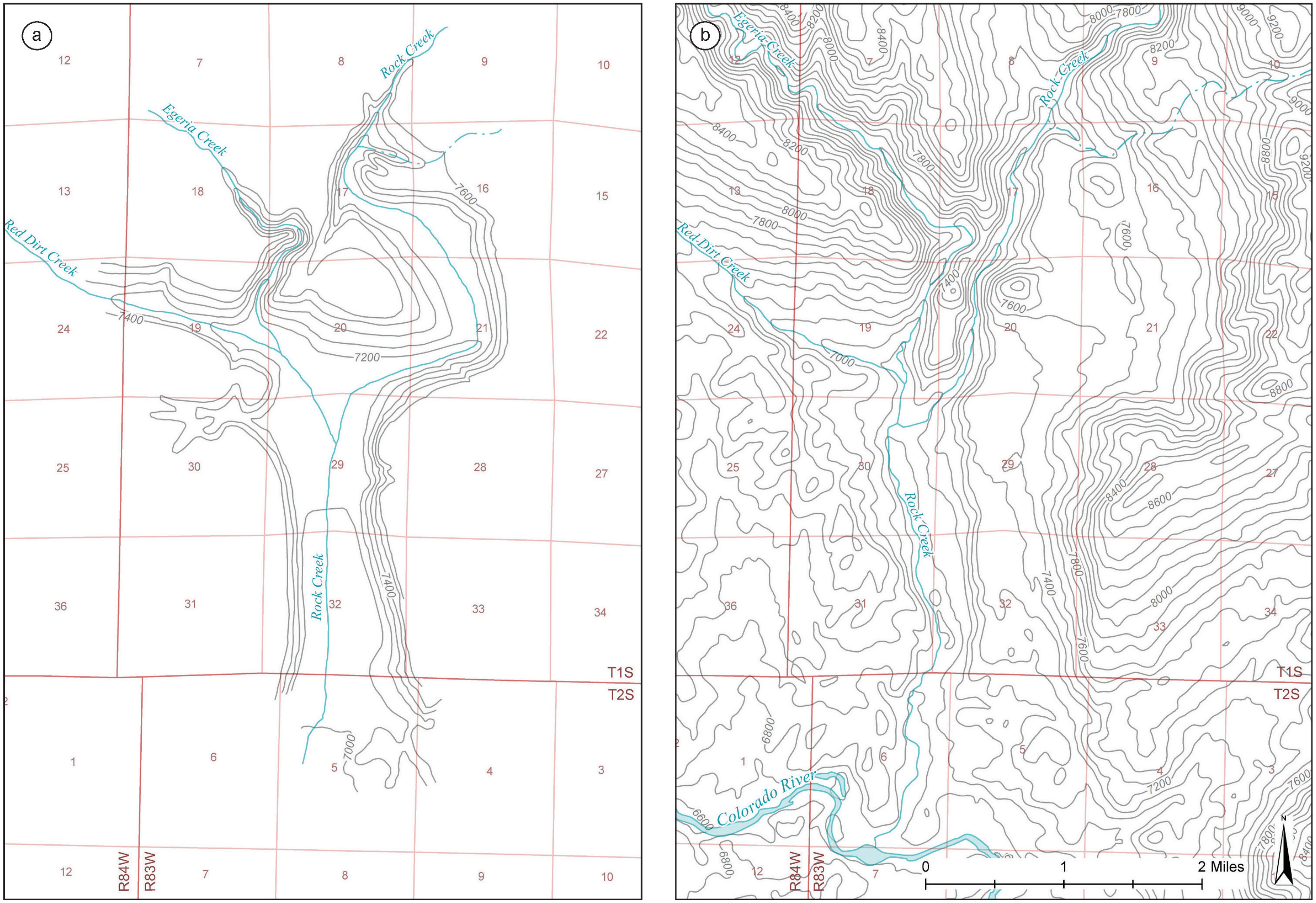


Figure 8. Topographic maps portraying pre-eruption paleotopography and present topography along Rock Creek. Contour interval is 100 feet. 8a. Pre-eruption paleotopography. Only contours up to 7,600 feet are shown. 8b. Present topography.

assumptions concerning stream gradients along with slopes and positions of valley walls. The topography was constructed using a 100-foot contour interval, and only elevations up to 7,600 feet are shown. All three streams are suggested to have been affected by the lava flows, since their positions vary from what is represented in the present topography (Fig. 8b). It appears the geographic location for both Rock Creek and Egeria Creek outside of where the basalt occurs has not changed significantly since the Pleistocene except to cut vertically. Rather than flowing south-southwest through sections 17 and 20 T1S R83W as it does now (Fig. 8b), Rock Creek once occupied a valley that wrapped eastward around a N80W-trending hill of Sawatch Quartzite centered in the north half of section 20 T1S R83W. Rock Creek then flowed due south upon entering section 29 T1S R83W (Fig. 8a), which is approximately 1 mile east of its present position in this area (Fig. 8b). Egeria Creek flowed southeast from section 19 into section 20 T1S R83W (Fig. 8a) through what is now occupied by the butte instead of continuing due south to meet Rock Creek in the NE ¼ of section 30 T1S R83W as it does today (Fig. 8b). Red Dirt Creek in section 19 T1S R83W was probably positioned 500 to 1,000 feet north of its present course, joining Egeria Creek in the area of what is now occupied by the butte (Fig 8a).

IV. ERUPTION PRODUCTS

i. Volcanic Sources

Crater is the better exposed of the two sources of volcanic materials for the McCoy basalt flows (Fig. 2). Located at the north end of the wide part of the flows in sections 16 and 17 T1S R83W, it rises about 220 feet above the surrounding flat lands underlain by the Middle Pleistocene basalts (Fig. 9). Using the break in slope as an indication of the base of the cinder cone, its diameter ranges from about 1,900 to 2,200 feet. Since lava flows frequently issue from the base of basaltic volcanoes (Williams and McBirney, 1979), an unknown thickness of cinder cone material was buried by the later flows and is currently unexposed.

The cinder cone is currently being mined for the light-weight aggregate of which it is composed (Fig. 10). The first reported mining occurred at Crater in 1953 (Martin and Kelly, 1956), and it has produced cinders sporadically since then. Kucera (1962) shows a photograph of Crater from the late 1950s, when mining had removed very little of the original materials.

Crater is composed primarily of red scoria lapilli with a thin outer mantle of black scoria lapilli (Fig. 11). Chester et al. (1985) note that the basaltic material erupted at cinder cones on Mt. Etna is typically black, but can be shades of red to yellow due to alteration by fumaroles. Similar fumaroles were probably the cause of the red scoria at Crater. Blocks and bombs, ranging up to 2 to 3 feet in diameter, are commonly interbedded with the lapilli (Figs. 11, 12). Steeper outer slopes measured on Crater are about 25°, which is similar to the slopes "approaching 30°" noted by Kucera (1962) prior to extensive modification by mining operations,

Figure 9. Photo of Crater looking southeast from Volcano. Tiered basalt flows exposed beneath as flat-topped plateau in lower right corner of photo.

Figure 10. Photo of cinder mining operations at Crater looking southwest from the top of Crater.

Figure 11. Photo of Crater's interior showing inner red scoria and outer black scoria. Blocks and bombs occur in the internal bedding that dips around 25° towards the edges of the volcano.

Figure 12. Photo of interbedded blocks and bombs occurring in Crater's interior. Internal bedding dips around 25° towards the margins of the volcano.

and are consistent with typical measurements of the internal bedding visible in the mined exposures (Fig. 12). At one location along the northeast side of Crater, exposed due to mining, is a zone containing layers of scoria and blocks dipping eastward up to 60° on the more interior part of the exposure, and the dip lessens to the more typical 25° near the outer surface of the cinder cone. Kucera (1962) mentions the original Crater had a crater at the top that was cut by a "shallow notch" on the south side. This original crater is unrecognizable today because of the extensive redistribution of material due to mining.

Wood (1980), based on a study of the morphometric evolution of cinder cones, states that cinder cones are frequently built rapidly, often reaching their final heights in just a few days. Lava flows begin erupting almost immediately, and will last on average just a matter of a few weeks. There is no evidence that Crater behaved any differently than these numerous well-documented historic cones studied by Wood (1980). The height-to-basal-width ratio (H_{co}/W_{co}) for Crater (about 0.11) is less than the 0.18 average H_{co}/W_{co} determined by Wood (1980) for 83 fresh cinder cones in a world-wide study. This lower ratio for Crater is understandable considering the Middle Pleistocene age and the extensive re-shaping by ongoing mining activity. Hooper and Sheridan (1998) report an average H_{co}/W_{co} of 0.135 ± 0.028 for 91 Middle Pleistocene scoria cones in the San Francisco volcanic field in Arizona. This same group of cones had an average maximum slope angle of 25.4° ± 3.7°. These morphometric parameters are quite similar to those determined for the equivalent-aged Crater volcanic landform. Inbar and Risso (2001) report decreasing average H_{co}/W_{co} ratios (from 0.17 to 0.09) and decreasing average slope angles (from 31° to 19°) for cinder cones of increasing age (Holocene to Pliocene) in the Payun Matru volcanic field of Argentina.

Volcano, west of Rock Creek in the NW¼ of section 17 T1S R83W about 6,000 feet northwest of Crater (Fig. 2), is the other source of basalt contributing to the McCoy flows. This volcanic feature has about the same diameter as Crater, but the base of the volcanic landform is some 400 feet higher than the base of Crater, having been emplaced near the top of a ridge west of Rock Creek. The topographic expression of Volcano is notably more subtle than the classic cinder cone form of Crater. Volcano is best exposed on the east side, where the railroad has cut through it (Fig. 13). Donner (1949) reports that at the time of his visits, cinders were actively being mined from this location and used as railroad ballast. Volcano is composed almost exclusively of red scoria. The layers of cinders dip inward (Fig. 13) rather than outward like at Crater, likely because this eruptive source was forming on a steep slope of Rock Creek canyon and much of the cinder material, along with basalt, was pouring immediately into the canyon. Visual inspection of exposed walls in both Crater and Volcano indicate that Volcano contains

Figure 13. Photo of Volcano looking northwest from Crater. Railroad cut exposes inward dipping internal bedding. Farm buildings in foreground are same buildings visible in Figure 9.

relatively more blocks interbedded with the lapilli than Crater. It is unclear from the surface expression how much volcanic material was erupted from Volcano relative to extrusions from Crater.

ii. Basaltic Lava Flows

The basaltic lava flows that erupted from Crater and Volcano during the Pleistocene have distinct features that resemble aa lavas rather than pahoehoe. Aside from the vesicles of the scoraceous material occurring at the source, vesicle shapes among the basalts are very irregularly shaped. The basalts also lack the lava tubes that are common in pahoehoe flows. Instead, a number of outcrops reveal lava levees and typify the open channel flows of aa lavas.

The intraflow structures of these basalts are consistent with the structural cooling patterns that have been recognized in tiered basaltic lava flows studied by Spry (1962), Saemundsson (1970), Long and Wood (1986), and DeGraff and Aydin (1987): a brecciated flow top, an upper colonnade, an entablature, a lower colonnade, and a basal zone that is highly fractured or pillowed with hyaloclastite (Fig. 4). Figure 14 depicts an outcrop of a tiered flow within the McCoy basalts that consists of a lower colonnade of well-formed columns, an entablature of thin and irregular-shaped columns, and an upper colonnade of larger wavy columns.

While the occurrence of colonnades in the McCoy basalts indicates where the lavas experienced undisturbed conductive cooling, the occurrence of entablatures, hyaloclastites, and pillow basalts indicate where cooling was assisted by aqueous chilling. Based on the occurrences of hyaloclastites and pillow basalts at the base of many of the outcrops that neighbor Rock Creek and Egeria Creek (Figs. 6, 7), these lavas flowed into their pre-eruption drainage systems when water was present. A most conspicuous feature due to their large sizes and presence among the outcrops is the occurrence of entablatures, which provides supporting evidence for such an event to have occurred since the source of water that created the rather tall and extensive entablatures originated from flood events of these two fluvial systems after they were impounded by the lava flows.

