Nonequilibrium Regolith Thickness in the Ouachita Mountains

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ABSTRACT

Interpretations of regolith and soil thickness in the context of landscape evolution are typically based on the notion that thickness is controlled by the interaction of weathering rates and erosion and tuned to topography. On sideslopes of the Ouachita Mountains, Arkansas, however, there is a high degree of local spatial variability that is largely unrelated to topography. This indicates nonequilibrium in the sense that there is no evidence of a balance between rates of weathering and removal, as is postulated in some conceptual models in geomorphology and pedology. Johnson's soil thickness model is applied as an alternative to interpret local variations in regolith thickness. At the study sites, regolith thickness is not generally related to slope, curvature, elevation, or pedogenic development in the solum. This indicates that variability in thickness is related chiefly to processes and controls acting in the lower regolith, below the solum. The primary controls of variability are local lithological variation, variable structural resistance associated with fractures and bedding planes in strongly tilted Paleozoic sedimentary parent material, and point-centered pedological influences of trees. A steady state regolith may be relatively rare. Results of this study suggest that an equilibrium regolith thickness is most likely in uniform lithology with a high degree of lithologic purity, less likely in interbedded sedimentary rocks, and more unlikely still if the latter are titled and fractured. Equilibrium thickness would also be more likely where the effects of bioturbation are more areally uniform (as opposed to the point-centered effects of individual trees) and where the biomantle is above the weathering front.

Introduction

Several models of landscape evolution postulate the development of a steady state equilibrium regolith thickness, implying a more or less spatially uniform regolith cover within areas with similar environmental controls. In some situations, however, regolith and soil thickness exhibit a high degree of local spatial variability, implying nonequilibrium. The purpose of this study is examine the spatial variability in regolith thickness in the Ouachita Mountains, Arkansas. In addition to attempting to understand regolith and landscape evolution, as well as soil variability at our sites, we hope to also address more general theoretical questions of (non)equilibrium regolith. The thickness of soil and regolith is a fundamental property related to the mass balance and allocation of weathering products, the weathering- or transport-limited nature of landscape evolution, and storage of water, carbon, nutrients, and other elements. Thickness is also a fundamental property relevant to the use and management of land and soil resources.

In this study, equilibrium (a term that is variously and poorly defined in geology) refers to a steady state in the case of regolith thickness, implying that the production of weathered debris is approximately balanced by thinning processes such as erosional removal to maintain a relatively constant thickness. In the spatial domain, this would be manifested as minimally variable regolith thickness within any area of negligibly variable geology and topography that has been subjected to the same history of environmental changes and disturbances. Following Renwick (1992), we distinguish between disequilibrium and nonequilibrium. A disequilibrium system is one that is moving toward steady state but that has not had sufficient time to achieve it—in this case, a regolith cover that is thickening or thinning toward some steady state thickness.

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Nonequilibrium systems are inherently dynamically unstable or dominated by frequent disturbance and do not develop a steady state equilibrium. Nonequilibrium regolith thickness would be characterized by thickening or thinning that can continue until limited by external factors, with no particular tendency to maintain constant thickness. In the spatial domain, this is manifested as variable thickness within areas of similar geology, topography, and other environmental controls.

The concept of equilibrium regolith or soil thickness is explicit or implicit in most of the best-known models of landscape evolution. At least as far back as Davis (1892) and Gilbert (1909), it has been suggested that weathering rates decline with soil thickness and that hillslope transport flux is proportional to slope gradient. Penck (1924) more explicitly described such a situation in his discussion of the "renewal of exposure" concept, whereby the production of weathered debris is inversely related to the thickness of the regolith cover. Where conditions allow regolith to accumulate, eventually a steady state condition will be reached where debris production at the weathering front is balanced by erosional removals at the surface (Penck 1924). Several hillslope and regolith evolution models are based on the production of material by weathering, a decline in weathering rates as regolith gets thicker (sometimes as a simple negative exponential function, sometimes with rates peaking under a relatively thin soil or regolith cover), slope transport by soil creep, and fluvial transport (e.g., Young 1963; Ahnert 1976; Armstrong 1980). Perhaps the best-known expression of this conceptual framework is that of Carson and Kirkby (1972); their framework continues to be employed in various forms with numerous elaborations and with different numerical solution schemes up to the present (e.g., Dietrich et al. 1995; Heimsath et al. 1997, 1999, 2001; Minasny and McBratney 1999; Furbish and Fagherazzi 2001).

Steady state soil thickness is also implicit in the concept of mature zonal soils developed by Dokuchaev (1883) and expounded on by subsequent generations of pedologists. This general phenomenon is described as self-regulation by Lisetskii (1999). Although Lisetskii's work (1999, p. 1091) focused on humus accumulation, it gives evidence for "more active soil formation in conditions of denudation" and states that "during the initial stages of soil development, soil-forming processes are nonequilibrium." Equilibrium regolith/soil thickness characterized by a balance between soil production and erosion and tuned to topography provides the basis for the work of Heimsath et al. (1997, 1999, 2001), who present methods for testing equilibrium thickness. They present radionuclide data that indicate an exponential decline of soil production with depth (consistent with the renewal of exposure concept) and show that soil thickness varies inversely with slope curvature. Carter and Ciolkosz (1991) found that the thickness of surficial (O, A, and E) horizons was unrelated to slope in soils developed on sandstone in Pennsylvania and concluded that the rate of soil formation exceeds the rate of erosion. This is implicitly based on a notion of soil thickness as a function of rates of formation versus removal, although the authors also speculate that effects of erosion on steep slopes are masked by lateral movement of throughflow and by the effects of tree throw. Similar conclusions were reached by Lisetskii (1999) on the basis of studies of dated surfaces in the Russian steppes.

Heimsath and others (1999) postulate that if the rate of bedrock conversion to mobile regolith is a function of local soil thickness, then on uniform bedrock, a hillslope approaching dynamic equilibrium should have a uniform soil/regolith mantle. Conversely, they maintain that variations in soil depth would produce variations in soil production and a non- or disequilibrium condition. The notion of feedbacks between regolith thickness and weathering rates producing a steady state thickness and spatial uniformity is also supported by Small et al. (1999) and Anderson (2002). In the temporal domain (or, more realistically, in stratigraphic interpretations of the regolith), a steady state–weathering profile characterized by a balance of erosion and weathering rates may appear to be unchanging (Ollier and Pain 1996; Pain and Ollier 1996). The feedback between soil or regolith thickness and weathering rates, generally characterized by an exponential decline in weathering with thicker regoliths, has been confirmed by several studies using cosmogenic radionuclides (Heimsath et al. 1999, 2000; Braun et al. 2001; Anderson 2002), though results differ on whether a critical threshold thickness is required before the relationship holds. Weathering rates may also decline with soil age (Markewich et al. 1989; Taylor and Blum 1995; Birkeland 1999), although it is not clear to what extent the decline is related to soil thickness as opposed to other factors such as depletion of weatherable minerals.

Although theoretical landscape evolution models and soil zonalism concepts may imply that uninterrupted pedogenesis leads to a steady state soil, disturbances and interruptions are acknowledged to occur, and none of the theories or models explicitly holds that steady state equilibrium regolith thickness is an inevitable outcome. Further, it is widely accepted that the relief of the bedrock weathering front may increase over time because of self-reinforcing positive feedback. That is, small initial variations such as structural weaknesses are preferentially weathered, with subsequent reinforcement due to increased moisture collection, greater exposure, and so on (e.g., Twidale 1991; Viles 2001). If such etch surfaces are unconformably soil mantled, then there must be a highly variable soil thickness. Such situations are particularly common in karst regions, where locally thickened soils occur in buried or partially buried subsurface solutional features and also in many tropical and subtropical landscapes where etching at the weathering front is an important process (Twidale 2002). Other recent models suggest that stability and steady state or instability and deterministic chaos are both possible within the range of realistic, plausible parameter values even when only three phenomena are considered: (1) surface removals; (2) regolith or soil thickness; and (3) weathering as a function of thickness (Phillips 1993, 1995; Minasny and McBratney 1999; D'Odorico 2000; Furbish and Fagherazzi 2001). This implies that stable steady state thickness would not necessarily occur even when no other factors have a significant influence on depth or thickness of the weathered mantle.

