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Relative-age relationships of debris flow deposits in the Southern Blue Ridge, North Carolina

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Abstract

Periods of increased landscape instability in the Southern Blue Ridge were assessed with relative ages of three sequences of debris flow deposits. The sequences consist of a series of lobate deposits that are expressed as step-like landforms on the floors of host valleys. Data were collected at three sites from soil pits on the toe and apex of debris flow deposits. Relative ages were obtained by qualitatively and statistically examining data on clast weathering, soil color, clay content, and iron species. Consistent results among the indicators of relative age demonstrate that they have utility in warm to temperate, humid environments. At each site, the topographically highest debris flow deposits are slightly older than those at lower elevations. One deposit at each of the three sites has a relative age that is very similar to that of one deposit at the other sites. This similarity in age indicates that an external factor, such as extreme precipitation, accounts for the formation of debris flows at approximately the same time in the geological past. One of the sites, however, also has deposits that are clearly younger than the deposits at the other sites, which indicates that intrinsic factors also affect the formation of debris flows in the region. © 1997 Elsevier Science B.V.

Keywords: age dating; debris flow; Blue Ridge; soils; weathering

1. Introduction

The Southern Blue Ridge has received little attention from pedologists and/or geomorphologists. Although periglacial phenomena of the region have been studied to some extent (e.g., Michalek, 1968; Mills, 1981; Clark and Ciolkosz, 1988), little is known about alluvial and colluvial deposits that were not affected by periglacial conditions. One prevalent geomorphological component of these other morpho-climatic zones are debris flow deposits, the most common and spectacular form of mass wasting in the region (Scott, 1972; Mills et al., 1987).

The frequent occurrence of debris flows has raised many questions about the origin and distinctive pedological characteristics of these forms in the Southern Blue Ridge (Mills and Allison, 1995b). It has been suggested that formation of debris flows in the Southern Blue Ridge is associated with periods of post-glacial climate change (Mills, 1981, 1982, 1983; Kochel and Johnson, 1984), but intrinsic fac-

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tors may also control the formation of debris flows (Mills, 1983; Wells and Harvey, 1987; Zimmerman and Haeberli, 1992). According to Mills (1982) the influence of extrinsic controls on the formation of alluvial and colluvial deposits can be verified if groups of deposits of similar age exist and if they date to post-glacial times. The rationale for the present research centers on this lack of age control in debris flow deposits of the Southern Blue Ridge. The general objective of the research is to identify periods of increased landscape instability in the region by applying dating techniques to debris flow deposits.

We use 'debris flow deposit' as a descriptive term for the deposits that were studied. They consist of bouldery diamicton with sedimentary characteristics and fabric that are consistent with a debris flow origin (Liebens, 1996). The deposits, which have an undulating topography, occur as elongated lobes on the floor of small valleys in steep basins and resemble 'slow flow' deposits (coulées) as defined by Tricart (1977). The lobes are more or less parallel to the axis of the valley and usually are bordered laterally by two streams. This suggests that the material traveled through the valley for some distance and that it did not enter the valley as colluvium via footslopes. While performing this research, we observed that debris flows, characterized by boulder levees, log dams, and superelevation, continue to occur in the region at the present day and produce deposits that are visually very similar to those studied.

Given the absence of material suitable for absolute-age dating, we used relative-age dating techniques. Relative-age dating has been successfully employed to quantitatively estimate the age of a surface through known rates of soil formation (e.g., Knuepfer, 1988), and to qualitatively compare the ages of a series of surfaces for which no information on rate is available (Phillips, 1990; Markewich and Pavich, 1991; Whittecar and Ryter, 1992; Woodward et al., 1994). Because no rates of soil formation are available for the Southern Blue Ridge, we applied the latter approach to determine the relative ages of debris flow deposits and to contrast these relative ages within and between sites. Clast weathering, soil morphology, and iron content, all of which increase with age, served as proxies for the degree of soil development and weathering. Although these relative-age indicators have been tested extensively, they have seldom been used in warm areas where annual precipitation exceeds 100 cm (Birkeland, 1990). The application in the present research is, therefore, an evaluation of the applicability of the method to more humid areas. Interpretation of relative-age data has often been qualitative (e.g., Arduino et al., 1986; Whittecar and Ryter, 1992) but this work is based on values that are statistically significant.

Techniques for relative-age dating that utilize soils data are based on the principle that the degree of soil development is most strongly dependent on time when other soil-forming factors (Jenny, 1941) remain more-or-less constant at all sampled locations. Under these conditions, soil development can be used to compare the relative ages of soils and geomorphic surfaces in different locations. Several problems, however, remain associated with the use of soil development as a relative-age indicator. The technique assumes that soil development is continuous, although it can be static, episodic or even regressive (Johnson and Watson-Stegner, 1987; Switzer et al., 1988; Johnson et al., 1990). Phillips (1990) cautioned against using soil development as an indicator of the relative age of the parent material of soils because surficial processes (i.e. erosion and deposition) may have inhibited pedologic development. Moreover, soil development may be static or even regressive for periods of time (Johnson and Watson-Stegner, 1987), in which case the age of a geomorphic surface advances whereas soil development on that surface does not.

