

Weathering and vegetation effects in early stages of soil formation

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Received 23 October 2006; received in revised form 19 February 2007; accepted 28 March 2007

Abstract

Bedrock surfaces in the Ouachita Mountains, Arkansas, exposed by spillway construction and which had not previously been subjected to surface weathering environments, developed 15–20 cm thick soil covers in less than three decades. All open bedrock joints showed evidence of weathering and biological activity. Rock surfaces and fragments also showed evidence of significant weathering alteration. The results suggest a soil production function whereby weathering and increases in thickness are initially rapid. The rapid initial rate (5 to 10 mm year⁻¹) is facilitated by a weathering-favorable regional climate, local topography favoring moisture and sediment accumulation, and aggressive vegetation colonization. The ages of the trees on the bedrock benches suggests that a short period (<10 years) of pedogenic site preparation is necessary before trees can become established. Initial chemical weathering within newly-exposed rock fractures in resistant sandstone strata and chemical weathering of weak shale layers, coupled with accumulation of organic and mineral debris in fractures and microtopographic depressions facilitates plant establishment, which accelerates local weathering rates.

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Keywords: Weathering; Vegetation; Pedogenesis; Regolith; Ouachita Mountains; Feedbacks

1. Introduction

The relative importance of various processes and controls in determining the type and nature of soil and regolith covers is a classic problem in geomorphology and pedology (see reviews by Paton et al., 1995; Ollier and Pain, 1996; Birkeland, 1999; Schaetzl and Anderson, 2005). The influence of factors such as biota, climate, parent material, and topography varies not only with the geography of those and other environmental controls, but also with the age or stage of soil development. Parent material, for example, is thought in many cases to be of primary importance in early stages of soil development, whereby in later stages other factors such as climate may be paramount (Chesworth, 1973; Mason et al., 1994). This study seeks to shed light on the role of weathering of freshly-exposed bedrock parent material and vegetation in the first few decades of soil and regolith development on exposed bedrock surfaces in the Ouachita Mountains, Arkansas. The study is motivated in part

by previous work on soils and weathering profiles in the region indicating a key role for local lithological and structural variations, and for the effects of individual trees, in controlling regolith evolution and soil spatial variability (Phillips and Marion, 2004, 2005, 2006; Phillips et al., 2005a,b).

We define soil as unconsolidated material above unweathered parent material which has been significantly modified relative to the parent material(s). Regolith includes soil, and also weathered rock which may retain the structure and fabric of the parent materials. While some geologists use the term “soil” to refer to all unconsolidated material overlying intact bedrock, this is not consistent with pedological uses of the term. Because of the thin soil and regolith cover, and the early stage of its development, it is difficult in some cases to distinguish between them. We thus use both soil and regolith to describe the weathered mantles we are discussing. Soil and regolith development refers to increases in thickness over time, as well as modifications of chemical, physical, and biological properties relative to the underlying rock.

This project is also concerned with exploiting an opportunity to determine rates of soil formation on recently-exposed bedrock surfaces. This can not only shed light on formation rates in general, but may also contribute to an understanding of

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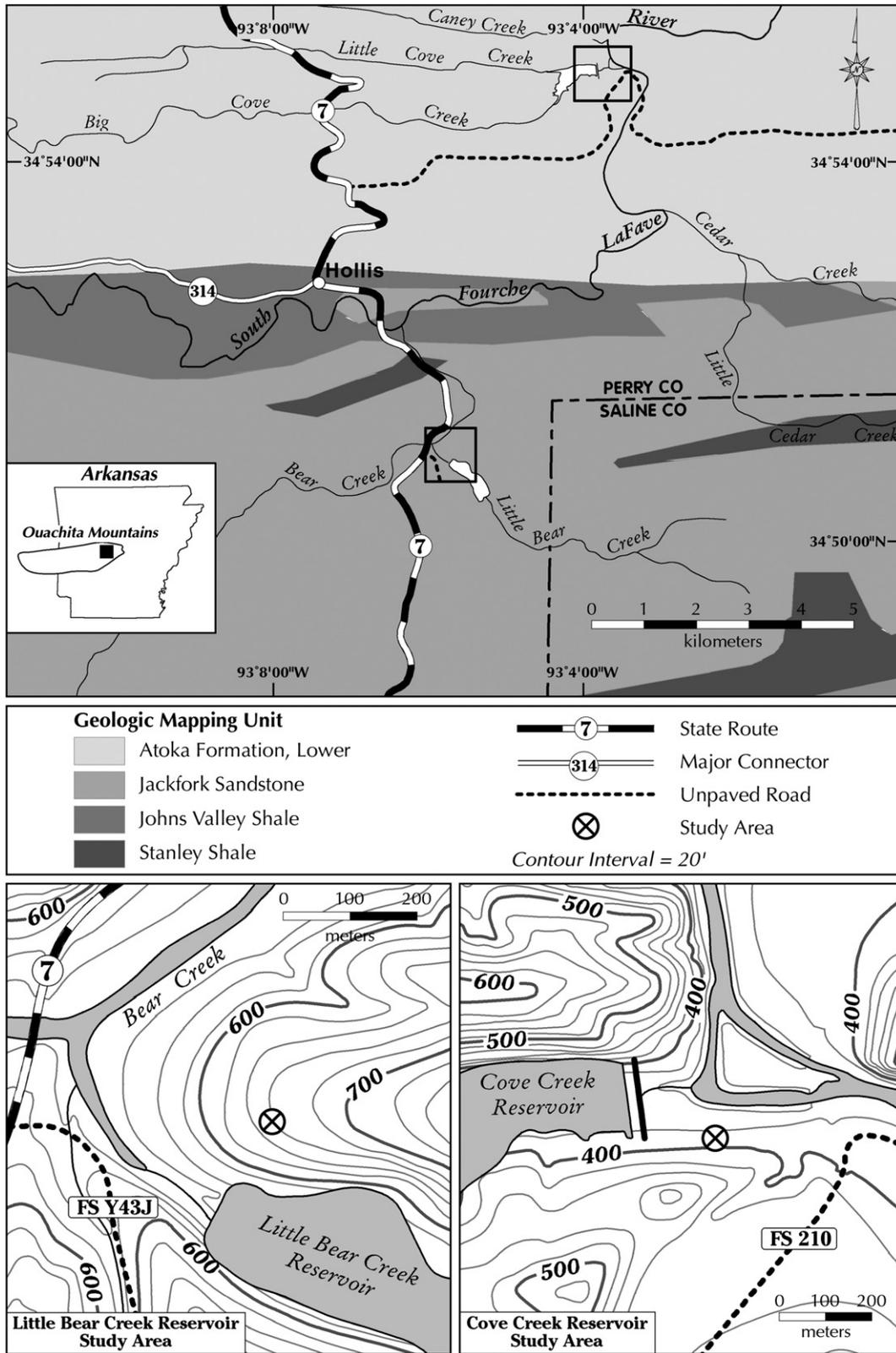


