

Episodic Soil Succession on Basaltic Lava Fields in a Cool, Dry Environment

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Holocene- to late Pleistocene-aged lava flows at Craters of the Moon National Monument and Preserve provide an ideal setting to examine the early stages of soil formation under cool, dry conditions. Transects were used to characterize the amount and nature of soil cover on across basaltic lava flows ranging in age from 2.1 to 18.4 ka. Results indicate that on flows <13 ka, very shallow organic soils (Folists in Soil Taxonomy) are the dominant soil type, providing an areal coverage of up to ~25%. On flows ≥ 13.9 ka, deeper mineral soils including Entisols, Aridisols, and Mollisols become dominant and the areal extent increases to $\geq 95\%$ on flows older than 18.4 ka. These data suggest there are two distinct pedogenic pathways associated with lava flows of the region. The first pathway is illustrated by the younger flows, where Folists dominate. In the absence of a major source of loess, relatively little mineral material accumulates and soils provide only minor coverage of the lava flows. Our results indicate that this pathway of soil development has not changed appreciably over the past ~10 ka. The second pedogenic pathway is illustrated by the flows older than 13.9 ka. These flows have been subject to deposition of large quantities of loess during and after the last regional glaciation, resulting in almost complete coverage. Subsequent pedogenesis has given rise to Aridisols and Mollisols with calcic and cambic horizons and mollic epipedons. This research highlights the importance of regional climate change on the evolution of Craters of the Moon soilscapes.

Abbreviations: cal ka, calibrated radiocarbon years; CM, Craters of the Moon lava field; COM, Craters of the Moon National Monument and Preserve; ESRP, Eastern Snake River Plain; KB, Kings Bowl lava field; WP, Wapi lava field; WRB, World Reference Base.

Succession from bare lava to soil that supports climax vegetation is largely dependent on the well-recognized factors of soil formation including climate, organisms, relief, parent material, and time (Jenny, 1941). Well-dated Holocene to late Pleistocene lava flows offer a unique and time-constrained setting within which to study the initial stages and progression of soil development.

The roles of lichens, mosses, and vascular plants as drivers of soil succession on lava flows have long been debated. In a study on weathering of basalt in Hawaii, Jackson and Keller (1970) found that 1000-yr-old lichen-covered basalts had a mean weathering thickness of 0.142 mm, while lichen-free basalts had mean weathering rinds 0.002 mm thick. Bashan et al. (2002) suggest that specific plants are responsible for the physical and chemical destruction of rock surfaces. Alternatively, Cooper and Rudolph (1953) suggest that the role of lichen and moss in succession has been exaggerated and that although these early rock colonizers are responsible for minor rock decay, they are not essential to the formation of soil. Weathering of basalt occurs very slowly as shown by using the values calculated by Jackson and Keller (1970), where more than 70,000 yr is required to form a 1-cm-thick weathering rind on lichen-covered basalt in a warm, humid climate. In addition, rate of weathering rind advance increases with increasing mean annual precipitation and mean annual temperature (Sak et al., 2004). This process occurs more slowly in cooler, drier climates. Consequently, soil formation on lava flows under these conditions may be enhanced by sources of parent material such

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as those transported by wind and water rather than underlying the basalt.

Soils dominated by organic material (>20% organic C) are identified on lava flows in Hawaii and Idaho (Soil Survey Staff, 2008; Vaughan and McDaniel, 2009). Hawaiian organic soils have been observed in warm, humid climates where plant biomass production exceeds decomposition. A unique group of soils characterized by the absence of saturated conditions and an arid moisture regime, Torrifolists, are also mapped on lava flows on the Hawaiian mainland (Soil Survey Staff, 2008). These soils are composed of partially decomposed organic detritus from overlying or adjacent vegetation. Organic soil formation on lava flows in the cool, arid climate of Idaho follow similar, albeit less rapid patterns of formation to those in Hawaii (Vaughan and McDaniel, 2009).

In this study, we examined soil succession along a chronosequence of Holocene to late-Pleistocene-aged basaltic lava flows in the semiarid to arid environment of Craters of the Moon National Monument and Preserve (COM) in the Eastern Snake River Plain (ESRP) of Idaho. The specific objectives of this research were: (i) to determine the relationship between lava flow age and the coverage and type of soil; and (ii) develop a model of soil succession on lava flows at COM.

MATERIALS AND METHODS

Study Area

The ESRP is a 300-km long, 100-km wide, east-northeast-trending topographic depression. Quaternary basalt covers approximately 95% of the surface of the ESRP (Kuntz et al., 1992) with significant loess, sand dune, lake, and fluvial deposits also present. Volcanic landforms including basaltic lava flows, shield volcanoes, fissure vents, and rhyolitic domes dominate the landscape. Many of the basalts on the ESRP erupted along northwest-trending volcanic rift zones. The largest of these rift zones is the Great Rift along which numerous lava flows were erupted in three lava flow fields, Craters of the Moon (CM), Kings Bowl (KB), and Wapi (WP), during the late Pleistocene to Holocene (Fig. 1). These lava flows provide an ideal situation for investigating soil formation as they have been extensively described and dated using radiocarbon and paleomagnetic studies (Kuntz et al., 1985, 1986a, 1986b, 1987, 1992; 2007). Lava flow ages range from 2.1 to >18.4 cal ka (calibrated using Stuiver et al., 2005; Stuiver and Reimer, 1993).

