

Organic Soils on Basaltic Lava Flows in a Cool, Arid Environment

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Holocene-aged basaltic lava flows offer a unique opportunity to study the initial stages of soil formation. In the cool, dry climate at Craters of the Moon National Monument and Preserve (CROM) in southern Idaho, organic soils (Histosols in *Soil Taxonomy*) are the dominant soil on recent lava surfaces. Unsaturated Histosols, or Folists (Folic Histosols in World Reference Base [WRB]), occupy crevices and depressions on the lava surface and support vegetation adapted for life in this harsh environment. These soils are comprised of either a thin fibric (Oi horizon) over a hemic (Oe horizon) or a single, relatively homogenous Oe horizon over relatively unweathered basalt bedrock. The parent material for organic soils is biologic rather than geologic in origin with parent vegetation growing in crevices supplying the necessary organic debris. Soil acidity is directly influenced by the type of vegetation growing in the soil, with more acidic leaf litter creating lower pH soils while more alkaline plant debris generates soil with more neutral pH. Within these shallow soils (12–35 cm), organic C content (mean 333 g kg^{-1}) is proportional to fiber content and cation-exchange capacity (CEC) and inversely proportional to bulk density. Compared with Folists of wetter climates, those forming at CROM have substantially higher bulk densities with a mean of 0.41 g cm^{-3} . The influence of loessial mineral material likely accounts for the increased mineral content and subsequent increase in bulk density. Knowledge of the morphological, physical, and chemical properties of Folists at CROM is essential to improve our understanding of the ecological significance of Folists and co-evolution of soils and plant communities in a cool, arid environment.

Abbreviations: AEC, anion exchange capacity; CEC, cation exchange capacity; CROM, Craters of the Moon National Monument and Preserve; cal. ka, calibrated thousands of years before present; SPEC, sodium pyrophosphate extractable color; WRB, World Reference Base.

Folists are the suborder of Histosols in *Soil Taxonomy* dominated by organic soil materials that are not saturated for more than 30 cumulative days (Soil Survey Staff, 2006). According to Smith (1986), a primary author of *Soil Taxonomy*, the rationale behind the concept of Folists came from soils on the island of Hawaii where forest vegetation grows on lava and litter accumulates in cracks between the blocks of lava. Smith had a difficult time convincing his constituents in the Midwestern USA that these were, in fact, soils. Typically organic soils in wet, poorly drained regions are thick, moist, and do not rest directly on hard rock. The Hawaiian Folists receive considerable precipitation yet drain readily because of the porous nature of the underlying bedrock (Smith, 1986). Throughout the rest of the USA, Folists are typically located in high-elevation forested areas (Reiger, 1983; Wakeley et al., 1996). However, they have been identified in a variety of settings ranging from the low-elevation forests on Amchitka Island in southwestern Alaska (Everett, 1971) to for-

est canopies of old-growth redwood trees in northern California (Enloe et al., 2006).

A specialized great group of Folists, Torrifolists, represents well-drained organic soils with aridic moisture regimes. Hawaiian Torrifolists have been identified and classified by the Natural Resources Conservation Service (NRCS) and include the Honokohau and Noio series that formed in an aridic moisture regime and an isohyperthermic temperature regime (Soil Survey Staff, 2008a). These are very shallow to moderately deep, well to somewhat excessively drained soils formed in organic materials mixed with minor amounts of volcanic ash over a'a and pahoe-hoe lava (Soil Survey Staff, 2008a). However, there are currently no Torrifolists recognized in the continental USA.

Through an agreement with NRCS and the National Park Service, we conducted research throughout CROM to examine the extent of tephra influence on mineral soils. Upon closer examination of vegetation growing on lava flows, Folists, rather than tephra-rich mineral soils, were identified occupying crevices in the relatively unweathered lava. Before this research, lava flows were mapped as either bare lava with a minor mineral soil component or exclusively bare lava. The results from this research reveal that organic soils represent an early, fundamental component of ecosystem succession on basaltic lava flows in a cool, arid climate.

We investigated the morphological, physical, and chemical characteristics of Folists on Holocene-aged lava flows at CROM. The uniqueness and ecological importance of these soils required a detailed study involving numerous representative soil profiles from this semiarid to arid environment. The objectives of this research were to (i) characterize organic soils forming on vari-

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ous-aged basaltic lava flows at CROM, (ii) examine the relationship between the physical and chemical characteristics that make Folist unique in this environment, and (iii) determine the unique environmental factors that lead to the formation of Folist in an arid environment.

MATERIALS AND METHODS

Study Area

Craters of the Moon National Monument and Preserve is located in the eastern Snake River Plain of southern Idaho (Fig. 1) and encompasses 2800 km² of lava flows, and other volcanic features, including the southeasterly trending Great Rift. The Monument contains three relatively young (late-Pleistocene to Holocene) lava fields that extend from the Great Rift: the Craters of the Moon, Kings Bowl, and Wapi lava fields. Two morphologically distinct types of basaltic lava, a'a and pahoehoe, spread across the CROM landscape. A'a lava is relatively more viscous while flowing than pahoehoe lava and therefore contains abundant cracks and voids as well as numerous broken lava blocks. Pahoehoe flows are characterized as having smooth, ropy, or hummocky surfaces with few cracks that formed because of lava contraction during the cooling process.

The elevation at CROM ranges from 1800 m in the north to 1500 m at the southern margin of the Wapi lava field. Mean annual air temperature at CROM is 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, 2008).