The vast majority of the outcrops occur along the western edge of the flow extent, having been carved by Rock Creek and Egeria Creek since emplacement. Also along the western edge

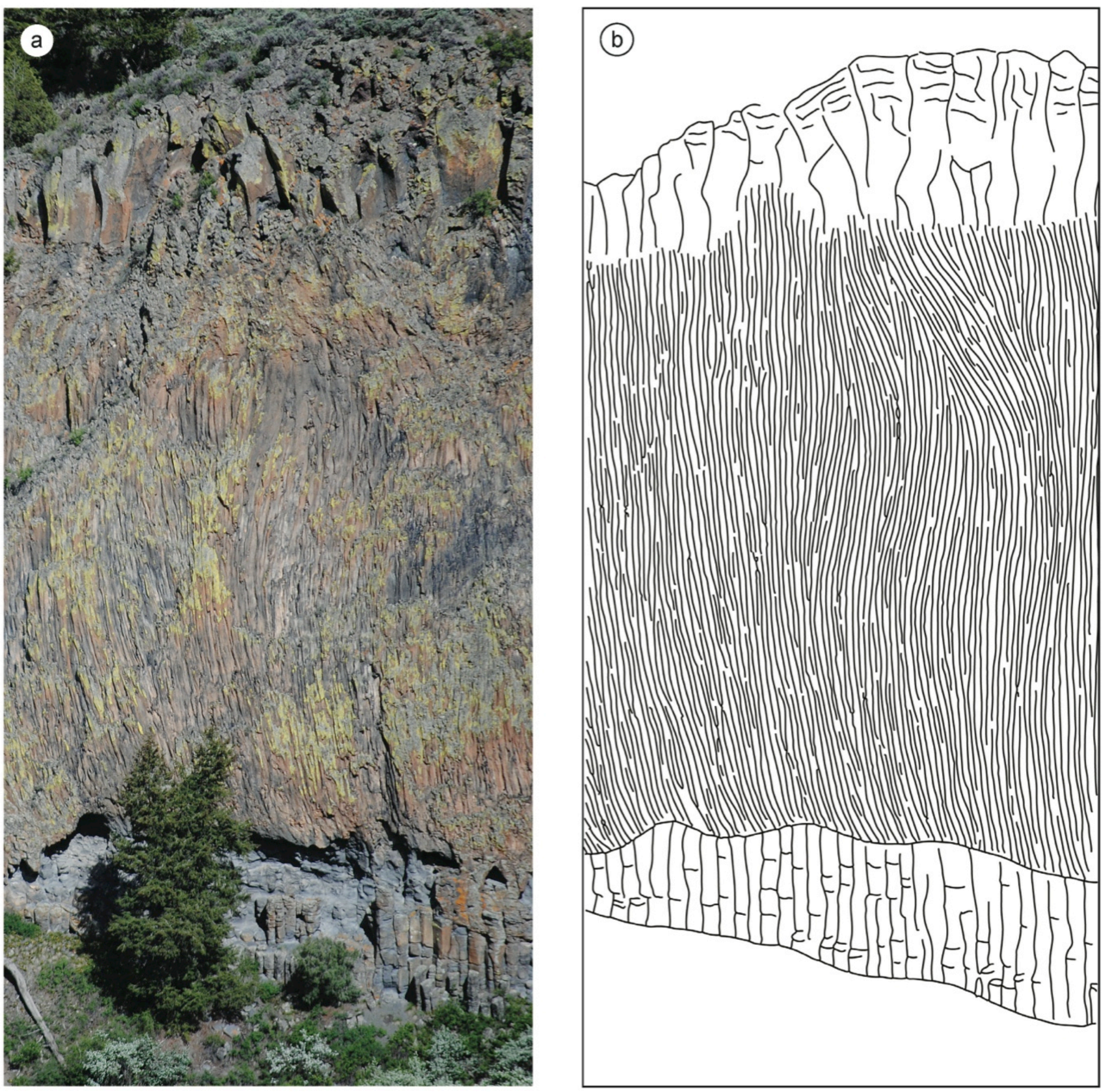


Figure 14. Typical tiered flow in the McCoy basalts. Outcrop height is around 150 feet. This exposure is a part of the tiered flow shown in Figure 9. a. Photo showing lower colonnade, entablature, and upper colonnade in the tiered flow. b. Sketch of the tiered flow showing major joint surfaces among the three structural zones.

of the flows is a large mass of dipping Paleozoic strata that separates the basalts occurring in sections 19 and 20 T1S R83W from those in section 17 T1S R83W (Fig. 2). The absence of basalt exposures between these two areas spans just over a half-mile. Using the intraflow structures as a guide, a sequence of flow events is established for the basalt outcrops occurring within the study area outlined in Figure 2. Because of the lack of exposures in sections 16 and 21 T1S R83W it is unclear how individual basalt flows may correlate in between the two areas of separated exposures, so each area is interpreted and discussed separately regarding its flow sequences.

The basalts of the southern zone include those that make up the west, south, and east walls of the butte which straddles sections 19 and 20, along with the extensive exposure to the east of the butte across Rock Creek valley in section 20 (Fig. 15). The northern zone includes the basalts exposed along the east canyon wall of Rock Creek from section 17 northward into the southern portion of section 8 (Fig. 15). The tiered basaltic lava flows in these zones show complex patterns in many of the outcrops that can be a representation of a multi-tiered flow of one flow event, one-tiered and two-tiered flows of a series of flow events, or a combination of both. DeGraff and Aydin's (1987) cooling direction criteria was utilized as the primary method for differentiating tiered flows and distinguishing flow events.

a. Southern Zone

The basalts in the southern zone (Fig. 15) best constitute a series of stacked one-tiered and two-tiered flows. The one-tiered flows occur as a suite of stacked colonnades, where each colonnade ranges 10 to 20 feet in height. Figure 16a shows an exposure of a suite of stacked colonnades ranging up to 100 feet tall. Lateral boundaries are apparent at the margins of each of the colonnades, dividing the suite into approximately five separate colonnades (Fig. 16b). Rather than a structural boundary between the colonnades that clearly defines separate flow events, many of the individual colonnades appear to integrate with its surrounding colonnades at the margins (Fig. 16a). Here, columns show irregular shapes and orientations because their morphologies become influenced by surrounding flows during cooling (Fig. 16a). This suggests the time elapsed between flow events was short enough to not allow any significant weathering of the flow tops.

Plumose structures are apparent among the colonnades situated towards the bottom of the exposure and demonstrate upward cooling directions (Fig. 17). Thus, these accessible colonnades are lower colonnades. It is uncertain if all of the colonnades at this exposure are

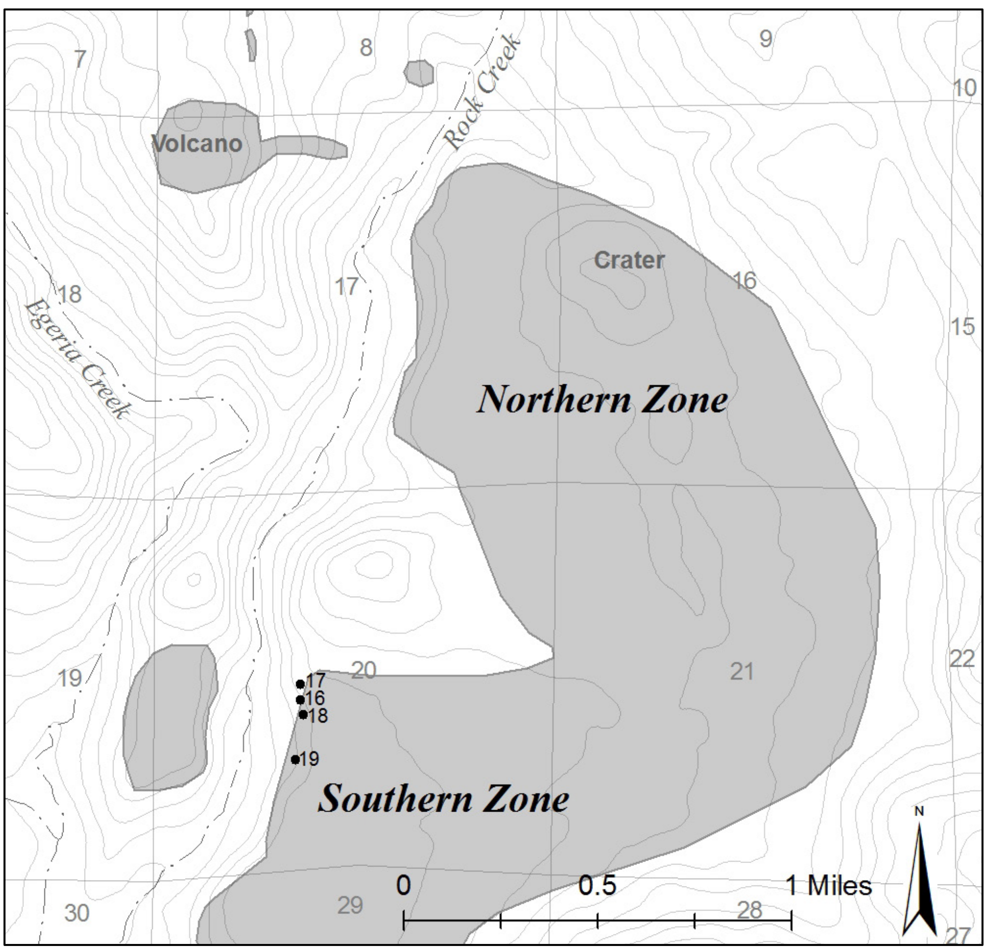


Figure 15. Location map of the study area for figures within the southern zone as identified by their figure number.

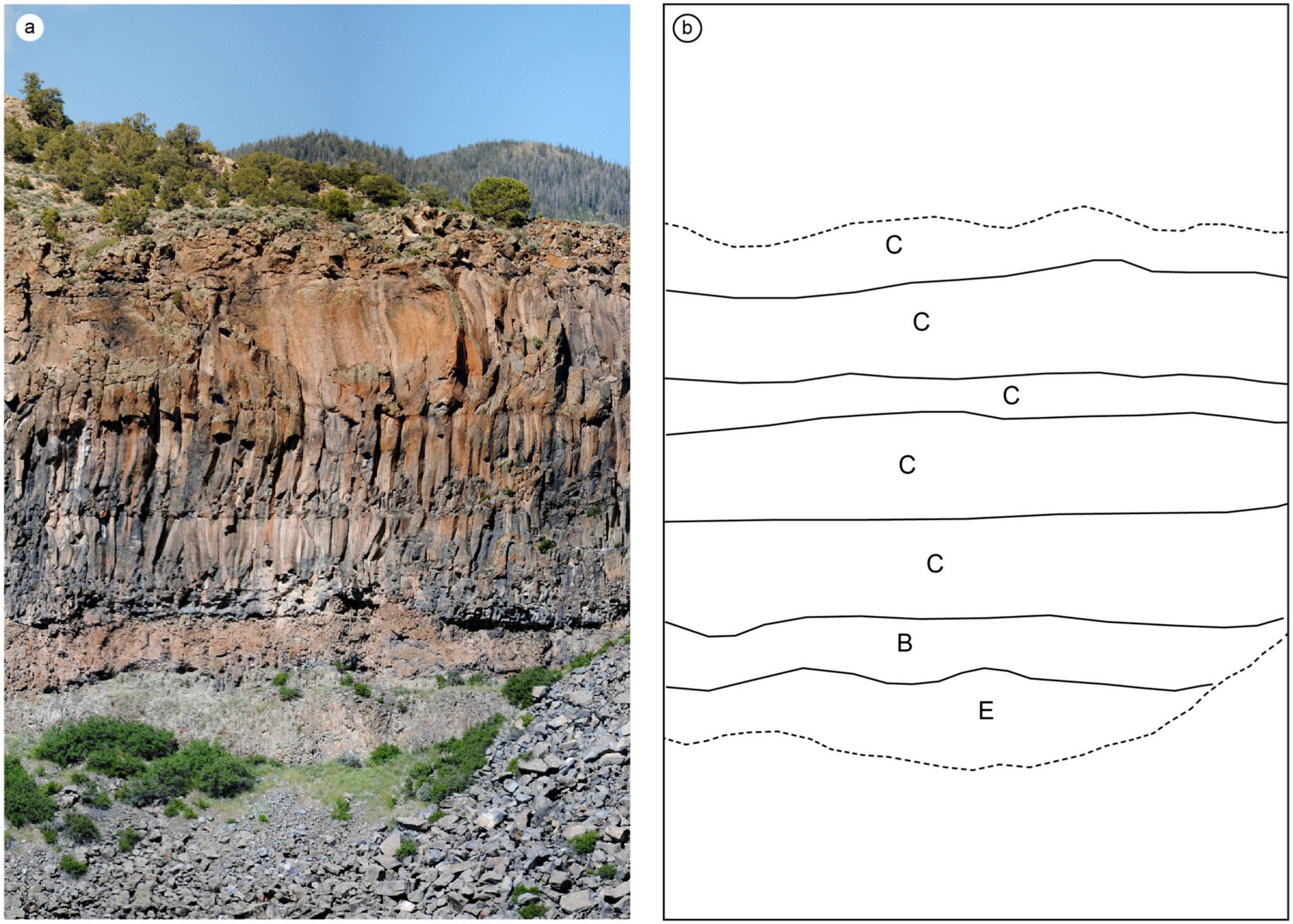


Figure 16. Interpretation of intraflow structures among a section of tiered flows within the southern zone. a. Series of stacked colonnades overly a brecciated zone and an entablature. Boundaries between each colonnade coalesce, wheras boundaries of the flow breccia and entablature are well-defined. b. Inferred intraflow structures. Symbols represent colonnade (C), breccia (B), and entablature (E). Dotted lines outline the outcrop. Solid lines are inferred boundaries between intraflow structures.

lower colonnades since plumose structures could not be observed among the inaccessible upper-most colonnades. Assuming the upper-most colonnades are also lower colonnades, the suite of colonnades can be divided into five one-tiered flows.

The two-tiered flows are significantly taller than the individual colonnade layers described previously, ranging 50 to 100 feet. Each two-tiered flow consists of a lower colonnade and an entablature, where the entablature comprises approximately 80 percent of a flow's thickness. Many of the two-tiered flows in the southern zone seemingly lack upper colonnades since entablatures are frequently overlain by the lower colonnades of other two-tiered flows. However, some of the entablatures of two-tiered flows are overlain by colonnades that may be an upper colonnade belonging to the same two-tiered flow or a lower colonnade of a separate one-tiered flow. It is unclear which circumstance may apply, because these colonnades are often too high upon the exposure to observe a cooling direction for the plumose structures. The plumose structures among colonnades that are situated directly beneath entablatures consistently demonstrate upward cooling directions, making them lower colonnades. The cooling direction of plumose structures among the thin and hackly columns of entablatures is seen in one entablature for the entire study area (Figs. 16, 18). These plumose structures are situated towards the top of the entablature and expectantly demonstrate downward cooling directions.