At 1600 km², the CM lava field is the largest dominantly Holocene basaltic lava field in the lower 48 states (Kuntz et al., 1992). The CM lava field contrasts with other lava fields in the ESRP because it is a composite, polygenic field composed of at least 60 lava flows and 25 tephra cones that formed during at least eight eruptive periods over the past 18.4 cal ka (Kuntz et al., 1986b, 2007). Most other ESRP lava fields are monogenic, with a single eruptive episode. The KB lava field is the smallest of the three fields and formed approximately 2.4 cal ka during a single fissure eruption and explosive episode (Kuntz et al., 1992). The WP lava field is identical in age to the KB lava field, however, it began as a fissure eruption that eventually produced a low shield volcano. Volcanic eruptions at COM were only locally explosive, depositing tephra (mostly cinders, lapilli, and coarse ash) <1 to 2 km from active vents. As a result most lava flows are not blanketed with tephra.

The composition of the basaltic lava throughout COM has been described in detail by Kuntz and others (1986a). Two morphologically different types of lava spread across the landscape at COM. Pahohoe is characterized as smooth, ropy lava that travels slowly and resists extensive tearing or fracture formation at the surface. A'a has a thick upper zone of loose clinkery debris that travels more rapidly creating extremely irregular surfaces. Soon after lava spreads across the landscape, it begins to cool and fractures form as a result of contraction.

Loess is extensive throughout the ESRP (Bettis et al., 2003) with late Pleistocene flows being influenced and subsequently buried to varying degrees by episodic loess deposition. Stratigraphic studies show that at least four loess units separated by buried soils are present (Pierce et al., 1982; Lewis and Fosberg, 1982; Bettis et al., 2003). The loess units are believed correlative with regional Rocky Mountain glaciations at approximately 160 to 140, 70 to 30, and 24 to 12 ka, while the soils represent intraglacial periods of relative landscape stability and low eolian input. Geomorphic surfaces younger than about 13 ka typically lack significant loess cover, therefore, Holocene lava flows within COM, are largely loess-free.

Mean annual air temperature ranges from 6°C in the north to 9°C in the south; mean annual precipitation ranges from 380 mm in the north to 240 mm in the south (Western Regional Climate Center, 2009). The distribution of soil moisture and temperature regime for mineral and organic soils on lava flows and rangeland across COM is complex due to the amplified effects of wind and exposure. Soil temperature regimes range from frigid to mesic while soil moisture regimes range from aridic to xeric (Fig. 1) (Soil Survey Staff, 2006). Mean wind directions for the COM area are southwest-west (between 225° and 270°) with average wind speeds of 2 to 3 m s⁻¹, decreasing to 1 to 2 m s⁻¹ during the summer (University of Idaho Library, 2000).

Elevation at COM ranges from 1800 m at the northern edge of the CM lava field to 1500 m at the southern margin of the WP lava field. Topographic relief on the lava flows at COM is minimal with slope gradients generally <1% except in localized areas of substantial deflation on select flows where the slope can range up to 90%. Deflation occurs in areas where lava flowed through a tunnel or tube below the lava surface. As the lava flow declined, the upper surface of the tunnel weakened and deflated to the existing lava surface.

Field Procedures

Crevices containing organic soils were identified, characterized, and sampled on pahohoe lava flows aged 2.1, 3.9, 7.6, 8.3, 8.8, and 13.9 cal ka (Fig. 1). Four crevices, or cracks, of varying sizes were sampled on each aged flow. Samples were not collected from crevices on a'a flows because soil was absent from these areas. Vegetation was identified, sampled, and removed at the soil surface. Soil, including coarse fragments, was removed and sampled from cracks in the lava. The deepest horizon in contact with consolidated rock was sampled separately and reserved for radiocarbon dating. Soil morphology was described using standard methods (Schoeneberger et al., 2002; Soil Survey Staff, 2006). Where present, mineral soil profiles were sampled and described to lithic contact. Mineral soils were identified and described to lithic contact on 3.9, 8.3, 12.6, 13.9, and 18.4 cal ka lava flows.

Transects were examined on pahoehoe flows ranging in age from 2.1 to 18.4 cal ka and on a'a lava aged 2.1 to 13.9 cal ka. Each site was georeferenced and transects were measured in four randomly selected directions from a central point. A 100-m tape was laid across the surface of the lava and the type of surficial material (bare lava, mineral soil, organic soil, loose rock over mineral soil, loose rock, lichen or moss over lava, crack or void, shallow organic soil [<3 cm] over mineral soil) was documented at 1-m intervals. Using these data, percentage cover was calculated for each type of surface material on the flows. Classification as *bare lava* included bare lava, loose rock, crack or void, and lichen or moss over lava. Classification as *mineral soil* included mineral soil, loose rock over mineral soil, and shallow organic soil over mineral soil. *Organic soil* was defined by the presence of organic soil materials containing $\geq 20\%$ organic C.

Laboratory Procedures

Two samples from organic soils on a pahoehoe flow aged 2.1 cal ka were analyzed for ^{14}C using the accelerator mass spectrometry technique at Beta Analytic Inc. (Miami, FL). The materials analyzed were a wood fragment (2.1 wood) and a homogenized peat sample (2.1 peat). An additional peat (8.3 peat) and wood (8.8 wood) sample were analyzed from organic soils on pahoehoe lava aged 8.3 and 8.8 cal ka, respectively. All radiocarbon ages were calibrated using CALIB 5.0.2 (Stuiver et al., 2005). To determine whether a soil was classified as mineral or organic, C content was analyzed on the <2 -mm soil fraction via dry combustion (Nelson and Sommers, 1996).

RESULTS

Lava Flows

Data collected along transects across pahoehoe lava flows indicate that the percentage of mineral soil increases while the percentage of bare lava surface decreases with lava flow age ($p < 0.05$) (Fig. 2; Table 1). Transects measured on the oldest lava flow (18.4 cal ka) show an areal coverage of 95% ($\pm 1\%$) mineral soil and 5% ($\pm 1\%$) bare lava while the flows 12.6 cal ka and younger have an average of 11% ($\pm 1\%$) mineral soil, 72% ($\pm 1\%$) bare lava ($\pm 4\%$), 16% ($\pm 3\%$) organic soil. Folists are the dominant soils on pahoehoe flows aged 2.1 through 12.6 cal ka. These are well-drained Histosols that contain $>20\%$ organic C (Table 2). On flows 13.9 and 18.4 cal ka, shallow to deep mineral soils, Entisols or Aridisols, are dominant.

