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Rock fragment distributions and regolith evolution in the Ouachita Mountains, Arkansas, USA

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Abstract

Rock fragments in the regolith are a persistent property that reflects the combined influences of geologic controls, erosion, deposition, bioturbation, and weathering. The distribution of rock fragments in regoliths of the Ouachita Mountains, Arkansas, shows that sandstone fragments are common in all layers, even if sandstone is absent in parent material. Shale and sandstone fragments are produced at the bedrock weathering front, but the shale weathers rapidly and intact fragments are rare in the solum. Sandstone is weathered from ridgetop outcrops and transported downslope. Some of these fragments are moved downward, by faunalturbation and by transport into pits associated with rotting tree stumps. Upward movement by treethrow is common, resulting in a net concentration of rocks near the surface. However, the highest fragment concentrations are in the lower regolith, indicating active production at the weathering front. The regolith is a dynamic feature, reflecting the influences of vertical and horizontal processes, of active weathering at the bedrock interface, and of surficial sediment movements. The role of trees in redistributing rock fragments suggests that significant regolith mixing occurs over time scales associated with forest vegetation communities, and that forest soils have likely been extensively mixed within Holocene and historic time. Copyright © 2005 John Wiley & Sons, Ltd.

Keywords: **regolith; rock fragments; bioturbation; soils; weathering; Ouachita mountains**

Introduction

The goal of this paper is to determine the processes and/or environmental controls responsible for the distribution of rock fragments in soils and weathering mantles in the Ouachita Mountains, Arkansas, and the implications for regolith evolution. We are motivated chiefly by interests in the relationship between regolith and landscape evolution, and in the coevolution of soils, landforms, and ecosystems, but there are numerous other rationales for studying rock fragments in soils. For example, the distribution of rock fragments has important implications for geomorphology and Quaternary sciences, with respect to interpretation of soils, palaeosols and weathering profiles (Pain and Ollier, 1996); surface exposure dating of clasts (Watchman and Twidale, 2002); and evaluating potential burial mechanisms for archaeological artifacts (Johnson, 1990; Balek, 2002).

Soils containing rock fragments are widespread globally, occurring on erosional and depositional landforms, and have impacts on soil use and management, erodibility, surface roughness, and infiltration and other hydrologic properties (Ericksson and Holmgren, 1996; Poesen and Lavee, 1994; van Wesemael *et al*., 1996, 2000; Wijdenes *et al*., 1997). Rock fragment (RF) content also plays an important role in soil taxonomy, for example in the recognition of lithologic discontinuities, and in family-level classification (Schaetzl, 1998; Soil Survey Staff, 1998). The location of fragments within a soil profile, and the processes by which they came to occupy these positions, may also play a role in interpretations of archaeological sites (Balek, 2002; Johnson, 1990; Leigh, 1998; Mercader *et al*., 2002), where the extent to which subsurface lithics are buried in the position of original deposition or mobile within the soil is a key consideration. Similarly, understanding of the effects of tillage and other physical soil disturbances (Wijdenes *et al*., 1997), and of some forms of bioturbation (Balek, 2002; Cox *et al*., 1987; Small *et al*., 1990) on RF distributions is critical to assessing the relative importance of those processes.

The production, destruction, and movement of rock fragments in regolith reflects the combined, interacting influences of both surface and subsurface, geogenic and pedogenic, and vertical and lateral processes. Rock fragment distributions also integrate the effects of erosion and deposition processes, weathering, translocation and mixing, and geological inheritance. Therefore an examination of rock fragment distributions within the regolith is intimately related to more general models of hillslope and landscape evolution. Carson and Kirkby (1972) set out a conceptual framework for integrating weathering, erosion, deposition, and transport in the evolution of hillslope forms and regolith covers. Later efforts to quantitatively model hillslope and regolith evolution reflect this framework. A few of the many examples include Ahnert (1987), Anderson (2002), Armstrong (1980), Howard (1994) and Kirkby (1985). This general class of models may be both informed and tested by knowledge of the distribution of rock fragments within the regolith.

More directly, assessments of rock fragments may make a critical difference in interpretations of landscape evolution. Subsurface stone lines, for example, are in many cases interpreted as either buried erosional lag surfaces, or as the base of a surficial biomantle (Johnson and Balek, 1991). Clearly, there is a huge difference with respect to implications for landscape evolution. Likewise, the extent to which surficial rock fragment layers may be transported from upslope, left behind as weathering residuals of a downwasting surface, or brought to the surface by tillage or treethrow leads to potentially fundamentally different conclusions about pedogenesis, hillslope evolution, and landscape stability (e.g. Cox *et al*., 1987; Poesen and Lavee, 1994; Small *et al*., 1990; Teeuw, 1991; van Wesemael *et al*., 1996; Phillips and Marion, 2004). These are just two examples of how understanding of rock fragment distributions is linked to understanding of landscape evolution.

In relating soil properties to regolith evolution, morphological properties may be preferable to at least some chemical, physical, and biological properties because of the slower response time and greater persistence of morphological properties. Rock fragments in particular are a persistent morphological feature. The emplacement or movement of rock fragments in the regolith by any process, ancient or contemporary, leaves evidence that is not as easily obscured or obliterated as that of many other pedogeomorphic signatures, such as biological or chemical properties which may be rapidly modified, or more easily destroyed physical properties such as structural aggregates. The study of soils and weathering mantles in general has long been linked to landform and landscape evolution, and specific rock fragment features such as stone lines or zones have been used to piece together landscape evolution (e.g. Cox *et al*., 1987; Johnson and Balek, 1991; Mercader *et al*., 2002; Teeuw, 1991). RFs in soils and weathering profiles have been shown to be key in interpreting erosion surfaces, biomantles, and lithological discontinuities. However, we believe that the general RF characteristics of the regolith have been underused as a tool in deducing regolith evolution. As a persistent regolith property reflecting the combined influences of geologic controls, weathering, pedoturbations, translocation, erosion, and deposition, RFs can potentially reveal much about regolith development – if the various effects above can be disentangled.

Rock fragments are defined as particles ≥2 mm in diameter with horizontal dimensions less than that of a soil pedon (generally <1 m^2). In the US Department of Agriculture system, fine and medium gravels are rock fragments <20 mm, coarse gravel is 20 to 75 mm, cobbles are 76 to 250 mm, stones are 250–600 mm, and boulders >600 mm in diameter. The term 'stone' is also used in a more general way to refer to RFs up to cobble size, as in references to stone lines and stone zones.