Due to its higher resistance to erosion (Long and Wood, 1987), entablatures often protrude over lower colonnades as overhanging cliffs, making the boundary where the two meet very distinct (Fig. 19). Also because entablatures have a higher resistance to erosion, where a lower colonnade rests upon an entablature of another two-tiered flow forms a very recognizable boundary, which delineates the margins of a flow and marks a separation between flow events. However, similar to the behavior of one-tiered flows, flow margins are more obscure where a

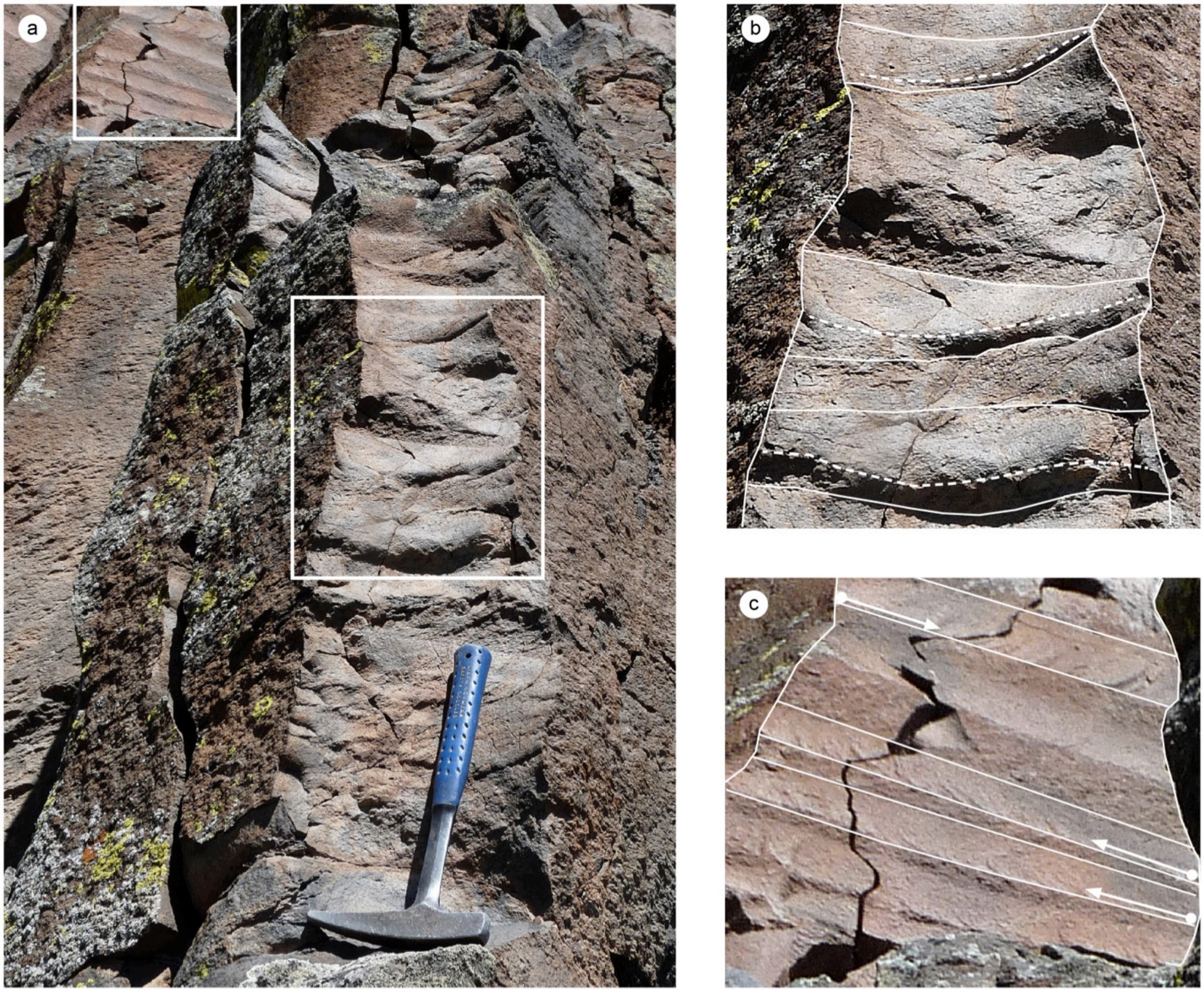


Figure 17. Interpretation of plumose structure growth directions of column faces on colonnades located near a flow base in Figure 16. a. Horizontal bands appear among column faces. Each band is a plumose structure that represents individual crack formed during cooling. Rectangles outline b and c. b. Solid lines outline the column face and individual plumose structures. Overhangs delineate plume axes as shown by dotted lines. Each axis is situated towards the bottom of the plume indicating upward cooling directions. c. Solid lines outline the column face and individual plumose structures. Arrows are on the plume axes and show propagation directions as determined by the hackle (short curved lines located towards the bottom of the plume). Dots show crack origins. Axes and origins are situated at the bottom of the plume indicating upward cooling directions.

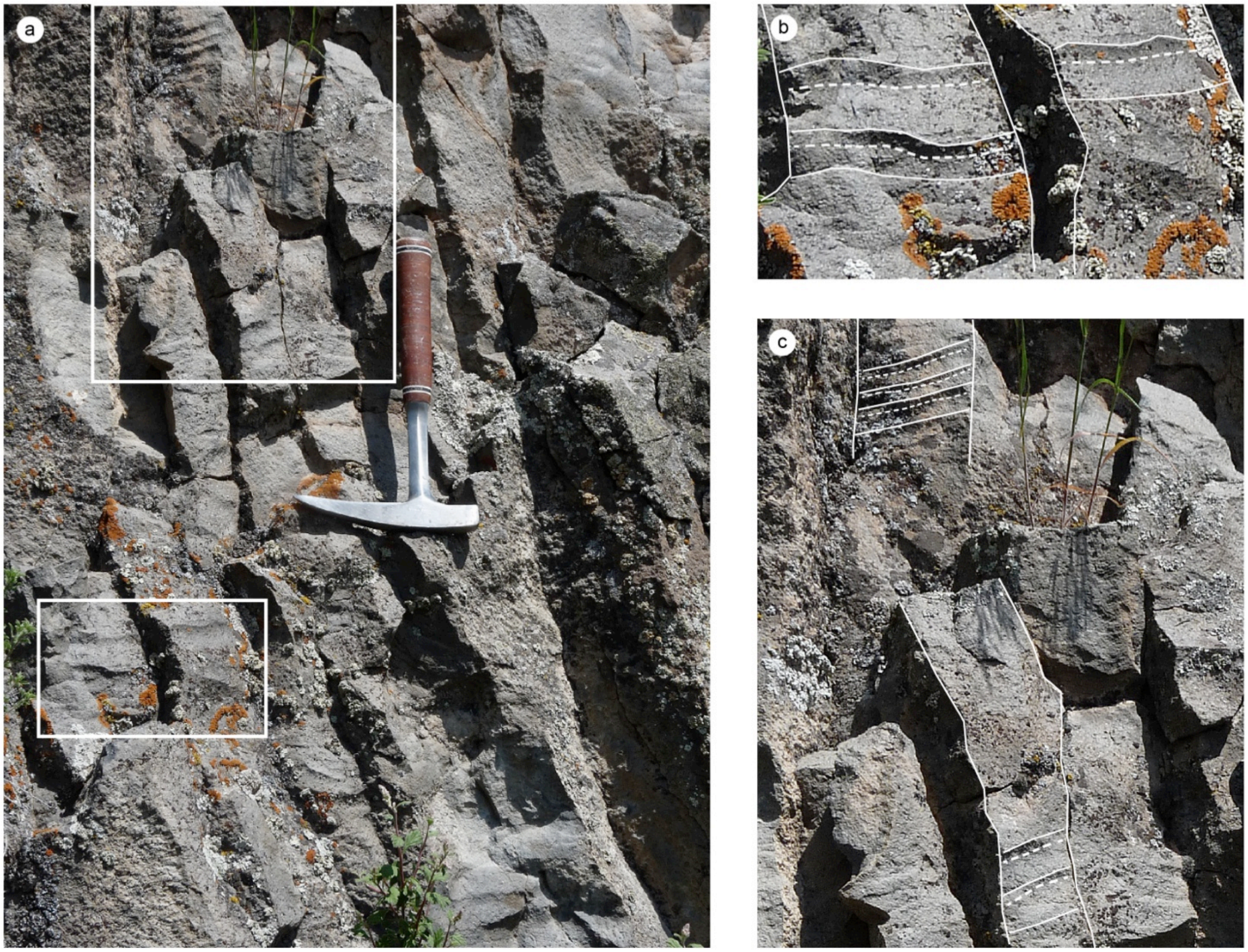


Figure 18. Interpretation of plumose structure growth directions of column faces on an entablature located in Figure 16. a. Horizontal bands appear among column faces. Rectangles outline b and c. b, c. Solid lines outline the column faces and individual plumose structures. Ledges delineate plume axes as shown by dotted lines. Each axis is situated towards the top of the plume indicating downward cooling directions.

lower colonnade of a two-tiered flow overlies a colonnade of a one-tiered flow as columns of each colonnade inter-finger.

The basalts in the southern zone exhibit many peculiar arrangements of tiered flows that suggest the lava rheology was rather complex. Figure 20 shows a complicated sequence of colonnades occurring along the south wall of the butte that drape over entablatures and stack on

Figure 19. Boundary between entablature and lower colonnade pronounced by the entablature's overhanging cliff.

top of other colonnades. Donner (1949) was the first to describe the peculiar arrangement of tiered flows along the south wall of the butte and suggested that an entablature and overlying colonnade comprise a single flow within the sequence of flows represented on the south wall of the butte (Fig. 21). However, although his explanation of a single flow here is similar to that of a two-tiered flow, recent workers such as Saemundsson (1970), DeGraff and Aydin (1987), and Long and Wood (1986) explain a two-tiered flow must contain a lower colonnade and an overlying entablature. As such, the peculiar arrangement of intraflow structures occurring along

Figure 20. Photo of the south wall of the butte. Located in the southern zone, it shows a complicated sequence lava flows given the complicated arrangement of entablatures and colonnades.

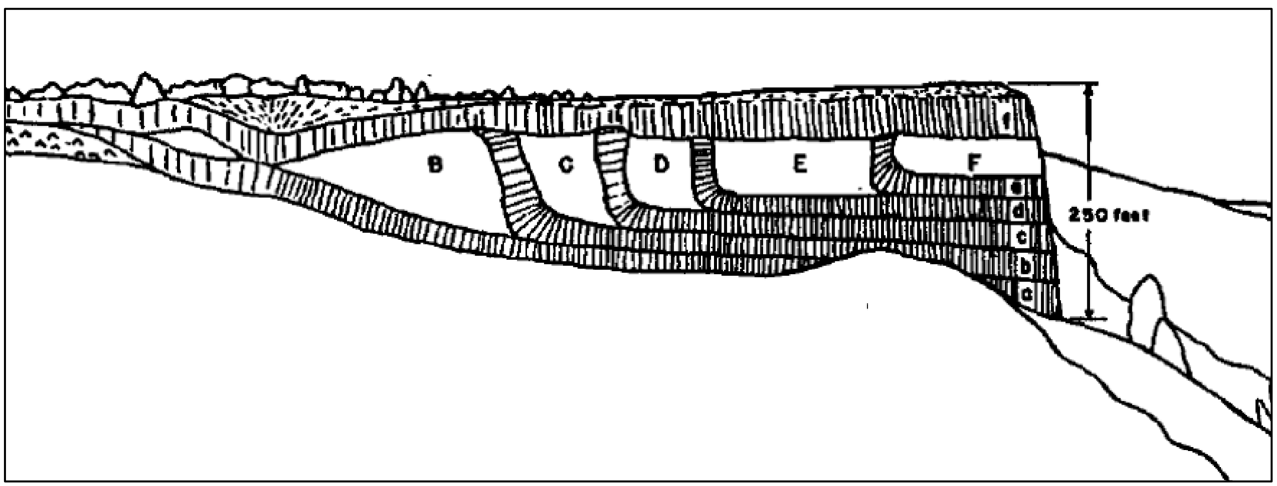


Figure 21. Donner's (1949) interpretation of flow events along the south wall of the butte. The parts of the lava labeled with capital letters are assumed to be parts of the flows labeled with the same lower case letters.

the south wall of the butte (Fig. 20) show a sequence of two-tiered flows that develop into one-tiered flows where the entablatures disappear.

Additionally, Donner (1949) interprets the tiered flows along the south wall of the butte as it relates to lava rheology. He suggests the exposure is composed of a series of stacked lava flows poured over older lava levees. Donner (1949) explains that the lava levees remained as its flow center continued to drain, alluding to an open channel flow mechanism. Once the first flow had been established, the succeeding flows continued along the drained lava channels, confining themselves to its previous flow's stagnant levees, where subsequent flows also formed similar open channel flows within the confinements of the previous flow's channel walls.