Fig. 1. Study area map.

feedbacks between soil thickness and rock weathering. While it seems clear that beyond some threshold thickness, bedrock weathering rates slow down as thickness increases, the maximum weathering rate may sometimes occur on exposed

rock, and other times under a thin cover (Heimsath et al., 2000; Anderson, 2002; Wilkinson et al., 2005).

The study sites are blasted bedrock benches created during construction of dam spillways about 20 to 30 years prior to our

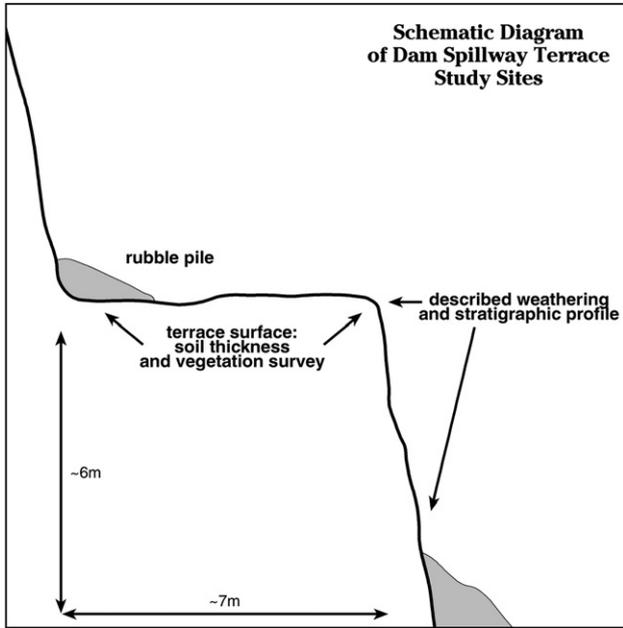


Fig. 2. Schematic of typical study site. Dimensions shown are typical of the LBC site.

field work. The setting is such that the examined surfaces were previously unexposed within 10 m of the surface, and thus not influenced by near-surface processes. This differs from previous studies of soil formation on mine spoils and similar deposits because of the exposure of fresh horizontal bedrock surfaces with no pre-weathering or previous pedological effects. The present study also differs from studies of weathering of cultural or building stone due to the opportunity for both soil and vegetation covers to develop.

2. Study area and methods

2.1. Study area

The study sites are bedrock benches at spillways associated with Little Bear Creek (LBC) and Cove Creek (CC) dams in the Ouachita National Forest, Arkansas (Fig. 1). In both cases flood control dams were constructed to regulate downstream flows, and high-flow emergency spillways were excavated adjacent to the dams. Horizontal benches were created by blasting to stabilize the spillway side slopes, and the resulting debris removed by heavy equipment (Fig. 2). The lowermost bench surfaces are well below the original surface, and thus not previously influenced by surficial and near-surface processes.

The Ouachita Mountains consist of parallel, east–west striking ridges and intermontane basins, approximately 100 km wide (north–south) and 320 km long. Ridgetop elevations are generally 230 to 850 m, and local relief varies from 75–530 m, generally increasing from east to west.