Background

Fragments of rock may be introduced to the regolith in three general ways. First, they may already be present in the parent material, as for example in glacial till. Second, they may be produced *in situ*, mainly by weathering of bedrock, but also by the formation of indurated features such as ferricretes or silcretes. Third, they may be transported in by mass wasting, erosion, or human agency. However introduced, clasts may be moved vertically or horizontally. Thus the presence, location, and nature of rock fragments may provide clues to a number of geomorphic processes and controls. For example Teeuw (1991) identified 10 catena types in tropical Sierra Leone based on their gravel layers or stone lines. The type of clasts dominating each catena was found to be indicative of specific topographic and geomorphic process environments, and the gravel layers were found to be useful as palaeoenvironmental indicators. Cox *et al.* (1987) were able to hypothesize the surface rock fragment spatial patterns and gravel/pebble ratios likely to be produced by three alternative mechanisms postulated for the formation of Mima mounds in the Columbia plateau. They found that RF evidence was consistent with movement primarily by fossorial rodents. The specific geomorphic situation can constrain the possibilities for fragment placement. In the South Carolina sandhills, for example, any lithic materials must be transported by humans, and in the sites studied by Leigh (1998) only aeolian, bioturbation, and colluviation processes are candidates for artifact burial. Leigh (1998) concluded that bioturbation appears to be the primary burial process.

Surface RF movements are dominantly downslope, and due to mass movement and fluvial or glacial transport processes, though humans and other organisms may be locally significant. Rock fragments may become more concentrated at the surface over time due to erosional removal of fines, or to upward movement (Poesen and Lavee, 1994). Mechanisms for vertical movement of fragments in soils reviewed by Poesen and Lavee (1994) include faunalturbation (burrowing, tunnelling, mounding, or surface trampling), floralturbation (tree uprooting), cryoturbation (freeze–thaw), argilliturbation (shrinking and swelling of clays), gravitational settling, crystal growth and wasting, seismiturbation (seismic movements), and human agency.

Other mechanisms indentified in the literature include rock displacement by tree root growth, and the deposition of locally displaced or upslope rocks in stump rot holes (Lutz and Griswold, 1939). More generally, in a forest environment tree establishment has at least three process implications for rock fragments. First, the presence of the tree prevents the import of rock fragments by processes such as mass wasting and faunalturbation to the spot occupied by the bole. Second, displacement of soil by tree growth may move fragments in the soil away from the tree. Third, there is the possibility of treethrow and the subsequent redistribution of coarse clasts. All three phenomena either impoverish the growth site of rock fragments or inhibit input of new fragments. Tree uprooting can 'mine' RFs from the root zone, and they subsequently become concentrated at the surface as finer materials are eroded from rootwads and treethrow mounds (Johnson, 1990; Schaetzl and Follmer, 1990; Small *et al*., 1990).

Rock fragments anywhere in a weathering mantle may also be present through inheritance from parent material, or as resistant remnants of bedrock weathering. Though bedrock is unlikely to be perfectly isotropic, as a general rule in more-or-less uniform lithology without mixing we might expect the volume and size of fragments to increase, and the degree of weathering to decrease, from the surface to the bedrock weathering front (e.g. Certini *et al*., 2003). By similar reasoning, if fragments are not moved within the regolith, then fragment distributions in soils derived from RF-containing sediments should mirror those of the parent material (allowing in some cases for some diminution of fragments by post-depositional weathering).

Study area

The Ouachita Mountains are a complex of parallel, east–west trending ridges and intervening basins covering an area approximately 100 km wide (north–south) and 320 km long (east–west) in central Arkansas and eastern Oklahoma (Figure 1). Ridges are narrow with moderately steep slopes and sharp, even crests. Ridgetop elevations range from 230 to 850 m above sea level, and local relief varies from 75 to 530 m, generally increasing from east to west.

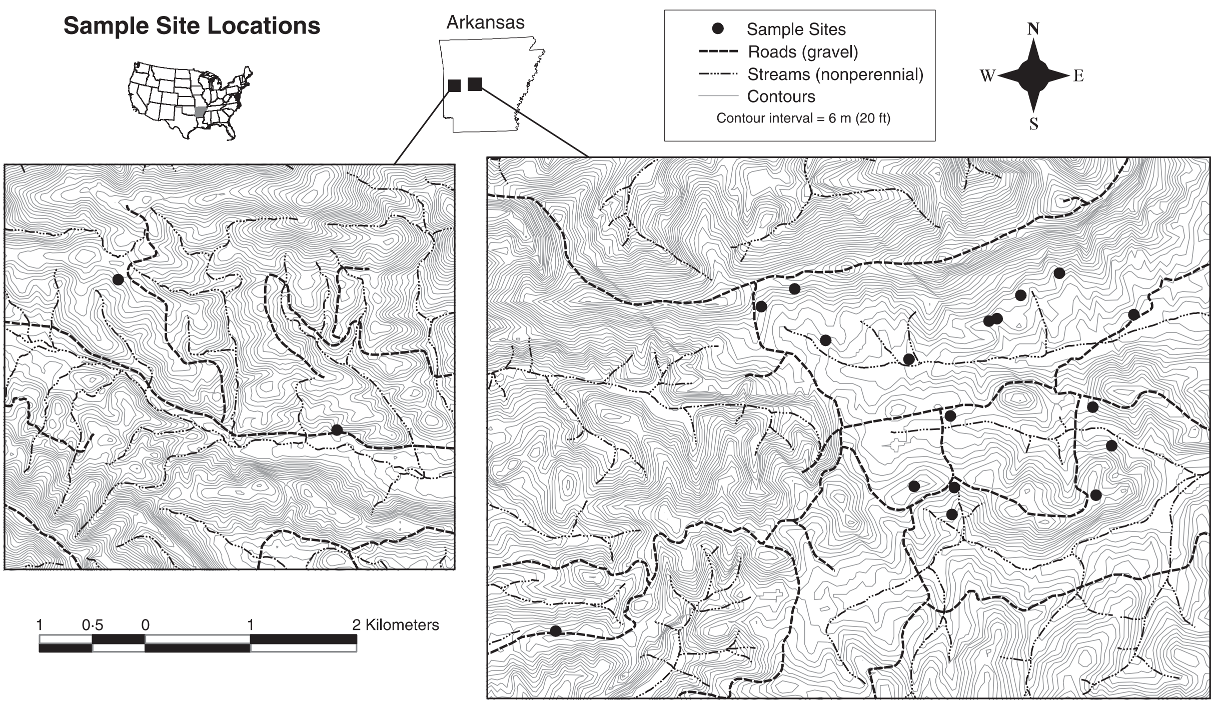

Figure 1. Study area.