Nonequilibrium regolith thickness may have multiple origins. Chaos inherent in the feedbacks between weathering, thickness, and erosion could account for local spatial variability in thickness even in areas of apparently uniform geomorphic and pedologic controls (Phillips 1993; Minasny and McBratney 1999). Increasing relief of soil-mantled weathering fronts, as previously described, is another possibility. It is also possible that the effects of local disturbances such as tree throw or other pedologic effects of trees (Phillips and Marion 2004) or burrowing animals account for variations in regolith thickness. This is particularly likely where dynamical instabilities cause the effects of the latter to be disproportionately large or long lived relative to the disturbance. Finally, steady state equilibrium concepts of regolith thickness are based on the interplay of surface removal and production of debris by weathering. Soil and regolith thickness may be influenced by a much larger suite of processes (Johnson 1985; Johnson et al. 2005), resulting in deepening, upbuilding, surficial removals, and subsurface removals.

Some comments on terminology are pertinent. "Regolith" is generally defined as all unconsolidated material overlying solid bedrock or undisturbed, unweathered sedimentary deposits. Geologists and geomorphologists often use soil thickness in a way that is roughly synonymous with regolith thickness, particularly in the context of hillslope or landscape evolution. However, pedologists and soil scientists often use a more restricted definition of soil, which would include the uppermost, most highly altered portions of the regolith but not saprolites or lowermost portions of weathering profiles. We recognize that soil and regolith are not the same as a general proposition, but in the study area, they generally coincide and are defined as material overlying the Cr horizon. The latter is a weathered bedrock layer, with intact structure, fabric, and bedding of the rock. Cr horizons are often saprolite but are generally operationally defined in the field on the basis of whether they can be broken or penetrated with a spade. We prefer the term "regolith" here because we believe the implications of this work are relevant to weathered mantles in general.

This project is based in part on simple ergodic reasoning: If a small area of similar lithology, climate, vegetation, and history is characterized by a steady state equilibrium regolith thickness, then the thickness should be minimally variable where topography is constant and directly related to topography otherwise. Obvious deviations from this (e.g., significant local variability and weak relationships with topography) indicate nonequilibrium. In the study area, our earlier work (Phillips and Marion 2004, 2005) revealed substantial variation in soil and regolith morphology within small areas of uniform geology. This led us to question the concept of equilibrium regolith thickness and motivated this study. Untangling the relative importance of various processes of deepening, upbuilding, and removals may allow the interpretation of regolith thickness variations in terms of the interacting geomorphic, pedologic, and biological processes involved.

Theory

Weathering, Erosion, and Soil Production. Using Minasny and McBratney's (1999) notation, the soil production function is

$$\frac{\partial h}{\partial t} = -\left(\frac{\rho_r}{\rho_s}\right)\left(\frac{\partial e}{\partial t}\right) + D\left(\frac{\partial^2 z}{\partial x^2}\right). \quad (1)$$

This equation states that regolith production (thicker h) depends on the weathering rate (lowering of the rock weathering front e) and soil erosion, which is dependent on the diffusivity (D) and slope curvature ($\partial^2 z/\partial x^2$). The densities of rock and regolith (soil) are represented by ρ_r, ρ_s. Some version of equation (1) is a standard model for regolith thickness, though more involved models exist that incorporate more complex relationships between weathering and regolith thickness, advective and diffusive transport (or multiple transport processes), and various values of D.

The feedback between erosion and weathering is typically expressed by

$$\left(\frac{\partial e}{\partial t}\right) = W = -P_0 e^{-bh}, \tag{2}$$

where W is the weathering rate, P_0 is the potential weathering rate at $h = 0$ (exposed rock), and b is the rate at which weathering decreases as regolith thickness increases. In some cases, particularly with respect to chemical weathering, the maximum weathering rate occurs where a relatively thin regolith exists, presumably because of the more reliable moisture supply. An example function to describe this trend is (Ahnert 1987):

$$W = P_0(1 + k)\left(\frac{h}{h_c} - \frac{h^2}{h_c^2}\right), \tag{3}$$

where h_c is the critical thickness and k is a constant. In many modeling schemes, a formula such as equation (2) is used when $h \leq h_c$; otherwise, equation (3) or its equivalent is used.

Even when deposition as well as erosion is allowed, this conceptual model hinges on the assumption that bedrock weathering is the sole process of soil and regolith deepening. When forms of this model are used to estimate soil production functions, it is also assumed that $\partial h/\partial t = 0$ at a given point (i.e., steady state soil thickness; Heimsath et al. 1997, 1999, 2001). D'Odorico (2000) has shown that even this steady state model is unstable when $h < h_c$, with minor changes resulting in a shift to one of two preferred states ($h = 0$ or $h = h_c$).

This article was motivated by observations in our study area of local-scale soil variability that does not seem consistent with equilibrium regolith thickness and by evidence of the importance of biomechanical processes in addition to weathering in regolith deepening and other aspects of regolith evolution (Phillips and Marion 2004, 2005). Thus, we adopted a conceptual model incorporating biological processes more explicitly, which might account for nonequilibrium thickness.

Soil Thickness Model. The soil thickness model of Johnson (1985; Johnson et al. 2005) conceptualizes soil thickness (T) as a function of deepening processes (D), upbuilding (U), and removals (R):

$$T = (D + U) - R. \tag{4}$$

Deepening processes, including weathering at the bedrock weathering front, thicken the soil from the bottom downward. Upbuilding thickens the soil from the top upward because of processes such as sedimentation and organic matter accumulation. Removals are most obvious at the surface (erosion) but also include mass lost because of leaching, volatilization, and other processes. Johnson's work places a particular emphasis on bioturbation, which can (among other things) function as a deepening process at the base of the biomantle (which may, in some cases, correspond with the base of the soil or regolith) and also can play a role in upbuilding via biological volume expansion (e.g., roots). Traditional geomorphological models portraying regolith or soil thickness as an outcome of the interaction of weathering and surface erosion can be viewed as a special case of the soil thickness model, where the other processes in the latter are considered to be absent or of negligible importance.

In many environments, bioturbation and other biological influences on soils and weathering mantles are significant and sometimes dominant (Johnson 1990, 2002; Schaetzl et al. 1990; Paton et al. 1995; Vasenev and Targul'yan 1995; Leigh 1998; Balek 2002; Gabet et al. 2003). Given this and the fact that previous work in the study area has shown that biomechanical processes are critical in effecting local variations in soil morphology and rock fragment distributions (Phillips and Marion 2004, 2005), it makes sense to incorporate potential biological effects in any study of regolith thickness variations.

Our use of the soil thickness model will consider two aspects of deepening: weathering at the regolith/bedrock interface or weathering front (W) and deepening by bioturbation (B; e.g., root invasion of bedrock fractures or faunalturbation of weathered rock). These are not, of course, independent, given that much chemical weathering is biologically facilitated and the role of weathering in preconditioning rock for rooting and burrowing. Upbuilding is considered to be potentially linked to surface sediment accretion (A), organic matter accumulation (O), and volume expansion (V) due to biological processes such as roots and burrows. Our consideration of removals allows for surface removals due to transport by erosion (water being the most likely agent in the study area) and mass wasting (E) and consumption by fire, uptake, and harvesting (C_{surf}).

Subsurface removals can be similarly categorized as a result of transport such as leaching or pipe erosion (L) or consumption such as volatilization or uptake (C_{sub}). Note that subsurface mass removals will not result in volume or thickness reductions unless they are associated with settling or collapse. This is not necessarily the case because isovolumetric weathering can occur, where the loss of mass in solution is not accompanied by surface lowering (Cleaves et al. 1970; Cleaves 1993; Ollier and Pain 1996). Symbolically,

$$T = (W + B) + (A + O + V) - (E + L + C_{surf} + C_{sub}). \quad (5)$$

Assessing Thickness Processes

The basic approach is to link the terms in equation (5) to field observations. Because the processes themselves cannot be directly observed, the key is to determine what type of signatures or functional relationships would be associated with the operation of a given process.