In the present study, time is assumed to be the main factor that caused pedogenic differences between debris flows, because climate, vegetation, topography and parent material are generally similar at all three sites (see below). Because the sites are located within 13 km of each other and at approximately the same elevation (640 m to 750 m amsl), climate and vegetation can be expected to have been similar at the three sites in the past as well.

2. Study area

The drainage basin of the Little Tennessee River, south of its confluence with the Tuckasegee River, was initially surveyed for the presence of suitable sites (Fig. 1). This part of the basin lies largely within Macon County, NC, but also extends northward into Swain County, NC, and southward into Georgia. The terrain of the basin varies greatly from level floodplains and alluvial terraces close to the trunk river to steep and nearly vertical rock cliffs on backslopes and interfluves. Elevations range from ~ 600 m on the main floodplain to > 1600 m at the highest peaks. Colluvial deposits occur commonly in many landscape positions, but particularly on footslopes, throughout the basin. Debris flow deposits are most prevalent on the valley floor of relatively small, low-order stream valleys with steep-sloping backslopes. Many of these valleys have a step-like longitudinal profile in the lower reaches because of the presence of two or three lobate deposits that are often elongated parallel to the valley. Streams are frequently found on both sides of the debris flow deposits, imparting a convex cross-section to the valley floor (Fig. 2).

The Ultisols and Inceptisols found here have formed predominantly in regolith weathered from metamorphic and metasedimentary rocks under mixed-hardwood forest. Most of the regolith has been transported at some time in the past, and the only landscape positions where residual, saprolitic soils can be found are thought to be the ridge tops

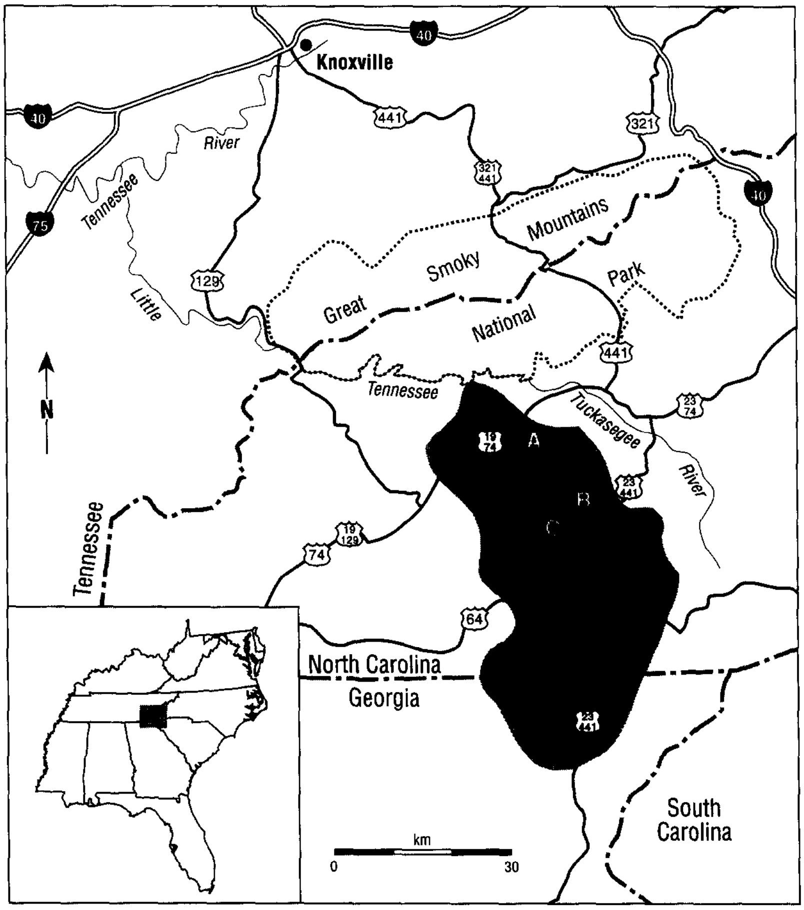

Fig. 1. Location of the Little Tennessee River basin south of its confluence with the Tuckasegee River. Rectangles at *A*, *B* and *C* indicate location of Alarka, Bradley and Hidden Valley site, respectively.