The Ouachitas are chiefly composed of highly folded and faulted Palaeozoic sedimentary rocks. Sediments were deposited from the Early Ordovician to Middle Pennsylvanian (Upper Carboniferous), and originated from a wide variety of marine sources (Stone and Bush, 1984). The strata feature alternating layers of sandstone and shale (McFarland, 1998) along with lesser amounts of quartzite, novaculite, and chert. The area was uplifted and extensively deformed through sequential periods of folding, decollement, and faulting from the Middle Pennsylvanian through the Permian, (Stone and Bush, 1984). Subaerial erosion is believed to have been almost continuous since the Middle Pennsylvanian (Stone and Bush, 1984).

The sample sites in this study are within three lithologic units: the Stanley Shale, Jackfork Sandstone, and Atoka Formation. These units are extensive in the Quachita Mountains and 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. The Stanley Shale contains the most shale, the Jackfork includes the most sandstone, and the Atoka Formation consists of roughly equal proportions of sandstone and shale (McFarland, 1998). Where exposed, the 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. Side slopes are often underlain by shale, with sandstone outcrops common.

The study area climate is humid subtropical. Average daily summer temperatures range from 20 to 30 °C, while winter temperatures range from 4 to 10 °C. Mean annual precipitation is 1300–1400 mm, occurring primarily as rain during warm-season thunderstorms or autumn and winter frontal events. Precipitation is distributed fairly evenly throughout the year, with the maximum monthly precipitation typically occurring during the spring. Humidity is high from the late spring to early autumn, but decreases substantially outside this period.

All the study 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 (USDA Forest Service, 1999). The present composition of the forest vegetation has existed only during the last 4000 years (Delcourt and Delcourt, 1991). Prior to the start of Euro-American settlement approximately 200 years ago, it is believed that forest stands were generally more open than today and had somewhat different composition and structure. The dramatic decrease in fire frequency during this period may explain these changes (Foti and Glenn, 1991).

Conceptual Model

We conceptualize the regolith at a given time and place as having three levels or layers with respect to the possibilities for gains or losses of RFs, recognizing that in cases of thin regolith not all layers may be present, and that over time erosion and downwasting may remove surface layers and expose former subsurface layers at the surface. The surface layer includes the ground surface *per se* and the surficial soil horizons (O and A horizons). The surface layer is subject to both inputs and outputs from surface processes; any effect of surface processes on RFs in the subsurface is indirect and mediated through the surface layer. The lower layer is the lowermost weathered zone, immediately above the weathering front. This layer often corresponds with a C horizon, though occasionally in the study area it is the lowermost B horizon, which sometimes grades directly into a Cr or R horizon. The lower layer may receive inputs of fragments due to parent material weathering, as the weathering front migrates downward. The intermediate or middle layer is insulated from additions of rock from the surface and the weathering front. Therefore fragments in this layer must be inherited weathering remnants, or translocated within the regolith. The middle layer is typically associated with B horizons, though it may also or alternatively include E and upper C horizons.

Starting with this three-layer model, we first attempt to identify all common processes responsible for fragment emplacement and movement, and then to eliminate those that are absent or highly unlikely in the study area. Second, we consider the possible mechanisms or controls of gains or losses to each layer. Finally, we consider empirical field tests for those mechanisms or controls. Thus we will discuss the RF processes after describing the study area.

Rock fragments in the Ouachita regolith

The study sites are all on side slopes underlain by bedrock. Therefore two of the three mechanisms for introducing rock fragments – weathering of parent rock, and slope transport – are possible. Inheritance from sediments is irrelevant to the study sites, none of which are formed on or in unconsolidated sedimentary deposits.

Table I lists the possible processes by which rock fragments may be moved laterally or vertically in the regolith, surface or subsurface, at the Ouachita study sites. Table II lists rock fragment movement processes which are known to occur in general, but which are believed to be absent or unimportant in the study area, along with a brief justification. Potential gains and losses of fragments to each layer are discussed below and summarized in Table III.

Table I. Rock fragment movement processes to be accounted for or evaluated in the study area

1. Faunalturbation: fine material movement and rock fragment undermining by burrowing, tunneling, or mounding fauna.
2. Floralturbation
   A. Tree uprooting
   B. Rock displacement by root growth
   C. Rock fall into stump holes
3. Mass wasting: including creep, debris flows, avalanches, rock falls, slumps, etc.
4. Gravitational settling
5. Erosion (fluvial or wash)
6. Tillage

Table II. Rock fragment movement processes not considered in the study area

1. Trampling by megafauna: limited grazing history on Ouachita sideslopes; minimal tramping by native fauna, and major displacements reflected in mass wasting.
2. Cryoturbation: rare in subtropical climate.
3. Argilliturbation: low content of smectitic clays; absence of vertic soil features.
4. Aeolian processes: minimal wind influence in steep, fully vegetated landscape.
5. Crystalturbation: not observed; unlikely in shale/sandstone.
6. Seismiturbation: area has been tectonically stable throughout the Quaternary; any surface movements initiated by seismic activity reflected in mass wasting.
7. Human agency (logging, mining, off-road vehicles, etc.): potential effects minimized by site selection; local effects reflected in mass wasting.

Table III. Potential increases and decreases in rock fragment concentrations at the study sites

Layer	Gains	Losses
Surface	deposition from upslope	transport downslope
	outcrop weathering	downward movement
	upward transport	faunal undermining
	tillage	gravity settling
	tree throw	clast weathering
	erosional winnowing	
Middle	outcrop weathering	clast weathering
	transport from surface	upward movement
	faunal undermining	tillage
	gravity settling	tree throw
Lower	production at weathering front	clast weathering
	transport from surface as in middle layer*	upward movement as in middle layer*

* if regolith is relatively thin

Surface layer

There are five potential types of mechanism for adding RFs or increasing relative rock concentrations in the surface layer. Absolute additions of fragments include deposition from upslope due to mass wasting or erosion, weathering of bedrock outcrops at the surface, and upward transport of subsurface fragments via tillage and treethrow. Erosional winnowing – the preferential removal of fines – could result in an increase in the concentration of rocks at the surface without, or independently of, absolute additions.

Tree uprooting can result in a net increase in rocks at the surface (Johnson, 1990; Schaetzl and Follmer, 1990; Small *et al*., 1990). Effects of tillage processes are, generally, to enrich the surface in rock fragments at the expense of the plough layer, with the coarsest fragments accumulating at the top and the finest rock fragments at the bottom of the tilled layers (Poesen and Lavee, 1994; Wijdenes *et al*., 1997; Wijdenes and Poesen, 1999).