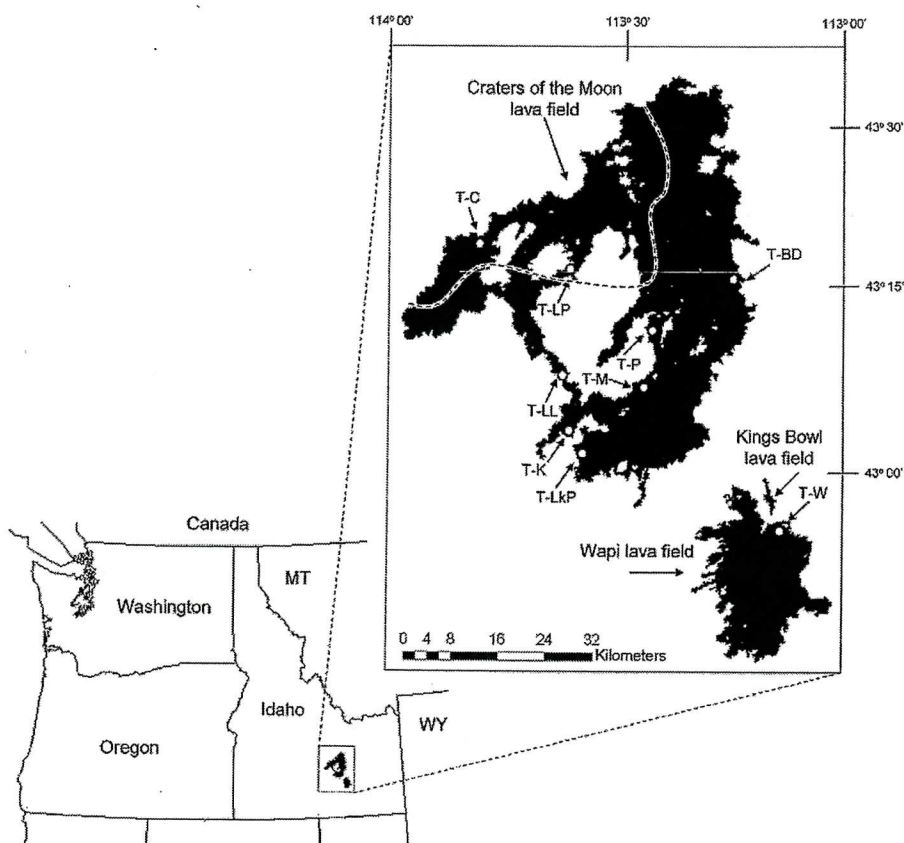


Fig. 1. Location of COM in southern Idaho. Arrows pointing to the white circles refer to the location of the transects: T-C, Carey (13.9 cal ka); T-LP, Little Park (7.6 cal ka); T-BD, Blue Dragon (2.1 cal ka); T-P, Pronghorn (12.6 cal ka); T-M, Minidoka (3.9 cal ka); T-LL, Laidlaw Lake (8.3 cal ka); T-K, Kimama (18.4 cal ka); T-LkP, Larkspur Park (6.3 cal ka); and T-W, Wapi (2.4 cal ka). Dashed line in inset indicates the boundary between the xeric soil moisture regime to the northwest and aridic soil moisture regime to the southeast.

Alternatively, the results from transects measured on a'a lava flows show little relationship between flow age and percentage of mineral or organic soil cover (Fig. 2). Flows aged 2.1 to 13.9 ka had an average of 3% organic soil cover across sixteen measured transects. There was no mineral soil detected on any of the a'a transects. Due to the extreme surface roughness, including large crevices, of a'a lava, the type of surficial material is not related to lava age up to 13.9 ka. The amount and type of blown in mineral and organic material were likely similar to those accumulated on pahoehoe flows, however, this fine-grained material was transported through the clinkery a'a lava, accumulating below the surface.

Soil on Lava Flows

The parent material of soils forming on lava flows is a combination of eolian mineral and organic material, plant debris deposited by overlying vegetation, and rock fragments and mineral material weathered from the basalt rock. Organic material deposited by overlying vegetation accumulates more rapidly than it is decomposed in this climate, giving rise to shallow organic soils overlying lava. These soils are classified by their abundance of organic soil material with little to no (<0.1 m and less than one-third the total thickness) mineral soil material and belong to the soil order Histosol (Soil Survey Staff, 2006) and reference