The different intraflow structures are used in this study to decipher Donner's (1949) interpretation of the south wall of the butte. Since lava rheology and surface conditions largely govern the development of intraflow structures, the joint morphologies and arrangements of intraflow structures within the flow package are useful elements for determining the behavior of each lava flow. When the center of an open channel flow drains out, the static marginal levees that remain become the thickest portions of a basalt flow preserved in outcrop (Lipman and Banks, 1987). Of the flows among the south wall of the butte, the thicker two-tiered flows containing an entablature and lower colonnade are representative of the lava levees. Where the two-tiered flows merge into significantly thinner one-tiered flows marks the remaining channel floors of drained open channels.

Figure 22a illustrates the sequence of flow events that have been preserved along the south wall of the butte. Flow A was the first to flow through the southern zone (Fig. 22a). As such, it infilled the paleovalley of Egeria Creek, forming a tilted colonnade as it conformed to its valley walls (Fig. 23). It formed a levee in the center of the figure spanning up to 80 feet thick with near-vertical channel walls as shown by the two-tiered flow and developed an open channel that drained out as shown by the one-tiered flow that extends east of the levee representing the remaining channel floor. After flow A had drained out, flow B later infilled the valley of flow A forming similar levees against its near-vertical channel walls and drained open channels at the flow's center. The levee of flow B occurs on the south wall of the butte as the two-tiered flow directly east of flow A, where a near-vertical zone of horizontal colonnade columns has formed against flow A's near-vertical channel walls. Flow B's channel bottom extends eastward from its levee as a one-tiered flow directly overlying the channel bottom of flow A. Subsequent flows C, D, and E similarly occupied the valleys of its preceding flows, forming levees and drained open channels that are respectively represented by their two-tiered and one-tiered flow structures.

A similar arrangement of flows A through E is visible on the east wall of the butte and on the wall to the east of Rock Creek (Figs. 22b, c). The flows outlined on the south wall of the butte are projected onto the outcrops based on the order of their arrangements and the elevations of the contact between each flow's lower colonnade and entablature. Elevations for these contacts were obtained using Leica Vector 1500 rangefinding laser binoculars, and data were taken at points near the preceeding flows for consistent readings across all data. The upper most entablature located along all three walls belongs to flow E (Figs. 22a, b, c). The entablatures of flows D, C, B, and A also occur at the three outcrops (Figs. 22a, b, c) with each flow's entablature-lower colonnade contact about 5 to 10 feet lower in elevation than its succeeding flow (Table 1). This elevation pattern is consistent on all three walls. The contact between flow A and B on the wall east of Rock Creek is covered by talus as shown by the approximate contact drawn in Figure 22c. Entablature-lower colonnade contacts average the same elevation across

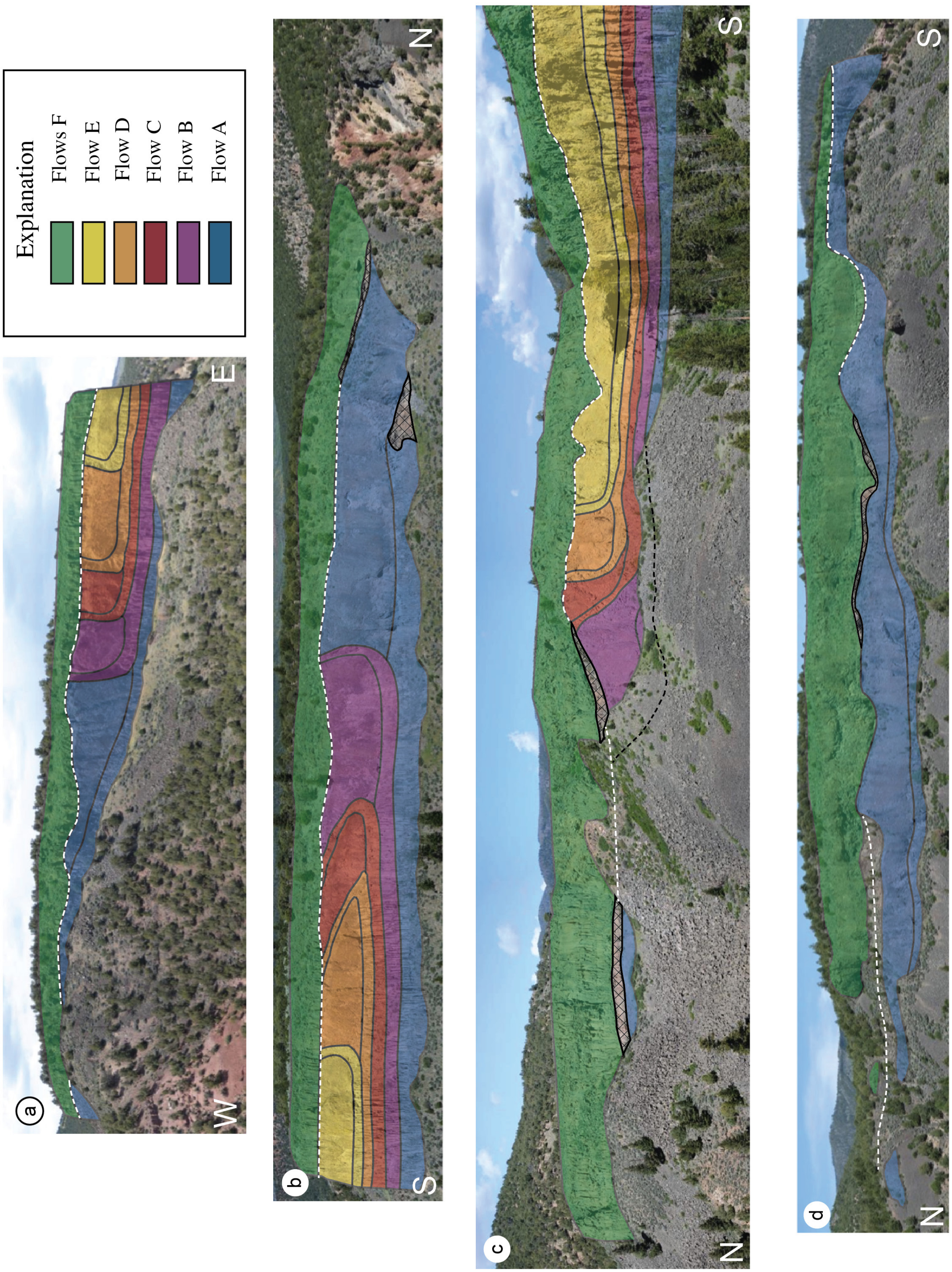

Explanation
Flows F
Flow E
Flow D
Flow C
Flow B
Flow A
a
W
E
b
S
N
c
N
S
d
N
S

Figure 22. Interpreted sequence of flow events for the exposures within the southern zone. Flows A through F are indicated by their respective colors. White dotted line indicates an approximate contact between the flows of F and its underlying flows. Crosshatch pattern represents breccia zones and is direct evidence for direct contacts between flow events. a. Flow sequences occurring along the south wall of the butte. This same wall is shown in Figs. 20 and 21. Exposure is 190 feet at its thickest. b. Flow sequences occurring along the east wall of the butte. Exposure is 205 feet at its thickest. c. Flow sequences occurring along the wall to the east of Rock Creek. Black dotted line in the center of photo indicates an approximate contact between flow A and B since the contact is covered by talus. Exposure is 190 feet at its thickest. d. Flow sequences occurring along the west wall of the butte. Exposure is 165 feet at its thickest.

flows E, D, and C at the south and east walls of the butte (Table 1). This seems plausible since they are at a proximal distance because of the positions of the exposures. However, the elevations across flows A and B are more distant between the south and east wall, so these contacts at the south wall average about 5 feet higher than those at the east wall (Table 1). The elevations for the entablature-lower colonnade contacts for flows B, C, D, and E on the east side of Rock Creek valley occur approximately 5-10 feet lower than those on the south and east walls of the butte (Table 1).

Based on each flow's spatial and morphological relationships, Figure 23 was constructed to show how flows A through E progressed through the changing topography. Flow A is shown to flow south through the paleovalley of Rock Creek and, additionally, turn east and back up into the paleovalley of Egeria Creek (Fig. 23). Flows B, C, D, and E show a similar path, confined to the levee walls, following the drained open channels of its previous flow, and backing up into the paleovalley of Egeria Creek (Fig. 23). This is evidenced by the higher elevations of the entablature-lower colonnade contacts amongst the butte near the paleovalley of Egeria Creek (Table 1).

After flow E, the lava valley created by drained open channel flows had now become completely filled, and the ensuing flows now capped and spread across the solidifying levees of

Table 1. Elevation of contact between the lower colonnade and entablature for flows A through E (feet).

	Flow				
Location	A	B	C	D	E
South wall of the butte	7255	7260	7270	7280	7290
East wall of the butte	7260	7265	7270	7280	7290
Wall east of Rock Creek	covered	7250	7260	7270	7280

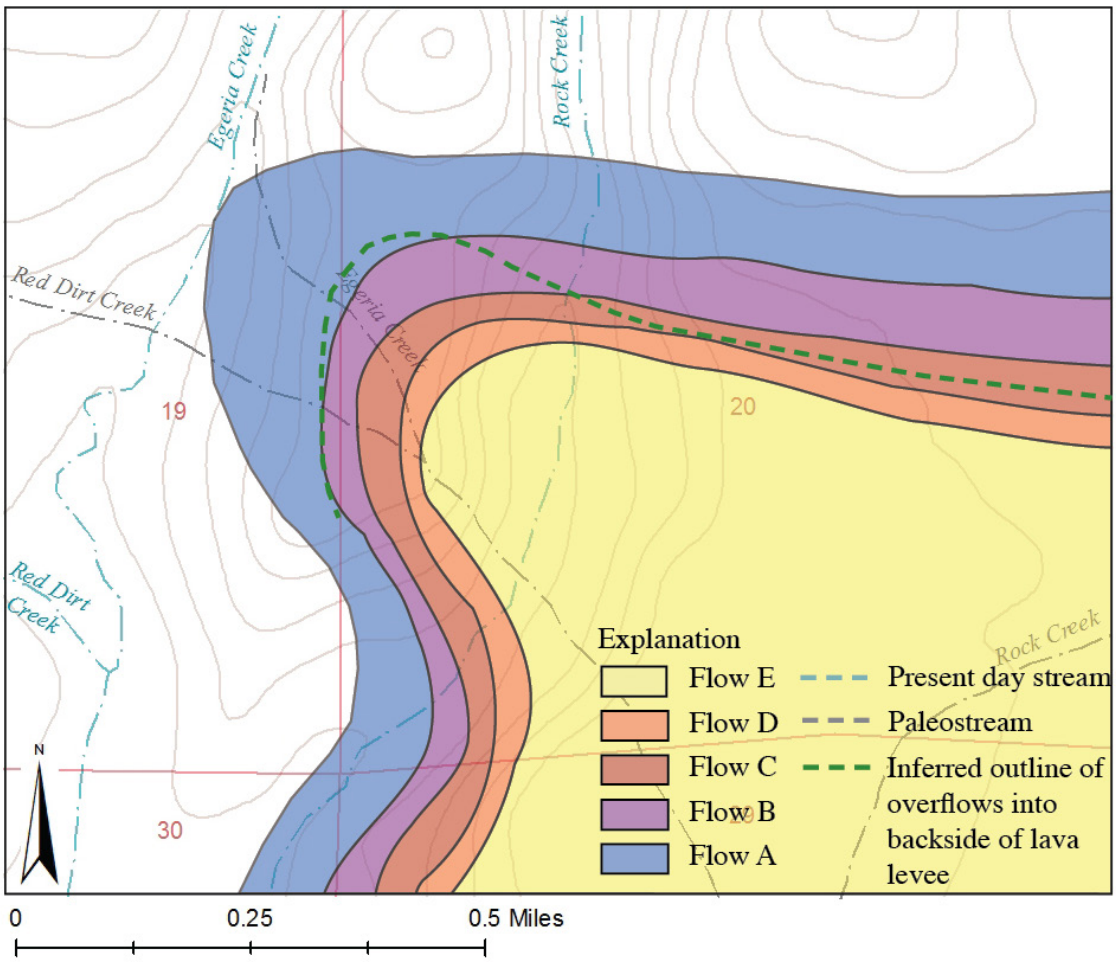


Figure 23. Plan view of flow paths as each flow progressed southward from Crater and Volcano. Diagram does not include flows of F since these flows spread laterally across the tops of its preceding flows. Green dashed line indicates the highest points among all of the entablatures projected across each of the exposures, which illustrates where spillover into the back-sides of the levees occurred. Topography represented is from Fig. 8b.

its former flows. These younger flows are predominantly one-tiered flows. Similar to the stacked colonnades of the previous flows, the columns of these flows coalesce with the columns of its surrounding flows, which make it difficult to differentiate separate flow events. Therefore, these flows have been grouped together and illustrated by the outline of F. Although cooling directions were not observed among the colonnades in F, the lower-most colonnade that directly overlies and caps the preceding flows may actually be the upper colonnade of flow E. When flow E filled the lava valley, excess lava may have spread laterally across the flow top. Because it is unclear whether or not flow E has an upper colonnade, an approximate contact is drawn between flow E and the younger flows F across much of the outcrops (Figs 22a, b, c, d). In areas where flow breccias occur between these flows marks a direct contact (Figs, 22b, c, d).