Vegetation types throughout CROM have been described by Day and Wright (1985; USDA NRCS, 2008). Utah juniper [*Juniperus osteosperma* (Torr.) Little] and limber pine (*Pinus flexilis* E. James) are the dominant tree species on the lava flows. Mountain big sagebrush [*Artemisia tridentata* Nutt. ssp. *vaseyana* (Rydb.) Beetle], antelope bitterbrush [*Purshia tridentata* (Pursh) DC.], fernbush [*Chamaebatiaria millefolium* (Torr.) Maxim.], and rubber rabbitbrush [*Chrysothamnus nauseosus* (Pall. ex Pursh)] are the common shrubs on the lava flows. The common grasses and forbs are bluebunch wheatgrass [*Pseudoroegneria spicata* (Pursh) A. Löve ssp. *Spicata*], Indian rice grass [*Achnatherum hymenoides* (Roem. & Schult.) Barkworth], needlegrass [*Achnatherum thurberianum* (Piper) Barkworth], squirreltail grass [*Elymus elymoides* (Raf.) Swezey], and Idaho fescue (*Festuca idahoensis* Elmer ssp. *idahoensis*). Generally, species composition is similar on the various-aged lava flows, but density varies considerably.

Field Procedures

Soil samples from pahoehoe lava flows within the CROM boundary were collected between June 2006 and July 2007 (Fig. 1). Cracks or crevices

containing organic soils were identified, described, and sampled on lava flows aged 2.1, 3.9, 7.6, 8.3, and 13.9 calibrated thousand years ago (cal. ka) (Kuntz et al., 1986). On each flow, four representative crevices encompassing the range of expression in vegetation type and soil volume were selected. Vegetation was identified, removed at the soil surface, and sampled. All soil material including coarse fragments (organic and mineral) was removed from the crevice and collected. Crevice volume was measured by lining the cavity with a heavy-duty, 3-mil plastic bag, then filling the hole with 6-mm-diameter plastic ball bearings (Soft Air USA, San Francisco, CA). The ball bearings were removed from the hole and the total crack volume was calculated by measuring the volume of ball bearings. Soil depth, color, horizonation, and boundaries were described using standard methods (Schoeneberger et al., 1998; Soil Survey Staff, 2006).

Laboratory Procedures

Soil samples were passed through a 2-mm-mesh sieve and the percentage of coarse fragments was calculated. Bulk density of the soil was determined by dividing the total oven-dry soil weight by the crack volume occupied by the soil as determined using the ball bearings. The volume of coarse fragments was calculated and subtracted from the total volume in the calculation of soil bulk density.

Soil pH was measured by adding 20 mL of 0.01 M CaCl₂ to 2.5 cm³ moist soil material (Soil Survey Laboratory Staff, 2004). A subset of samples was analyzed via both dry combustion and loss on ignition (LOI) (Nelson and Sommers, 1996) to determine the site-specific

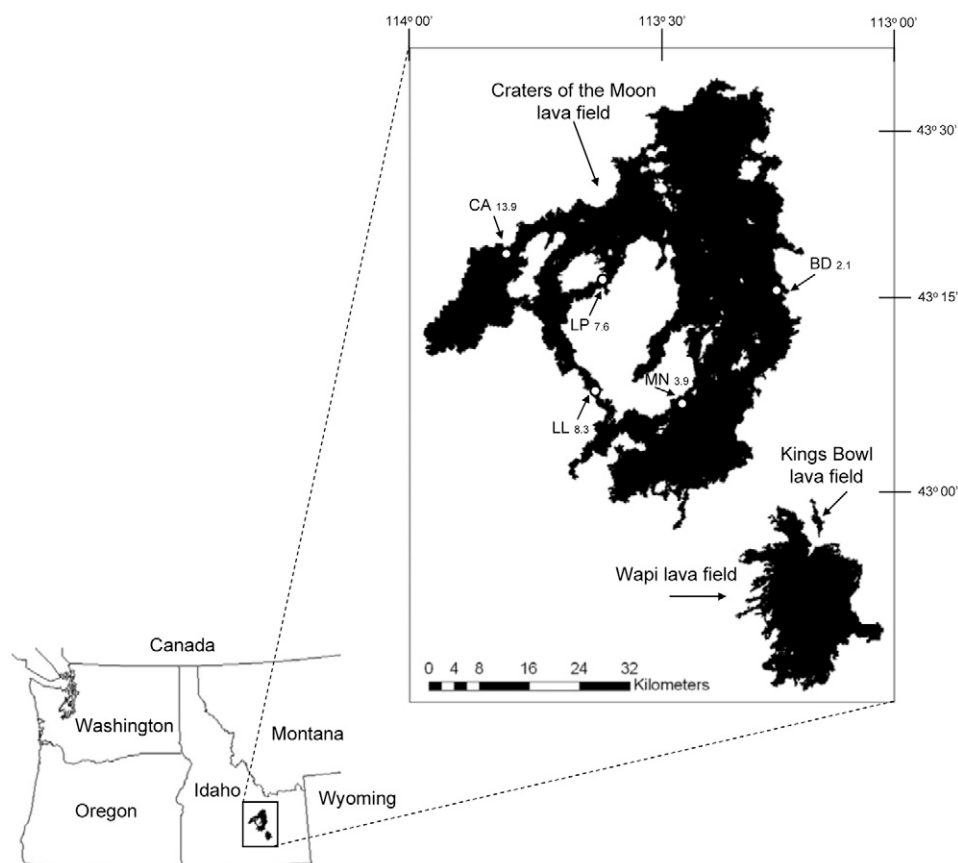


Fig. 1. Location of Craters of the Moon National Monument and Preserve (CROM) in southern Idaho. Black arrows point to sampling locations where BD is the Blue Dragon flow aged 2.1 cal. Ka (calibrated thousands of years before present), MN is the Minidoka flow aged 3.9 cal. ka, LP is the Little Park flow aged 7.6 cal. ka, LL is the Laidlaw Lake flow aged 8.3 cal. ka, and CA is the Carey flow aged 13.9 cal. ka.

Table 1. Morphological and physical properties of representative organic soils overlying pahoehoe lava. Four soil profiles from five lava flows are described. Each horizon designation represents a full soil profile with the omission of horizons less than 1 cm in thickness.