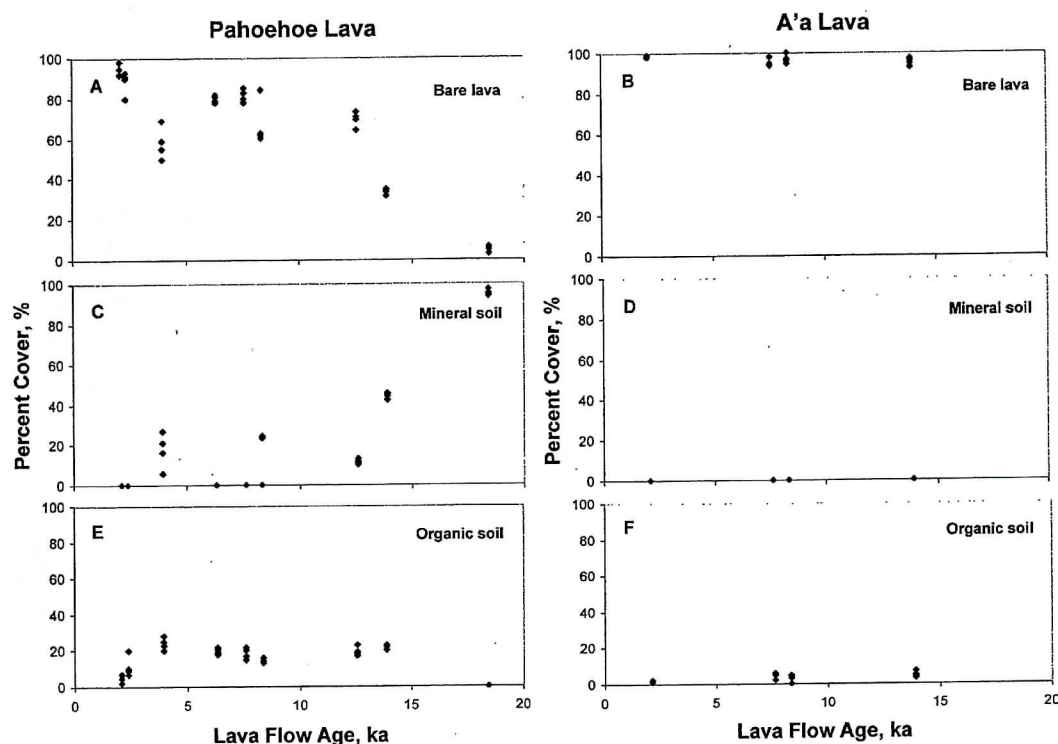


Fig. 2. Type and percentage of surface cover on pahoehe and a'a lava based on lava flow age. Percentage of (A and B) bare lava, (C and D) mineral soil, and (E and F) organic soil as a function of lava type and age. Each point represents the results from a 100-m transect measured on the corresponding aged lava flow. Surface cover was determined in meter intervals along a 100-m tape. Four transects oriented in random directions from a central random point were analyzed on each lava flow. Where only a single point is visible, point overlap has occurred.

soil group Histosol (IUSS Working Group WRB, 2006; Table 3 for WRB equivalent soil nomenclature). The particular type of Histosol that occupies cracks and lava surfaces at Craters of the Moon National Monument and Preserve is classified as a Lithic Torrifolist based on Soil Taxonomy (Soil Survey Staff, 2006) and a Follic Hemic Epileptic Histosol (Eutric) based on the WRB (IUSS Working Group WRB, 2006; Table 2). The defining characteristics of these soils are the absence of saturated conditions for more than 30 cumulative days (Soil Survey Staff, 2006), for-

mation under an aridic soil moisture regime, and lithic contact within 50 cm of the soil surface (Vaughan and McDaniel, 2009).

Several mineral soils have formed on lava flows at COM. The least developed are Lithic Torriorthents (Soil Survey Staff, 2006) and Cambic Leptosols (Eutric, Aridic) (IUSS Working Group WRB, 2006) composed of hemic materials overlying a shallow cambic horizon (Table 2). This classification illustrates these soils have undergone little soil development under an aridic soil moisture regime and have lithic contact within 50 cm of the soil surface (Soil Survey Staff, 2006; IUSS Working Group WRB,

Table 1. Description of age, dominant soil order, percentage soil cover, soil depth, soil material, and organic C range on select pahoehe lava flows at Craters of the Moon National Monument and Preserve. Values for percentage cover are means with standard error in parentheses.

Lava flow	Age†	Dominant soil ‡	Organic soil cover	Mineral soil cover	Depth range	Soil material/texture§	Organic C range¶
			%	%			
Blue Dragon	2.1	Folists	5 (2)	0 (0)	5–25	fibric/hemic	200–450
Wapi	2.4	Folists	12 (6)	0 (0)	5–25	fibric/hemic	200–450
Minidoka	3.9	Folists	24 (3)	18 (9)	5–25	fibric/hemic	200–450
Larkspur Park	6.3	Folists	20 (2)	0 (0)	5–25	fibric/hemic	200–450
Little Park	7.6	Folists	19 (3)	0 (0)	5–25	fibric/hemic	200–450
Laidlaw Lake	8.3	Folists	18 (1)	15 (12)	5–25	fibric/hemic	200–450
Pronghorn	12.6	Folists	19 (3)	11 (1)	5–25	fibric/hemic	200–450
Carey	13.9	Orthents	22 (1)	44 (1)	5–40	hemic/sil/fsl	10–300
Kimama	18.4	Cambids	0 (0)	95 (1)	20–50	sil/fsl	10–50
Other flows	> 20	Xerolls	0 (0)	100 (0)	100+	sil/sicl/fsl/cl	5–50

† ^{14}C dates calibrated using CALIB 5.0.2 (Stuiver et al., 2005).

‡ Based on Soil Taxonomy (Soil Survey Staff, 2006).

§ sil, silt loam; fsl, fine sandy loam; sicl, silty clay loam; cl, clay loam.

¶ Organic C range for entire profile.

Table 2. Profile descriptions of representative mineral soils from 2.1, 13.9, 18.4, and >20 cal ka lava flows at Craters of the Moon National Monument and Preserve (Fig. 3, Fig. 4). Soils on the 2.1 cal ka lava flows are classified as euic, frigid micro Lithic Torrifolists (Soil Survey Staff, 2006) and Follic Hemic Epileptic Histosols (Eutric) (IUSS Working Group WRB, 2006). Soils on the 13.9 cal ka lava flows are classified as loamy, mixed, superactive, frigid Lithic Torriorthents (Soil Survey Staff, 2006) and Cambic Leptosols (Eutric, Aridic) (IUSS Working Group WRB, 2006). Soils on the 18.4 cal ka lava flows are classified as loamy, mixed, superactive, frigid Lithic Xeric Haplocambids (Soil Survey Staff, 2006) and Leptic Cambisols (Ruptic, Yermic, Eutric, Aridic, Skeletic, Siltic) (IUSS Working Group WRB, 2006). Soils on the 13.9 cal ka lava flows are classified as coarse-loamy, mixed, superactive, frigid Xeric Haplocalcids (Soil Survey Staff, 2006) and Haplic Calcisols (Siltic) (IUSS Working Group WRB, 2006) (Natural Resources Conservation Service Pedon ID 94ID013001).