The two study areas are located within two different Pennsylvanian formations that together cover a substantial portion of the Ouachita Mountains. The LBC study area occurs within the lower Brushy Knob formation of the Jackfork

Sandstone Group (Fig. 1). The Jackfork is of Early Morrowan age and consists of interbedded sandstone and shale units, with minor inclusions of quartz, novaculite, and chert. Materials comprising the Jackfork were transported from their initial deposition sites by turbidity currents or gravity flows, and attain a combined thickness of 2000 m (Jordan et al., 1991). Jackfork sandstones are typically fine to medium grain with 86% quartz, 1.1% feldspar, 2.5% rock fragments, and 9.3% matrix (Morris, 1977). Grain cementation varies, but is higher in the northern part of the Jackfork (where LBC is located) due to the greater tectonic disturbance (Morris, 1977). Sandstone beds range from several centimeters to ten or more meters thick at LBC, and the lithology and bedding is similar to that reported for sites elsewhere within the Jackfork (Jordan et al., 1991). Jackfork shale beds are composed of illitic shale and mudstones, and occur intermixed with sandstones. At LBC, shale beds are thin (<1 m wide), although individual beds up to 20 m or more in thickness have been reported for Jackfork (Jordan et al., 1991). Both sandstone and shale beds are steeply inclined in the LBC study area and extensively faulted. The CC study area is located within the lower Atoka formation. The Atoka formation is younger (Atokan) than the Jackfork; but is very similar in deposition process, lithologic composition, bedding thickness, and structure. Atoka sandstones are somewhat finer grained than Jackfork sandstones (mean grain size=0.110 mm vs. 0.154 mm) and have higher lithic fragment content (Morris, 1985).

Within the Ouachita Mountains exposed shales are generally deeply weathered and highly erodible, whereas the sandstones are noticeably less altered and more durable. Ridgetops are composed of the more resistant sandstones, quartzites, and novaculites. Side slopes are often underlain by shale, with common sandstone outcrops.

The soils are predominantly Hapludults, and are generally acidic, with low base status, and with clay-rich argillic horizons. Surface textures are generally loam or sandy loam, while subsoil textures range from sandy clay loam to clay. Soils are discussed in more detail by Phillips and Marion (2005).

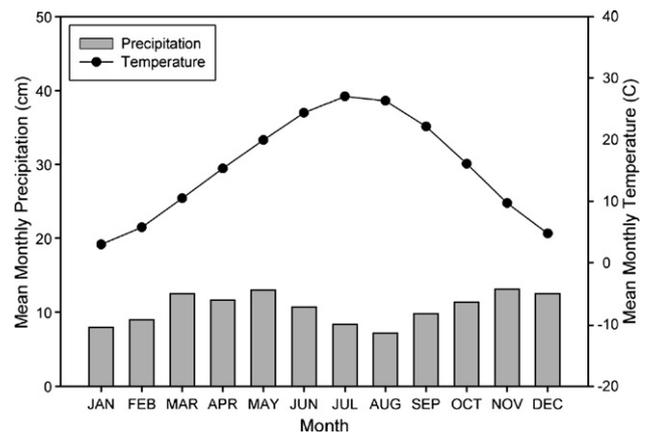


Fig. 3. Climograph for the study area, based on data from Nimrod, Arkansas, about 10 km north of the Cove Creek site (cooperative network ID 035200). Data are from National Oceanic and Atmospheric Administration, 2002. Monthly normals of temperature, precipitation, and heating and cooling degree days: Arkansas 1971–2000. Climatography of the United States No. 81. Asheville, NC: National Climatic Data Center. 26 p.

Table 1
Sampled surface area and number of samples for the four study sites

Surface	Area (m ²)	Profiles	Trees	Pits
Little Bear Cr. Lower	296	9	29	9
Little Bear Cr. Middle	245	3	0	0
Cove Creek Lower	502	7	13	20
Cove Creek Middle	300	0	22	18

The profiles column indicates scarp face weathering profiles; trees represents excavated trees growing on the terrace tread surfaces, and pits signifies other excavations to bedrock on the tread surfaces.

Climate is humid subtropical (Fig. 3). Slopes around the spillway sites are forested, and new forest growth is evident on the study surfaces. The LBC site is dominated by shortleaf pine (*Pinus echinata*) on both the rock surfaces and the nearby hillslope, while the latter also has an understory of hardwoods dominated by oaks (*Quercus* spp.). The CC site is similar, except loblolly pine (*P. Taeda*) is more common than shortleaf.

2.2. Methods

At both sites the lowermost surfaces were examined, to ensure that sampling accessed areas not exposed to near-surface processes before excavation. The terrace surfaces are flat. Their surface areas, and elevation above the spillway floor, were surveyed using a laser level, stadia rod, and measuring tape. The location of trees on the surfaces were also surveyed using the same methods, excluding debris aprons at the base of the terrace scarps.

Trees growing on the rock surfaces were excavated to determine regolith thickness at the tree base, and to ascertain the relationships to underlying joints, fractures, bedding planes or other structural features. The lithology was also recorded. In addition, soil/regolith thickness was measured at other points on the surfaces by digging through to bedrock. The surface area of the pits around the excavated trees varied according to tree size, ranging from 0.07 to 0.5 m². The other thickness measurement pits were about 0.015 to 0.020 m² in surface area (e.g., approximately circular holes with a diameter ~ 15 cm).