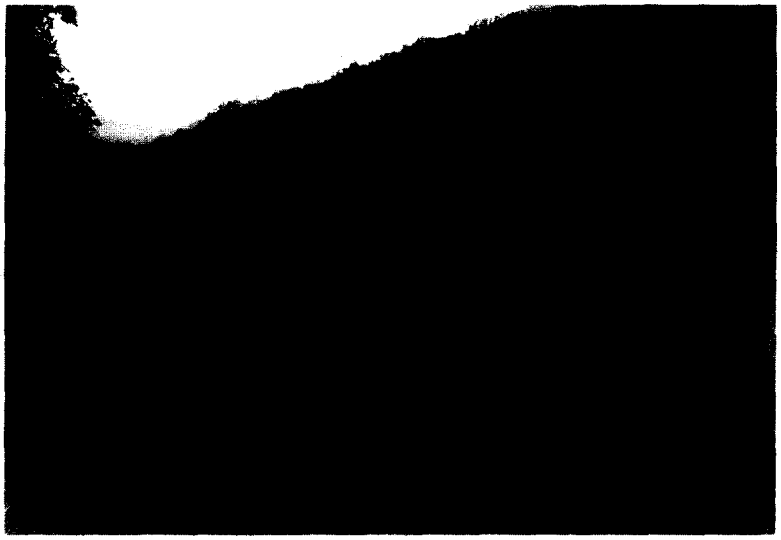

Fig. 2. Lower deposit at the Bradley site as seen when standing in soil pit BLa and looking downslope (toward SW). Note the convex cross-section of the deposit. The creeks at both sides are barely incised at this point. Person in center for scale.

and shoulder slopes (Thomas, 1996). Although shallow soils (< 0.5 m) occur on steep slopes in the high mountains, soils are usually moderately deep to very deep (> 1 m) elsewhere. Most soils have a loamy texture but clayey soils can be observed on low rolling hills close to the Little Tennessee River.

The climate of the area is humid temperate. Temperature and precipitation vary, however, as a function of elevation and aspect. Franklin, located in the center of the study area at 650 m elevation, has an average annual temperature of 14°C (summer 22°C, winter 4°C; Thomas, 1996) and receives approximately 130 cm of precipitation annually (snowfall = 20 cm). At the Coweeta Hydrologic Laboratory, in the southern part of the study area, the mean temperature for the year is 13°C (Douglas and Swank, 1975). Precipitation ranges from 170 cm at 750 m elevation to 250 cm at elevations around 1500 m. Most of the 133 storms that occur, on average, in the Laboratory annually have low intensities (Swift et al., 1988). Seventy percent of the precipitation falls with intensities of < 2 mm h^{-1} and precipitation rates surpass 10 mm h^{-1} only 4% of the time. Nevertheless, storms that potentially could trigger debris flows, with intensities as high as 75 mm h^{-1}, do occur with return periods of only 50 years (Swift et al., 1988).

3. Site selection and description

3.1. Site selection

Potential sites of debris flow deposition in the Little Tennessee River basin were identified from aerial photographs, topographic and geologic maps, and the preliminary soil survey of Macon County (Thomas, 1996). About 125 sites were evaluated in the field, and in 24 cases, sampled for characterization of the soils and sediments. Subsequently, three sites that had at least two topographic levels of juxtaposed and/or superposed debris flow deposits were chosen for study. To make between-site comparison of the relative ages meaningful, we selected sites that (1) occurred in small basins with uniform lithologies, (2) showed little signs of surficial erosion, and (3) had contrasting soil development on the debris flow deposits. To account for spatial variations in pedogenesis, an attempt was made to open a soil pit on the toe and apex of each deposit. Because surficial erosion must have been lowest near the

Table 1
Nomenclature and characterization of soil pits

Soil pit [a]	Deposit number	Geomorphic position	Slope (%)	Slope aspect [b]	Depth of soil pit (cm)
Alarka site					
ALf1	1	foot	15	W	187
ALf2	2	foot	16	W	193
AUf	3	foot	16	W	195
AUa	3	apex	16	W	213
Hidden Valley site					
HLf	1	foot	5	SE	200
HLa	1	apex	11	SE	187
HMf [c]	2	foot	15	S	223
HMa [c]	2	apex	15	S	248
HUf	3	foot	13	S	227
HUa	3	apex	23	S	211
Bradley site					
BLf	1	foot	12	W	125
BLa	1	apex	16	SW	187
BUa	2	apex	19	W	208

[a] The soil pits were assigned a three-letter code. The first letter stands for the site (A = Alarka, H = Hidden Valley, B = Bradley), the second letter refers to the position of the deposit in the sequence of each site (L = lower, M = middle, U = upper), and the third letter represents the position of the soil pit on the deposit (f = foot, a = apex). Because no soil pit could be opened on the apex of the lowest deposit in Alarka, a pit on the foot of another low deposit was opened. To distinguish between these two localities, a fourth digit ('1' or '2') was added to the code of the pedons on the lower Alarka deposits.

[b] W aspect means slope faces west; SE aspect means slope faces southeast; S aspect means slope faces south; SW aspect means slope faces southwest.