Regolith deepening by weathering at the weathering front (W) is indicated by weathering products (e.g., iron oxides and other secondary minerals) and the development of saprolites or Cr (weathered bedrock) horizons. Deepening due to bioturbation (B) would be indicated by evidence of biological instrusions such as root growth and animal burrows into Cr horizons and bedrock.

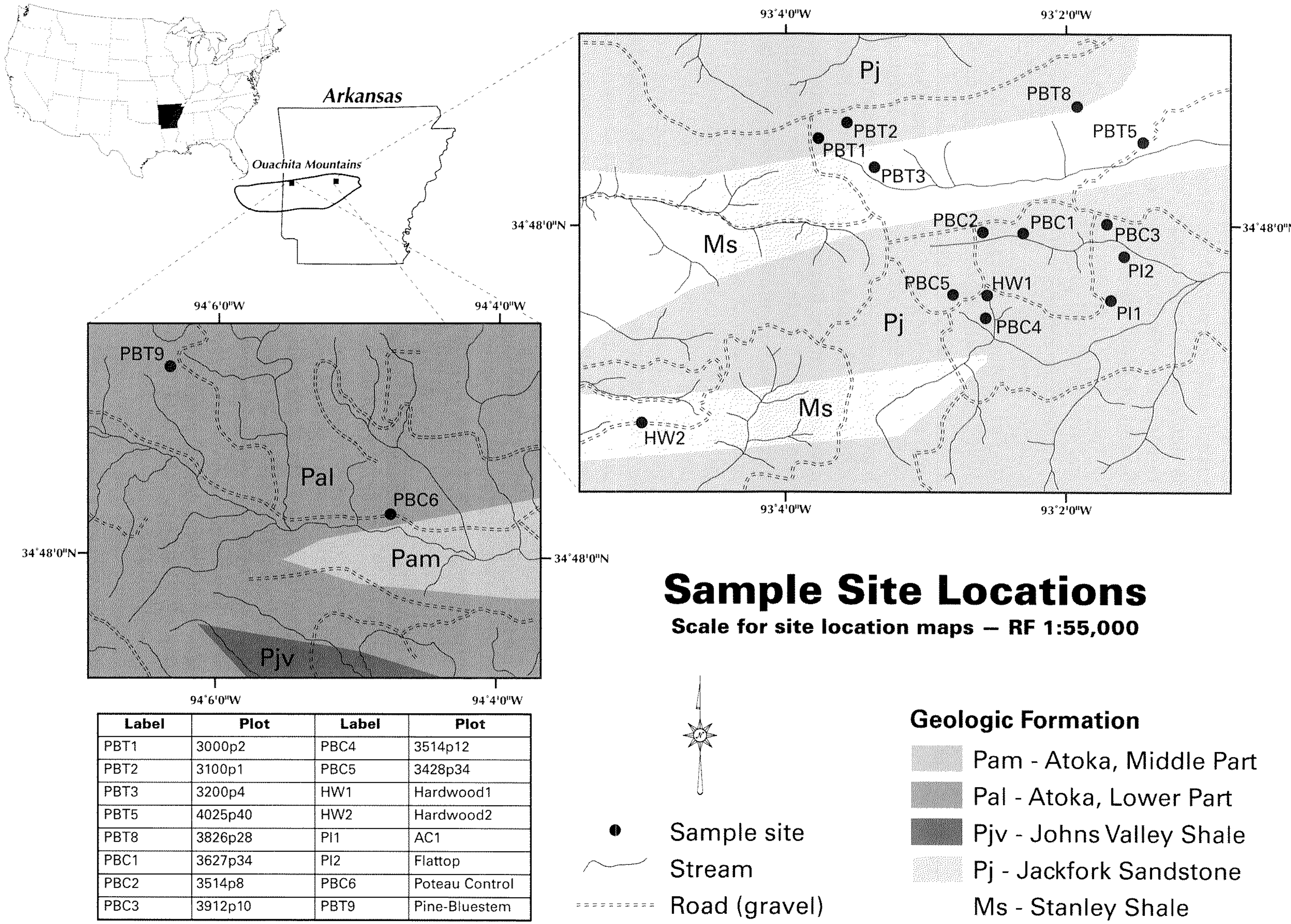
If upbuilding due to surface accretion (A) associated with sediment deposition is a significant process, there should be a systematic relationship between regolith thickness and topography, with thicker regoliths in topographic positions where deposition is likely or at least possible. Because aeolian inputs in the study area are minor, the suitable topographic settings would include depressions, toeslopes, and low-slope and low-elevation areas in general. Where such deposition is rapid or recent, additional evidence such as stratified surface deposits, cumulic surface horizons, lithological discontinuities, sharp textural contrasts, and other evidence may also be present. Upbuilding due to additions of organic matter (O) can occur as litter layer and O horizons thicken. Although the combined thickness of litter and O horizons was measured, this process has no direct impact on the regolith thickness data because the latter was measured relative to the top of the surficial mineral layer (A horizon). Volume expansion (V) may occur in conjunction with the invasion of roots and with animal burrowing. Root concentrations and pore space are indications of this process.

Surface removals by erosion and mass wasting (E) would be topographically controlled and associated with steeper slopes. Regolith thickness that is significantly influenced by erosion should be systematically related to slope gradients or curvature. Recent or rapid erosion may also be indicated by features such as erosion pavements, rills or gullies, and truncated soil profiles.

Subsurface removals (L) by leaching typically result in isovolumetric weathering in humid subtropical climates (Cleaves 1993; Pain and Ollier 1996). The bulk density of the lower regolith (C and Cr horizons) is typically about 1.35–1.7 g cm^{-3} in C and 1.7–1.9 g cm^{-3} in Cr horizons (Soil Survey Staff 2004). Bulk density of the underlying rock, based on 46 specific gravity tests on samples of the Atoka and 23 of the Jackfork Sandstone formations (two of the three formations underlying the study sites), is 2.57 g cm^{-3} (Kline 1999). The difference indicates some removal that is assumed to be dominantly associated with weathering and leaching. However, if the rock fabric is evident in these layers (as it is by definition in Cr horizons), this suggests that the removal has not resulted in any collapse, that the weathering is isovolumetric, and that this process does not lead to decreases in regolith thickness. Subsurface or surface consumption (C) of mass by fire, uptake, and so on, applies to organic matter. Because the organic matter content of the mineral horizons of soils in the study area is less than 2% in all samples tested and less than 0.5% in many cases, we assume that this process is not significant in the study area.

Study Area

Study sites are in the Ouachita Mountains within the Ouachita National Forest in Arkansas (fig. 1) and have been described in detail elsewhere (Phillips and Marion 2004, 2005). The Ouachitas are characterized by parallel, east-west-trending ridges and intermontane basins, with ridgetop elevations ranging from 230 to 850 m a.s.l. The bedrock is composed of extensively faulted and folded Paleozoic sedimentary rocks originating from a variety of marine sources (Stone and Bush 1984). The strata are typically alternating layers of sandstone and shale (Jordan et al. 1991) along with lesser amounts of quartzite, novaculite, and chert. The region was uplifted and extensively tectonically deformed from the middle Pennsylvanian through the Permian (Stone and Bush 1984). Subaerial erosion has



Label	Plot	Label	Plot
PBT1	3000p2	PBC4	3514p12
PBT2	3100p1	PBC5	3428p34
PBT3	3200p4	HW1	Hardwood1
PBT5	4025p40	HW2	Hardwood2
PBT8	3826p28	PI1	AC1
PBC1	3627p34	PI2	Flattop
PBC2	3514p8	PBC6	Poteau Control
PBC3	3912p10	PBT9	Pine-Bluestem

Figure 1. Study area showing locations of the study plots and the underlying geology

likely been ongoing since the Middle Pennsylvanian.