Tree species was recorded, along with the diameter at breast height (dbh), measured using a dendrological tape. The two or three largest trees on each sampled surface (as indicated by dbh) were cored with an increment borer to determine their age by counting annual growth rings. The surface area and number of samples on each surface is shown in Table 1.

The footwall exposures below each surface were sampled at several points along their length to record general lithology, and the strike and dip of bedding and structural features. This included nine sites on the lowermost and three on the second (of four) levels at LBC, and seven on the lowest surface at CC. At each of these profiles a surface with a width of 0.6 m and extending to the depth at which bedrock was exposed or could be readily excavated was examined. Rock strength was assessed using the index devised by Selby (1980), based on the ease of denting or breaking the rock with a geological hammer (very strong, strong, moderate, weak, very weak). A weathering grade was assigned using Selby's (1993) index. This six-class index

ranges from unweathered fresh rock through slightly, moderately, highly, and completely weathered rock to residual soil. The index considers rock strength, discoloration, proportion of mass decomposed or disintegrated, preservation of fabric and texture, and opening of discontinuities (Selby, 1993: 96).

The interior (exposed by breaking with a geological hammer) and exterior rock colors were determined using the Munsell notation in ambient natural light. Rock fragments were removed from bedrock with a geological hammer from intact bedrock just below the weathering profile. The interior and exterior color of these rock fragments was compared as an indicator of rock alteration. Soil profile development indices typically incorporate color differences between soil and parent material using a numerical scale to indicate rubification and melanization (Bilzi and Ciolkosz, 1977; Harden, 1982; Langley-Turnbaugh and Bockheim, 1997); this approach was adopted here to compare interior (fresh) and exterior (weathered) colors. Munsell hues from 5Y to 10R (increasing redness) have values of 20 to 80 points, in 10-point increments. Colors in the grey hues were assigned zero points. Ten points were assigned for each unit decrease in value, from 10 to 2. Five points were assigned for each unit increase in Munsell chroma from 0 to 4, and 10 points from chromas 4 to 8.

Fractures in the rock structure (a general term encompassing joints, fractures, and opened bedding planes) were assessed by measuring their width, spacing, and the extent to which they were open or infilled. Fractures were also assessed as to their continuity within the rock mass, and degree of interlocking. These assessments followed the methods of Selby (1993). Finally, the extent to which partings had evidence of roots, root hairs, fungal hyphae, or other biological activity was noted.

Immediately above each fracture and lithology sampling point, the regolith thickness was measured, and color, structure, and texture described using standard pedological methods (Soil Survey Staff, 1993). Redox and pH were determined in the

Table 2
Lithological and structural characteristics of the dam bench sample profiles

	Lithology	Strike	Dip
LBCL1	ss, sh	320	30
LBCL2	ss, sh	120	30
LBCL3	ss, sh	320	24
LBCL4	ss, sh	320	24
LBCL5	sh, ss	320	28
LBCL6	ss	No bedding	
LBCL7	ss, sh	320	15
LBCL8	ss, sh	190	40
LBCL9	ss, qz, sh	No bedding	
LBCM10	sh, ss	340	24
LBCM11	ss, qz, sh	340	35
LBCM12	ss, qz, sh	340	20
CC1	ss, sh	85	57
CC2	sh	85	57
CC3	ss	165	19
CC4	sh, ss	85	57
CC5	sh	85	57
CC6	ss	85	19
CC7	ss	85	19

Lithology key: ss = sandstone; sh = shale; qz = quartz.

laboratory from a 1:1 soil-water mixture using a Hanna HI8314 membrane meter.

3. Results

3.1. Lithology and structure

The general lithology is comprised of various combinations of sandstone and shale (Table 2). A few sample sites were almost entirely sandstone or shale, but in most cases sandstone and shale were interbedded. Some of the sandstones had quartz veins. The uppermost exposed rocks underlying the surveyed terrace surfaces were classified as dominantly sandstone in four and dominantly shale in two cases. Ten were sandstone with interbedded shale; three shale with interbedded sandstones. Rock strength was very strong in 12, strong in one and moderately strong in two cases; all were sandstones, with or without interbedded shale. Three sites were classified as very weak and one as weak. The former were all shale or shale with interbedded sandstone; the latter was sandstone with interbedded shale.

Significant but variable folding and contortion is evident. At LBC dips were quite variable, from 15 to 40° as measured near the terrace treads. Steeper dips, and even overturned folds, were evident in the lower parts of some exposures (Fig. 4). CC dips were either 19 or 57°. Major joint orientations at LBC were generally 160° by 340°. Strikes of the major joints at CC were very consistent, with major sets at 85° by 265° and 160° by 340°.

All sites had at least one visible joint or fracture at the local scale (Table 3), some of which may have been related to drilling or blasting in connection with spillway construction. Joints were predominantly open at all but four sites. Joints were all continuous and most were interlocking. Where multiple joints were present, spacing ranged from <1 cm to 69 cm. Typical spacing was in the range of 10 to 40 cm. In general, open joints were partly filled with soil, sediment, and organic debris.



Fig. 4. Fieldwork in progress on the lower terrace at the Little Bear Creek dam spillway site.