On abandoned agricultural fields in Spain, van Wesemael *et al*. (1996) found that RF cover increases non-linearly with slope due to selective erosion of fines on steeper slopes, with the effect even more pronounced for clasts greater than 25 mm in diameter. In general, erosional winnowing is often proposed or assumed as the source of many coarse surface lags, and the preferential removal of fines transported to the surface by soil fauna is sometimes a key mechanism in the coarsening of surface horizons more generally (Paton *et al*., 1995; Soil Survey Staff, 1975, p. 21).

Losses or reductions of the volume of rock fragments in the surface layer include erosion and mass wasting, destruction or diminution via weathering, and loss downward by gravitational settling or faunal undermining.

Given sufficient time, weathering should reduce the size of, and eventually destroy, RFs. The pace of this process is likely to be quite slow compared with some of the other processes considered, however. Downward movement due to animal digging and burrowing has been shown to occur in many soils, and may often result in the formation of subsurface stone lines and stone zones (Balek, 2002; Johnson, 1990; Johnson and Balek, 1991; Leigh, 1998; Paton *et al*., 1995). Gravitational settling of more than a few centimetres, in the absence of bioturbation or soil mixing, is most likely in loose soils. Localized exceptions may occur where rocks are locally displaced by tree growth, and then fall into the resulting pit when the tree rots or burns.

Middle layer

The middle layer is insulated from direct effects of some of the potential removals and additions operating at the surface, particularly those involving erosion and mass wasting – that is, the effects of these processes on the subsurface are mediated by processes within the surface layer. Some of the processes resulting in losses of fragments from the surface lead to additions to the middle layer. Likewise some losses from the middle are added to the surface.

The potential types of mechanism for increasing fragment concentrations in the middle layer include weathering of bedrock outcrops, and downward movement from the surface via gravity settling and faunal undermining. Losses of fragments from this layer can occur in response to upward movement via tillage and treethrow, and diminution or destruction due to weathering.

Lower layer

The major source of new RFs to the lower layer is production by weathering at the weathering front. Losses may occur due to further weathering of those clasts.

In general, the lower layer is considered too deep to be affected by additions via gravity settling or faunalturbation, or by losses upward via treethrow or tillage. However, where soils are thin, and depth to bedrock or a paralithic contact is only rarely greater than 150 cm and often less than 50 cm at the study sites, the middle and lower layers may be essentially combined, so that there is a two-layer regolith with respect to rock fragment distributions.

Methods

Sample design

The sample design was partly determined by the position of this work within a broader study of the silvicultural, ecological, and pedological effects of forest management and ecosystem restoration practices. There are 16 sample plots, 10 of which are in mixed pine–hardwood forests. The USDA Forest Service is seeking to restore some of the the shortleaf pine–bluestem communities which were common in the Ouachita National Forest at the time of European settlement. Two areas were delineated. In the treatment area, the mixed pine–hardwood stands which have generally replaced the pine–bluestem savannas are subjected to thinning of hardwoods and controlled burning; the control area is undisturbed. Within the treatment and control areas, five plots each were established for soil studies; soil morphology was studied before treatments, so rock fragment distributions are not affected by the recent thinning and burning. All 10 of these plots are on generally southern aspects. Six additional plots were established to represent other vegetation communities in similar topographic settings. Two were in closed-canopy pine-dominated forests, as opposed to the pine–bluestem savanna communities. Two were in hardwood-dominated stands. All the pine- and hardwood-dominated stands were on generally north-facing slopes, as they do not occur on southern aspects in the area. One plot was established in an area believed to be the Ouachita National Forest's closest approximation to a pre-European pine–bluestem community, which has been produced by more than two decades of controlled burning.

A final plot was established in a south-facing, pine-dominated stand identified by the Forest Service as being undisturbed since European colonization – never cleared, burned, or actively managed. The plots are circular, with a 20 m radius from centre points along previously established vegetation transects. All plots are on sides-lopes (e.g. both ridgetops and valley bottoms were avoided).

At each plot three soil pits were excavated with a backhoe (two plots with high degrees of topographic variability had four pits). An additional 20 'posthole' pits were dug by hand. These represent 10 pairs located by flagging the 10 largest pieces of coarse woody debris, and sampling the debris site and a nearby 'control' site. The original intent of this scheme was to examine the influence of woody debris on soil morphology. No significant differences between the debris/control pairs attributable to woody debris were detected, so in this study the small pits are treated simply as paired samples. The paired posthole pits were generally within 1 m of each other, but occasionally farther away (maximum 3·25 m) to avoid surface rock outcrops or trees. In addition, full-size soil pits were described at two other treatment plots in the same area in support of other ecological studies by the Forest Service. The term 'full-size' soil pits (approximately 1 m wide by 2 m long, with a depth of 1 m or to bedrock, whichever is deeper) is used to distinguish the larger pits from the posthole samples.

The backhoe pits were dug to or below bedrock, which generally occurred within 2 m. They were a minimum of 1 m wide and 2 m long. The posthole pits were 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 soil thickness. The large pits were described using standard US Department of Agriculture methods and procedures (Soil Survey Division Staff, 1993). In the posthole pits the depth and sequence of horizons was recorded, along with the texture and Munsell colour of the A and upper B horizons, rock fragment content of the B horizon, and depth to bedrock or a lithic or paralithic contact. Pedogenic features that were systematically recorded when encountered included stone lines and stone zones, redox features, and buried organic matter. The general lithology of rock fragments was also recorded by breaking at least five fragments per pit with a geological hammer.

The soil data were first collected in the treatment and control plots, and formed the basis for a preliminary study of rock fragments reported by Phillips and Luckow (2002). Based on these findings, subsequent fieldwork included more detail on rock fragment distributions in soil pits, as described below.

Treethrows were inventoried at each plot, and the dimensions of the rootwad measured. Stumps and standing dead trees were also inventoried, and the diameter at breast height (or at the top of the intact bole) was measured to estimate basal area. Detailed topographic surveys were also conducted of each plot, and the slope gradient and aspect at each soil pit or posthole pit pair was recorded.