[c] Soil pits HMf and HMa were in saprolite.

central long axis of the deposits, where slopes are minimal, all soil pits were located on the crests of the deposits. Names of sites and soil pit codes are provided in Table 1. For comparative purposes, the relative age of two saprolitic soils at the Hidden Valley site was also assessed (Table 1). To avoid

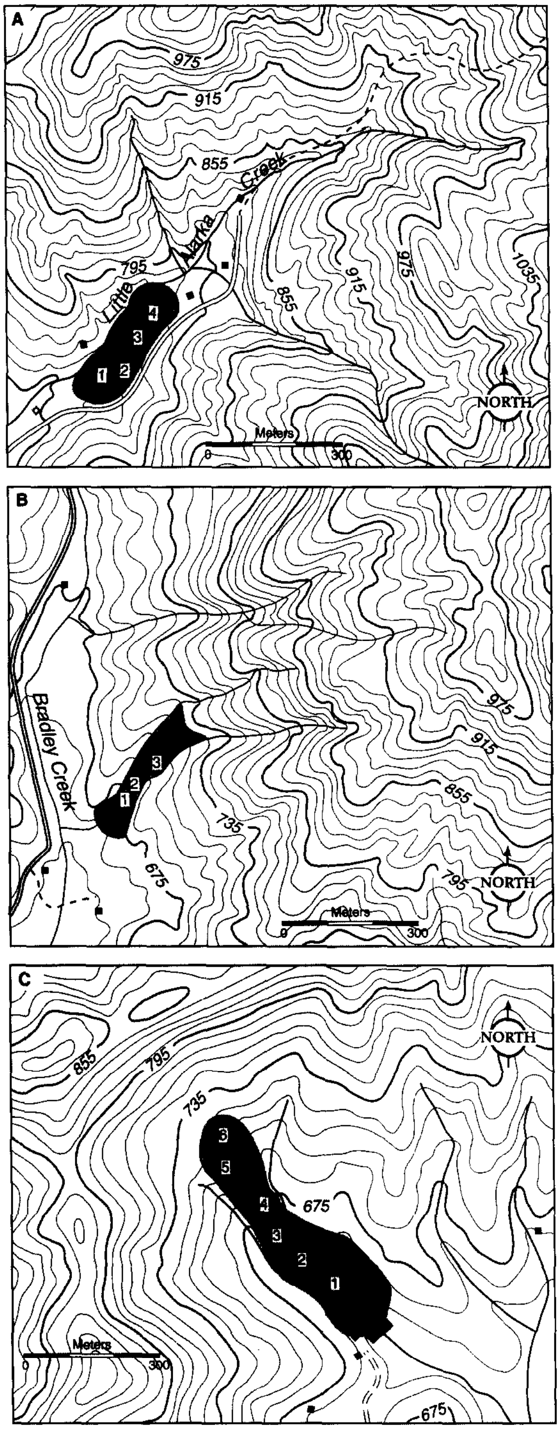

Fig. 3. Local topography at the study sites: (A) Alarka site, (B) Bradley site, (C) Hidden Valley site. Shaded areas indicate location of deposits studied. Individual deposits are not visible at this scale. Numbers represent location of soil pits. At Alarka site: *1* = ALf1, *2* = ALf2, *3* = AUf, *4* = AUa; at Bradley site: *1* = BLf, *2* = BLa, *3* = BUa; at Hidden Valley site: *1* = HLf, *2* = HLa, *3* = HMf, *4* = HMa, *5* = HUf, *6* = HUa.

undue influence of local climate variations on pedogenesis, and thus on the apparent age of the soils and the deposits, we chose sites with roughly comparable slopes and aspects (Table 1). Although some variation in aspect is present (from west at the Alarka site to south and southeast at Hidden Valley, and west and southwest at Bradley), aspect at latitudes such as those here (35°) is not as critical a factor in differential pedogenesis as at higher latitudes (Lee and Baumgartner, 1966). The sites occur in shaded valleys and, hence, the effect of aspect on local climate is controlled somewhat by the shading.

3.2. Site description

At the Alarka site, lobate deposits extend over a distance of approximately 500 m along the axis of the valley of Little Alarka Creek. The elevation of the floor of the valley is about 750 m amsl, more than 300 m lower than the tops of the surrounding mountains (Fig. 3). Lithologically, the drainage basin belongs to the Upper Precambrian Great Smoky Group (Hadley and Nelson, 1971). The bedrock is metasandstone, gneiss and interbeds of quartz-mica schist. The average slope of the basin is about 35%.

Soil pits were excavated on three deposits in the middle of the depositional area (Fig. 3). Each deposit is approximately 50 m wide and slightly longer than 70 m. Two deposits occur side by side at approximately the same elevation whereas the third one occurs upstream at a vertical distance of 10 m (Fig. 4). Along the long axis the deposits have an average slope of 16%, with short reaches that are slightly steeper and that represent the front of the deposit. These local variations in slope impart a well pronounced hummocky topography to the valley floor.

The soils on the deposits at the Alarka site are Umbric Dystrochrepts (Liebens, 1996). They are very deep (depth to C horizon > 187 cm) and usually present an A–E–Bt–BC–C profile. Most horizons have an extremely flaggy or extremely gravely fine sandy loam texture. The Bt horizons have a 7.5YR hue and a medium-grade structure.