Table 3
Joint characteristics

Site	Min joint spacing (cm)	Max joint spacing (cm)	Mean joint spacing (cm)	Continuous/interlocking	Max width (mm)	Organic fill
LBCL1	10	42	24.6	C, I	60	RH, FR, BF
LBCL2	5	20	8.8	C, I	40	RH, hy
LBCL3	12	16	14	C, I	90	RH, hy
LBCL4	12	27	20.6	C, I	40	RH, hy
LBCL5	9	24	14	C, I	2	RH, hy
LBCL6	10	24	17.3	C, I	5	RH, hy, FR
LBCL7	3	14	10.3	C, I	3	RH, hy, FR, CR
LBCL8	6	33	18.8	C, I	3	RH, hy, M, FR, CR
LBCL9	5	29	13.8	C, I	0	RH
LBCM10	7	14	10.2	C	0	none
LBCM11	4	14	9.2	C, I	11	RH, hy
LBCM12	6	25	11.8	C, I	2	RH, hy
CCL1	4	11	6.8	C, I		RH, hy
CCL2	0	0	0	NA	NA	RH, hy
CCL3	22	50	35.5	C, I	30	RH, hy, FR
CCL4	22	50	35.5	C, I	30	RH, hy
CCL5	1	8	4.5			RH, hy
CCL6	33	69	51	C, I	70	RH, hy
CCL7	0.4	0.9	0.53	C, I		RH, hy, M

C = continuous; I = interlocking. Where fills are shown with no open joints, fills occur in bedding planes. RH = root hairs; FR = fine roots; BF = biofilm; hy = root hyphae; CR = coarse roots; M = bryophytes (mosses).

3.2. Vegetation

Shortleaf pine (*Pinus echinata*) dominates the terrace surfaces at LBC (Fig. 5). In the surveyed area of the lowermost terrace surface, 22 of 29 trees were shortleaf pines, with dbh of 8 to 19 cm. The other trees were winged elm (*Ulmus alata*), all with DBH <5 cm. Twelve of the surveyed trees occupied joints in the rock surface; another eight were growing in toeslope rubble accumulations at the base of the scarp at the back of the



Fig. 5. Middle terrace surface at the LBC site.

terrace. An additional eight were located where relatively thick, steeply-dipping shale strata were exposed. Seven trees were not obviously associated with joints, debris, or shale.

At CC, loblolly pine (*Pinus taeda*) was dominant, accounting for 19 of 36 surveyed trees on the lower and middle (of three) terrace surfaces. Ten red cedars (*Juniperus virginiana*) were also found, along with three oaks (*Quercus spp.*). Pine diameters were 9 to 20 cm; cedars ranged from <5 to 22 cm. Rubble accumulations supported 23 of the trees, and 12 were growing in joints. No apparent relationship between growth site and species was observed. The shortleaf vs. loblolly pine domination at the two sites reflects the dominant seed sources on the adjacent upper slopes.

The largest pine at the CC site was cored with an increment borer, indicating an age of 27 years in 2006, showing that the tree became established within a year after spillway construction. The second largest (by dbh) tree at the CC site was 19 years old. At LBC, the three largest trees on the two lowermost terraces were selected for coring. These were all aged 19 to 22 years in 2006.

3.3. Weathering

Assessed weathering grades were directly related to rock strength (Table 4). In 14 cases a grade of II (slightly weathered) was determined, 13 of which were associated with very strong or strong sandstones. Two sites with grade IV (strongly weathered), and two with a III/IV (moderately/strongly weathered) rating, were very weak or weak shales or sandstones with significant quantities of shale. One grade III was in sandstone of moderate strength.

Table 4
Weathering-related features of scarp-face profiles

Site	Soil depth (cm)	Regolith depth (cm)	Color change	Max color change	Weather-Ing grade	Rock strength
LBCL1	12	12	50	80	II	VS
LBCL2	0	70	50	80	II	VS
LBCL3	0	0	5	5	II	VS
LBCL4	31	51	5	5	II	VS
LBCL5	19	65	115	115	II	VS
LBCL6	20	37	115	115	III	MS
LBCL7	73	100	115	115	II	VS
LBCL8	21	70	170	170	II	VS
LBCL9	5	17	170	170	II	VS
LBCM10	38	53	5	5	II	VS
LBCM11	0	0	5	5	II	VS
LBCM12	0	0	80	80	II	VS
CCL1	8	32	50	60	III/IV	W
CCL2	10	10	5	5	III/IV	VW
CCL3	13	51	50	50	II	MS
CCL4	10	28	50	60	IV	VW
CCL5	5	5	5	5	IV	VW
CCL6	17	17	90	90	II	S
CCL7	5	5	100	100	IV	VS

Color change according to the index described in the text refers to the dominant exterior and interior colors of rock below the regolith, and the maximum contrast for multicolored samples. Rock strength: VS = very strong, S = strong, MS = moderately strong; W = weak; VW = very weak.