Horizon	Depth to R cm	Munsell color		Fiber content		SPEC†	Crevice volume cm ³	Bulk density g cm ⁻³	Mineral content %
		Dry	Moist	Unrubbed	Rubbed				
				—%—		10 YR			
<i>Blue Dragon lava flow (2.1 cal. ka)</i>									
Oi	15	10 YR 4/4	10 YR 4/3	80	64	7/4	1410	0.62	55.9
Oe	25	10 YR 5/4	10 YR 3/4	90	58	7/4	910	0.51	29.3
Oi	15	2.5 Y 5/4	2.5 Y 3/4	84	72	8/2	3190	0.43	60.2
Oe	12	10YR 4/4	10 YR 3/3	80	40	3/3	490	0.57	45.5
<i>Minidoka lava flow (3.9 cal. ka)</i>									
Oe	20	10 YR 5/4	10 YR 3/4	80	60	7/4	3120	0.30	26.2
Oe	18	10 YR 4/4	10 YR 3/3	78	58	5/6	3780	0.30	32.5
Oe	15	10YR 5/6	10 YR 4/4	98	48	7/2	1830	0.50	24.4
Oe	15	10 YR 4/3	10 YR 3/3	98	52	5/3	680	0.59	33.0
<i>Little Park lava flow (7.6 cal. ka)</i>									
Oe	12	10 YR 5/4	10 YR 3/4	98	60	6/4	1610	0.34	40.2
Oe	25	10 YR 5/4	10 YR 3/4	98	62	5/4	1480	0.25	26.6
Oe	18	2.5 Y 5/4	2.5 Y 3/4	90	56	5/4	2120	0.27	39.3
Oi	15	10 YR 4/3	10 YR 3/3	54	38	4/3	740	0.52	61.5
<i>Laidlaw Lake lava flow (8.3 cal. ka)</i>									
Oe	18	10 YR 4/4	10 YR 3/3	98	44	7/3	1460	0.38	49.6
Oe	12	10 YR 5/4	10 YR 3/4	94	46	7/2	1490	0.45	62.4
Oe	25	10 YR 4/4	10 YR 3/4	82	56	5/4	1720	0.38	34.7
Oe	15	10 YR 3/4	10 YR 3/3	98	66	6/4	2340	0.15	15.9
<i>Carey lava flow (13.9 cal. ka)</i>									
Oe	15	10YR 3/3	10 YR 3/2	92	62	6/4	1320	0.25	36.5
Oe	32	10 YR 4/4	10 YR 3/3	78	60	4/3	5450	0.10	37.0
Oi	25	10 YR 4/4	10 YR 3/3	82	40	5/3	2650	0.48	61.3
Oe	15	10 YR 5/4	10 YR 3/4	98	72	7/3	2820	0.32	29.1

† Sodium pyrophosphate extractable color.

relationship between organic matter and organic C. Mineral content was then calculated by subtracting the computed percentage of organic matter from 100. The <2-mm fractions of all samples were analyzed for percentage of C and N via dry combustion (Nelson and Sommers, 1996). Radiocarbon ages of lava flows from Kuntz and others (1986) were calibrated using CALIB 5.0.2 (Stuiver and Reimer, 1993).

Morphological horizons were analyzed for fiber content (unrubbed and rubbed) and sodium pyrophosphate-extractable color (SPEC) (Lynn et al., 1974; Soil Survey Laboratory Staff, 2004). For fiber content analyses, 2.5 cm³ of moist soil material were washed on a 100-mesh sieve, rubbed then washed, and blended then washed. The volume of the sample was measured using a 5-mL halved-syringe between each step. Soil was rubbed by hand for approximately 60 s or until no fine material (muck or mineral) was washed away with a steady stream of water. The volume of the material remaining on the sieve was measured. The soil was then pulverized using an electric blender for 60 s. This material was washed through a 100-mesh sieve and the final volume determined.

For SPEC, moist soil was placed in a saturated solution of sodium pyrophosphate for 24 h. Chromatographic paper was placed in this solution, then compared with Munsell color charts to determine SPEC. Fiber content and SPEC are used to classify soils as fibric, hemic, or sapric materials. Sodium-pyrophosphate index was calculated by subtracting SPEC chroma from value. Fibric materials have 40% or more fiber after rubbing or >75% unrubbed fiber by volume and a SPEC (value/chroma) of 7/1, 7/2, 8/1, or 8/3. Sapric materials have <16% rubbed fiber by volume. Hemic materials are determined as having an intermediate fiber content between fibric and sapric materials. Duplicate subsamples were analyzed and mean values are reported.

Cation exchange capacity, anion exchange capacity (AEC), and exchangeable bases were determined using a modified method originally developed by Sumner and Miller (1996). Cation exchange capacity and AEC were determined in an unbuffered solution by saturating the soil with NH₄Cl, rinsing excess solution with deionized water, and then replacing the adsorbed NH₄⁺ and Cl⁻ with K⁺ and NO₃⁻, respectively. Exchangeable cations (Ca, Mg, K, and Na) were collected during the extraction with NH₄Cl. Cation exchange was calculated by displacing NH₄⁺ and AEC from the displaced Cl⁻. Cations were measured using inductively coupled plasma atomic emission spectroscopy. Exchangeable NH₄⁺ was analyzed colorimetrically using a continuous flow analyzer. Base saturation was calculated by dividing the sum of bases by the CEC. Exchangeable Cl⁻ was measured using an ion chromatograph. Bulk density and mass percentage of the <2-mm soil fraction were used to convert CEC measurement on a mass basis (cmol_c kg⁻¹) to a volume basis (cmol_c L⁻¹).

Water retention at 1500 kPa was measured using ceramic pressure plates (Klute, 1986) on eight disturbed organic samples across the range of organic C contents. Mean values are reported from duplicate samples.