Horizon	Depth cm	Description
2.1 cal ka lava flow		
Oi	0–4	Brown (10YR 4/3) fibric materials; 5–10% angular basalt gravel; abrupt smooth boundary.
Oe	4–20	Dark brown (10YR 3/3) hemic materials; 5–50% angular basalt gravels and cobbles; abrupt smooth boundary.
2R	20+	Unweathered basalt bedrock. Depth to basalt rock ranges from 5 cm to more than 30 cm.
13.9 cal ka lava flow		
Oe	0–5	Dark brown (10YR 3/3) hemic materials; 5–15% angular basalt gravel; abrupt smooth boundary.
Bw	5–20	Yellowish brown (10YR 5/4) silt loam (14% clay); weak subangular blocky structure; 5–50% angular basalt gravels and cobbles; abrupt smooth boundary.
2R	20+	Unweathered basalt bedrock. Depth to basalt rock ranges from 10 cm to more than 30 cm.
18.4 cal ka lava flow		
A1	0–7	Dark brown (10YR 3/3) silt loam (15% clay); weak granular structure; many fine and very fine tubular pores; 5–10% angular basalt gravel; abrupt smooth boundary.
A2	7–15	Dark brown (10YR 3/3) silt loam (15% clay); weak granular structure; many fine tubular pores; 5% angular basalt gravel; clear smooth boundary.
Bw	15–40	Brown (10YR 4/3) silt loam (16% clay); weak prismatic parting to subangular blocky structure; 5–50% angular basalt gravels and cobbles; abrupt smooth boundary.
2R	40+	Unweathered basalt bedrock. Depth to basalt rock ranges from 30 cm to more than 50 cm.
> 20 cal ka lava flow		
A	0–8	Dark yellowish brown (10YR 3/4) silt loam (13% clay); weak granular structure; soft, friable, nonsticky, and nonplastic; common very fine, fine, medium, and coarse roots; many very fine tubular pores; slightly effervescent; clear smooth boundary.
AB	8–38	Brown (10YR 4/3) loam (16% clay); moderate subangular blocky structure; slightly hard, very friable, nonsticky, and nonplastic; common very fine, fine, medium, and coarse roots; common very fine and fine tubular pores; slightly effervescent; gradual wavy boundary.
Bk	38–86	Brown (10YR 5/3) loam (22% clay); strong subangular blocky structure; slightly hard, friable, slightly sticky, and slightly plastic; few fine roots; common very fine and fine tubular pores; 5% cobbles; violently effervescent; gradual wavy boundary.
Bkq	86–117	Brown (10YR 4/3) cobbly loam (8% clay); weak subangular blocky structure; slightly hard, friable, slightly sticky, and slightly plastic; few fine roots; common very fine and fine tubular pores; 20% cobbles; violently effervescent; clear smooth boundary.
2R	117+	Unweathered basalt bedrock. Depth to basalt rock ranges from 100 cm to more than 150 cm.

2006). Lithic Xeric Haplocambids (Soil Survey Staff, 2006) and Leptic Cambisols (Ruptic, Yermic, Eutric, Aridic, Skeletic, Siltic) (IUSS Working Group WRB, 2006) are moderately developed and consist of a vesicular A horizon overlying a cambic horizon that is in contact with unweathered basalt (Table 2). These soils also developed under an aridic soil moisture regime and have lithic contact within 50 cm of the surface, however, the accumulation of loessial mineral material creates a thicker solum than the soil mentioned previously. These soils have been identified on lava flows greater than 18 ka (Table 2).

Well-developed mineral soils derived from loess are abundant on lava flows <20 ka surrounding the CM, KB, and WP flows (Kuntz et al., 1987). Xeric Haplocalcids (Soil Survey Staff, 2006) and Haplic Calcisols (Siltic) (IUSS Working Group WRB, 2006) consist of an ochric epipedon, calcic horizon, and silica-rich calcic horizon over unweathered basalt. Depth to unweathered basalt ranges from 100 to >150 cm (Table 2). The Natural Resources Conservation Service has identified and mapped soils throughout this area with argillic horizons, calcic horizons, pet-

rocalcic horizons, and duripans. These subsurface diagnostic features indicate substantial development and therefore longer time of formation. In addition, mineralogical analyses of coarse silt in the surface (0–8 cm) and subsurface (25–46 and 89–140 cm) horizons of soils formed on flows older than 20 cal ka, reveal >44% quartz (Soil Survey Staff, 2010). These results imply that mineral material has been translocated and therefore represents colian input.

Table 3. Soil Taxonomy and World Reference Base equivalent nomenclature of soil described at Craters of the Moon.

Soil Taxonomy†	World Reference Base ‡
Torrifolists	Follic Histosols
Histosol	Histosol
Lithic Torrifolist	Follic Hemic Epileptic Histosol (Eutric)
Lithic Torriorthents	Cambic Leptosols (Eutric, Aridic)
Lithic Xeric Haplocambids	Leptic Cambisols (Ruptic, Yermic, Eutric, Aridic, Skeletic, Siltic)
Xeric Haplocalcids	Haplic Calcisols (Siltic)

† Based on Soil Taxonomy (Soil Survey Staff, 2006).

‡ Based on World Reference Base (IUSS Working Group WRB, 2006).