Table 5
Surface soil characteristics (upper 5 cm, excluding any litter layer)

Lbc terrace	Dam site	Surface soils		Consistency	Structure	pH
		Texture	Color			
Lower	1	CL	10YR 5/8	Friable	Wk med gran	6.05
Lower	2	CL	10YR 4/3	Friable	Wk med gran	6.61
Lower	2	CL	10YR 2/1	Friable	Wk med gran	5.78
Lower	3	CL	10YR 4/3	Friable	Wk med gran and wk med sbk	7.07
Lower	4	SL	10YR 5/6	Friable	Wk med sbk	5.69
Lower	5	CL	10YR 3/2, 10YR 4/4	Friable	Wk med gran	6.29
Lower	6	CL	10YR 4/3, 10YR 3/1	Friable	Wk med gran	5.77
Lower	7	CL	10YR 4/3	V. Friable	Wk fn2med gran	6.23
Lower	8	SL	10YR 3/3	Friable	Wk fn2med gran	5.27
Lower	9	SL	10YR 3/3	Friable	Wk fn2med gran	5.31
Mid	10	CL, SL, SiCL	10YR 4/2, 10YR 5/4, 10YR 4/1	Friable to v. Friable	Wk med2 coarse gran wk med sbk	5.62
Mid	11	SL	10YR 4/2	Friable	Wk fn2med gran	5.76
Mid	12	LS	10YR 4/6	V. Friable	Wk med gran	5.99
Cc						
Lower	1	CL	10YR 4/2	Friable	Wk fine gran	5.53
Lower	2	SCL	10YR 4/1	Friable	Wk fine gran	6.03
Lower	3	SCL	10YR 4/3	Friable	Wk med gran	5.86
Mid	4	SiC	10YR 4/2	Friable	Wk fn2coarse gran	5.76
Mid	5	CL	10YR 4/2	Friable	Wk med2coarse gran	6.13
Mid	6	CL	10YR 3/2	Friable	Wk fn2coarse gran	5.80
Mid	7	CL	10YR 3/1	Friable	Wk fn2coarse gran	6.20

Texture: CL = clay loam; SL = sandy loam; SiCL = silty clay loam; LS = loamy sand; SCL = sandy clay loam. Structure: wk = weak; med = medium; gran = granular; sbk = subangular blocky; fn2med = fine to medium; med2coarse = medium to coarse; fn2coarse = fine to coarse.

All open joints at all sites which could be observed had apparent discoloration. These discolorations included organic staining, apparent iron oxides, and combinations of the two. All open joints which could be observed contained root hairs and/or fungal hyphae (Table 3). Many also contained fine roots. Some, particularly near the terrace edge, had medium or coarse tree roots. Mosses and higher plants were growing in some joints, particularly where water was seeping.

The index of color alteration (of bedrock sampled from just below the regolith/soil) ranged from zero to 170.

3.4. Soil and regolith

Typical soil depth on the terrace surfaces was 15 to 20 cm, with means of 21.4, 14.9, and 15.0 cm, respectively, on the LBC lower, CC lower, and CC middle terraces. Soils were typically clay loam in texture, friable in consistency, with pH values in the slightly to moderately acid range (Table 5). Redox values ranged from 220 to 1100 mV, but were all within the oxidizing range. The soils had developed some weak granular structure.

The depth of unconsolidated debris measured at the scarp face sites (regolith thickness) sometimes exceeded the soil thickness (Table 4), and soil thicknesses at these sites were sometimes greater than is typical for the tread surfaces in

general. This reflects in part our selection of some measurement points in connection with major joints.

At LBC, mean soil depth beneath trees was slightly greater than at non-tree sites, but not statistically significantly so. On the lower terrace at CC, soil depth at tree sites was significantly greater than non-tree samples (22.3 vs. 13.8 cm), with smaller but significant differences on the CC middle terrace (17.6 vs. 13.8 cm).

4. Discussion

Creation of the bedrock benches by spillway construction resulted in the exposure of fresh bedrock to the surface environment. That environment is highly conducive to chemical weathering, with a warm, moist climate and abundant biological activity. The presence of vegetation communities and soil cover on adjacent slopes provided a ready seed source for vegetation to establish itself on the newly-exposed surfaces, as well as, presumably, populations of soil fauna and microorganisms.

The characteristics of the bench-terraces themselves also facilitate weathering. The construction operation involved drilling and dynamiting, which created additional fractures in the rock mass that could be exploited by water and biota. Further, the steep scarps separating the terrace treads are conducive to rock fall and dry ravel, supplying additional debris to the terrace tread below.

This combination of factors has produced rates of regolith and soil accumulation of more than 5 mm year^{-1} ; and approaching or exceeding 10 mm year^{-1} locally. Pillans (1997) compiled data from numerous published sources on soil formation and rock weathering rates. For rock weathering and soil formation over bedrock, rates range from 10^{-2} to $10^{-3} \text{ mm year}^{-1}$. The rates for soils formed on transported material such as alluvium, dune sand, and glacial till, range from about 10^{-2} to 10 mm year^{-1} (Pillans, 1997: Fig. 3). These results suggest that the earliest stages of regolith development are much faster than rates estimated over longer time periods, consistent with a nonlinear decrease in weathering and the rate of soil development over time. It also seems clear that fresh rock in a humid climate with aggressive biological activity may weather quite rapidly.