RESULTS AND DISCUSSION

Morphological Properties

There is considerable variation in the geometry of cracks and crevices on pahoehoe lava flows at CROM. The depth of sampled crevices (*n* = 20) filled with soil material ranged from 12 to 32 cm with a mean of 18 cm. Crevices that contained organic soil material and were shallower than 12 cm were not sampled. Some cracks with organic soil material were deeper than 32 cm, with a maximum of approximately 35 cm. Sampled crevice volumes ranged from 490 to 5450 cm³ with a mean of 2030 cm³ (Table 1). Both smaller and larger crevices were observed on the lava flows, but the sampled crevices represent the typical range in sizes. Crevice morphology varies from shallow, wide depressions to deep, narrow cracks. Crevices that provide more shelter from wind naturally accumulate more organic material than shallower, less-protected crevices. There does not appear to be a relationship between mean crevice volume and lava flow age.

A representative schematic of a typical Folist profile is shown in Fig. 2 (Table 2). Surface horizons are generally Oi with most profiles consisting of one subsurface 12- to 35-cm-thick Oe horizon (Fig. 3). The organic material is dominantly derived from overlying vegetation as evidenced by the visible leaves, seeds, and twigs within the soil. In addition, some organic material may be blown in from nearby organic soils and/or organic materials that

have accumulated on the surface of the lava. Most soils contain numerous gravel- and cobble-sized coarse fragments of basalt rock throughout the profile. On average, coarse fragments comprise 23% of the crevice volume and 65% of the total soil weight. Organic soil materials and plant roots are closely associated with the gravel- to cobble-sized fragments that were commonly moist when removed from the soil in July. Soil organic matter and plant roots were woven through and collected in the abundant vesicles of basalt fragments. These fragments have a mean density of 2.05 g cm^{-3} , store water, and are likely responsible for at least some water retention during the dry, hot summer months (Tokunaga et al., 2003). Near the soil-basalt interface, moisture was regularly observed either glistening on the rock surface or as soil moisture. A combination of mineral soil and sapric material ranging from a 0.1-cm dusting to 2 cm typically rests directly on the rock surface.

Physical Properties

The bulk density of organic soils on pahoehoe flows ranges from 0.15 to 0.62 g cm^{-3} with a mean of 0.41 g cm^{-3} . These values are higher than those reported for peat in Minnesota, Wisconsin, and Michigan (Boelter, 1969; Nichols and Boelter, 1984) and Folists in southeastern Alaska (D'Amore and Lynn, 2002). However, the values are similar to measurements made on Folists in northern New York (Witty and Arnold, 1970). The accumulation of loessial mineral material on lava flows at CROM has resulted in higher mineral content and therefore higher bulk densities. Mineral contents range from 16 to 61% by weight of the organic soils sampled (Table 1). This loessial material is composed of mixed mineralogies, some of which originated as tephra erupted from volcanic vents in the northern portion of CROM.

Based on rubbed fiber content and pyrophosphate index, 20% of the organic soils analyzed are classified as fibric and 80% are hemic (Fig. 4). Most of the soils sampled fall into the hemic category, which represents those organic soil materials that are intermediate in decomposition and contain some fibrous material remaining after rubbing. Hemic soil material generally occurs in fractures in the lava, either alone, below a small amount of fibric material, or above a thin horizon of mineral soil that was blown in and enriched in organic C from the overlying organic material.

The soils have mean values of unrubbed fiber content of 88% ($\pm 11\%$), rubbed fiber content of 55% ($\pm 10\%$), and pyrophosphate index of 2.3 (± 0.4), respectively. The high percentage of unrubbed fiber demonstrates that a small percentage (12%) of material is loosely adhered and small enough to pass through the 100-mesh sieve without manipulation. The moderate rubbed fiber percentage shows that on average, 45% of the soil material passed through the sieve after considerable physical manipulation and therefore likely consisted of small fibers of intermediate decomposition. Low pyrophosphate index values between 0 and 2 are indicative of dark, well-decomposed soil material, whereas

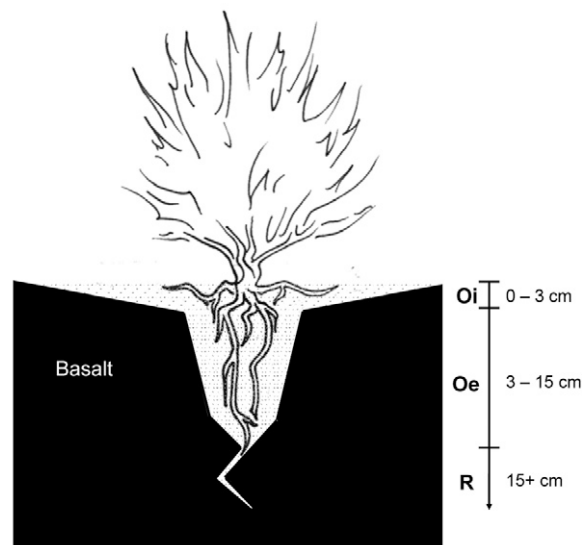


Fig. 2. Cross-section of organic soil profile overlying basalt. Schematic represents dominant soil composed of fibric and hemic soil materials. Depth to hard rock (R) ranges from 5 to 35 cm.

higher numbers, >2 , suggest lighter, less-decomposed soil material. A pyrophosphate index of 2.3 implies a moderate amount of decomposition in the samples.

Elevated unrubbed fiber content, moderate rubbed fiber content, and moderate pyrophosphate index indicate that the decomposition rate is less than the rate of input from overlying vegetation. Decomposition is retarded by the cool, dry climate at CROM and results in the accumulation of organic debris that is capable of sustaining vegetative growth. The mechanisms involved in decomposition are likely related to observed fungal and insect activity capable of breaking down organic material as well as additional unobserved biological and chemical processes.