Sample sites are within three lithologic units: the Stanley Shale, Jackfork Sandstone, and lower Atoka Formation. All three units are common in the Ouachita Mountains. They are similar in that they all consist of steeply dipping, extensively faulted, intermixed beds of fine- to medium-grained sandstones and fine-grained shales. The formations differ in age and in the relative proportions of each rock type (Jordan et al. 1991; McFarland 1998). Exposed shales are 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. Sideslopes are often underlain by shale, with sandstone outcrops common.

Soils are described in detail elsewhere (Phillips and Marion 2005). The single most common series mapped at the study sites is the Sherless (Typic Hapludult), which is formed in shale-dominated parent material. The most common series formed in sandstone-dominated sites is Pirum (Typic Hapludult). Climate in the study area is humid subtropical. All sample sites are forested. Current forest vegetation consists of oak-hickory (i.e., hardwood dominated), shortleaf pine (pine dominated), and oak-pine (mixed pine-hardwood) forest types.

Methods

Sample Design and Data Collection. The sample design was partly determined by the role of this work within a broader study of the silvicultural, ecological, and pedological effects of forest management and ecosystem restoration practices in connection with efforts of the USDA Forest Service to restore the shortleaf pine–bluestem communities that were common in the Ouachita National Forest at the time of European settlement. This sample design has been described before (Phillips and Marion 2004, 2005), and the 16 sample plots include 10 in the mixed pine-hardwood stands that have generally replaced the pine-bluestem savannas, two hardwood-dominated sites, and two closed-canopy pine-dominated sites. In addition, one plot was established in the Ouachita National Forest's closest approximation to a pre-European pine-bluestem community, produced as a by-product of more than 2 decades of controlled burning to optimize habitat for the red-cockaded woodpecker and one in a pine-dominated stand identified by the Forest Service as undisturbed—never cleared, burned, or actively managed. The plots are circular, with a 20-m radius (≈0.13 ha). Most plots have southern aspects, the exceptions being the hardwood-dominated and closed-canopy pine-dominated stands because these forest types are not found on southerly aspects. All are on sideslopes, with the exception of one that is on a minor ridgetop.

Three soil pits were excavated with a backhoe at each of the 16 plots (two plots with high degrees of topographic variability had four pits). Twenty "posthole" pits were dug by hand at each plot. These are 10 pairs representing soils underlying coarse, woody debris and immediately adjacent nondebris sites (carbon and nutrient contents of these samples will be compared in separate studies). In this study, the small pits are treated simply as paired samples. The pairs were generally within 1 m of each other but occasionally slightly farther away to avoid rock outcrops or trees. The pairs were deliberately selected to be identical in slope, topographic curvature, and elevation (within 5 cm).

Backhoe pits, each a minimum of 1 m wide and 2 m long, were dug to or below bedrock. The posthole pits typically consisted of approximately circular pits about 30 cm in diameter. Most pits extended to bedrock or a lithic or paralithic contact; in some cases, additional augering was necessary to sample the entire regolith thickness. Thickness is measured as the distance from the top of the mineral surface (A horizon) to the top of a R (bedrock) or Cr (weathered bedrock) horizon. Cr horizons in the study area are essentially saprolite. Although Cr is weathered and softer than intact bedrock, it retains the structure, fabric, and dominant coloration of the parent rock. Measurements were made using a folding ruler directly on the described pit faces or in the posthole pits. The large pits were described using standard USDA methods and procedures (Soil Survey Division Staff 1993). In the posthole pits, the depth and sequence of horizons were recorded, along with the texture and Munsell color of the A and upper E horizons, rock fragment content of the B horizon, and depth to bedrock or a lithic or paralithic contact. Stone lines and stone zones, redox features, and buried organic matter were systematically recorded if encountered. The general lithology of rock fragments was determined by breaking at least five fragments per pit with a geological hammer.

Underlying geology was assessed in three ways. Detailed 1 : 24,000 scale geological field maps were obtained from the Arkansas Geological Commission. In the posthole samples, the lithology was recorded on the basis of material encountered at the lithic or paralithic contact and was shale or sandstone in every case. In the full soil points at each site, interbedding of shale and sandstone (and occasionally quartz) could also be observed and recorded.

Detailed topographic surveys of each plot were made with a total station or laser level and prism rod. Additionally, the slope gradient and aspect at each soil pit or posthole pit pair was independently recorded using a compass and clinometer. Digital elevation models (DEM) and topographic maps were compiled using Surface III (Kansas Geological Survey 1994). Surveyed points were converted to a square grid using distance-weighted averaging and a nearest-neighbor search. Slope gradients for each node were calculated on the basis of the adjacent node with the greatest elevation difference. Curvature was calculated as the second derivative of slope.

Data Analysis. The relationships between regolith thickness and topography were assessed by regressing thickness against slope gradient, elevation, and slope curvature. Because the sample pairs of posthole pits were chosen to be identical in terms of elevation (within 5 cm), slope gradient, and slope curvature, each pair of soil pits is associated with a single value of slope gradient, curvature, and elevation. Data analyses were conducted separately for the coarse, woody debris pits and the paired control pits for the entire data set and for the mean thickness of the pairs. Results of the latter are presented here because no qualitative differences or differences in whether results were statistically significant were obtained with the different dependent variables. The elevation variable is normalized to the center of the plot so that regolith thickness is compared with the relative elevation within each plot. Statistical significance is reported for the 95% ($\alpha = 0.05$) level. Evidence for the deepening, upbuilding, and removal processes was discerned from the profile and pit descriptions.

Results

Regolith Thickness. Regolith thickness in the study area ranged from 0 (rock outcrops) to 183 cm. Because we did not sample rock outcrops or thin veneers over rock, the range of thickness in the data is 15–183 cm. As a result, statistical summaries slightly overestimate mean regolith thickness and underrepresent the variability by eliminating sites with thickness <15 cm. For the entire data set,

Table 1. Summary of Regolith Thickness Trends by Study Plot

Plot	Mean	SD	Range	MPD	Comments
3200p4	82.4	11.5	58–104	7.8	Slight tendency for thicker regolith on gentler slopes and convexities, thinner on concavities
3826p28	61.4	14.2	38–92	12.6	Mostly sandstone parent material
4025p40	54.4	8.4	47–71	7.7	...
3100p1	85.5	14.5	54–123	18.5	Slight tendency for thicker regolith on concavities
3000p2	83.9	22.5	37–125	16.5	Slight tendency for thicker regolith on higher elevations; five sandstone pedons are thinnest on site
3428p34	59.4	9.6	47–87	10.2	...
3514p12	53.0	8.0	38–71	8.6	Slight tendency for thicker regolith on gentler slopes
3514p8	64.0	13.4	48–98	6.7	Slight tendency for thicker regolith on gentler slopes; eight sandstone pedons generally thinner than others
3912p10	60.1	9.0	42–80	7.6	Seven sandstone pedons thinner than most others
3627p34	74.9	20.7	44–122	19.3	Some tendency for thicker regolith on gentler slopes and on convexities, thinnest on concavities
Hardwood 1	55.5	12.4	35–73	5.9	Twelve sandstone pedons slightly thinner in general than eight shale
Hardwood 2	71.3	14.0	40–>118	16.4	Four thickest pedons include two sandstone
AC1	55.9	12.4	37–85	12.0	...
Flattop	55.9	10.1	41–77	8.0	Generally, thicker soils on gentlest slopes
Poteau control	62.4	20.3	15–78	15.2	Shale pedons thicker than sandstone
Pine-bluestem	75.0	8.5	57–89	9.5	...

Note. All numerical values in centimeters. SD = standard deviation; MPD = mean difference between paired samples.

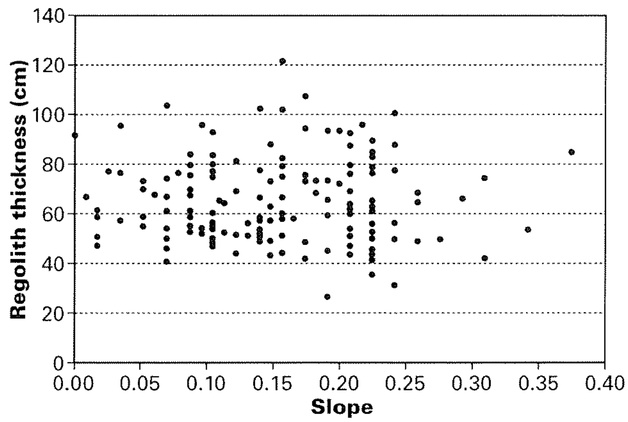


Figure 2. Mean regolith thickness (average of paired samples) plotted against slope gradient.

mean thickness is 65 cm, with a standard deviation of 16.8.