At the Hidden Valley site three clearly separated topographic levels occur between two unnamed streams that drain into Iotla Branch. The lowest level is at an elevation of 650 m amsl, approximately 240 m lower than the crests of the surrounding ridges (Fig. 3). This level corresponds to the present-day floodplain and is almost 200 m wide across-valley and 160 m long in the direction of the valley axis. In its lower part it is crossed by one of the unnamed streams. The contact with the second, middle, level is expressed as a steep (40%), 10 m high escarpment.

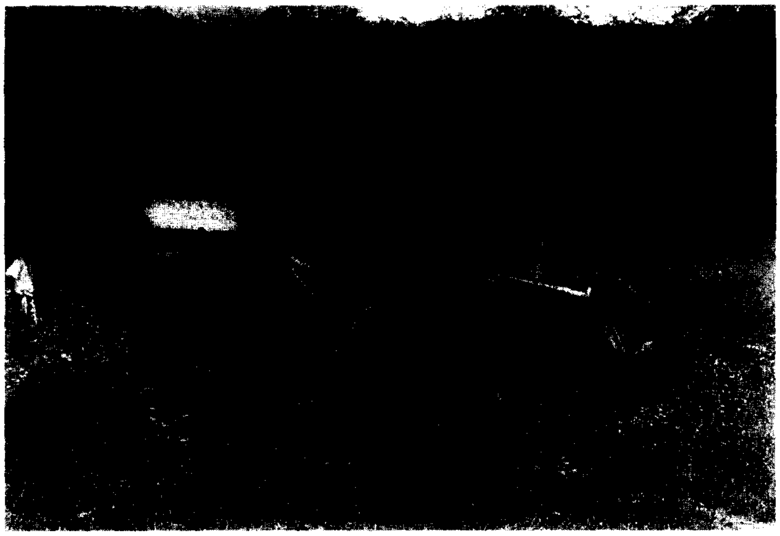

Fig. 4. Overview of the deposits at the Alarka site. The back-hoe is opening soil pit ALf1 on the lower deposit. The upper deposit is visible at the right as an undulation in the topography. Note the large boulders at the surface of the upper deposit. Little Alarka Creek is to the left (NW) of the deposits.

The top of the middle level is about 75 m wide, relatively flat (10% slope) and gradually slopes up toward the front of the highest level. The highest level also has a steep front (30%) about 10 m high, but its top is nearly horizontal. It grades into the mountain side with a well defined break of slope. The sequence of the three topographic levels is 510 m long and covers a total difference in elevation of 80 m.

The soils on the lowest level are Humic and Typic Hapludults (Liebens, 1996; Thomas, 1996). They have relatively thin sola (< 90 cm) and slightly gleyed C horizons. The B horizons have a 5YR hue and a loam or clay texture. The soils on two highest deposits are not distinguishable from those on the hillsides; both are mapped as Typic Hapludults (Thomas, 1996). On these higher deposits soils are very deep (depth to C horizon > 210 cm). Argillic Bt horizons display colors in the 2.5YR range and have a clay texture. The rocks in Hidden Valley are of Middle and Late Precambrian age (Hadley and Nelson, 1971) and consist mainly of gneiss, some of which is very rich in quartz, and biotite schist.

At the Bradley site the deposits occur in a small, unnamed, tributary valley of Bradley Creek (Fig. 3). The drainage basin of the unnamed valley has a relative relief of 350 m, between 650 m and 1000 m amsl, and slopes with an average gradient of 35%. The basin is crossed by the Hayesville fault which separates rocks of the Great Smoky Group from Middle Precambrian rocks (Hadley and Nelson, 1971). Gneisses, usually rich in quartz, dominate the lithology but metasandstone is also present.

This site is similar to Hidden Valley in that two creeks border the deposits. In the middle reaches the creeks are deeply incised in separate V-shaped ravines. Near the confluence with Bradley Creek the ravines unite into a wide valley (Fig. 3). The creeks occupy the two sides of the valley floor, rather than an intermediate position, and are barely incised at all at this point (Fig. 2). Distinct deposits or topographic levels are not as readily identifiable here as at the two other sites. Only slight topographic undulations, 1 to 2 m in height, hint at the presence of different deposits. Soil pits were excavated on two of these undulations. The depositional area has an elongated shape and is 280 m long and 90 m wide. At the confluence with Bradley Creek the deposits are no longer confined by valley walls and become fan-shaped. The slope of the valley floor increases from about 12% to more than 20% on the fan-shaped front.

Soils on the deposits are mapped as well-drained Humic Hapludults (Thomas, 1996), but may be better characterized as Typic and Umbric Dystrochrepts (Liebens, 1996). They typically have an A–Bw1–Bw2–C sequence of horizons. The Bw horizons have a weakly developed structure, are devoid of cutans and have a 7.5YR hue. The texture of the surficial horizons is loamy but most subsurface horizons are coarser-textured and have a high amount of coarse fragments (> 50%).