There is an inverse relationship between bulk density and rubbed fiber content ($p < 0.05$) (Fig. 5a). As rubbed fiber content increases, bulk density decreases. Fibrous material is lighter in weight and more voluminous than hemic or sapric material (Buttler et al., 1994; Rabenhorst and Swanson, 2000). Thus, accumulation of mineral and sapric material and ensuing decrease in rubbed fiber content likely leads to higher bulk density.

Gravimetric water content at permanent wilting point (-1500 kPa) ranges from 54 to 107%, whereas volumetric water content ranges from 16 to 53%. Gravimetric water content is proportional to organic C content (Fig. 6), indicating that higher C content results in greater water retention in droughty conditions. For comparison, a surface mineral soil sample from an adjacent rangeland within CROM retained 11% gravimetric water and 13% volumetric water at -1500 kPa . Organic soils in crevices on lava flows have the capability to retain substantial volumes of water that are potentially plant available during the dry, summer

Table 2. Profile description of a typical euic, frigid micro Lithic Torrifolist (Soil Survey Staff, 2006) and Follic Hemic Epileptic Histosol (Eutric) (IUSS Working Group WRB, 2006) at Craters of the Moon National Monument and Preserve.

Horizon	Depth	Description
	cm	
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.



Fig. 3. Utah juniper (*Juniperus osteosperma*) growing in organic soil accumulated in a crevice on pahoehoe lava.

months. In contrast to other studies (Rabenhorst and Swanson, 2000), little relationship is observed between water retention and the degree of decomposition of organic materials. Fibric material contains larger pores and more fibrous organic debris than hemic soil materials, and therefore it should retain less water than more decomposed hemic and sapric materials. However, fibric and hemic organic materials at CROM show little trend in water retention as a function of unrubbed fiber content.

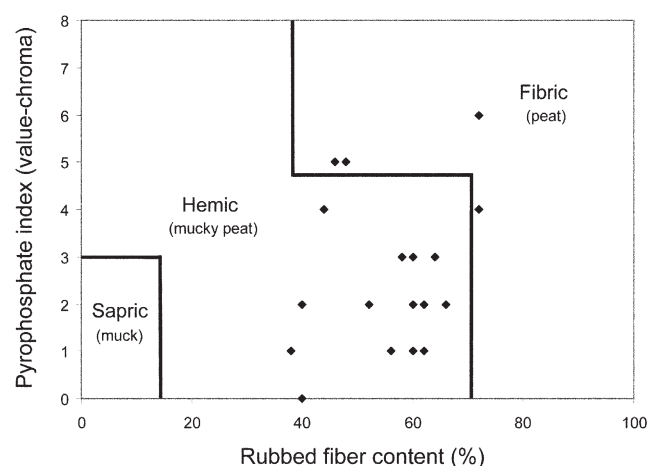


Fig. 4. Range in type of organic soil materials sampled on pahoehoe lava flows at CROM. Most organic soil material is classified as hemic indicating intermediate decomposition between the well-decomposed sapric material and less-decomposed fibric material. Note that two points (56,1) directly overlap and the pyrophosphate index of one sample is less than 0 and therefore not shown on this graph.

Chemical Properties

Organic C contents range from 209 to 467 g kg⁻¹ with a mean of 333 g kg⁻¹ (Table 3). Mineral contents range from 46 to 602 g kg⁻¹ based on the empirical relationship determined by analyzing organic samples using LOI and dry combustion [organic C = 0.464(organic matter) + 2.4175; $r^2 = 0.85$]. For comparison, organic samples analyzed by USDA-NRCS ($n = 393$) had mean organic C content of 313, 347, and 372 g kg⁻¹ for sapric, hemic, and fibric materials, respectively (Rabenhorst and Swanson, 2000). These values are similar to those measured at CROM where the C content increase and accompanying mineral content decrease reduces the bulk density (Fig. 5b). As crevice volume increases, C content increases slightly while bulk density decreases (Fig. 5c). As rubbed fiber content increases, C content also increases (Fig. 5d). This relationship is a result of the higher C content of fibrous materials in the soil.

The C/N ratios range from 20 to 27 with a mean of 23 (Table 3). More highly decomposed organic materials, Oa and Oe, generally have lower C/N ratios (Lévesque et al., 1980; Lee et al., 1988) compared with less-decomposed Oi horizons. As a result, sapric and hemic materials are typically more nutrient-rich than less decomposed peat. Sapric, hemic, and fibric materials analyzed by USDA-NRCS ($n = 181$) had mean C/N ratios of 21, 25, and 27, respectively (Rabenhorst and Swanson, 2000). Hemic and fibric samples from CROM have a mean C/N ratio of 22 and 26, respectively, and therefore are comparable with the values calculated for other Folists across the country.

Cation-exchange capacity ranges from 24.6 to 65.8 cmol_c kg⁻¹ with a mean of 45.2 cmol_c kg⁻¹ (Table 3).

Because of the low mass of organic soil occupying crevices on lava flows at CROM, CEC on a volume basis provides a value that is comparable with the values measured in mineral soils. On a volume basis, CEC is substantially less due to the low bulk density of the organic soil materials and ranges from 8.3 to 33.6 cmol_c L⁻¹ with a mean of 18.1 cmol_c L⁻¹. The lowest CEC values were measured on the four fibric soil samples (Table 3). Greater decomposition of organic materials has been reportedly related to an increase in CEC (Wells and Davey, 1966; Van Cleve and Noonan, 1971). Mean CECs for hemic and fibric materials analyzed by USDA-NRCS are 88 and 83 cmol_c kg⁻¹, respectively, and 44 and 21 cmol_c L⁻¹ on a volume basis (Rabenhorst and Swanson, 2000). The CEC of organic soils at CROM is lower than values reported across the USA. When compared with CEC values of mineral soils in the area (16 cmol_c kg⁻¹, 24 cmol_c L⁻¹), organic soils on lava flows have comparable CEC values (Soil Survey Staff, 2008b).