Chemical weathering is important—colors and redox measurements indicate oxidation of iron, and rock fragments and rock faces show clear evidence of chemical alteration in comparison to the fresh interiors. Stainings or discolorations, due apparently to various combinations of oxide coatings, organisms and organic matter, and soil infill were present in every rock parting which could be observed.

4.1. Soil thickness and weathering feedbacks

The rapid rates at which a thin incipient soil cover has formed in less than three decades are consistent with the notion that regolith formation is at a maximum for exposed rock or under a very thin regolith. The thickness of the soils on the terrace treads relative to thickness of typical upland soils in the region (usually $<1 \text{ m}$ and often $<0.4 \text{ m}$; Phillips et al., 2005b) is also consistent with an initially high and exponentially

declining rate of soil thickness growth over time. The results do not resolve the issue of whether weathering is maximum on exposed rock or with some threshold soil cover, but they do suggest that (in this case at least) that if there is an optimal regolith thickness for promoting weathering it is thin ($<15 \text{ cm}$) and forms rapidly.

This situation is likely related to climate, local topography, and vegetation. Abundant precipitation and humidity, and flat surfaces, make the moisture storage capacity of soil less of a limiting factor in weathering than in drier climates or more steeply sloping sites. The pines and red cedar in the study area are capable of exploiting thin, nutrient poor soils, and joints in rock outcrops. The proximity of the benches to a seed source of vegetation capable of colonizing the rocky surfaces has likely contributed to the rapid weathering.

The local spillway topography in essence provided each terrace surface with a source of upslope material. Shale outcrops and layers, in particular, weather rapidly and were observed to have debris fans from the scarp faces down to the tread surfaces. Sandstone fragments are also apparently delivered to the tread surfaces. The terrace surfaces can also be presumed to collect runoff. This moisture may accelerate chemical weathering.

Results of this study suggest that a steadily declining (typically modelled as an exponential function) rate of regolith formation over time and a similar trend in weathering with regolith or soil thickness, is more likely where the combination of soil-forming factors (or the more comprehensive list of factors influencing weathering rates; see Pope et al., 1995) are such that moisture storage at rock surfaces is not severely limiting, where surface transport processes provide fresh bedrock fragments, and where vegetation capable of colonizing rocky surfaces is present.

4.2. Vegetation and weathering feedbacks

Roots, root hairs, and fungal hyphae were ubiquitous in rock partings, and trees on the terrace treads were preferentially established in joints, local surface exposures of weaker shale, and debris at the scarp bases, which is largely associated with the weathering out of shale beds. Structure and lithology clearly influence vegetation establishment, and vegetation obviously exploits joints, fractures, and bedding planes.

The association of roots with weathered joints is a classic problem of cause, effect, and sequence, or a chicken-and-egg problem—to what extent do the roots cause or promote weathering, as opposed to root exploitation of openings already weathered by other processes? The age of the trees on the surfaces suggest that several years of exposure are required in most cases for trees to become established. As loblolly and shortleaf pines generally become established within a year following fire or clearance in this region (Guldin et al., 1994; Cain and Shelton, 2001), and are observed growing in fractures on natural rock outcrops in the Ouachitas, this suggests that some minimal pedogenic site preparation is required before trees can be established, probably in the form of weathering of fractures and the deposition of organic matter and transported material in fractures and depressions.

Despite a lag time of several years for tree establishment, this study suggests that roots rapidly exploit freshly exposed fractures. The ubiquity of root and root hair occupancy in <30 year old exposures is consistent with this assertion, as is the fact that the older trees became established very soon after spillway construction.

5. Conclusions

Bedrock surfaces recently exposed by construction in the Ouachita Mountains, Arkansas, which had not previously been exposed to surface weathering environments, developed 15–20 cm thick soil covers in less than three decades. All open bedrock joints showed evidence of weathering and biological activity. Rock surfaces and fragments also showed evidence of significant weathering alteration.

The results suggest a soil production function whereby initially rapid weathering and increasing thickness occurs, rather than maximum production after an incipient cover has developed. The rapid initial rate (5 to 10 mm year⁻¹) is apparently facilitated by a weathering-favorable regional climate, local topography favoring moisture and sediment accumulation, and aggressive vegetation colonization.

Do roots exploit pre-weathered rock partings, or do they sometimes colonize newly-exposed rock and facilitate weathering? These results suggest the latter. Tree roots that apparently became established within a few years of exposure of previously unexposed rock were found in joints, and all observable open joints had roots, root hairs, fungal hyphae, or other biota.

Acknowledgements

This project was supported by U.S.D.A. Forest Service Cooperative grant SRS 01-CA-11330124516. Outstanding field assistance was provided by Linda Martin, Taro Futamura, and “Ouachita John” Davenport.