Rock fragments

Volumetric RF contents were estimated for each horizon in the soil pits on the basis of strike tests with a thin (1 mm diameter) metal rod or the tip of a soil knife. The rod or blade is inserted randomly at least 10 (and up to 40) times in each horizon to 1 cm. A strike is recorded if a rock is encountered. At pits in the treatment and control plots the general size class of the fragments was estimated, and the general lithology recorded. At the 19 pits in the six other plots, the angularity of fragments was also recorded using standard sedimentological categories ranging from rounded to angular. The orientation of fragments was also recorded. Rather than the general size class, in these 19 pits the median diameter of the largest fragment in each horizon was measured. Finally, the proportion of the surface covered with rock fragments or outcrop was estimated on the basis of strike tests with the pick end of a geological hammer in an area within 0·5 m of the described face.

In the posthole pits a minimum of five fragments from each pit was broken with a geological hammer to determine general lithology. The RF content of B horizons was recorded on the basis of *in situ* strike tests. A fragment content of 35 per cent is a key threshold in soil taxonomy separating skeletal from non-skeletal families. We established another key threshold at 70 per cent based on our field observation that this represents an approximate boundary between 'rocky dirt' and 'dirty rock', e.g. stony soils versus matrix-supported clasts. Because of the difficulty in estimating fragment contents in the postholes, the emphasis was on correctly categorizing B-horizon fragment content as less than 35, greater than 70, or 35 to 70 per cent. A stone line or zone was defined as an area with at least 70 per cent rock fragments, and with a concentration at least 20 per cent higher than immediately adjacent layers.

The 320 posthole pits were each categorized with respect to presence/absence of a surface stone line, zone or pavement; presence/absence of a subsurface stone line or zone; and rock fragment abundance in the B horizon (<35, 35 to 70, or ≥70 per cent). The combinations of these categories lead to 12 rock fragment classes, ranging from the rockiest (surface stone line or zone, subsurface stone line or zone, and B horizon RF content ≥70 per cent) to the least rocky (no stone lines or zones; B horizon RF content <35 per cent).

Results

General rock fragment patterns and trends

In general, soils of the Ouachita Mountains are quite rocky, though the rock fragment content varied greatly both within and between sample plots. One of the most striking findings was the presence of sandstone fragments in all 58 soil pits and all 320 posthole pits. It is no surprise that sandstone is common, given the sandstone ridgetops throughout the study area, and the parent geology of interbedded shales and sandstones. However, sandstone fragments were found even where the parent material exposed in the pits is entirely shale. A number of outcrop exposures were examined throughout the Ouachita National Forest, which confirmed that sandstone surface fragments, at least, are common even where there are not local sources of sandstone within the parent material.

Several varieties of sandstone were encountered, varying in colour, texture, grain size, purity, and density. Quartzite and other metamorphic fragments were also relatively common, as were shale fragments. The shales are relatively soft and weather rapidly, however, and intact shale fragments were rarely found above the C horizon even in shaley parent material.

The vertical distribution of rock fragments by horizon is important in evaluating some of the processes described in the previous section. Concentration of rock fragments at the surface, for example, could reflect upslope inputs and upward translocation, with the latter also indicated by relative impoverishment of the middle layers. Production of fragments at the weathering front would be indicated by high fragment contents in the lower layer.

Of the 58 full soil pits, 34 (59 per cent) had the highest rock fragment (RF) concentrations in the lowest soil horizon (that is, the lowest C or occasionally B horizon above a Cr or R layer). Only 13 pits (22 per cent) had the lowest RF content in the A horizon. More commonly (31 pits, 53 per cent), the minimum RF volume occurred in the second horizon (usually a B horizon, but occasionally an E, AB, BA or other horizon). In an additional six cases the A horizon RF percentage was at least 10 per cent higher than in the second horizon. Thus 64 per cent (37 pits) had vertical distributions consistent with upward movement (concentration in the A at the expense of the subsoil).

In the 19 pits where rock fragment orientations were measured, in three cases no preferred orientation could be detected at all, even in the upper parent material. In an additional seven cases, there was no detectable RF orientation above Cr or R horizons – the A, E, B, and C horizons had no consistent orientation. In four of the 19 pits, orientations presumably associated with parent material dip were measured in one or more C horizons, but not in the solum. In the other five pits, preferred orientations were found at some point within the solum, though never in an A or E horizon, except in one profile (PC3) where an orientation was measured in an AB horizon. In all but one pit (again, PC3), RF dips measured in sola or C-horizons were identical to parent material dips. In PC3, RFs in the AB horizon are oriented, but not in the CB and C horizons below it. In two pits (HW1-4 and PB1) orientations were measured for shale fragments, but not for sandstone RFs in the same horizon. In three pits differing orientations were measured in different horizons of the same profile. Pit HW2-1 showed horizontal bedding in the BC horizon but near-vertical in the Cr horizons below it. In PC2 a dip of 35° was found in the Bt horizon, compared to 42° in the C and Cr horizons below. PB1 had a 50° orientation in the Bt3 horizon, with horizontally bedded shale fragments and unoriented sandstone fragments in the underlying C horizon.

No significant trends in RF angularity were noted. Most ranged from subrounded to subangular. Rounded fragments were rare. Angular rocks were mainly shale channers (flat fragments up to 150 mm long).

The number of the 320 posthole pits in each rock fragment category is shown in Figure 2. Classes including a surface stone line are indicated for 139 samples (43 per cent), and 182 samples (57 per cent) were in classes that include a subsurface stone line. Of these, 121 pits (38 per cent) are accounted for by the three classes which include both surface and subsurface stone lines or zones.

More than half (195; 61 per cent) of the small pits have B horizon RF percentages less than 35, while about 20 per cent (63 pits) have more than 70 per cent RFs. The remainder (62; 19 per cent) are in the 35 to 70 per cent category.

Surface and B-horizon rock fragment concentrations were compared to slope gradients, curvature, and shape categories using regression where possible and non-parametric statistics for categorical variables. No statistically significant relationships were found. Figure 3, for example, shows the plot of A-horizon RF percentage versus slope gradient for the 58 soil pits. There is no apparent relationship, confirmed with a regression coefficient of determination (R^2) of only 0·04. The lack of a relationship is probably at least partly attributable to the broadly similar sideslope topographic settings of the plots – that is, if samples included the entire ridgetop-to-valley bottom rather than being restricted to midslopes, it is more likely that correlations between RF concentrations and variables such as elevation, slope, curvature, and geomoprhic position would be discovered.