4. Methods

Clast weathering, soil color, clay content and an iron species ratio were used as proxies for the relative ages of the debris flows. To determine clast weathering, we collected 50 clasts at random from the 13 soil pits. Two pits (HLa, HMa) could not be sampled in this manner because of the paucity of clasts. Determination of the degree of weathering of clasts for the purpose of relative-age dating has traditionally involved measuring weathering rind thickness (e.g., Knuepfer, 1988; Mills, 1988; Whittecar and Ryter, 1992) and percentage of weathered clasts (e.g., Miller, 1979; Mills, 1982, 1988). Because of the metamorphic nature, clasts in the study area possess foliation planes and weathering did not proceed uniformly inward by rind-thickening. Enough variability in the degree of weathering was observed, however, to assign clasts semi-objectively to one of three groups: little, intermediately, and highly weathered. The semi-objective allocation of a clast to a certain group was based on (1) the physical soundness of the clast as determined by sharp blows with a rock hammer, (2) the dominant color of the inside of the clast, and (3) the alteration of minerals as seen under a 10 × hand lens.

We used three rubification indices to represent the color of the soils in the reddest horizon of each pedon. The most frequently used rubification indices in chronosequence studies are the Buntley–Westin index (Buntley and Westin, 1965), the Hurst index (Hurst, 1977) and the redness rating of Torrent et al.

(1983). Munsell hue has also been used as a color index (Mills, 1982, 1986; Markewich and Pavich, 1991), but is a less refined measure than the three indices used here. The Buntley–Westin index quantifies the hue (10R = 7, 2.5YR = 6, 5YR = 5, 7.5YR = 4), which is then multiplied by chroma. It is closely allied with the intensity of weathering, stage of soil development and drainage (Buntley and Westin, 1965). The Hurst index quantifies hue (10R = 10, 2.5YR = 12.5, 5YR = 15, 7.5YR = 17.5) and multiplies it by the value/chroma fraction. It is a crude proxy for the total amount of iron in a soil (Hurst, 1977). The redness rating is calculated by the formula:

$$(10 - \text{YR hue}) \cdot \text{chroma}/\text{value} \qquad (1)$$

and has been correlated with hematite content (Torrent et al., 1983; Graham et al., 1989).

We calculated three parameters to represent clay contents: percent clay (g/100 g) in the most clay-rich horizon, clay mass (g cm^{-3}) of the most clay-rich horizon, and clay mass in g cm^{-2} summed over the thickness of the solum. Clay mass in a unit column of the solum and percent clay have been shown to be good relative-age indicators in pedological settings similar to those of the present study (Markewich and Pavich, 1991; Leigh, 1996). Percent clay was determined for all horizons with the pipette method (Soil Survey Laboratory Staff, 1992). The clay mass of the most clay-rich horizon was then obtained by multiplying the percent clay of the appropriate horizon by its bulk density in g cm^{-3}. Bulk density was determined with the core method (Soil Survey Laboratory Staff, 1992). The clay mass per cm^2 of a solum-thick column was derived by multiplying the clay mass of each horizon by its thickness and by integrating the results over the solum.

Iron species ratios are generally considered to be better relative-age indicators than are data for individual iron species alone (Rebertus and Buol, 1985; Arduino et al., 1986; McFadden and Weldon, 1987). Ratios with the total amount of iron in the denominator have an advantage because they compensate for variations in the parent material. We used the ratio of total ferric iron (Fe_d) divided by total iron (Fe_t). This ratio is a measure for the amount of iron released during weathering and has been used successfully by Rebertus and Buol (1985) and Arduino et al. (1986). Fe_d was extracted with sodium citrate–bicarbonate–dithionite according to procedures described in Jackson et al. (1986). Fe_t was determined with an HF acid extraction method (Lim and Jackson, 1982). The Fe concentration in the extracts was analyzed on a directly coupled plasma spectrometer. Because considerable variation occurred in the Fe_d/Fe_t ratio with depth, the profile weighted mean ratio for each pedon was computed by the formula:

$$\Sigma(\text{ratio}_i \cdot \text{thickness}_i)/\text{solum thickness} \qquad (2)$$

where i designates horizons in the solum.

For each proxy listed above, an index representing the degree of its development was calculated and sites were assigned, qualitatively and quantitatively, to relative-age groups. For this grouping we treated the color and clay content indexes as one set of data representing soil development. A classification was, therefore, carried out three times; for the clast weathering index, the soil development indexes, and the iron content index. The qualitative grouping was based on a visual evaluation of the indexes. For the quantitative evaluation, a *K*-means cluster analysis procedure, with 50 iterations and 4 groups, was applied to standardized values for the indexes. This procedure produces non-hierarchical clusters by maximizing between-cluster variation. It was repeated three times, once on each set of indexes. A clustering with more than four groups was deemed inappropriate considering the number of pedons studied (13) and the perceived temporal resolution of the technique. Qualitative and quantitative classification approaches were used in conjunction because it is important to have control over the physical meaning of a classification while maintaining objectivity. Because cluster algorithms are sensitive to small changes in the data, the technique should be accompanied by a subjective evaluation of the results (Harbor, 1986).