Table 1 shows regolith thickness tendencies for each plot. Within a given plot, regolith thicknesses of measured pedons varied by 30–88 cm when comparing the thickest and thinnest samples. This represents considerable variation, considering the small areas of the plots, the range relative to typical thicknesses, and the fact that some plots actually have minimum thicknesses of, or approaching, zero. The standard deviations were generally 8–20 cm. Highly localized variability in regolith thickness is indicated by the difference between the paired samples, which were generally a meter or less apart in identical (except with respect to coarse, woody debris) settings. The mean difference between adjacent pits is 11.4 cm, with a standard deviation of 10.9. In 60 (of 160) cases, the difference is 5 cm or less, while in 29 cases, the difference is 20 cm or more. The thickness difference between adjacent pairs ranges from 0 to 62 cm. The correlation between the sample pairs is statistically significant but surprisingly weak ($R^2 = 0.38$), given their adjacency.

In general, the variability in thickness over short distances and small areas is suggestive of nonequilibrium. A few general trends are apparent from the comments in table 1. There is some tendency in some plots for thicker soils to be associated with gentler slopes and vice versa. These relationships are generally weak and noisy, however, and not present in every plot. In some plots, there is also evidence of weak relationships with slope convexity/concavity, but these are spotty and inconsistent. A second trend is a general tendency for soils formed in sandstone parent material to be thinner than those formed in shale.

Topographic Relationships. If regolith thickness is significantly influenced by removals from upper slopes and deposition in depressions and lower slopes within plots, a significant relationship between thickness and elevation would be expected. The correlation between regolith thickness and elevation for the entire data set shows no significant relationship over the roughly 200-m elevation range (not shown). For each plot, regolith thickness was regressed against elevation relative to the center of the plot. There were no statistically significant relationships.

A relationship between slope gradients and thickness would be expected if erosional or mass wasting removal is an important control of thickness due to the well-known relationships between mass wasting, water erosion, and slope gradients. Although some individual plots showed weak relationships between slope and regolith thickness (see table 1), the highest coefficients of determination were $R^2 = 0.47$ and $R^2 = 0.35$. All other values were less than 0.20. Average thickness for each pair of samples is plotted against slope gradient in figure 2; there is no statistically significant relationship. The same results were obtained using the individual sample values. The same general results were obtained whether using slopes measured in the field with clinometers (presented in fig. 2) or slopes calculated from the DEM.

Slope curvature (rate of change in slope gradient) may be more closely related to the mass balance at a point than to steepness or gradient, but there was also no statistically significant relationship between regolith thickness and curvature. The rela-

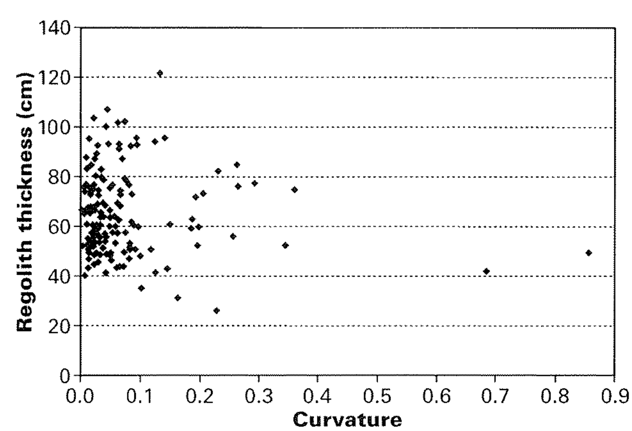


Figure 3. Regolith thickness plotted against slope curvature.

Table 2. Depth to Bedrock (cm) for Sample Pit Pairs

Slope segment	Depth values		
	Mean	SD	n
Convex	69.7	19.3	34
Straight	62.5	14.8	82
Concave	66.4	17.3	44

Note. SD = standard deviation.

tionship for the entire data set (using the average thickness value of each pit pair) is shown in figure 3. Thickness versus curvature regression analyses were also prepared for each individual plot, with linear, exponential, power function, and second-order polynomial fits attempted. In 12 cases, there was no statistically significant relationship. In one of the other four cases, the best fit line was a negative linear trend (thickness decreasing as curvature increases) and in another a positive linear trend. In a third case, the best fit trend was a positive exponential, and the fourth was a second-order polynomial, with thickness decreasing up to a curvature of about 0.15 and increasing thereafter. With the exception of the polynomial ($R^2 = 0.7$), all coefficients of determination were <0.45.

Each pair of pits was also classified in the field as occurring on convex, straight, or concave slope segments. Mean regolith thicknesses among the three groups showed no statistically significant differences according to a t-test (tables 2, 3).

Lithology. The geological framework of the study plots is shown in table 4 (see also fig. 1). All the mapped formations (Stanley Shale, Jackfork Sandstone, and lower Atoka formations) contain both shale and sandstone strata. The percentage of the soils on the plots associated with underlying shale varies from 35% to 100%, with only two plots dominated by sandstone rather than shale (3826 p28 and hardwood 1). Dip angles recorded on the geological map reflect the often steep and highly variable dips in the region, ranging from 20° to 65° for the study plots and approaching vertical in the study vicinity more generally. Strikes are generally 80°–85° though locally variable in the vicinity of the numerous faults in the region. The role of local lithological and structural variability did not become apparent until late in the data collection, and the dip or orientation of underlying strata was not measured in soil pits at 10 of the plots. This was measured at the pine and hardwood plots, as well as the pine-bluestem and Poteau control plots. Table 5 shows that the orientation of bedding often varies substantially at the plot scale.

Mean regolith thickness for the 238 pits in soils formed in dominantly shale parent material was greater than that of the 82 pits where the parent material is dominantly sandstone (66 vs. 55 cm). This is consistent with the general observation of thinner regoliths on sandstone-derived soils in the plots where both parent materials were present (though note the exception of the hardwood 2 plot). The difference would be even more pronounced if outcrop sites were sampled because these were predominantly sandstone (others were quartz or other metamorphics).

Sandstone surface fragments were common at every site, even if there was no sandstone in the underlying bedrock. This indicates mass wasting of sandstone from the ridgetops to the sideslopes. All soils sampled on shale had some degree of vertical textural contrast, typically with loam A horizons and clay loam or silty clay loam Bt horizons. The C horizons are almost always the same texture as B horizons and were distinguished from the latter mainly on the basis of the presence of recognizable remnants of shale, massive rather than subangular blocky structure, and the absence or scarcity of clay films.

Three common features of the shale-derived soils are the presence of clay films in the Bt horizons, indicating translocation; a lack of texture contrast between the Bt and C horizons; and the presence of sandstone fragments at the surface and often throughout the profile even if there is no sandstone in the underlying parent material. The rock fragments in the solum lack bedding or consistent orientation, indicating that they are not simply inherited from the parent rock. Together, these indicate a significant role for upbuilding because, in many cases, the ridgetop sandstones are the only plausible source of the coarser surficial material and sandstone fragments. Weathering of these clasts, plus associated sandy debris, likely accounts for the loamy surface layers in soils otherwise formed from shale. If surface-down translocation of clay weathered from the parent material were the primary source of clay in the Bt horizons, the argillic horizons should be significantly finer and have higher clay content than the C horizons, but this is not the case.

Table 3. Significance Tests for Depth to Bedrock

Slope segment	Test for significant differences		
	t statistic	df	Significant?
Convex versus straight	.0594	114	No
Convex versus concave	.4353	76	No
Straight versus concave	.2125	124	No

Note. df = degrees of freedom.