In summary, rock fragments are common in the study regoliths, and occur throughout the profile. Surface sandstone fragments are particularly ubiquitous, and RFs throughout the regolith are overwhelmingly sandstone, regardless of the underlying lithology. Vertical distribution trends indicate that production of fragments at the bedrock weathering

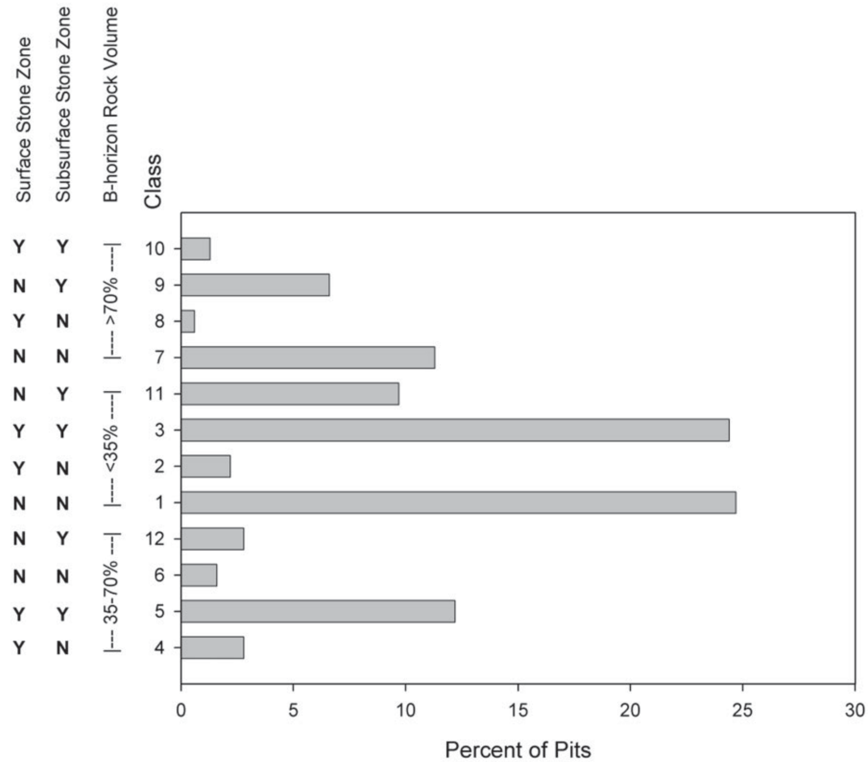

Figure 2. The percentage of the 320 posthole pits in each of the 12 rock fragment classes.

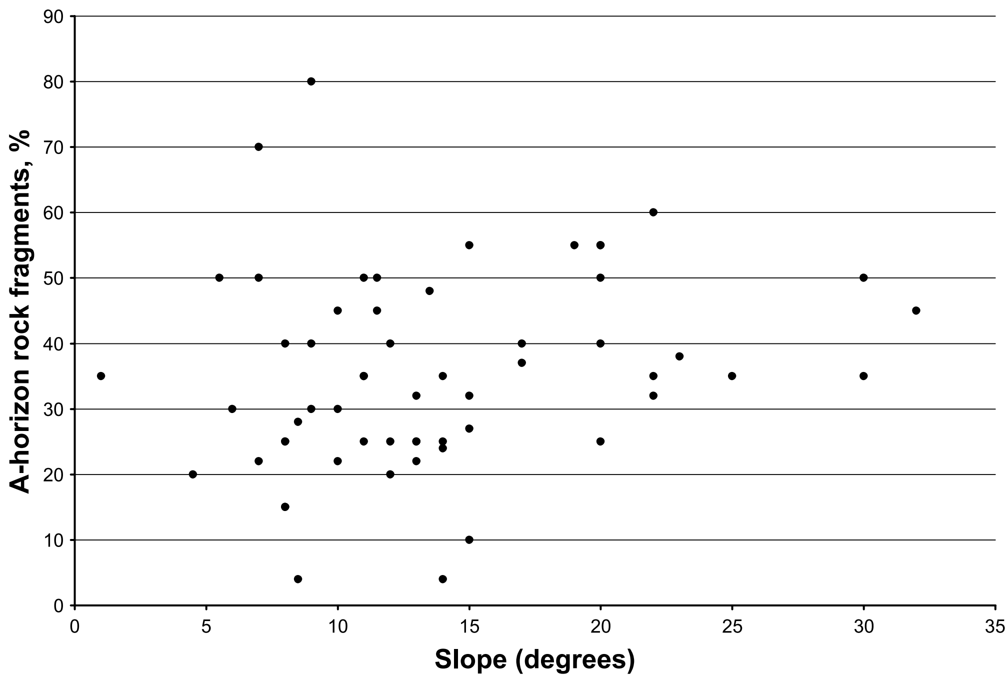

Figure 3. Surface layer (A horizon) rock fragment content (percentage volume) versus slope gradient (degrees).

front, and upward transport via 'mining' of stones from the subsoil are both significant processes. Subsurface stone lines or zones are common in the posthole pits, but not in the full-size soil pits, suggesting common local stone concentrations but not laterally extensive stone lines or zones. Finally, topographic factors do not appear to exert significant controls, though in a broader context landscape position, slope, and curvature are likely to be important.

Tree throws and stumps

The inventory of treethrows, stumps, and standing dead trees is a snapshot; results are likely to vary considerably according to whether, or how recently, events such as storms, fires, pest infestations, logging, or other human impacts have occurred. These results have been discussed elsewhere (Phillips and Marion, 2004), and will be reviewed here briefly in the context of the potential role in rock fragment transport. Notwithstanding the contingent 'snapshot' nature of the data, the inventories do give a general idea of the portion of the soil surface influenced by tree effects. If anything, the data underestimate tree influences, as they do not include living trees. Further, stumps obviously attributable to logging activity were deliberately excluded, though the pedologic effects of the trees and the stumps are unlikely to differ from those of natural stumps and dead trees. In retrospect, it was a mistake to exclude these features.

Plots vary greatly in the incidence of treethrow, ranging from none, to six throws with a rootwad surface area of more than 20 m^2. There was an average of 1·3 treethrows per plot, with a rootwad surface area of 2·4 m^2. Total mean volume of material moved by treethrow was about 1·1 m^3 per plot. Because this is estimated based on rootwad measurements, which will not reflect soil which was not part of (or which has fallen from) the rootwad, this can be considered a minimum volumetric estimate. All plots had treethrows nearby (i.e. visible from within the plot), even if none were found within the plot boundary. Plots averaged about nine standing dead trees and stumps (18 total), but basal areas were relatively small (mean of 0·14 and 0·43 m^2) for standing dead trees and stumps, respectively. However, due to exclusion of sawed stumps the inventory is biased toward smaller trees.