Calcium is the dominant base cation on the exchange sites, with lower concentrations of Mg, K, and Na (Table 3). Base saturation is $\geq 45\%$ in all soils with a mean value of 69% (Table 3). Much of the Ca likely originated from windblown mineral soil rich in CaCO₃, as evidenced by the calcic and petrocalcic horizons formed in the surrounding rangelands (Soil Survey Staff, 2008b). Base saturation of organic soils is often very low when the input of bases is from an ombrotrophic system (neutral to alkaline) not in contact with mineral soil such as the case in highly organic soils. The base saturation is high in minerotrophic systems (acidic) that receive nutrients from mineral-rich groundwater or in the case at CROM, from mineral-rich eolian inputs.

Anion exchange capacity is not typically measured on organic soils because of the expectation of low values. Mean AEC of all samples is $16 \text{ cmol}_c \text{ kg}^{-1}$ with a range of 7.2 to $39.4 \text{ cmol}_c \text{ kg}^{-1}$. The AEC may be derived from Fe and Al minerals that have weathered from the basaltic rock, tephra, or loessial material or protonation of amine groups at low pH. The AEC of organic soils at CROM is an order of magnitude greater than the AEC measured in arboreal soils forming on tree limbs in California that likely receive little mineral soil inputs (Enloe et al., 2006). Organic C content of the organic soils is proportional to the CEC (Fig. 5e) and AEC (Fig. 5f), whereas it is inversely proportional to the percentage base saturation.

Soil pH (0.01 M CaCl_2) ranges from 3.4 to 5.7 with a mean value of 4.5 (Table 4). Soils forming under more acidic vegetation, such as limber pine, generally have pH values less than 4.2; soils supporting more basic vegetation, such as antelope bitterbrush or mountain big sagebrush, typically have higher pH values. The difference in pH values between vegetation types is indicative of vegetational control over soil pH. Such control could conceivably dictate site suitability for germination and establishment of other plants.

Swanson and Grigal (1989) examined the relationship between vegetation and soil pH in peatlands of Minnesota and found that acidic, sphagnum parent material led to the formation of acidic, fibrous soil material whereas woody vegetation led to the accumulation of near-neutral, more-decomposed humus. This study also revealed that soils can be composed of several layers of organic material that relate to distinct types of vegetation that were previously growing at this location. Soil properties, therefore, reflect these past vegetation types through differences in chemical and physical properties. Soils forming on lava flows at CROM therefore may represent a mixture of past and present vegetation growing in the same crevice. For example, an abundance of leaves and twigs were observed in crevices below a plant with vastly different properties. (i.e., fernbush leaves accumulated below an actively growing sagebrush).

Soil Classification

Organic soils forming on pahoehoe flows are classified based on *Soil Taxonomy* as euic, frigid, micro Lithic Torrifolists; dysic, frigid, micro Lithic Torrifolists; euic, frigid, Lithic Torrifolists; and dysic, frigid, Lithic Torrifolists (Soil Survey Staff, 2006; Fig. 3). Based on the WRB for Soil Resources, these soils are classified as Follic Fibric Epileptic Histosols (Dystric), Follic Fibric Epileptic Histosols (Eutric), Follic Hemic Epileptic Histosols (Dystric), and Follic Hemic Epileptic Histosols (Eutric) (IUSS Working Group WRB, 2006). The difference between the classifications is related to soil acidity, depth, and using WRB, decomposition state. Soils with more acidic parent vegetation typi-

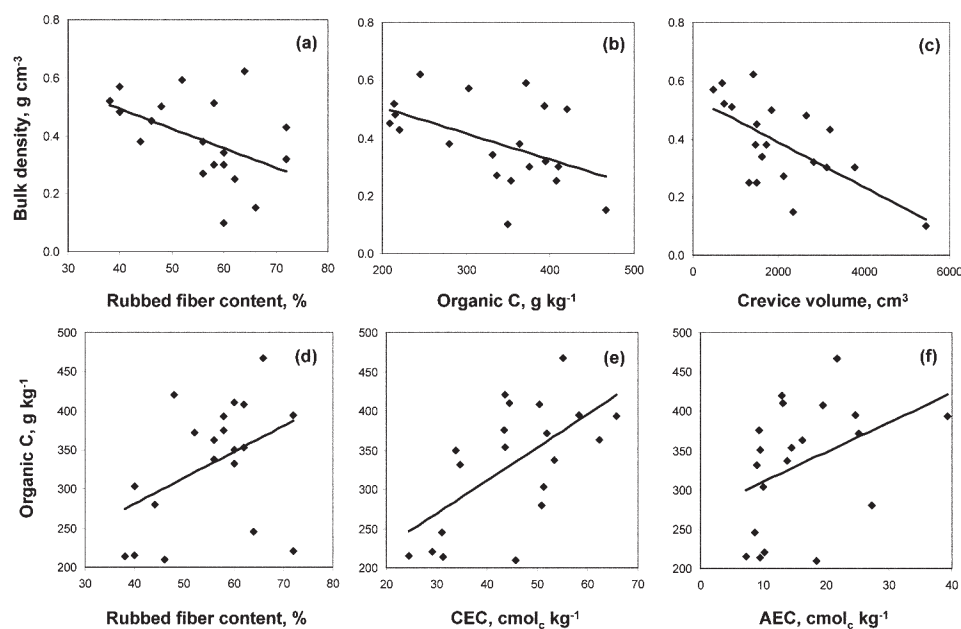


Fig. 5. Bulk density as a function of (a) rubbed fiber content, (b) organic C content, and (c) crevice volume in soil samples collected on lava flows throughout CROM. Organic C content as a function of (d) rubbed fiber content, (e) cation-exchange capacity (CEC), and (f) anion exchange capacity (AEC) in soil samples collected on lava flows throughout CROM. Note different scales.

cally have pH values below 4.5 and are classified as euic (Eutric), whereas soil with more basic parent vegetation have pH values above 4.5 and are classified as dysic (Dystric). Vegetation exerts control over particular physical and chemical properties of Folists (Lévesque et al., 1980; Rabenhorst and Swanson, 2000). In *Soil Taxonomy*, Folists < 18 cm thick are given the family differentiation *micro*, whereas those extending deeper are not assigned a soil depth class. Lithic Folists (Epileptic Follic) have lithic contact within 50 cm of the soil surface and are composed mainly of unsaturated organic materials. In the WRB, hemic and fibric soil materials are differentiated at the prefix level. The *Torric* designation implies formation in an aridic/torric soil moisture regime.