Table 4. Geology of the Study Plots

Plot	Formation	Dip	Lithology postholes (%)	Pits
3200p4	Ms	30	100 sh	sh (1), sh w/ss (1), ss w/sh (1)
3826p28	Ms	20	70 ss, 30 sh	ss (2), sh w/ss (1)
4025p40	Ms	35	90 sh, 10 ss	sh (3)
3100p1	Ms	25	100 sh	sh (2)
3000p2	Ms	25	75 sh, 25 ss	sh (2), ss (1)
3428p34	Ms	10	80 sh, 20 ss	sh (2), ss (2)
3514p12	Pj	35	85 sh, 15 ss	sh (2), sh w/ss (1)
3514p8	Pj	55	55 sh, 45 ss	sh (2), sh w/ss (1)
3912p10	Pj	26	65 sh, 35 ss	sh (2), sh w/ss (1)
3627p34	Pj	55	65 sh, 35 ss	sh (2), sh w/ss (1)
Hardwood 1	Pj	65	65 ss, 35 sh	sh (2), ss (1), ss w/sh (1)
Hardwood 2	Ms	35	60 sh, 40 ss	sh w/ss (2), ss w/sh (1)
AC1	Pj	63	95 sh, 5 ss	sh (2), qz w/sh (1)
Flattop	Pj	35	95 sh, 5 ss	sh (2), ss (1)
Pine-bluestem	Pal	40	90 sh, 10 ss	sh (3)
Poteau control	Pal	65	55 sh, 45 ss	sh (2), ss w/sh (1)

Source. Mapped formations and dip angles from Boles, Nimrod SE, and Paron SW Quadrangles (*Geology*). 1995. Little Rock, Ark. Geol. Comm., scale 1 : 24,000; Lambert conformal conic projection. Unpublished CoGeoMap Project field maps by C. Stone and B. Haley. On file at Arkansas Geological Commission, 3815 West Roosevelt Road, Little Rock, Arkansas 72204.
Note. The study includes mapped formation, dip angles, and the lithology of posthole samples (percent of samples with dominantly shale or sandstone Cr or R horizons) and full-size soil points (lithology as observed in pits). Interbeds are listed with the dominant lithology first (e.g., sh w/ss = shale with interbedded sandstone). Ms = Stanley Shale; Pj = Jackfork sandstone; Pal = lower Atokia; sh = shale; ss = sandstone; qz = quartz.

Analysis of rock fragment distributions indicates that vertical mixing of the soil is extensive, with tree throw and the downward movement of mass into tree stump holes being particularly important (Phillips and Marion 2004). This can account for the presence of enough sand and silt in Bt and C horizons to give a clay loam texture.

Pedogenic Development. The depth to the top of B horizon (=thickness of A and E horizons) is plotted against regolith thickness in figure 4. A positive relationship would suggest a strong role for upbuilding and/or for processes such as vertical translocation or faunalturbation that would tend to increase A and E horizon thicknesses as significant determinants of regolith thickness. A negative relationship would indicate erosion (profile truncation). However, there is no significant relationship.

Lisetskii (1999) suggests that the ratio of total B horizon thickness to that of total A and E horizon thickness is an index of pedogenic development. When this index is calculated for the study area soils and plotted against regolith thickness (fig. 5), the relationship is statistically significant but weak.

The development of B horizons and their depth is likely to be influenced most strongly by eluviation/illuviation processes and/or by mixing in a surficial biomantle. The weak relationship between regolith thickness and pedogenic development suggests that variations in thickness are not controlled by pedogenic processes in the solum or upper regolith.

Bioturbation. There is no strong evidence of plot-scale effects of vegetation cover on regolith thickness. The mean thicknesses for the two hardwood-dominated, four pine-dominated, and 10 mixed pine-hardwood plots (63.4, 62.3, and 68.3 cm, respectively) did not differ significantly from each other or the overall mean value (65 cm).

The sample plots contained 21 tree throws, described in more detail by Phillips and Marion (2005). The thickness of the rootwad can be assumed to represent the zone containing the majority of the coarse root mass and thus the depth in which most rooting occurs. Examination of the tree throw pits indicates that material down to a Cr or R horizon was typically removed. Thickness of the rootwads ranged from 19 to 100 cm (mean = 45). Although this is less than the mean regolith thickness, the tree throw data reflect the fact that uprootings are more common in shallower soil.

Descriptions of the full-size soil pits noted roots in the horizon just above a Cr or R horizon (e.g., within a C or lower Bt horizon) in every case. These data indicate root penetration to the base of the regolith.

Faunal activity and faunalturbation of the regolith is common in the study area, but there was no systematic evidence of burrowing at the base of the regolith. As we have noted elsewhere, 57% of the

Table 5. Dip Angles in Degrees

Plot	Map	Pit	Comments
Hardwood 1	65	40, 17, 0, 0	...
Hardwood 2	35	55, 32, 17	In one pit, bedding varied from 10° to 90° on various pit faces. In another, dips ranged from 0° to 17°.
AC1	63	46, 41, 15	...
Flattop	35	48, 30, 22	...
Pine-bluestem	40	19, 0, 0	One pit has sandstone fragments in upper regolith oriented at 50°.
Poteau control	65	40, 42, 42	One pit has sandstone fragments in upper regolith oriented at 70°.

Note. Recorded on geological maps (Map) and in lower soil pits (Pit), measured as deviations from horizontal (0°) at six study plots.

posthole pits had a subsurface stone line or zone (at least 70% rock fragments by volume; rock content at least 20% greater than adjacent horizons; Phillips and Marion 2004). However, no subsurface stone lines or zones were identified in the 58 full-size soil pits. This suggests that the posthole pits were frequently penetrating local stone concentrations that are not laterally extensive enough to be recognized as a stone line or zone in a soil pit. This is consistent with point-centered processes such as rock deposition in stump holes rather than areally extensive processes such as faunalturbation, which can create stone lines in some situations (Johnson 1990; Balek 2002).

Even though sawn stumps were excluded, there was a mean of nine stumps and 8.9 standing dead trees per plot (Phillips and Marion 2004). Because tree throw usually involves living trees, the >18 stumps and standing dead trees per plot compared with the mean of 1.3 tree throws indicates that "standing death" resulting from harvesting, trunk break, disease, fire, and so on, is more common than uprooting.

Roots and pores were observed, along with occasional evidence of faunal burrows, in the solum and C horizons of every full soil pit. This indicates some volume expansion due to biological activity. Root penetration into saprolites and bedrock, typically accompanied by oxidation around the root channel, was also observed in some pits.

Discussion and Interpretations

Regolith thickness in the study area is nonequilibrium; that is, there are no indications of the relatively uniform cover that would be expected within small, relatively homogeneous areas where production of regolith by weathering of bedrock is approximately balanced by erosional removals and the regolith thickness is tuned to slope gradients and curvatures. Equilibrium (and dis- or nonequilibrium) is, of course, an emergent and scale-contingent property (Renwick 1992). It is assumed here that the general weathering and pedogenetic regime has been present throughout the Holocene and that the biological effects we believe are critical here operate on the scale of multiple generations of forest (e.g., centuries).

Deepening by weathering is essentially ubiquitous, as indicated by an abundance of weathering products in the lower regolith and the development of saprolites and Cr horizons. Regolith deepening due to faunalturbation does not appear to be widespread. The general correspondence of rooting depths with regolith thickness is consistent with deepening processes associated with trees, but it is difficult to prove cause and effect. The presence of oxidation around roots and observation of roots penetrating fractures and bedding planes below the regolith suggests that locally enhanced weathering around roots penetrating the parent rock may be an important process.

The lack of association between regolith thickness and topographic variables suggests that depositional upbuilding and erosional truncation are not major controls of variations in regolith thickness. This is not to say that these processes are insignificant. With the exception of the Poteau control site, all have been logged. In the Ouachita region, logging is often associated with periods of accelerated erosion, but these periods are short because of rapid vegetation recovery in the subtropical climate. There is also no historical or archaeological evidence that the sideslopes typifying our study site were ever cultivated, and there is no field evidence of recent cultivation (e.g., remnant furrows and agricultural artifacts). No active erosion pavements or gullies were noted in the field except in the immediate vicinity of logging skid trails in a few instances.