From the perspective of transferring rock fragments from the subsurface to the surface, the depth of treethrow impacts is important. These were estimated from rootwads. The depth of uprooting ranged from 19 to 100 cm, with a mean of 45 cm.

Sixteen posthole pits in various plots were in a rotted stump flush with the ground surface, or a stump hole. These were deliberately chosen during the latter stages of field data collection to explore ideas about influences of trees other than treethrow. In five of these cases there was clear field evidence of surface transport of RFs into the stumphole depression.

Interpretations

The results suggest three widespread aspects of rock fragment distributions in the study area that should be accounted for. These are the ubiquity of sandstone fragments regardless of the underlying parent material, the highest concentration of RFs generally occurring in the lower layer, and some tendency for rock fragment concentration at the surface and depletion in the middle layer.

Sandstone fragments

Sandstone RFs are ubiquitous, even though sandstone parent material is not. There are two potential explanations for this. One is that the sandstone fragments are residuals – representatives of beds, lenses or veins of sandstone within dominantly shale facies that have been partly weathered away. The second is that the sandstone ridgetops and upper slope shoulders are shedding sandstone fragments, which are transported downslope by mass wasting and erosion, thus supplying sandstone to residual soils derived from shales or additional clasts to soils derived wholly or partly from sandstone.

Outcrop exposures in the Ouachitas sometimes display veins of sandstones and metamorphics in dominantly shale lithologies. Sandstone boulders, which could be remnants of lenses or localized layers, are also occasionally observed. It is likely, therefore, that some of the sandstone fragments where the parent material observed in soil pits does not contain evident standstone are indeed residuals. However, this is not likely to be the general explanation due to the lack of any evident dip or preferred orientation in many horizons. RFs that are remnants of an *in situ* sandstone body should be preferentially oriented at a consistent dip. This is rarely the case in the study area, particularly in the upper regolith.

Slope gradients at the study sites typically range from about 5 to 30°, with locally steeper slopes within the plots and generally steeper slopes near the ridgetops. These gradients are sufficient to allow rock creep, which is apparently supplemented by more rapid mass movements and by transport in flash floods in headwater channels. Such channels were observed in the field, though plots were generally sited to avoid them. Thus, in our samples downslope movement is overwhelmingly due to mass wasting processes, of which we believe rock creep is the most important.

A ridgetop source for sandstone RFs is also consistent with the more or less ubiquitous surface cover within and between plots. Fragments that are dominantly weathering residuals would be expected to be more localized.

Finally, the sandstone RFs in regolith derived from non-sandstone parent material are not confined to the surface and A horizon. The ubiquity of unoriented subsurface fragments indicates downward movement.

Lower layer concentrations

The tendency for RF percentages to be highest in the lower layer is readily explained by production at the weathering front. The higher proportion of shale as opposed to sandstone fragments in this layer is consistent with this notion, as is the much greater tendency of lower-layer fragments to exhibit the same dip as parent material strata.

Upper layer enrichment and middle layer depletion

Erosional winnowing is one potential explanation of relative RF concentrations near the surface, and is no doubt locally important. It is not viable as a general explanation, however. The 16 sample plots were examined for morphological evidence of erosion and mass wasting, including rills, gullies, erosion pavements, exposed tree roots, exposed subsoils, and slump or slide scars. These indicators were absent, except locally in the vicinity of logging roads, skid trails, and foot or off-road-vehicle trails. Finally, if erosional winnowing were a major cause of the enrichment of the surface with rock fragments, both geomorphic intuition and previous work (van Wesemael *et al*., 1996) would indicate a positive relationship between rock fragment concentration and slope gradient, as erosion in vegetated environments is strongly related to slope.

Tillage is also known to deplete the lower tillage layer of fragments, enriching the surface. This is ruled out at the study sites. There is little incentive for farming the steep, rocky slopes, and no visible evidence (furrows, agricultural artifacts or machinery, Ap horizons) of previous tillage. There is also no historical or archaeological evidence that Ouachita sideslopes were ever farmed to any significant extent (Strausberg and Hough, 1997).

The other possibility is treethrow, the net effect of which is to mine RFs from the root zone and concentrate them at the surface. Treethrow is common in the study area, and was presumably more so before logging and commercial forestry, as more trees would live long enough to suffer uprooting rather than being cut. The depth of treethrow (19 to 100 cm; mean 45 cm) is consistent with mining of upper B and enrichment of A horizons with RFs.

Subsurface fragments

As noted, subsurface sandstone fragments apparently not derived from the underlying parent material are common. In addition, recall that 57 per cent of the 320 posthole pits had subsurface stone lines or stone zones, and 39 per cent had B horizon RF percentages >35.

It is revealing that stone lines are not observed in road cuts and other exposures in the area, and that none of the 58 full-size soil pit descriptions include subsurface stone lines. Identification of a stone line or zone in a full pit would require that the feature be more-or-less continuous along at least one face, implying a minimum horizontal length dimension of about 1 m. In the posthole pits, however, stone concentrations on the order of 30 cm in length could result in the identification of a stone line or zone. This suggests that the stone concentrations in the posthole pits are localized, and not the areally extensive features geomorphologists usually think of as stone lines.

The latter are generally interpreted as representing the base of a biomantle, where faunal activity eventually causes larger particles to settle near the base of the most intense faunalturbation, due to undermining and erosional winnowing of fine material brought to the surface by soil fauna (Balek, 2002; Johnson, 1990; Leigh, 1998; Paton *et al*., 1995). An alternative interpretation of some stone lines is that they represent lags from former erosion surfaces which are subsequently buried (Johnson and Balek, 1991; Mercader *et al*., 2002). In either case the stone line or zone would be expected to be areally extensive rather than point-centred.

Faunalturbation certainly occurs in the Ouachitas. We observed evidence such as ant mounds, burrows, worm casts, and other features, but this evidence was not pervasive enough to suggest that faunal activity is as extensive as in some subtropical environments, where areally extensive stone lines or zones may accumulate at the base of the biomantle (Johnson, 1990, 1993; Paton *et al*., 1995).

An alternative explanation is the accumulation of rock fragments in pits associated with stump rot (or combustion) or treethrow. Stump holes might be filled by rocks originally displaced by tree or root growth, and stump or treethrow holes can accumulate clasts transported from upslope.

Note that treethrow is invoked to simultaneously explain surface accumulation, and subsurface depletion of fragments, along with the development of highly localized subsurface stone concentrations. While we would not necessarily expect all three phenomena at every treethrow site, where they existed this would create two stone-rich zones, one on the surface and one in the subsurface, with much lower stone concentrations in between.