DISCUSSION

A'a Lava Flows

Clinkery a'a lava contains countless voids and cracks in which windblown material passes through and eventually accumulates below the lava surface. As a result of this fractured network, water is widely dispersed throughout the lava rather than being pooled in shallow depressions as on pahoehoe flows. When the voids in a'a lava fill with enough windblown material to approach the surface, succession will likely proceed as on the pahoehoe flows.

The oldest a'a lava flow identified and sampled within the CM lava field is 13.9 cal ka. Mineral soil cover on this flow was negligible with no indication of mineral soil accumulation along the 100-m transects. Mineral material that is deposited on a'a lava surfaces is likely eolian material blown onto the lava surface or washed deep into fractures in the lava. Geologic maps of the COM area indicate that a'a lava flows older than 13.9 cal ka have not been identified (Kuntz et al., 2007).

Pahoehoe Lava Flows

The transformation of a pahoehoe lava surface dominated by bare lava to mineral soil does not follow a linear trend over time (Fig. 2). Rather, numerous factors related to crevice volume, vegetation type, seed source, and type and source of soil material influ-

ence this progression (Fig. 3, Fig. 4). Crevices with larger volumes accumulate more soil material and therefore maintain a larger area for vegetation to inhabit. When plants grow above the lava surface, windblown silts begin to build up above the lava surface as long as roots, litter, and canopy protect it from erosion. In addition, the type of vegetation influences the rate and type of soil accumulation. Large, woody shrubs such as mature mountain big sagebrush (*Artemisia tridentata* Nutt. ssp. *vaseyana* Rydb.), antelope bitterbrush (*Purshia tridentata* Pursh), and fernbush [*Chamaebatiaria millefolium* (Torr.) Maxim] deposit more organic debris and accumulate more windblown material and than smaller, low-profile vegetation such as forbs and juvenile shrubs.

Organic soils on lava flows represent active C pools. Younger C is continually added to the soil through deposition of local organic debris and organic-rich eolian material (Fig. 3). Since the radiocarbon signature is the result of a mixture of material added to the soil, ^{14}C ages can be difficult to interpret. The ^{14}C ages represent a dynamic system that exhibits considerable variation over time. The ^{14}C ages determined for the two samples each of wood (2.1 wood and 8.8 wood) and peat (2.1 peat and 8.3 peat) indicate that the material analyzed was living within the last 50 yr. It is a reasonable assumption that the C sampled from the crack was from a recently living root, leaf, branch, or other portion of the parent plant.

This does not necessarily indicate that the soil formed within the past 50 yr, rather the decomposition rate may be such that C turnover is <50 yr or the samples analyzed do not represent older, more resistant material in the soil.

Organic C content on lava flows at COM increases over time, even after the introduction of complete mineral soil cover (Fig. 5). Because organic soil is less dense than mineral soil, the C content for the same volume of soil is quite similar. Also, the thickness of mineral soil is greater than that of organic soil on younger flows. Therefore, due to increases in soil bulk density, thickness, and coverage over time, the organic C content increases (nonlinearly) to near 4000 kg per m^2 of soil or lava by the time lava flows are completely covered in mineral soil.

Soils formed in windblown mineral material (loess) eventually dominate lava flow surfaces at COM. Our data show that the type of mineral material surrounding the lava flows greatly influences the rate of accumulation. Easily erodible silt and very fine sand provide a ready source.

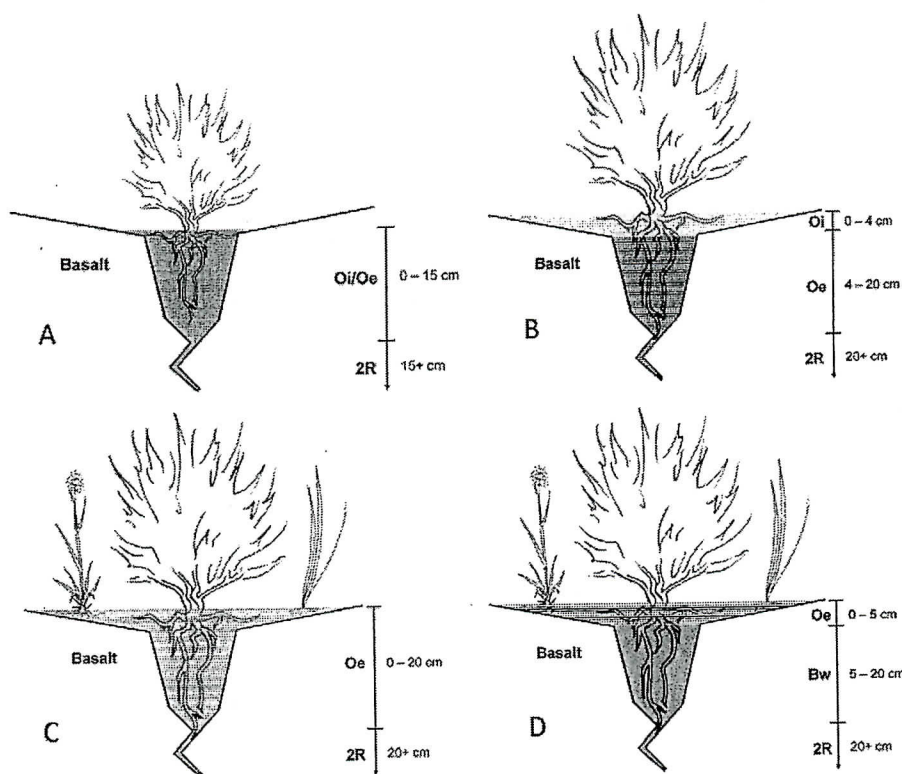


Fig. 3. Generalized model of soil succession in the presence of limited eolian inputs on late-Pleistocene and Holocene-aged pahoehoe lava flows in a semiarid to arid environment at COM. Primary soils are formed when small amounts of mineral and organic material are blown in. (A) Vegetation begins to grow and deposit organic debris, further increasing soil volume. (B) As vegetation grows larger, organic debris accumulates on the lava surface and undergoes decomposition from fibric to hemic materials (2.1 cal ka, Lithic Torrifolist, Table 2). (C) Eventually the volume of organic soil provides more cover so that additional vegetation inhabits the soil. Windblown material is trapped by areal portions of plants leading to a dominantly mineral soil with a thin O horizon (D) (13.9 cal ka, Lithic Torriorthent, Table 2).