However, soil morphology does indicate that colluvial deposition of material derived from upslope

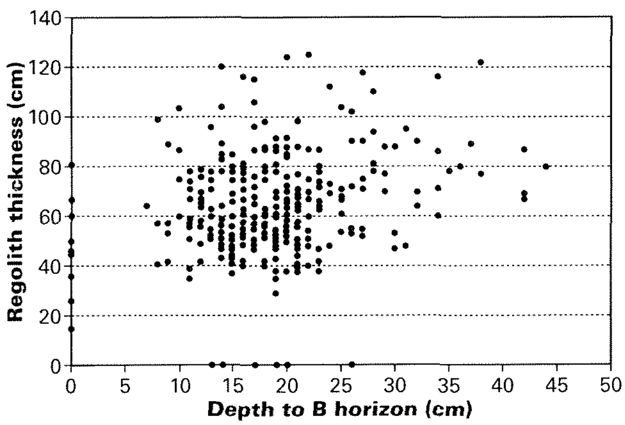


Figure 4. Regolith thickness plotted against depth to the top of the B horizon.

is common. This, plus the lack of significant relationships between indicators of pedogenic development associated with solum morphology, suggests that the variability in regolith thickness may be mainly attributable to processes acting in the lower regolith and at the weathering front.

This is further supported by systematic variations associated with sandstone versus shale parent material. Because of the complex geology of the Ouachitas, including interbedding of shales and sandstones and severe folding and contorting of strata in some cases, it is typical to find local variations in parent material lithology. Large boulders (median diameters of >0.5 m) were removed from some soil pits in otherwise shale-dominated material. This suggests that mass-wasted sandstone boulders may function as local pockets of sandstone parent material.

The local spatial variability in regolith thickness is apparently associated primarily with local lithological variability and with the localized pedologic influence of trees. This claim arises partly from the lack of any other plausible source of the local variations but is supported by field observations. Local thickening of soils can be associated with root penetration into weathered rock and with the infilling of holes created by both tree three and stump rot. Phillips and Marion (2004, 2005) have linked local pedodiversity in the area to these effects, and local variations in soil thickness associated with effects of trees is well established from studies in other areas (Lutz and Griswold 1939; Zinke 1962; Crampton 1982; Schaetzl et al. 1990; Vasenev and Targul'yan 1995; Barrett 1997).

Localized veins, lenses, or transported boulders (most commonly of sandstone within shale) may also lead in general to systematic differences in regolith thickness, presumably associated with the more rapid weathering of shale, a conclusion supported by the systematic differences in thickness of soils overlying shale and sandstone. Tree rooting is concentrated just above the weathering front, but roots were observed in soil pits penetrating bedding planes, with evidence of preferential weathering (oxides in root channels). It is reasonable to speculate that such root penetration is facilitated by more vertical bedding orientations, and thus the local variabilities in substrate dip may contribute to local variations in regolith thickness.

As discussed in the "Introduction," complex local variability in regolith thickness could arise solely because of the interactions of weathering rates and soil thickness, where the feedbacks between the two are strong. This phenomenon may be operating in the Ouachitas, but the field evidence indicates that variations in the parent rock and local effects of trees are important in controlling local thickness variations. Thus, even if the feedbacks between erosion, thickness, and weathering are in the stable range that would produce steady state equilibrium thickness, this outcome would be highly unlikely.

This study suggests that a steady state equilibrium regolith thickness is more likely in homogeneous lithology and in the case of sedimentary rocks with horizontal bedding. Steady state is also more likely where biological effects are more uniformly distributed, as opposed to the point-centered effects of trees in forest environments. In more complex lithologies and under forest cov-

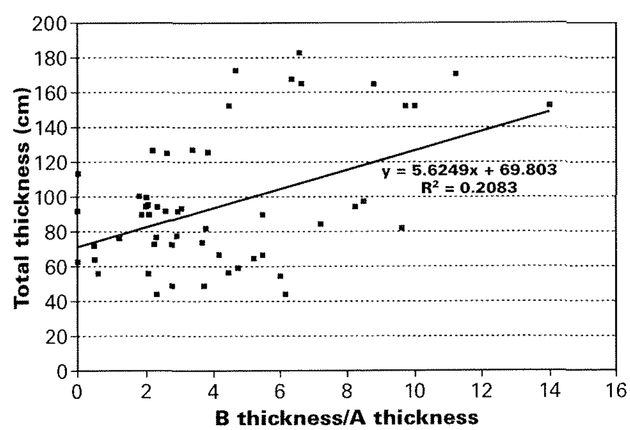


Figure 5. Regolith thickness plotted against an index of pedogenic development, total B horizon thickness/total A and E horizon thickness.

er, nonequilibrium regolith thicknesses are more likely.

The results also indicate that the weathering versus erosion framework for examining regolith thickness may be too simplistic for interpreting soils and weathering profiles in many situations. The soil thickness model, which incorporates biological influences, and the possibility of both thickening and thinning at both the surface and the weathering front, appears to be preferable as an interpretive tool.

Conclusions

Regolith thickness on sideslopes of the Ouachita Mountains exhibits a high degree of local spatial variability that is largely unrelated to topography. This indicates nonequilibrium in the sense that there is no evidence of a balance between rates of weathering and removal, as is postulated in some conceptual models in geomorphology and pedology.

Variability in regolith thickness is not generally related to topography or to pedogenic development in the solum although mass wasting of material from ridgetops is a significant upbuilding process. This indicates that variability in thickness is related chiefly to processes and controls acting in the lower regolith, below the solum. The primary controls of variability are threefold. First, local lithological variation associated with layers, lenses, or transported boulders of sandstone within strongly tilted shale parent material is associated with differential thicknesses, with thicker soils on the more weatherable, less-resistant shales. Second, the strongly tilted Paleozoic sedimentary rocks comprise a substrate that exhibits substantial variability in resistance due to fractures and bedding plains. Preferential weathering in the latter helps produce an irregular weathering front topography. Third, point-centered pedological influences of trees appear to be responsible for some localized variation in regolith thickness. Floralturbation at the weathering front and in the lower regolith because of tree throw is significant, but root penetration and associated weathering facilitation may be even more important. It is likely that the latter mechanism is important in the preferential weathering of fractures and bedding planes.

A steady state regolith characterized by consistent thickness within relatively homogeneous areas and by close relationships between thickness and topographic variables such as slope gradients and curvatures may be relatively rare. Results of this study suggest that an equilibrium regolith thickness is most likely in uniform lithology, with a high degree of lithologic purity, less likely in interbedded sedimentary rocks, and more unlikely still if the latter are tilted and fractured. Equilibrium weathering profiles would also be more likely where the effects of bioturbation are more areally uniform (as opposed to the point-centered effects of individual trees) and where the biomantle is above the weathering front.

Conceptualizing soil, weathering profile, or regolith thickness as a balance between removal and production rates is certainly plausible in some situations and is no doubt a useful abstraction over broad spatial and temporal scales. However, interpretations of regolith thickness in the field are generally better served by the soil thickness model, which assigns a greater role for bioturbation and which accounts for gains and losses of mass and volume at all depths.

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REFERENCES CITED

Ahnert, F. 1976. Brief description of a comprehensive three-dimensional model of landform development. Z. Geomorphol. Suppl. 35:1–10.

———. 1987. Process-response models of denudation at different spatial scales. Catena Suppl. 10:31–50.

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.

Armstrong, A. C. 1980. Soils and slopes in a humid temperate environment: a simulation study. Catena 7: 327–338.

Balek, C. L. 2002. Buried artifacts in stable upland sites and the role of bioturbation: a review. Geoarchaeology 17:41–51.

Barrett, L. R. 1997. Podzolization under forest and stump prairie vegetation in northern Michigan. Geoderma 78:37–58.

Birkeland, P. W. 1999. Soils and geomorphology. 3rd ed. New York, Oxford University Press, 430 p.