Soil Development as a Function of Lava Type and Age

Follic cover on a'a lava is much less abundant than on pahoehoe lava (Fig. 7). Due to the clinkery, rough nature of a'a lava, soil material that accumulates on the surface settles downward

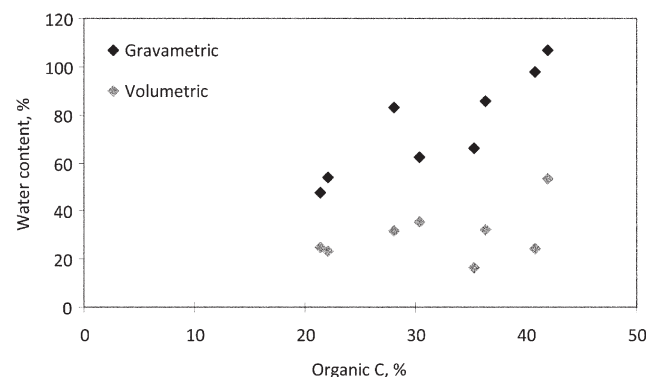


Fig. 6. Water content measured on select organic soil samples as a function of organic C content. Water content by volume was calculated using bulk density values for the corresponding soil samples. Water retention at the permanent wilting point (1500 kPa) is presented.

Table 3. Chemical properties of organic soils in crevices of pahoehoe lava.

Horizon	Depth to R	C	N	C/N	CEC†	AEC‡	Exchangeable				BSS	CEC†
							Ca	K	Mg	Na		
cm		-g kg ⁻¹ -			cmol _c kg ⁻¹	—cmol _c kg ⁻¹ —				%	cmol _c L ⁻¹	
Blue Dragon lava flow (2.1 cal. ka)												
Oi	15	245	9.5	26	31.1	8.7	20.5	2.7	5.8	0.2	94	19.3
Oe	25	393	18.9	21	65.8	39.4	22.8	1.5	5.2	0.1	45	33.6
Oi	15	221	8.9	25	29.1	10.1	17.4	2.1	4.7	0.1	84	12.5
Oe	12	303	14.3	21	51.3	10.1	34.3	1.1	5.3	0.1	80	29.3
Minidoka lava flow (3.9 cal. ka)												
Oe	20	410	19.3	21	44.4	13.1	20.5	2.3	6.0	0.1	65	13.3
Oe	18	375	14.4	26	43.4	9.3	24.0	1.7	7.0	0.1	76	13.0
Oe	15	420	17.2	24	43.6	12.9	26.6	1.2	6.7	0.2	80	21.8
Oe	15	372	18.6	20	51.9	25.1	21.7	1.7	3.9	0.2	53	30.6
Little Park lava flow (7.6 cal. ka)												
Oe	12	332	13.2	25	34.6	9.0	23.0	1.3	3.9	0.2	82	11.8
Oe	25	408	17.2	24	50.3	19.5	17.5	0.9	4.3	0.1	45	12.6
Oe	18	337	16.2	21	53.3	13.8	22.9	4.4	7.8	0.1	66	14.4
Oi	15	214	8.1	26	31.3	9.5	20.4	1.5	3.1	0.2	80	16.3
Laidlaw Lake lava flow (8.3 cal. ka)												
Oe	18	280	12.8	22	50.7	27.2	21.7	4.1	5.4	0.3	62	19.3
Oe	12	209	9.5	22	45.7	18.5	16.6	2.3	3.9	0.2	51	20.6
Oe	25	363	15.5	23	62.4	16.3	30.9	2.4	10.2	0.1	70	23.7
Oe	15	467	22.2	21	55.0	21.8	25.5	3.7	8.8	0.2	70	8.3
Carey lava flow (13.9 cal. ka)												
Oe	15	353	15.5	23	43.6	14.6	18.9	2.8	5.5	0.1	63	10.9
Oe	32	350	15.0	23	33.8	9.4	22.1	2.5	5.5	0.1	90	19.9
Oi	25	215	8.1	27	24.6	7.2	15.5	1.1	3.3	0.2	82	11.8
Oe	15	394	19.7	20	58.2	24.7	23.6	1.1	4.9	0.2	51	18.6

† CEC, cation exchange capacity unbuffered.

‡ AEC, anion exchange capacity.

§ BS, base saturation.

through the cracks in the lava through the action of wind and water. Morphological, physical, and chemical characteristics of Folists on a'a are similar to those observed on pahoehoe lava. However, when the initial organic and mineral material is deposited on a'a lava, it does not accumulate near the surface as it does on pahoehoe lava. More material and time are required before sufficient mineral and organic soil accumulates on a'a lava to support vegetation.

A relationship between organic soil development and lava flow age is not evident. The stage of decomposition and abundance of Folists does not change as a function of flow age (data not shown). Fibric soil materials were identified and sampled on pahoehoe flows aged 2.1, 7.6, and 13.9 cal. ka throughout CROM. Organic soil succession likely occurs soon after lava cools. The soils present within crevices have been forming for thousands of years and represent parent material deposited by several different vegetation types over time. Rather than a relationship between soil properties or lava flow age, a clearer connection is identified with parent vegetation and/or crevice volume.