A final, qualitative assignment of deposits to relative-age groups was carried out based on the results for all proxies. This final classification was evaluated statistically with discriminant analysis. Mills and Allison (1995b) employed discriminant analysis, in combination with cluster analysis, as a means of grouping relative-age data, and evaluated the output visually. Discriminant analysis, however, can be considered to be the opposite of cluster analyses because it uses existing groups and constructs functions that produce maximum difference between those groups (Davis, 1986). Because of purely mathematical reasons, discriminant analysis always gives a high significance to groups derived from cluster analysis when the data set conforms to all assumptions of the methods; thus, a circularity occurs in the testing of the output of cluster analysis by discriminant analysis (Harbor, 1986). The only valid means of using discriminant analysis with groups of relative-age data is to use one set of data to generate the clusters and another to test them, or to test groups based on personal judgment (Harbor, 1986). In other words, discriminant analysis can be used as a quality check for a non-statistical grouping of data into discrete classes. It is this latter approach that was employed here. The statistical significance of the separation between the groups produced by the discriminant functions, and thus the quality of the initial grouping, was assessed by Wilks's lambda (Dowdeswell and Morris, 1983) and Hotelling's T^2 test (Davis, 1986). Three relative-age indicators (% intermediately weathered clasts, Buntley–Westin index, and percent clay) were excluded from the discriminant analysis to avoid redundancy. Because the variance of these three proxies was described by one of the remaining proxies, the total variance of the proxies was not compromised.

5. Results

5.1. Clast weathering

Clear differences occur in the degree of weathering of the clasts at the three sites (Table 2). The Alarka site has many clasts with little weathering whereas the Hidden Valley site, and especially the saprolitic soil HMf, has many highly weathered clasts. At the Bradley site, clasts are distributed more evenly over the three weathering classes.

Within the Alarka and Hidden Valley sites, a systematic variation occurs in degree of weathering of the clasts between the lowest and highest debris flow deposits. Pedons that are in lower landscape positions (ALf1, ALf2 at the Alarka site, HLf at the Hidden Valley site), have proportionately fewer highly weathered clasts than pedons that are located on higher deposits (AUf, AUa at the Alarka site; HMf, HUf, HUa at the Hidden Valley site; Table 2).

Table 2
Clast weathering data

Soil pit [a]	Low [b] (%)	Intermediate [b] (%)	High [b] (%)	Cluster assignment [c]
Alarka site				
ALf1	50	42	8	1
ALf2	57	37	6	1
AUf	20	54	26	2
AUa	18	59	22	2
Hidden Valley site				
HLf	27	48	25	2
HMf	4	14	82	4
HUf	3	63	34	3
HUa	5	26	69	4
Bradley site				
BLf	14	55	31	2
BLa	25	51	24	2
BUa	26	52	22	2

[a] Clast weathering was not determined for soil pits HLa and HMa because not enough clasts were available for sampling.
[b] Degree of weathering, see text for criteria.
[c] Based on *K*-means cluster analysis procedure.

The results of the cluster analysis confirm these visual observations (Table 2). The pedons at the Alarka site were assigned to clusters 1 and 2 whereas those at the Hidden Valley site were concentrated in clusters 3 and 4. At Alarka, the two lower pedons, ALf1 and ALf2, do not co-occur with the two higher pedons, and in Hidden Valley HLf does not co-occur with any of the higher pedons. This corroborates the apparent difference in age between pedons and hence, deposits, at different topographic levels. All pedons at the Bradley site are concentrated in cluster 2. The general concentration of the pedons at a site into a few groups indicates that the within-site relative-age difference of the deposits is smaller than the between-site age differences.

5.2. Soil development

The indices of soil development (Figs. 5 and 6) consistently point to a relatively young age (low values) for the soils at Alarka, similar to intermediate age for those at Bradley and an older age (high values) for the soils at Hidden Valley. Considering

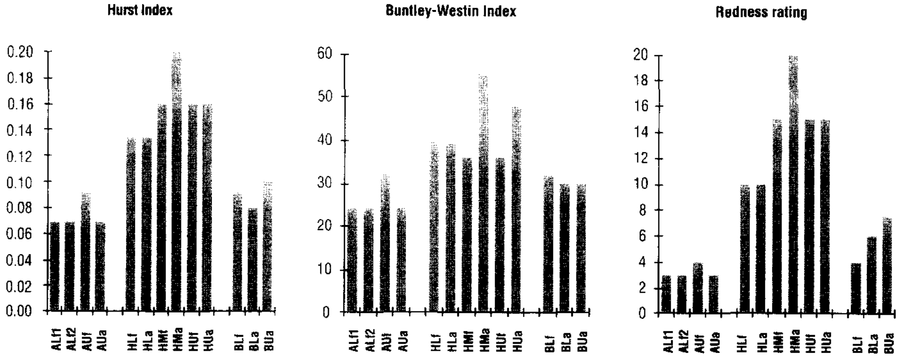

Fig. 5. Rubification indices for the reddest horizon of each soil. Graph of Hurst index shows reciprocal of index. Higher values imply redder and/or more vivid colors and point to more advanced soil development. See Table 1 for nomenclature of soil pits.