A substantial number of the posthole pits (38 per cent; 121 pits) exhibit both surface and subsurface stone lines. Of these 78 (24 per cent of the total) also have B-horizon RF contents less than 35 per cent.

Subsurface fragments can also arise due to depositional burial more generally. This occurs in some cases in the study plots due to colluviation, but is not common due to the topographic setting. Colluvium refers to all materials in transport or temporary storage on hillslopes, regardless of the transporting process. Gravitational settling is also possible, but given the high clay content of the study area soils (most B horizons are clay loam or finer), settling below the A horizon is unlikely.

The downward movement of rock fragments is therefore judged to be primarily due to bioturbation, with the deposition and subsequent burial of RFs in stump holes and tree uprooting pits an important mechanism.

Discussion and Synthesis

In the introduction the potential gains and losses of fragments from the surface, middle, and lower layers were identified. These may now be reconsidered on the basis of the field evidence.

The surface layers of the Ouachita sideslope regoliths are characterized by net gains, due to mass wasting and localized fluvial transport. The ubiquitous sandstone lithology of RFs points to ridgetop outcrops as the primary source. Weathering of outcrops or veins of sandstone within the study plots is locally important, but not ubiquitous. Concentration of rock fragments at and near the surface, and losses from subsurface layers, occurs due to upward transport by treethrow, but erosional winnowing and upward transport by tillage are not important. Faunal undermining and weathering of the RFs probably accounts for downward movement of some rocks, and for destruction or diminution of some clasts. Gravity settling independent of other disturbances is unlikely, except for the case of RFs falling into stumphole depressions. Production of fragments at the weathering front is important.

Shale rock fragments are produced at the weathering front, but break down rapidly and are rare in the solum. Shales in general are rapidly weathered, and the Ouachita shales are typical in this regard (McFarland, 1998; Stone and Bush, 1984). The widespread occurrence of weathered shale Cr horizons which can be penetrated by an auger are consistent with this. Sandstone clasts, and fragments of other more resistant rocks, are produced at the weathering front in some cases, by weathering of outcrops or veins within otherwise shaley parent material in others, and ubiquitously by weathering of ridgetop outcrops. The latter essentially shed off the ridgetops, moving downslope. Thus all sample sites have a surface source of fragments, and many have subsurface sources as well.

Whatever their source, it is clear that both upward and downward movements are possible, and that biomechanical effects of trees are important in both cases. This suggests that significant mixing of the regolith occurs at the time scale of the lifespan of a tree or tree cohort.

Many conceptual models of weathering and soil formation are based on a combination of primarily top-down vertical processes within the soil or weathering mantle, and surface erosion or deposition. They are also based on a notion of an increasingly thick soil or weathering mantle over time (in the absence of surface removals) as the weathering front migrates downward. This implies a surface-to-weathering-front gradient in age of the weathering material (oldest to youngest) and degree of weathering (most to least). These models have been augmented or replaced with broader, more complex schemes that emphasize the role of bioturbation within the regolith, the formation of biomantles, and attaching importance to a much broader suite of processes than weathering front migration, vertical translocation, and surficial erosion/deposition (e.g. Heimsath *et al*., 2002; Johnson, 1990, 1993; Johnson *et al*., 1990; Johnson and Watson-Stegner, 1987; Paton *et al*., 1995; Pope *et al*., 1995; Pain and Ollier, 1996). Generally, the study slopes receive inputs of rock fragments by weathering at the weathering front, and from upslope, as weathering of exposed sandstone on the ridgetops produces fragments which are transported downslope. These fragments are vertically and horizontally mixed within the regolith due to a combination of floral, faunal, and gravity-driven processes.

The distribution of rock fragments in the Ouachitas suggests regolith development actively influenced by both surface and subsurface processes, and characterized by upward, downward, and lateral movements. It suggests a crucial role for bioturbation, particularly pedomechanical effects of trees, and a regolith that is, in essence, churning itself regularly. It also suggests that even in what would be considered residual soils, colluvial inputs (in this case sandstone rock fragments from upslope) may be quite important.

Conclusions

Rock fragments are common in regoliths on sideslopes of the Ouachita mountains, Arkansas, but vary considerably in their abundance and vertical distributions within the regolith. Examination of 58 soil pits and 320 smaller 'posthole' pits shows that sandstone fragments are common at all layers of the regolith, even when there is no sandstone observed in the parent material. Shale, and sometimes sandstone, fragments are produced by weathering at the bedrock weathering front, but the shale weathers rapidly and intact fragments are rare in the solum. The sandstone is largely weathered from ridgetop outcrops and transported downslope by mass wasting and erosion. Some of these fragments are moved downward, by faunalturbation and by transport into ephemeral pits associated with rotting tree stumps. Upward movement of fragments by treethrow is common, resulting in a net concentration of rocks near the surface as compared to the rest of the root zone. The highest fragment concentrations are in the lower regolith, however, indicating active production at the weathering front.

The Ouachita regolith is a dynamic feature, reflecting the influences of both vertical and horizontal processes, of active weathering at the regolith–bedrock interface, and of surficial sediment movements. In this, the results of this study are consistent with earlier studies and conceptual models of soils and regolith (for instance Heimsath *et al.*, 2002; Johnson, 1993; Pain and Ollier, 1996; Paton *et al.*, 1995). Rock fragments are mobile within the regolith due to biological activity. The role of trees in redistributing rock fragments suggests that significant changes may occur, at least locally, over time scales of decades to centuries, e.g. the time frames associated with forest vegetation change and the life cycles of trees. We can expect, therefore, that many forest soils have been significantly mixed over historic time, and extensively mixed over multiple vegetation generations in the Holocene.

Though geomorphologists may be atypical in this regard, soil and regolith is typically regarded as either a sequential accumulation of surface material or the residuum of a downward-migrating weathering front. Rock fragment distributions in the Ouachita regolith suggests that both these views are incorrect, or at least incomplete. Material added to the surface, for example, be it aerosol pollutants or archaeological artifacts, may be moved and mixed, vertically and horizontally, within the entire regolith. Material produced at the weathering front may get closer to the surface by means other than surface downwasting. And features within the regolith, be they fossils, datable materials, or other environmental indicators, cannot be assumed to occupy the position at which they were formed or deposited. Regolith studies are of great importance not just to geomorphologists and pedologists, but also to ecologists, hydrologists, archaeologists, engineers, planners, and others. A conceptual framework is based on a dynamic, continuously mixed regolith influenced by surface and subsurface, lateral and vertical, geogenic and biogenic and pedologic processes.

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