Flow breccias occur on the backsides of the lava levees of flow A and B on the wall to the east of Rock Creek and flow A on the east and west wall of the butte (Fig. 22b, c, d, 16). This suggests that when the flows began backing into Egeria Creek at the time of the eruption, water flow from Egeria Creek became dammed and began forming a pool against the lava levees. The flow breccias that formed signify this damming event. After flow E completely filled the lava-filled valley, the flows of F began capping the flow tops, pouring over the backs of the oldest levees, and flash freezing to create these brecciated basalts (Fig. 23). Additionally, the flows that preceded the younger flows of F may have also spilled over onto the back-sides of the levee walls if their volume exceeded the constraints of the previous flow’s drained open channel. The complex morphology of the flows of F occurring on the west wall of the butte signify the intermittent spill-overs that took place once the lavas began flowing across the flow tops (Fig. 22d). These complex features may also include spill-overs from flows A through E, however.

Figure 23 demonstrates where the flows spilled into the back-side of the lava levees using the interbedded flow breccias and highest points of entablatures occurring at each of the outcrops.

b. Northern Zone

The outcrops occurring in the northern zone (Fig. 24) host predominantly two-tiered flows. Most of the two-tiered flows in this zone are significantly thicker than those in the southern zone, ranging up to 150 feet thick. This is likely due to the fact that these flows are much closer to the source than the flows in the southern zone (Fig. 24); flow volume builds up near the source and thins and spreads laterally as flow progresses. Like the two-tiered basaltic lava flows in the southern zone, all of the two-tiered flows in the northern zone consist of a lower colonnade and an entablature, where the entablature comprises most of the flow's thickness. However, some of the basalts in this zone also show a clearly defined upper colonnade. Although plumose structures among these upper colonnades were not accessible, the columns are much thicker and wavier than the columns of the corresponding lower colonnades (Figs. 14, 25). Additionally, these upper colonnades are seen wrapping around the edge of the flow and merging with the thinner, well-formed columns of the lower colonnade (Fig. 25).

Also like the flows of the southern zone, the flows in the northern zone show a complicated morphology that suggests the lava rheology was similarly complex. The two northern most exposures each show a single two-tiered flow morphology (Fig. 26a). However, the large and extensive exposure directly south shows an arrangement of two-tiered flows (Fig. 26b) similar to those found in the southern zone (Fig. 22). This suggests that the lava levee-channel relationship that was interpreted for the southern zone may be applied to this area of the northern zone.

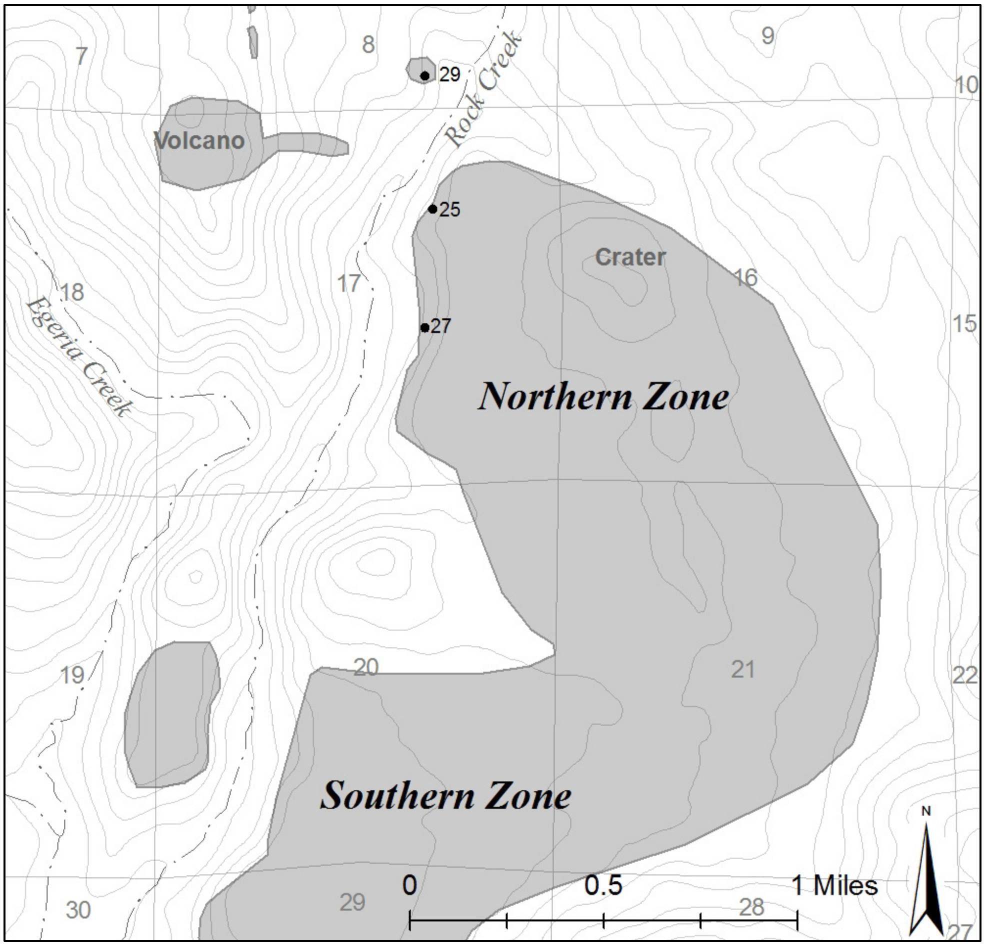


Figure 24. Location map of the study area for figures within the northern zone as identified by their figure number. Topography represented is from Fig. 8b

Plumose structures located among lower colonnades that directly underlie three separate entablatures of the large, extensive exposure in Figure 26b show upward cooling directions (Fig. 27) and delineate flows I, II, and III (Fig. 26b). Plumose structures were not identified on the lower colonnade of flow IV. However, based on the pattern interpreted in the southern zone (Fig. 22) and its similar morphology at this outcrop, flow IV has been interpreted as a separate flow rather than a multi-tiered flow within flow III (Fig. 26b). The one-tiered flows occurring in the northern zone represent the remaining channel floors of the lava flows, whereas the two-tiered flows represent the remaining lava levees or undrained lava channels (Fig. 26b). Like the

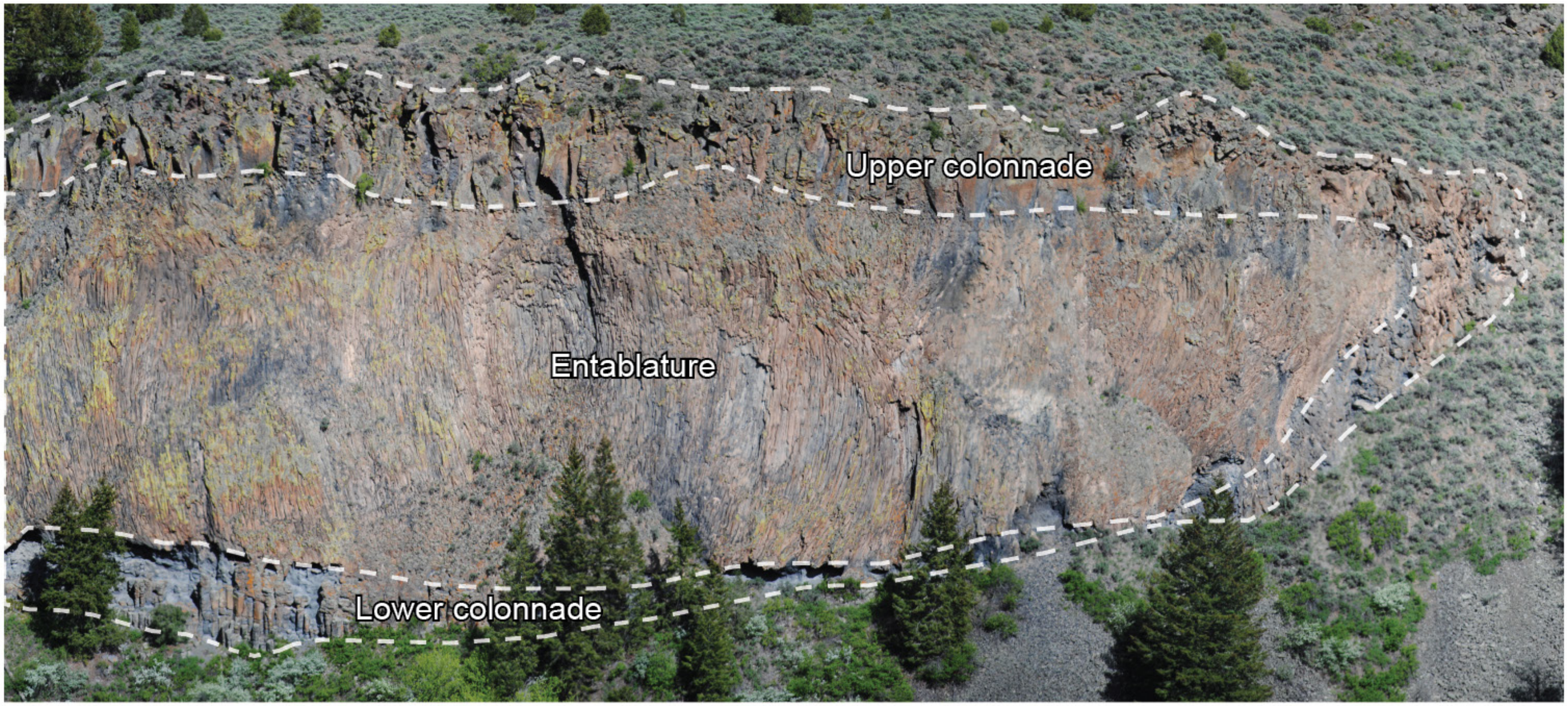
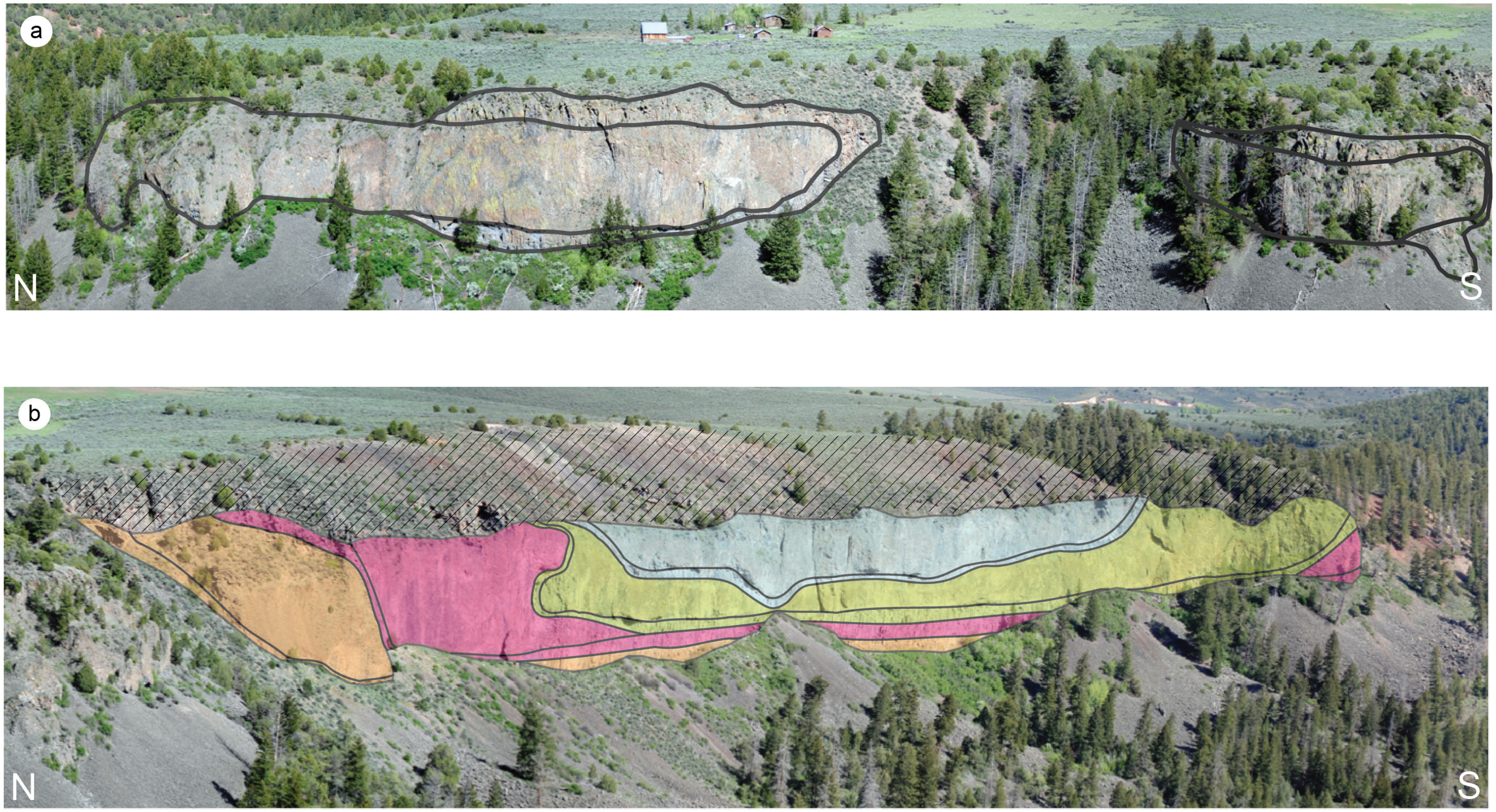


Figure 25. Outcrop in the northern zone displaying a well-defined upper colonnade, entablature, and lower colonnade. Height of outcrop spans up to around 150 feet.