The material surrounding the western region of COM is a combination of fine-textured alluvium (fines in glacial outwash deposited by the Little Wood River) and loessial material capping older lava flows, both of which can be transported by wind.

Desert pavement was observed on the surface of soils with vesicular A horizons. The pavement is composed of a protective gravel or stone layer that developed when basalt fragments broke from the lava surface through freeze-thaw processes and other physical weathering. The rock fragments remain at the soil surface and continue to collect additional windblown mineral material by gradual uplift of the rocks and sheltering of soil particles. These observations support the theory that desert pavement formation as an accretional rather than deflationary process (Anderson et al., 2002; McFadden et al., 1986, 1987; Wells et al., 1985, 1987, 1995). Desert pavement has been identified on pahoehoe lava flows as young as 2.1 ka and as old as 18.4 ka.

Studies concerning loess accumulation on basaltic lava have focused on flows greater than 180 ka. Wells et al. (1985) described four stages of soil formation on Pliocene to late-Pleistocene basalt flows in the Cima volcanic field in California. Their research highlights the generation of well developed argillic and calcic horizons as well as petrocalcic rubble. Evidence of these features is documented in the Soil Survey of Craters of the Moon National Monument and Preserve, however, the features have not been identified on late-Pleistocene and Holocene aged lava flows (United States Department of Agriculture, Natural Resources Conservation Service, United States Department of Interior, and National Park Service, 2010).

Generation of Loess

During the Rocky Mountain Pinedale glaciation at approximately 24 to 12 ka, discharge of streams and rivers draining to the ESRP greatly increased due to outwash directly from glaciers in highlands surrounding the ESRP and from thicker snowpacks in unglaciated catchments (Pierce et al., 1982). Sediments suitable for eolian transport were deposited along the Snake River between 24 and 13 ka (Phillips et al., 2008), in Lake Terreton between 22 and 11.6 ka (Mark and Thackray, 2002), and on undated fans located where mountain streams entered the ESRP (Kuntz et al., 2007; Pierce et al., 1982). In addition, catastrophic flooding from glacial Lake Bonneville deposited fine-grained sediment at several locations in the ESRP at 17.4 cal ka (O'Connor, 1993; Malde, 1968).

Although eolian transport pathways have not been systematically traced with geochemical or isotopic methods, all of these deposits were likely sources of loess. The topography of the ESRP

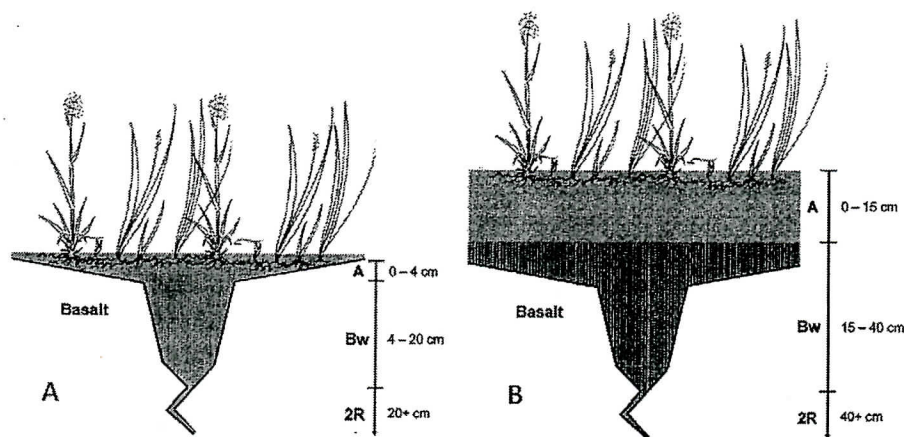


Fig. 4. Generalized model of soil succession in the presence of significant eolian inputs on late-Pleistocene and Holocene-aged pahoehoe lava flows in a semiarid to arid environment at COM. (A) When appreciable amounts of loess are available, thin vesicular A horizons develop above Bw horizons that are eventually dominated by herbaceous vegetation. (B) Mineral material continues to accumulate to the point where lava surfaces are no longer visible between crevices (18.4 cal ka, Lithic Xeric Haplocambid, Table 2) and eventually most of the lava flow is covered by mineral soil.

is favorably oriented to funnel the strong westerly winds typical of mid-latitude North America. This produces dominantly west-southwest winds in the ESRP. Regional thickness and particle size data (Lewis and Fosberg, 1982) show that the Snake River was a major loess source and suggest that transport was by the same prevailing west-southwest winds that dominate modern climate. During the Pinedale glacial climate, the Snake River was a large braided stream with a floodplain 10 to 30 km wide. It may have operated similar to modern high latitude rivers with high discharge and flooding during spring and early summer meltout, and low discharge during winters when the glacial outwash system was largely frozen. During the winter, clay, silt, and fine sand on vegetation-free braid plains are mobilized as loess by strong drying winds. Smaller streams draining to the ESRP may have operated in a similar fashion. At COM, the elongation of late Pleistocene-Holocene cinder cones (visible in Kuntz et al., 2007) is parallel to local prevailing winds. This supports loess transport by predominantly west-southwest winds. If true, the closest sediment source consists of Pinedale-age glacial outwash along the Little and Big Wood Rivers west of COM. Soils on older lava flows may also have been local sources of loess if vegetative cover was reduced or disturbed.