Braun, J.; Heimsath, A. M.; and Chappell, J. 2001. Sediment transport mechanisms on soil-mantled hillslopes. Geology 29:683–686.

Carson, M. A., and Kirkby, M. J. 1972. Hillslope form and process. Cambridge, Cambridge University Press, 457 p.

Carter, B. J., and Ciolkosz, E. J. 1991. Slope gradient and aspect effects on soils developed from sandstone in Pennsylvania. Geoderma 49:199–213.

Cleaves, E. T. 1993. Climatic impact on isovolumetric weathering of a coarse-grained schist in the northern piedmont province of the central Atlantic states. Geomorphology 8:191–198.

Cleaves, E. T.; Godfrey, A. E.; and Bricker, O. P. 1970. Geochemical balance of a small watershed and its geomorphic implications. Geol. Soc. Am. Bull. 81:3015–3032.

Crampton, C. B. 1982. Podzolization of soils under individual tree canopies in southwestern British Columbia, Canada. Geoderma 28:57–61.

Davis, W. M. 1982. The convex profile of badland divides. Science 20:245.

Dietrich, W. D.; Reiss, R.; Hsu, M.-L.; and Montgomery, D. R. 1995. A process-based model for colluvial soil depth and shallow landsliding using digital elevation data. Hydrol. Processes 9:383–400.

D'Odorico, P. 2000. A possible bistable evolution of soil thickness. J. Geophys. Res. 105B:25,927–25,935.

Dokuchaev, V. V. 1883. Russian Chernozem. *In* Kaner, N., trans. Selected works of V. V. Dokuchaev (1967). Jerusalem, Int. Program Sci. Transl., p. 1–419.

Furbish, D. J., and Fagherazzi, S. 2001. Stability of creeping soil and implications for hillslope evolution. Water Resour. Res. 37:2607–2618.

Gabet, E. J.; Reichmann, O. J.; and Seabloom, E. W. 2003. The effects of bioturbation on soil processes and sediment transport. Annu. Rev. Earth Planet. Sci. 31:249–273.

Gilbert, G. K. 1909. The convexity of hilltops. J. Geol. 17:344–350.

Heimsath, A. M.; Chappell, J.; Dietrich, W. E.; Nishiizumi, K.; and Finkel, R. C. 2000. Soil production on a retreating escarpment in southeastern Australia. Geology 28:787–790.

———. 2001. Late Quaternary erosion in southeastern Australia: a field example using cosmogenic nuclides. Quat. Int. 83–85:169–185.

Heimsath, A. M.; Dietrich, W. E.; Nishizumi, K.; and Finkel, R. C. 1997. The soil production function and landscape equilibrium. Nature 388:358–361.

———. 1999. Cosmogenic nuclides, topography, and the spatial variation of soil depth. Geomorphology 27: 151–172.

Johnson, D. L. 1985. Soil thickness processes. Catena Suppl. 6:29–40.

———. 1990. Biomantle evolution and the redistribution of earth materials and artifacts. Soil Sci. 149: 84–102.

———. 2002. Darwin would be proud: bioturbation, dynamic denudation, and the power of theory in science. Geoarchaeology 17:7–40.

Johnson, D. L.; Domier, J.; and Johnson, D. N. 2005. Animating soil thickness processes. Geomorphology, forthcoming.

Jordan, D. W.; Lowe, D. R.; Slatt, R. M.; and 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. *In* American Association of Petroleum Geologists 1991 Annual Convention (Dallas, TX, April 4–7, 1991). Guidebook for the Dallas Geological Society field trip 3. Little Rock, Ark. Geol. Comm., p. 1–20.

Kansas Geological Survey. 1994. Surface III user's manual. Lawrence, Kan. Geol. Surv., 84 p.

Kline, S. W. 1999. Arkansas resources for crushed stone construction aggregate. *In* Howard, J. M., ed. Contributions to the geology of Arkansas. Vol. 4. Little Rock, Ark. Geol. Comm. Misc. Publ. 18-D:1–65.

Leigh, D. 1998. Evaluating artifact burial by eolian versus bioturbation processes, South Carolina sandhills, U.S.A. Geoarchaeology 13:309–330.

Lisetskii, F. N. 1999. Soil catenas in archeological landscapes. Eurasian Soil Sci. 32:1084–1093.

Lutz, H. J., and Griswold, F. S. 1939. The influence of tree roots on soil morphology. Am. J. Sci. 237:389–400.

Markewich, H. W.; Pavich, M. J.; Johnson, R. G.; and Gonzalez, V. M. 1989. A guide for using soil and weathering profile data in chronosequence studies of the coastal plain of the eastern United States. U.S. Geol. Surv. Bull., p. 1589-D.

McFarland, J. D. 1998. Stratigraphic summary of Arkansas. Little Rock, Ark. Geol. Comm. Inf. Circ. 36.

Minasny, B., and McBratney, A. B. 1999. A rudimentary mechanistic model for soil production and landscape development. Geoderma 90:3–21.

Ollier, C. D., and Pain, C. F. 1996. Regolith, soils, and landforms. Chichester, Wiley, 316 p.

Pain, C. F., and Ollier, C. D. 1996. Regolith stratigraphy: principles and problems. AGSO J. Aust. Geol. Geophys. 16:197–202.

Paton, T. R.; Humphries, G. S.; and Mitchell, P. B. 1995. Soils: a new global view. New Haven, CT, Yale University Press, 213 p.

Penck, W. 1924. Morphological analysis of landforms. Czech, H., and Boswell, K. C., trans. London, Macmillan.

Phillips, J. D. 1993. Instability and chaos in hillslope evolution. Am. J. Sci. 293:25–48.

———. 1995. Time lags and emergent stability in morphogenic/pedogenic system models. Ecol. Model. 78: 267–276.

Phillips, J. D., and Marion, D. A. 2004. Pedological memory in forest soil development. For. Ecol. Manag. 188: 363–380.

———. 2005. Biomechanical effects, lithological variations, and local pedodiversity in some forest soils of Arkansas. Geoderma 124:73–89.

Renwick, W. H. 1992. Equilibrium, disequilibrium, and nonequilibrium landforms in the landscape. Geomorphology 5:265–276.

Schaetzl, R. J.; Burns, S. F.; Small, T. W.; and Johnson, D. L. 1990. Tree uprooting: review of types and patterns of soil disturbance. Phys. Geogr. 11:277–291.

Small, E. E.; Anderson, R. S.; and Hancock, G. S. 1999. Estimates of the rate of regolith production using ^{10}Be and ^{26}Al from an alpine hillslope. Geomorphology 27: 137–150.

Soil Survey Division Staff. 1993. Soil survey manual. Washington, DC, USDA, Agricultural Handbook 18, 437 p.

Soil Survey Staff. 2004. National soil survey characterization data. Lincoln, NE, Soil Surv. Lab., Natl. Soil Surv. Center. http://ssldata.nrcs.usda.gov/.

Stone, C. G., and Bush, W. V. 1984. Summary of the geology of the central and southern Ouachita Mountains, Arkansas. *In* Stone, C. G., and Haley, B. R., eds. A guidebook to the geology of the central and southern Ouachita Mountains, Arkansas. Little Rock, Ark. Geol. Comm., p. 65–75.

Taylor, A., and Blum, J. D. 1995. Relation between soil age and silicate weathering rates determined from the chemical evolution of a glacial chronosequence. Geology 23:979–982.

Twidale, C. R. 1991. A model of landscape evolution involving increased and increasing relief amplitude. Z. Geomorphol. 35:85–109.

———. 2002. The two-stage concept of landform and landscape development involving etching: origin, development, and implications of an idea. Earth Sci. Rev. 57:37–74.

Vasenev, I. I., and Targul'yan, V. O. 1995. A model for the development of sod-podzolic soils by windthrow. Eurasian Soil Sci. 27:1–16.

Viles, H. A. 2001. Scale issues in weathering studies. Geomorphology 41:63–72.

Young, A. 1963. Soil movement on slopes. Nature 200: 129–130.

Zinke, P. J. 1962. The pattern of individual forest trees on soil properties. Ecology 43:130–133.