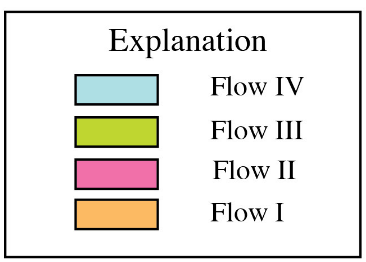


Figure 26. Interpreted sequence of flow events for the exposures within the northern zone. a. Black line outlines colonnades and entablatures of two isolated basalt exposures, each displaying two-tiered flow morphology. Farm buildings in upper background are same buildings visible in Figs. 9 and 13. Exposure is approximately 150 feet at its thickest. b. Flow sequences occurring on large exposure east of Rock Creek and south of exposures in Fig. 26a. Line pattern indicates the steep covered slope of weathered basalt. Exposure is approximately 160 feet at its thickest.

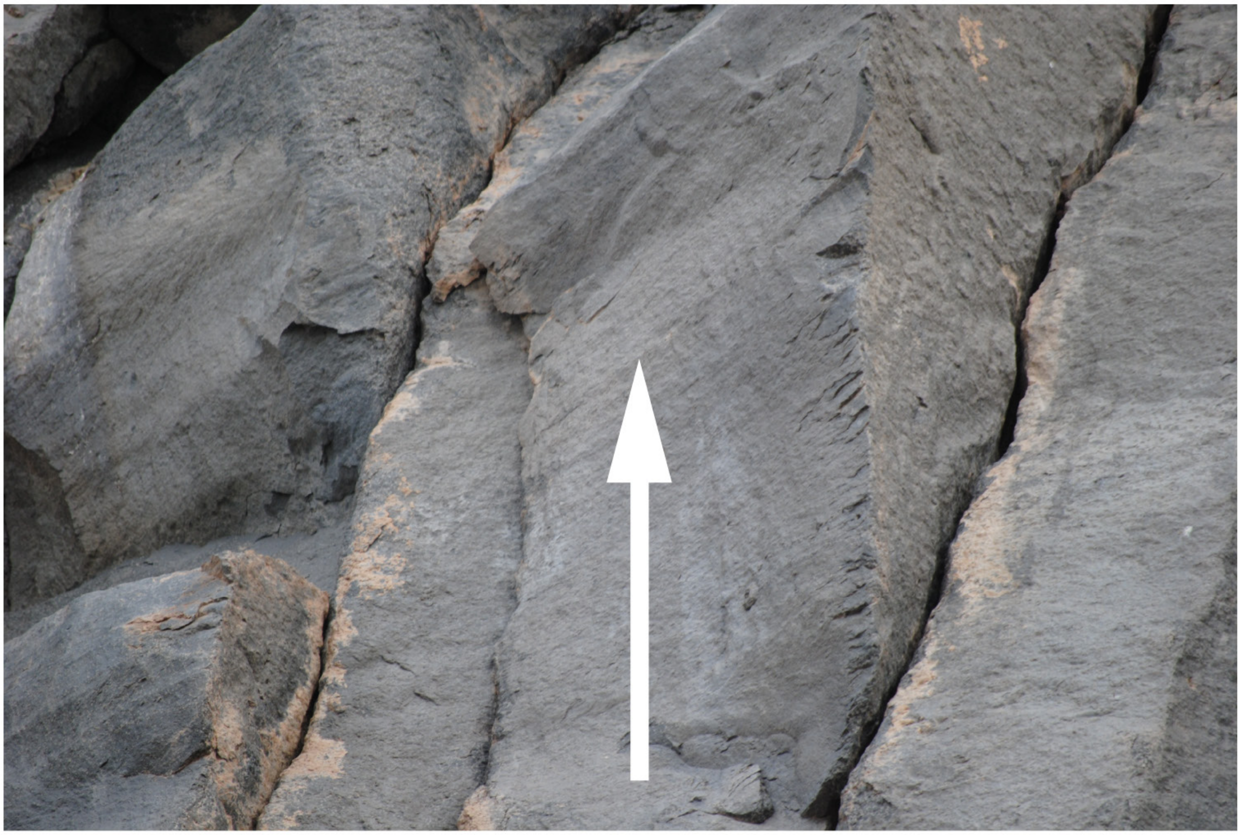


Figure 27. Fringe occurring along the right edge of the column face indicate an upward cooling direction.

flows of the southern zone, the boundaries of these flows often blend together suggesting the time between flow events is comparable to those in the southern zone.

Since there are no basalt exposures to the west of Rock Creek at similar elevations (Fig. 24), these exposures are proximal to the western flow extent for the flows that erupted from Crater. Figure 26b illustrates the sequence of flow events that occurred on the large, extensive wall to the south of the two isolated basalt outcrops shown in Figure 26a. Flow I (Fig. 26b) is the first of these four flows, which backed up into the paleovalley of Rock Creek and continued to drain southward down the valley. The flow formed a tilted colonnade along the valley walls and a large levee along the north side of the paleovalley as seen by the two-tiered flow (Fig.

26b). As the flow drained south, a single colonnade developed representing the remaining channel floor (Fig. 26b). A levee at the south side of the paleovalley in section 17 was not observed for flow I (Fig. 26b). Flow II backfilled into the emptied lava channel of flow I forming two levees and a drained open channel at the flow center as flow II progressed southward (Fig. 26b). The levee to the north is significantly larger than the levee to the south, with near-vertical zone of horizontal colonnades columns against its near-vertical channel walls. Additionally, the northern levee formed overhanging walls as seen by the s-shaped lower colonnade of flow III (Figs. 26b, 28), which conformed to the levee walls when backfilling into the drained open channel of flow II. Flow III lacks a one-tiered colonnade portion of the flow that is representative of the lava channel floor (Fig 26b). It remains a two-tiered flow across the exposure but thins near the flow center, so it is assumed that flow III had not completely drained when flow IV back-filled into its active lava channel.

After completely filling the lava valley created by open channel flows, flow IV may have capped and spread across the solidifying levees of its preceeding flows. However, it is uncertain since all that remains above the exposure is an approximate 75-degree covered slope of weathered basalt that extends roughly 40 feet above the outcrop (Fig. 26b). Since entablatures have a higher resistance to erosion than colonnades, the covered slope of weathered basalt may be a series of one-tiered flows that capped and spread laterally across the solidifying levees – similar to those in the southern zone – that eroded away while the more resistant two-tiered flows remained intact.

The two basalt exposures to the north of the large, extensive exposure (Fig. 26a) each show a single two-tiered flow with an upper colonnade that wraps around its entablature along sloping paleovalley walls to become a lower colonnade (Fig. 25). A smaller outcrop of a two-

Figure 28. Dashed white line delineates the overhanging levee wall of flow II.

tiered flow showing only the entablature and lower colonnade features occurs just 50 feet to the northwest of the northwest margin Crater (Fig. 24). These three occurrences suggest that the lava erupted from Crater flowed into two tributaries of paleo-Rock Creek (Fig. 8a, 24) in addition to backing up and flowing into Rock Creek itself. In order for a single two-tiered flow morphology to have developed, the lava that flowed into the tributaries must have pooled and remained stagnant rather than be allowed to drain and leave only stagnant marginal levees. The smaller constraint and their positions relative to Rock Creek may have caused these tributaries to pool rather than drain out. It remains unclear whether these three occurrences belong to the same flow or are of separate flow events, or whether these three occurrences belong to any of the flows outlined in Figure 26b.

Figure 29. Photo of a small basalt outcrop occurring along the west side of Rock Creek in section 8. The outcrop's thickness averages 40 to 70 feet. Leadville Limestone exposures are visible in the lower quarter of this photo.

The small basalts on the west side of Rock Creek north of Crater occur at elevations higher than the large exposures to the east. Two small outcrops with two-tiered flow morphology occur in section 8 (Figs. 24, 29), and the base of these basalts occur 40 to 80 feet higher than the base of the large exposure to the east. A small outcrop with a blocky appearance occurs west of Rock Creek in section 17 T1S R83W, and the base of these basalts occur 50-60 feet higher than the top of the large exposure on the east side of Rock Creek. This flow likely erupted from Volcano, which is located 200 feet above this outcrop and 100 feet to the west. The blocky morphology suggests these lavas were rather mobile while cooling – likely flowing down the steep slopes below Volcano – and did not remain stagnant to develop the well-behaved columns so common among the other outcrops. It is unclear whether the small outcrops within section 8 T1S R83W resulted from the lavas erupted from Volcano to the west or the backing up of lavas erupted from Crater to the east.

V. FLOOD EVENTS AND COOLING RATES

i. Flood Events

The varying intraflow structures among tiered basalt flows are representative of a flow's cooling history and thus provide insight for the environment into which the lavas were emplaced. Entablatures are particularly important features for they signify a quenched flow center formed by an event that induces more rapid cooling than the undisturbed conductive cooling mechanism that forms the commonly occurring colonnade structures. The most likely explanation for such an event to occur is for water from the environment to invade the solidified part of the cooling lava flow along propagating cooling joints (Saemundsson, 1970; Long and Wood, 1986).

Egeria Creek and Rock Creek are the likely source of water that formed the entablatures within the McCoy basalts. The thick flows that erupted from Crater and Volcano rapidly invaded these stream valleys and caused temporary damming and disruption of the drainage systems. Within a short period, perhaps a few months to a year, water topped the cooling lava flows, and influx into the solidified portion of the flows along joints and cracks increased the cooling rates. The thin channel bottoms and other one-tiered flows had already solidified into well-formed colonnades at the time of water ingress and were unaffected by the increased cooling rates. However, much of the thick levees were apparently still molten when flooding occurred, resulting in the remaining cooling lava to rapidly quench and form entablatures. Because multi-tiered flows do not occur in the Pleistocene basalts at McCoy, the lavas and the southern zone and northern zone were probably quenched by a single flood event from Egeria Creek and Rock Creek, respectively.

Because joints develop perpendicular to isotherms, it is possible to identify where within the flows water ingress occurred. All joints are arranged near-vertical at the top of the entablatures within the McCoy basalts, which indicates that water entered from the solidified flow top. Much of the entablatures show near-vertical jointing throughout the entablature exposure (Fig. 30), with the exception of many of the entablatures that developed within the lava levees (Fig. 31). These joints range from vertical to near-horizontal within a single exposure (Fig. 31). This change in orientation suggests that in addition to water flowing along columnar joints near the flow top, water flowed downward along fractures between the channel walls and its succeeding flows, altering the isotherm pattern.

Figure 30. Near-vertical joints across the extent of an entablature occurring along the east Rock Creek valley wall within the southern zone.

ii. Streamflow Impoundment Analysis

A model of the dam that obstructed stream flow from pre-eruption Rock Creek was constructed to assess the amount of time it would take for Rock Creek (and by implication Egeria Creek) to fill its valley as a reservoir before overtopping the obstruction and flooding the tops of the basalt flows. In order to model the time required to fill that reservoir, a number of parameters need to be assumed: the location and height of the lava dam, the shape of Rock Creek valley prior to the eruption, and pre-eruption Rock Creek's discharge rate. Using these estimated parameters will allow one to calculate the volume of water and, essentially, the time required to fill the reservoir and pour across the top of the basalt flows.

Figure 31. Joints of entablatures along the south wall of the butte oriented near-vertical near the top of the flow and near-horizontal to the east (right side in photo) where the entablature meets the lower colonnade of the succeeding flow.