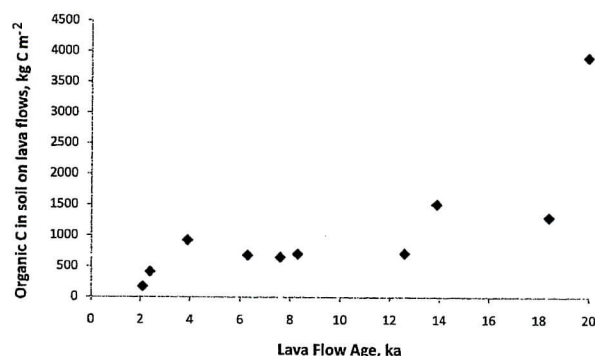


Fig. 5. Organic C content in organic and mineral soil as a function of lava flow age. Values calculated using percentage of mineral and organic soil cover, mean organic C content of soil, and mean soil thickness.

Direct dating of loess by optical and thermal luminescence in the ESRP indicates deposition occurred throughout the Pinedale between 25 and 28 to 16 to 12 ka (Phillips et al., 2008; Pierce et al., 1982; Forman et al., 1993). Loess deposition on lava flows at COM abruptly terminated between 13.9 and 12.6 cal ka. This evidence for a period of enhanced loess transport and deposition is supported regionally by a variety of proxies including dating of glacial moraines in surrounding mountain ranges (Licciardi and Pierce, 2008; Phillips et al., 2008; Thackray et al., 2004), chronology of pluvial lake levels (Oviatt, 1997; Mark and Thackray, 2002), and analysis of shifts in vegetation with palynology and packrat midden studies (Bright and Davis, 1982; Beiswenger, 1991).

In summary, the initiation of regional (Pinedale) glaciation at approximately 24 ka led to transport of abundant fine-grained sediment onto the ESRP and major loess deposition until full deglaciation at 12 to 13 ka. This corresponds to soil patterns on lava flows observed at COM. Abundant mineral soil cover (95%) is only observed on the oldest 18.4 cal ka pahoehoe flow (Table 1). This flow would have been emplaced during a period in which there was abundant loess transport and deposition on the Snake River Plain. On the 13.9 cal ka flow mineral soil cover decreases to 44%, corresponding to an overall decline in eolian deposition across the region. With cessation of major loess deposition around 12 cal ka, relatively little mineral soil cover is observed on flows 12.6 cal ka and younger (Table 1).

Model of Soil Succession

Soil succession on lava flows at COM appears to be a two-stage process. The first stage is biological in nature and occurs in the absence of an abundant source of loess. It is initiated when a seed successfully germinates within the shelter of a crevice (Fig. 3). The roots advance through any existing translocated debris and secure the plant to the lava by entering even smaller cracks within the lava. Organic debris from the parent plant accumulates more rapidly than it is decomposed in this cool, dry environment. Plant debris continues to accumulate (Fig. 2E), covering a larger area and volume on the lava so that additional plants are able to inhabit the newly deposited organic material and further contribute to the soil volume. Organic soil cover on pahoehoe flows at COM reaches a maximum around 25% coverage (Fig. 2E) (Vaughan and McDaniel, 2009).

A second pathway of soil succession on pahoehoe lava begins after an environmental shift resulting in increased available mineral material for deposition (Fig. 4). The influx of mineral material occurs rapidly due to an episodic or significant change in environmental conditions, that is, climate change. As mentioned previously, the climate at COM has shifted from glacial to post-glacial over the past 20 ka, leading to changes in the surface stability throughout the Snake River Plain. The addition of mineral material led to the formation of Entisols. Mineral horizons, high in organic matter, were visually identified in contact with bedrock, however, the origin of the organic material could not be determined. Two theories can explain this phenomenon. First, initial organic-rich Folists were buried by eolian material result-

ing in a greater concentration of organic C at depth. Second, current root systems below the soil surface concentrate at the impermeable bedrock interface where water accumulates.

Over time, Entisols on lava flows eventually develop into shallow Aridisols possessing cambic horizons. Older Pleistocene lava flows surrounding the CM, KB, and WP lava fields are covered by deep, well-developed Mollisols. Additional development leads to even deeper soils with calcic horizons, petrocalcic horizons, and/or duripans. Argillic horizons form in soils >14.5 ka while duripans require more approximately 130 ka to form (Othberg et al., 1997).

SUMMARY

Our results imply that soil succession on pahoehoe lava flows in the semiarid to arid environment at COM proceeds in the following manner: a) mineral and organic material are blown in to form primary soil material; b) plants are then able to grow and deposit additional organic debris; c) vegetation grows larger and organic debris accumulates on the lava surface and undergoes decomposition from fibric to hemic materials; d) organic soil provides more cover so that additional vegetation growth occurs in the soil leading to greater amounts of windblown material being trapped by areal portions of plants leading to a dominantly mineral soil; e) finally, mineral material continues to accumulate to the point where lava surfaces are no longer visible between crevices and most of the lava flow is covered by mineral soil. Primary succession of organic soil provides the essential habitat for plants and animals adapted for life in the existing cool, dry climate. In this environment, secondary succession has been triggered by climatic shifts, including regional glaciation, transport of abundant eolian sediment sources throughout the ESRP, and subsequent loess deposition. Rather than a uniformly progressing process, soil formation on pahoehoe lava flows is a two-stage process. In this environment, a lava has not had sufficient time to capture the necessary windblown material to fill the large interstices and cover the lava surface. Substantially more time is necessary before vegetation will subsist on this rough terrain. The formation of soil on basaltic lava at COM likely follows a divergent pattern from similarly aged lava in more humid, tropical environments where weathering of basalt and biomass production is more rapid and eolian sediment less abundant.

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