References

- Anderson, R.S., 2002. Modeling the tor-dotted crests, bedrock edges, and parabolic profiles of high alpine surfaces of the Wind River range, Wyoming. *Geomorphology* 46, 35–58 (17:41–51).
- Bilzi, A.F., Ciolkosz, E.J., 1977. A field morphology rating scale for evaluating pedological development. *Soil Science* 124, 45–48.
- Birkeland, P.W., 1999. *Soils and Geomorphology*, 3rd ed. Oxford University Press, New York.
- Cain, M.D., Shelton, M.G., 2001. Secondary forest succession following reproduction cutting on the upper coastal plain of southeastern Arkansas, USA. *Forest Ecology and Management* 146, 223–238.
- Chesworth, W., 1973. The parent rock effect in the genesis of soils. *Geoderma* 10, 215–225.
- Guldin, J.M., Baker, J.B., Shelton, M.G., 1994. Midstory and overstory plants in mature pine-hardwood stands on south-facing slopes of the Ouachita/Ozark National Forests. In: Baker, J.B. (compiler), *Proceedings of the Symposium on Ecosystem Management Research in the Ouachita Mountains*. USDA Forest Service Southern Research Station, General Technical Report SO-112, New Orleans, pp. 29–50.
- Harden, J.W., 1982. A quantitative index of soil development from field descriptions: Examples from a chronosequence in central California. *Geoderma* 28, 1–28.
- Heimsath, A.M., Chappell, J., Dietrich, W.E., Nishiizumi, K., Finkel, R.C., 2000. Soil production on a retreating escarpment in southeastern Australia. *Geology* 28, 787–790.
- Jordan, D.W., Lowe, D.R., Slatt, R.M., Stone, C.G., 1991. Scales of geological heterogeneity of Pennsylvanian Jackfork Group, Ouachita Mountains, Arkansas: applications to field development and exploration for deep-water sandstones. American Association of Petroleum Geologists 1991 Annual, Guidebook for the Dallas Geological Society field trip 3. Little Rock, Ark. Geol. Comm., pp. 1–20.
- Langley-Turnbaugh, S.J., Bockheim, J.G., 1997. Time-dependent changes in pedogenetic processes on marine terraces incoastal Oregon. *Soil Science Society of America Journal* 61, 428–440.
- Mason, J.A., Milfred, C.A., Nater, E.A., 1994. Distinguishing soil age and parent material effects on an Ultisol, north-central Wisconsin, USA. *Geoderma* 61, 165–190.
- Morris, R.C., 1977. Petrography of Stanley-Jackfork Sandstones, Ouachita Mountains, Arkansas. Symposium on the geology of the Ouachita Mountains, vol. 1. Arkansas Geological Commission, Little Rock, AR, pp. 146–157.
- Morris, R.C., 1985. Slope and axial fan systems in carboniferous rocks, frontal Ouachita Mountains, Oklahoma and Arkansas. In: Morris, R.C., Mullen, E.D. (Eds.), *Alkaline Rocks and Carboniferous Sandstones, Ouachita Mountains — New Perspectives: a Guidebook for the Regional Meeting of the Geological Society of America*, pp. 1–5. Geological Society of America, Fayetteville, AR.
- Ollier, C.D., Pain, C.F., 1996. *Regolith, Soils, and Landforms*. John Wiley, Chichester.
- Paton, T.R., Humphries, G.S., Mitchell, P.B., 1995. *Soils: a New Global View*. Yale University Press, New Haven, CT.
- Phillips, J.D., Marion, D.A., 2004. Pedological memory in forest soil development. *Forest Ecology and Management* 188, 363–380.
- Phillips, J.D., Marion, D.A., 2005. Biomechanical effects, lithological variations, and local pedodiversity in some forest soils of Arkansas. *Geoderma* 124, 73–89.
- Phillips, J.D., Marion, D.A., 2006. The biomechanical effects of trees on soils and regoliths: beyond treethrow. *Annals of the Association of American Geographers* 96, 233–247.
- Phillips, J.D., Luckow, K., Marion, D.A., Adams, K.R., 2005a. Rock fragment distributions and regolith evolution in the Ouachita Mountains. *Earth Surface Processes and Landforms* 30, 429–442.
- Phillips, J.D., Marion, D.A., Luckow, K., Adams, K.R., 2005b. Nonequilibrium regolith thickness in the Ouachita Mountains. *Journal of Geology* 113, 325–340.
- Pillans, B., 1997. Soil development at snail’s pace: evidence from a 6 Ma chronosequence on basalt in north Queensland, Australia. *Geoderma* 80, 117–128.
- Pope, G.A., Dorn, R.I., Dixon, J.C., 1995. A new conceptual model for understanding geographical variations in weathering. *Annals of the Association of American Geographers* 85, 38–64.
- Schaetzl, R.J., Anderson, S., 2005. *Soils: Genesis and Geomorphology*. Cambridge University Press, New York.
- Selby, M.J., 1980. A rock-mass strength classification for geomorphic purposes: With tests from Antarctica and New Zealand. *Zeitschrift für Geomorphologie* 24, 31–51.
- Selby, M.J., 1993. *Hillslope Materials and Processes*, 2nd ed. Oxford University Press, Oxford.
- Soil Survey Division Staff, 1993. *Soil Survey Manual*. Agricultural Handbook, vol. 18. U.S. Department of Agriculture, Washington, DC.
- Wilkinson, M.T., Chappell, J., Humphreys, G.S., Fifield, K., Smith, B., Hesse, P., 2005. Soil production in heath and forest, Blue Mountains, Australia: influence of lithology and palaeoclimate. *Earth Surface Processes and Landforms* 30, 923–934.