The dam is positioned between the valley walls of present-day Rock Creek at the northern boundary of section 17 T1S R83W (Fig. 32). The location was chosen as it represents the northernmost occurrence of basalt within the Rock Creek drainage. Assuming the canyon north of the dam appears much like present-day Rock Creek canyon (except at a higher elevation), the current topography of the U.S. Geological Survey (1972) 1:24,000 topographic map is used to mimic the shape of the former canyon (Fig. 32). The top of the levee is assigned an elevation of 7,600 feet, which is the approximate elevation for the top of the highest known

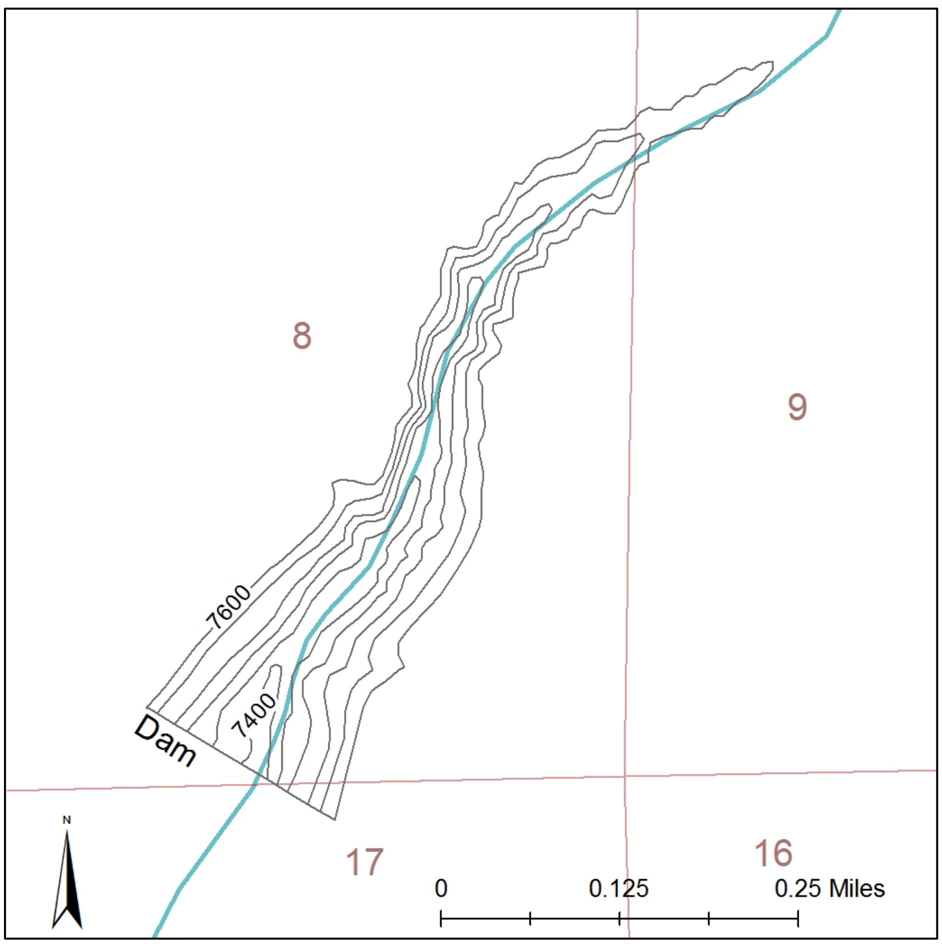


Figure 32. Model of pre-eruption Rock Creek with lava dam. Top of dam positioned at 7,600 feet elevation. Contour lines (feet) mimic present topography of Rock Creek valley (U.S. Geological Survey, 1972). Contour lines above 7,600 feet not shown. Contour interval 40 feet.

basalt exposure in this area. Mimicking the existing topography, 7,600 feet replaces the 7,400-foot contour line shown at this location in Figure 8b. The bottom elevation of the dam and pre-eruption Rock Creek is at 7,400 feet, which is the approximate bottom elevations of the basalt exposures in the area. Hence, 7,400 feet replaces the 7,200-foot contour line in Figure 8b. The area within each contour line extending north of the dam was calculated using ArcGis 10.0 software, and each area was multiplied by the contour interval to determine volume. Each interval's volume was then summed for an estimation of the total volume of water required to fill the reservoir, which amounts to 126 million cubic feet.

Discharge rates of pre-eruption Rock Creek must be used to determine the time required to fill the dammed valley to the level where flooding would initiate across the basalt flow tops. Assuming discharge rates of pre-eruption Rock Creek are similar to present rates of discharge, a range of time is estimated using the highest and lowest mean monthly discharge rates for Rock Creek measured near Crater between October 1984 and September 1999 (U.S. Geological Survey, 2014). The lowest mean monthly discharge rate of these 180 months occurred in August 1990 at 1.55 cubic feet per second (cfs), and the highest occurred in May 1997 at 305 cfs. These discharge rates yield a time range of a minimum of 5 days and a maximum of 2.6 years for water to completely fill the Rock Creek reservoir and inundate the basalt flow tops. Rock Creek's discharge rate assumingly would not remain at 1.55 cfs for an approximate 3-year period, so the lowest mean annual discharge rate could be used to determine the maximum reservoir filling time instead of using the lowest mean monthly rate. The lowest mean annual discharge rate for Rock Creek occurred in 1990 at 17.8 cfs, which amounts to a maximum time of 82 days. Therefore, the flood event that quickly solidified the still-molten lava levees and filled open channels and created the large and extensive entablatures within the McCoy basalts most likely occurred within 5 to 82 days (about one week to 3 months) after the eruption.

iii. Cooling Rate Analysis

In order to explain quenching of a lava flow's center by flood water ingress, Long and Wood (1986) developed models that illustrate the cooling history of a 40-meter-thick basalt flow by both conductive cooling and convective cooling. Thermal properties used in these model calculations include thermal diffusivity, density, heat capacity, latent heat, and thermal conductivity. In Long and Wood's (1986) models (Fig. 33), temperature is plotted as a function of dimensionless time (kt/l^2), which enables a single set of curves to be applied to flows of any thickness. Their results for a lava flow cooling purely by conduction show an expected cooling history, where the central parts of the flow cool more slowly through the solidus than do the top and bottom margins (Fig. 33a). They concluded that the quenching of the flow center that is evident in two-tiered and multi-tiered flows cannot occur if the flow cools in an undisturbed conductive manner.

As undisturbed conductive cooling cannot explain rapid quenching of the flow center, Long and Wood (1986) also developed a model that mimics convective removal of heat by water (Fig. 33b). Water is a viable medium for removal of heat by convection from within the flow due to its high heat capacity, latent heat of vaporization, and low viscosity. In this model, water penetrates the solidified part of a flow to the upper solidus, and the lava is instantaneously quenched to freezing temperature at that depth. Assuming a continuous influx of water, the quenching interface follows the solidus down through the lava flow, quenching the melt to freezing temperature as it continues to cool and pass through the solidus. Long and Wood (1986) initiates flooding at $kt/l^2 = 0.015$ (Fig. 33b) where lava is instantaneously solidified as

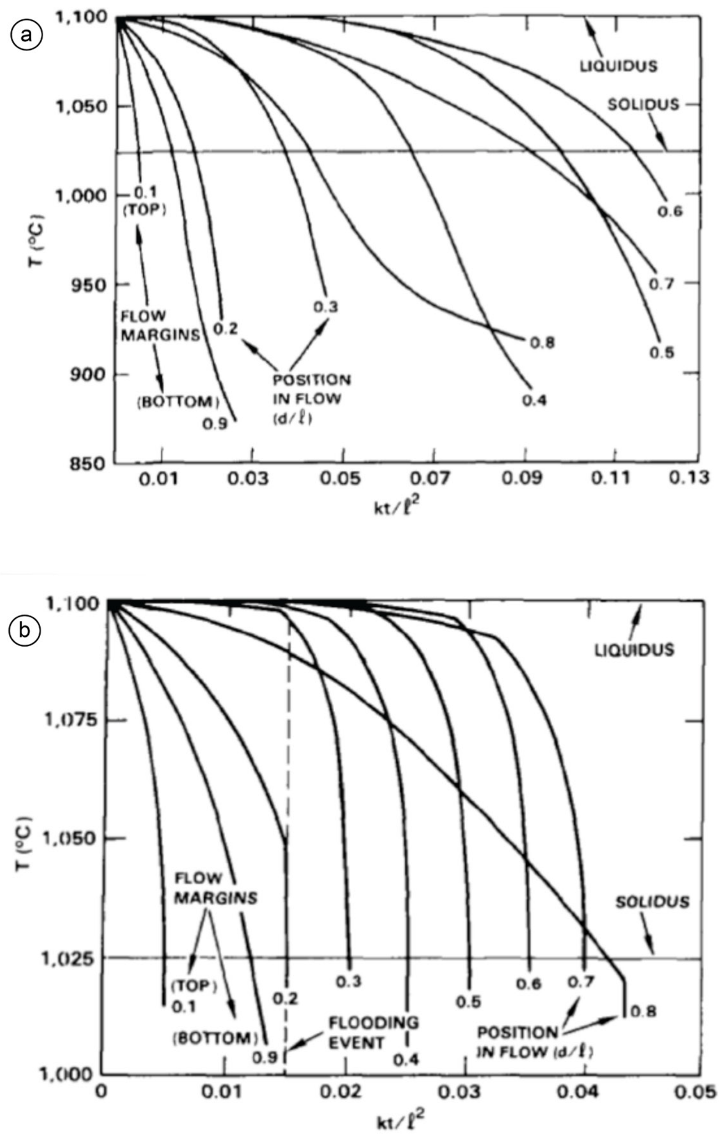


Figure 33. Cooling history for different relative positions in a flow. Temperature plotted versus dimensionless time. Curves are for relative positions in a flow. T = temperature, k = thermal diffusivity, t = time, l = flow thickness, d = position of flow measured from top. a. Cooling is solely by conduction. b. The effect of a single flooding event with progressive movement of quenching interface on the cooling history of a flow. Flooding initiated at $kt/l^2 = 0.015$ (Long and Wood, 1986).

soon as a particular depth reaches the solidus. With the continuously migrating quenching front, the model's results show a rapidly quenched zone comprising 50 percent of the flow thickness (d/l = 0.2 to 0.7) interpreted as the entablature, two rapidly cooled zones (d/l = 0.1 and 0.9) interpreted as the flow top and flow bottom, and a slowly cooled zone (d/l = 0.8) interpreted as the lower colonnade (Fig. 33b). The contact between the entablature and the lower colonnade represents the position where the upper solidus meets the lower solidus and solidification of the flow is complete (Long and Wood, 1986).

Long and Wood's (1986) model for a basalt flow experiencing convective cooling (Fig. 33b) may be applied to the basaltic lava flows at McCoy to estimate the time taken to solidify.

Table 2. Calculations for the McCoy basalts within the southern zone based on Long and Wood's (1986) convective cooling model[b]

Location[a]	d/l	l (m)	kt/l^2	t (y)
Flow A				
SB	0.8	30	0.042	3.0
EB	0.8	30	0.042	3.0
WB	0.8	27	0.042	2.4
Flow B				
SB	0.8	27	0.042	2.4
EB	0.8	30	0.042	3.0
Flow C				
SB	0.8	26	0.042	2.3
EB	0.8	26	0.042	2.3
EW	0.8	24	0.042	1.9
Flow D				
SB	0.8	24	0.042	1.9
EB	0.8	23	0.042	1.8
EW	0.8	18	0.042	1.1
Flow E				
SB	0.8	18	0.042	1.1
EB	0.8	20	0.042	1.3
EW	0.7	18	0.040	1.0

[a]SB is the south wall of the butte. EB is the east wall of the butte. WB is the west wall of the butte. EW is the wall to the east of Rock Creek
[b]Refer to Figure 33 for explanation of other symbols

This value is significant because it places an upper limit for the time elapsed before the impounded water inundates the basalt flow tops. It is important to note, however, that in Long and Wood's (1986) model, flooding is initiated at $kt/l^2 = 0.015$ and the flow immediately becomes quenched between $d/l = 0.1$ and 0.2. The flows at McCoy may have experienced slightly different conditions than those modeled in Figure 33b, so the time intervals determined using the model may vary from those that occurred in the McCoy flows.

For each two-tiered flow within the southern zone at McCoy, thickness (l) was measured at the thickest portion of the flow (Table 2). The contact between the entablature and lower colonnade, which is the position of the flow at the point of complete solidification (d/l), was also measured for each of these flows (Table 2). Using the point where the position curves (d/l) intercepts the solidus on Long and Wood's (1986) model allows one to determine the value for dimensionless time (kt/l^2) (Fig. 33b, Table 2). Once determined, kt/l^2 can be manipulated to estimate the time taken for each flow to completely solidify.

Thicker flows take longer to completely solidify than the thinner flows (Table 2). In the 30-meter-thick flows A and B of the southern zone (shown in Fig. 22), the moving water front would make the flow completely solid in approximately three years, whereas the 20-meter-thick flow E would take approximately one year to solidify (Table 2). In comparison, using the Long and Wood (1986) pure conduction cooling model (Fig. 33a), the 30-meter-thick flows would completely solidify in about 8 years and the 20-meter-thick flow would completely solidify in 3 to 4 years. Additionally, because all the two-tiered flows within the southern zone were quenched by the same flood event and the shortest time for complete solidification is approximately one year, it can be inferred that flooding of the flow tops within the southern zone must have occurred within about one year after the eruption event.

VI. CONCLUSIONS

Prior to the volcanism that occurred north of McCoy, Colorado, the area's physiography during the Pleistocene probably appeared much like it does today. Rock Creek, Egeria Creek, and Red Dirt Creek were the major active drainage systems in the area. Today, around five miles of ancient Rock Creek is buried beneath basaltic lava flows, as well as smaller segments of the old channels of Egeria Creek and Red Dirt Creek. The topography prior to the eruption was determined by locating intraflow structures and other features that indicate being at or near the paleosurface, including hyaloclastites composed of basalt and bedrock fragments, basalt in direct contact with in-place bedrock and gravel-filled paleochannels, and bedrock – in-place or float – and stream-rounded gravel float occurring near basalt.

The 0.66 Ma volcanic eruptions that occurred at McCoy produced two cinder cones, Crater and Volcano, composed of red and black scoria lapilli. Their height-to-basal-width ratios (0.11) are similar to other Pleistocene cinders at various localities worldwide (Hooper and Sheridan, 1998; Inbar and Risso, 2001; Wood, 1980). Based on the absence of massive basalt proximal to Volcano and because the base of Volcano is approximately 300 feet higher than the top of the basalts that are exposed across Rock Creek valley, Crater probably produced most, if not all, of the lava flows that currently occupy the paleovalleys.

Upon exiting the vent(s), basaltic lavas preferentially flowed south along the old fluvial system of Rock Creek. Some lava flowed north up Rock Creek's paleovalley and down into smaller tributaries, but most of it returned south. As flow progressed southward and intersected the old fluvial system of Egeria Creek, some flow was diverted west where it backed up into Egeria Creek's paleovalley, but again continued to drain south following Rock Creek's old drainage before flow finally ceased.