The influence of fire in this ecosystem was evidenced by the presence of charred organic materials and small amounts of charcoal observed in several crevices. It was not evident whether this material burned in situ or if it was transported after a fire. The distance between crevices varies from 0 m to >10 m, and therefore fire would more easily spread across lava with a greater density of soils and vegetation.

SUMMARY

Organic soil formation on lava flows at CROM represents the primary stage of soil succession. Chemical properties of organic soils at CROM and their classification have not been presented. Folists provide the necessary habitat, nutrients, and moisture for vegetation and wildlife in this cool, dry climate. Pioneer plants that colonize lava flows supply the necessary nutrients and shade that lead to improved conditions for less tolerant vegetation to inhabit the lava. Bulk density, CEC, pH, C/N ratio, and fiber content are all influenced by the type of parent vegetation. However, these effects on Folists at CROM may be less pronounced because of the combination of vegetation that has grown in the crevice in the past. The plant or plants currently growing in a crevice on the lava are not necessarily the same plant or combination of plants that was growing in that crevice in the past. Therefore, Folists on lava flows at CROM represent a combination of properties inherited from the vegetation growing in that crevice throughout time.

In the semiarid to arid climate at CROM, Folists form as a result of the accumulation of organic debris from vegetation. The reason for the accretion is that the rate of organic material decomposition is reduced because of cool temperatures and the absence of abundant soil moisture. Soil profiles are generally shallow to basalt contact and composed primarily of hemic soil materials. As a result of loessial mineral influence, soil bulk density measured in crevices on lava flows is higher than typically

Table 4. Soil pH and current dominant vegetation growing in select soils overlying pahoehoe lava.

Horizon	Depth to R cm	pH	Vegetation type
<i>Blue Dragon lava flow (2.1 cal. ka)</i>			
Oi	15	4.1	<i>Juniperus osteosperma</i>
Oe	25	4.1	<i>Pinus flexilis</i>
Oi	15	4.5	<i>Chamaebatiaria millefolium</i>
Oe	12	4.7	<i>Purshia tridentata</i>
<i>Minidoka lava flow (3.9 cal. ka)</i>			
Oe	20	4.0	<i>Juniperus osteosperma</i>
Oe	18	4.3	<i>Artemisia tridentata</i>
Oe	15	3.5	<i>Pinus flexilis</i>
Oe	15	4.7	<i>Chrysothamnus nauseosus</i>
<i>Little Park lava flow (7.6 cal. ka)</i>			
Oe	12	4.8	<i>Juniperus osteosperma</i>
Oe	25	3.4	<i>Pinus flexilis</i>
Oe	18	5.6	<i>Artemisia tridentata</i>
Oi	15	4.2	<i>Juniperus osteosperma</i>
<i>Laidlaw Lake lava flow (8.3 cal. ka)</i>			
Oe	18	5.0	<i>Purshia tridentata</i>
Oe	12	4.9	<i>Chrysothamnus nauseosus</i>
Oe	25	5.7	<i>Chamaebatiaria millefolium</i>
Oe	15	4.3	<i>Artemisia tridentata</i>
<i>Carey lava flow (13.9 cal. ka)</i>			
Oe	15	3.9	<i>Pinus flexilis</i>
Oe	32	4.1	<i>Artemisia tridentata</i>
Oi	25	4.5	<i>Chamaebatiaria millefolium</i>
Oe	15	5.2	<i>Artemisia tridentata</i>

recorded for Folists in other settings. Organic soil formation in semiarid to arid climates offers a unique opportunity to sequester organic C and retain moisture in a region that typically stores little C and is droughty. More importantly, Folist formation in this environment influences ecosystem function and evolution. Soil succession and subsequent habitat generation on lava flows encourages occupation by wildlife and vegetation adapted for life in this harsh environment.

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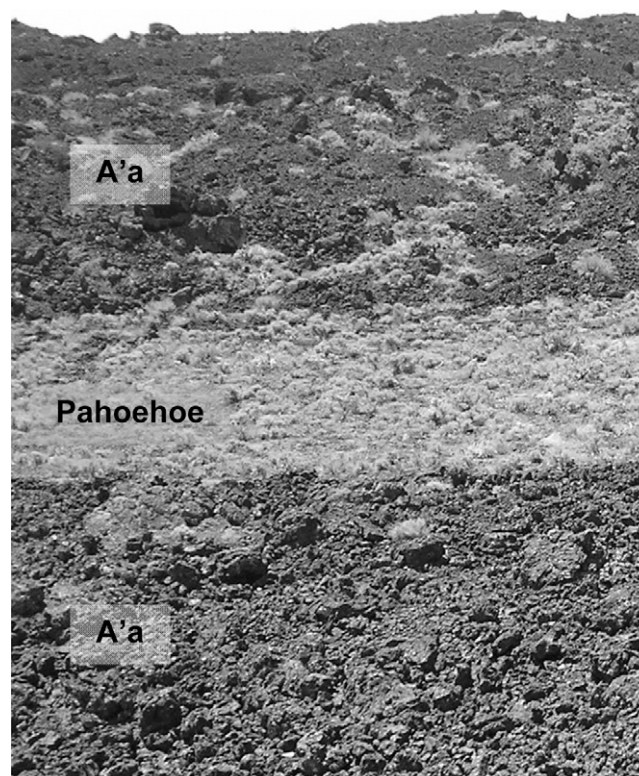


Fig. 7. A'a lava on either side of a pahoehoe lava flow. Notice the relative abundance of vegetation on the pahoehoe lava compared with the sparsely vegetated a'a lava. The blocky structure of a'a lava provides numerous cracks and voids where soil material and water infiltrate below the lava surface. Section of pahoehoe flow shown is approximately 3 m × 10 m.

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