The basalts at McCoy show characteristics that define these as aa lava flows. Characteristic rubbly surface textures and irregularly shaped vesicles commonly occurred near the flow tops. Additionally, peculiar arrangements of intraflow structures occurring along many of the exposures signify that these lavas flowed as open channels, which is another distinctive feature of aa lavas. Open channel flows consist of stagnant lava levees and fluid lava channels, in which many of the channels drain out. Open channel flows are identified by the two-tiered flows, which makes up the channel levees, that transition into thinner one-tiered flows, which represent the channel bottom. When the open channel flows at McCoy drained out with the levees remaining, subsequent flows followed the paths of the drained open channels and the confinements of the lava levees. This process is evident along many of the outcrops at McCoy as complicated sequences of colonnades that drape over entablatures and stack on top of other colonnades.

Once the lava valley(s) reached its capacity, the succeeding flows spread laterally, thinning and capping the tops of the cooling lava flows to form one-tiered flows. The lavas within the southern zone also poured over the backsides of the lava levees where they pooled and formed a basal hyaloclastite layer overlain by a thick sequence of one-tiered flows or a complicated sequence of two-tiered flows.

The eruption event likely lasted a matter of a few weeks. There is no evidence of any significant weathering or sediment deposition between individual flows that would indicate a long time period, and many of the columns appear to integrate and coalesce with columns of separate colonnades, suggesting the time between flow events was short enough to prevent significant cooling. Additionally, cinder cones are frequently built rapidly, often reaching their final heights in just a few days (Wood, 1980), and there is no evidence that Crater and Volcano behaved any differently.

When the lava flows invaded the old drainage systems of Rock Creek and Egeria Creek, they likely created dams that impounded stream flow. An analysis of the time required for Rock Creek (and by implication Egeria Creek) to fill its valley as a water reservoir before overtopping the obstruction and flooding the tops of the basalt flows yielded results indicating that the flood events occurred possibly within about one week to three months after the basalt emplacement. This estimate is dependent on a number of assumed parameters, including the location and height of the lava dam, the shape of Rock Creek valley prior to the eruption, and pre-eruption Rock Creek's discharge rate.

After flooding initiated, water penetrated the solidified portion of the lava flows along joints and fractures. At the time of water ingress, lava levees and undrained lava channels were still molten, while much of the thinner lava channel bottoms and other one-tiered flows that capped the flow tops had already solidified into colonnades. Water ingress increased the cooling rates of the still molten material, which solidified into entablatures. Using Long and Wood's (1986) model of convective removal of heat by water in a basalt, the flows at McCoy completely solidified within three years after the eruption. Additionally, some of these flows hosting entablatures may have taken just one year to solidify, thus the flood event occurred within about one year after the eruption event. This time estimate is consistent with the length of time required to fill the Rock Creek valley impoundment with water and begin water flooding.

Since the emplacement of the McCoy basalts, the topography has been altered due to continued stream incision of Rock Creek, Egeria Creek, and Red Dirt Creek. Rock Creek once occupied a valley that wrapped eastward around a northwest trending hill of Sawatch Quartzite. Since emplacement, this fluvial system has preferentially located to the western edge of the basalts, through the ridge of Sawatch Quartzite, finding it easier to erode either Precambrian rocks or the Paleozoic sedimentary rocks than these recently emplaced basalts. A small segment of Egeria Creek and Red Dirt Creek once flowed southeast through what is now occupied by the basalt butte, but these streams have also preferentially located to the western edge of the basalts since emplacement. Although all three streams were affected by the emplacement of the Pleistocene basaltic lava flows that erupted near McCoy, Colorado, it appears the geographic location for both Rock Creek and Egeria Creek outside of where the basalt occurs has not changed significantly since the Pleistocene except to cut vertically.

REFERENCES CITED

Armstrong, A.K., Mamet, B.L., and Repetski, J.E., 1992, Stratigraphy of the Mississippian System, South-Central Colorado and North-Central New Mexico: U.S. Geological Survey Bulletin 1787, 22 p.

Bailey, J.B., Harris, A.J.L., Dehn, J., Calvari, S., Rowland, S.K., 2006, The changing morphology of an open lava channel on Mt. Etna: Bulletin of Volcanology, v. 68, p. 497-515.

Budahn, J.R., Unruh, D.M., Kunk, M.J., Byers, F.M., Kirkham, R.M., and Streufert, R.K., 2002, Correlation of late Cenozoic basaltic lava flows in the Carbondale and Eagle collapse centers in west-central Colorado based on geochemical, isotopic, age, and petrologic data *in* Kirkham, R.M., Scott, R.B., and Judkins, T.W., eds., Late Cenozoic evaporite tectonism and volcanism in west-central Colorado: Boulder, Colorado, Geological Society of America Special Paper 366, p. 167-196.

Chester, D.K., Duncan, A.M., Guest, J.E., Kilburn, C.R.J., 1985, Mount Etna; the anatomy of a volcano: Stanford, California, Stanford University Press, 404 p.

Decker, R.W., and Decker, B., 1998, Volcanoes: New York, W.H. Freeman and Company, 321 p.

DeGraff, J.M., and Aydin, A., 1987, Surface morphology of columnar joints and its significance to mechanics and direction of joint growth: Geological Society of America Bulletin, v. 99, p. 605-617.

DeGraff, J.M., Long, P.E., and Aydin, A., 1989, Use of joint-growth directions and rock textures to infer thermal regimes during solidification of basaltic lava flows: Journal of Volcanology and Geothermal Research, v. 38, p. 309-324.

Donner, H.F., 1949, Geology of the McCoy area, Eagle and Routt Counties, Colorado: Geological Society of America Bulletin, v. 60, p. 1215-1248.

Favalli, M., Harris, A.J.L., Fornaciai, A., Pareschi, M.T., Mazzarini, F., 2010, The distal segment of Etna's 2001 basaltic lava flow: Bulletin of Volcanology, v. 72, p. 119-127.

Griffiths, R.W., 2000, The dynamics of lava flows: Annual Review of Fluid Mechanics, v. 32, p. 477-518.

Henderson, P., 1970, The significance of the mesostasis of basic layered igneous rocks: Journal of Petrology, v. 11, p. 463-473.

Hooper, D.M. and Sheridan, M.F., 1998, Computer-simulation models of scoria cone degradation: Journal of Volcanology and Geothermal Research, v. 83, p. 241-267.

Houck, K.J., 1991, Structural control on distribution of sedimentary facies in the Pennsylvanian Minturn Formation of North-Central Colorado: U.S. Geological Survey Bulletin 1787, 33 p.

Hulme, G., 1974, The interpretation of lava flow morphology: Geophysical Journal International, v. 39, p. 361-383.

Inbar, M. and Risso, C., 2001, Holocene yardangs in volcanic terrains in the southern Andes, Argentina: Earth Surface Processes and Landforms, v. 26, p. 657-666.

James, A.V.G., 1920, Factors producing columnar structures in lavas and its occurrence near Melbourne, Australia: Journal of Geology, v. 28, p. 458-469.

Kirkham, R.M. and Scott, R.B., 2002, Introduction to late Cenozoic evaporate tectonism and volcanism in west-central Colorado *in* Kirkham, R.M., Scott, R.B., and Judkins, T.W., eds., Late Cenozoic Evaporite Tectonism and Volcanism in West-Central Colorado: Boulder, Colorado, Geological Society of America Special Paper 366, p. 1-14.

Kucera, R.E., 1962, Geology of the Yampa District, northwestern Colorado [Ph.D. dissertation]: Boulder, University of Colorado, 844 p.

Larson, E.E., Ozima, M., and Bradley, W.C., 1975, Late Cenozoic basic volcanism in northwestern Colorado and its implications concerning tectonism and the origin of the Colorado River system: Geological Society of America Memoir 144, p. 155-178.

Leat. P.T., Thompson, R.N., Morrison, M.A., Hendry, G.L., and Dickin, A.P., 1988, Compositionally-diverse Miocene—Recent rift-related magmatism in northwest Colorado: Partial melting, and mixing of mafic magmas from 3 different asthenospheric and lithospheric mantle sources: Journal of Petrology, Special Volume 1, p. 351-377.

Leat., P.T., Thompson, R.N., Dickin, A.P., Morrison, M.A., and Hendry, G.L., 1989, Quaternary volcanism in northwestern Colorado: Implications for the roles of asthenosphere and lithosphere in the genesis of continental basalts: Journal of Volcanology and Geothermal Research, v. 37, p. 291-310.

Lidke, D.J., Hudson, M.R., Scott, R.B., Shroba, R.R., Kunk, M.J., Perry, W.J., Kirkham, R.M., Budahn, J.R., Streufert, R.K., Widmann, B.L., 2002, Eagle collapse center: Interpretation of evidence for late Cenozoic evaporite-related deformation in the Eagle River basin, Colorado *in* Kirkham, R.M., Scott, R.B., and Judkins, T.W., eds., Late Cenozoic Evaporite Tectonism and Volcanism in West-Central Colorado: Boulder, Colorado, Geological Society of America Special Paper 366, p. 101-120.

Lipman, P.W. and Banks, N.G., 1987, Aa flow dynamics, Mauna Loa 1984 *in* Decker, R.W., Wright, T.L., and Stauffer, P.H., eds., Volcanism in Hawaii: U.S. Geological Survey Professional Paper 1350, p. 1527-1567.

Lipman, P.W., and Mehnert, H.H., 1975, Late Cenozoic basaltic volcanism and development of the Rio Grande depression in the Southern Rocky Mountains: Geological Society of America Memoir 144, p. 119-154.

Lofgren, G., 1974, An experimental study of plagioclase crystal morphology: Isothermal crystallization: American Journal of Science, v. 274, p. 243-273.

Long, P.E., and Wood, B.J., 1986, Structures, textures, and cooling histories of Columbia River basalt flows: Geological Society of America Bulletin, v. 97, p. 1144-1155.

Lyle, P., 2000, The eruption environment of multi-tiered columnar basalt lava flows: Journal of the Geological Society [London], v.157, p. 715-722.

MacDonald, G.A., 1967, Forms and structures of extrusive basaltic rocks *in* Hess, H.H., and Poldervaart, A., eds., Basalts: The Poldervaart Treatise on Rocks of Basaltic Composition: New York, Interscience Publishers, p. 1-61.

Manson, V., 1967, Geochemistry of basaltic rocks: major elements *in* Hess, H.H., and Poldervaart, A., eds., Basalts: The Poldervaart Treatise on Rocks of Basaltic Composition: New York, Interscience Publishers, p. 215-269.

Martin, A.J. and Kelly, F.J., 1956, The Minerals Industry of Colorado *in* Minerals Yearbook Area Reports 1953: U.S. Bureau of Mines, v. 111, p. 235-273.

Nichols, R.L., 1936, Flow units in basalt: The Journal of Geology, v. 44, p. 617-630.

Rittmann, A., 1962, The ascent of magmas: Bulletin of Volcanology, v. 24, p. 315-318.

Rossi, M.J., 1997, Morphology of the 1984 open-channel lava flow at Krafla volcano, northern Iceland: Geomorphology, v. 20, p. 95-112.

Rowland, S.K., and Walker, G.P.L., 1990, Pahoehoe and aa in Hawaii: volumetric flow rate controls the lava structure: Bulletin of Volcanology, v. 52, p. 615-628.

Ryan, M.P. and Sammis, C.G., 1978, Cyclic fracture mechanisms in cooling basalt: Geological Society of America Bulletin, v. 89, p.1295-1308.

Saemundsson, K., 1970, Interglacial lava flows in the lowlands of southern Iceland and the problem of two-tiered columnar jointing: Jokull, v. 20, p. 62-77.

Soule, J.M., 1992, Late Precambrian to earliest Mississippian stratigraphy, geologic history, and paleogeography of northwestern Colorado and west-central Colorado: U.S. Geological Survey Bulletin 1787, p. U1-U35.

Sparks, R.S.J., Pinkerton, H., and Hulme, G., 1976, Classification and formation of lava levees on Mount Etna, Sicily: Geology, v. 4, p. 269-271.

Spry, A., 1962, The origin of columnar jointing, particularly in basalt flows: Geological Society of Australia Journal, v. 8, p. 191-216.

Tomkieff, S.I., 1940, The basalt lavas of the Giant's Causeway district of Northern Ireland: Bulletin of Volcanology, v. 6, p. 89-143.

U.S. Geological Survey, 2014, USGS surface-water monthly statistics for the nation: USGS 09060550 Rock Creek at Crater, CO: http://waterdata.usgs.gov/nwis/monthly/?format=sites_selection_links&search_site_no=09060550&agency_cd=USGS&referred_module=sw (July 2014)

U.S. Geological Survey, 1972, McCoy Quadrangle Colorado 7.5 minute series (topographic): U.S. Geological Survey, scale 1:24 000, 1 sheet.

Walker, G.P.L, 1993, Basaltic-volcano systems: Geological Society [London] Special Publications, v. 76, p. 3-38.

Wallace, A.R., 1995, Isotopic geochronology of the Leadville 1°×2° quadrangle, west-central Colorado—Summary and discussion: U.S. Geological Survey Bulletin 2104, 51 p.

Williams, H. and McBirney, A.R., 1979, Volcanology: San Francisco, California, Freeman, Cooper and Company, 397 p.

Wood, C.A., 1980, Morphometric analysis of cinder cone degradation: Journal of Volcanology and Geothermal Research, v. 8, p. 137-160.

Wood, C.A. and Kienle, J., eds., 1990, Volcanoes of North America: Cambridge, Cambridge University Press, 354 p.

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