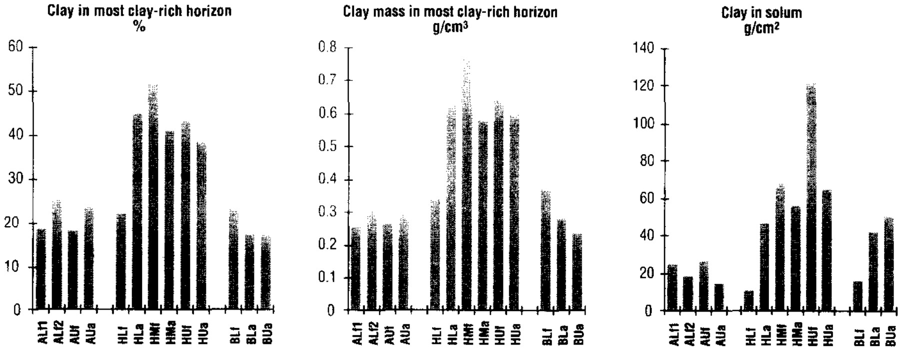

Fig. 6. Clay content indices for the soils. Higher values indicate more advanced soil development and point to greater age.

that the increase with time of indices of soil development, such as color and clay content, is not exponential (Birkeland, 1984), the soils at the Hidden Valley site must be considerably older than those at the other two sites.

Most indices show that pedon AUf, on the higher deposit at the Alarka site, is slightly older than the other Alarka pedons. The low values for the lowest pedon at Hidden Valley, HLf, are typical of young pedons. High values for the higher pedons at Hidden Valley indicate that, at this site as well, the highest deposit is older than the lowest. An avenue for the formation of younger deposits at lower elevations is provided by the streams along the sides of deposits. Through these channels, debris flows can pass existing deposits without disturbing the crests. The saprolite at Hidden Valley (HMf and HMa) has the highest values and, thus, is older than the deposits.

The cluster analysis, which was run on all six soil development indices, grouped the Alarka and Bradley pedons into one cluster, and separated the Hidden Valley pedons into three other clusters (Table 3). This shows that the within-site variation at the Alarka and Bradley sites is smaller than the within-site variation at the Hidden Valley site. A cluster analysis with three groups classified HLf together with the Alarka and Bradley pedons, indicating that the lower deposit at the Hidden Valley site is similar in age to the Alarka and Bradley deposits. This three-group cluster analysis left HMa, one of the pedons in saprolite, as the pedon that is most different from (and older than) the other pedons.

5.3. *Iron species ratio*

The results of this proxy corroborate the conclusions of the other relative-age indicators (Fig. 7).

Table 3
Results of cluster analysis for soil development indices and iron species ratio

Clusters based on soil development indices		Clusters based on iron species ratio	
Cluster assignment [a]	Soil pits	Cluster assignment [a]	Soil pits
1	All Alarka and Bradley soil pits	1	All Alarka soil pits, HLf, BUa
2	HLa, HMf, HUf, HUa	2	HLa, BLf, BLa
3	HLf	3	HMa, HUf, HUa
4	HMa	4	HMf

[a] Note that cluster labels are for identification purposes only and have no physical meaning. Clusters obtained in two runs are completely independent.

The soils of the Alarka site have relatively small Fe_d/Fe_t ratios, which generally are associated with young soils (Rebertus and Buol, 1985; Arduino et al., 1986; McFadden and Weldon, 1987). The pedons at the Hidden Valley site have Fe_d/Fe_t ratios characteristic of older soils. Based on the Fe_d/Fe_t ratio, the relative age of the soils at the Bradley site is intermediate to those of the other two sites.

The within-site variation at Alarka is smaller than the within-site variation at Hidden Valley and the between-site variation of the three sites. At the Alarka and Bradley sites no evidence exists that the higher deposits are older. In Hidden Valley the lowest deposit has lower Fe_d/Fe_t values and, therefore, is younger than the highest deposit. For the Bradley and Hidden Valley sites this conclusion is consistent with the results of the other relative-age indicators. The highest value, representing the oldest age, is reached again in one of the saprolitic soils (HMf).

The results of the cluster analysis (Table 3) confirm that little variation in relative age occurs at the Alarka site and that the pedons on the lowest deposit at Hidden Valley are more similar to pedons at the Alarka and Bradley site than to the other four deposits in Hidden Valley. One of the pedons in saprolite (HMf) is classified again in a separate group. When three clusters were used, HMf was added to the group containing HMa, HUf and HUa.

5.4. Discriminant analysis

The final assignment of pedons to relative-age groups was based on the results of all four relative-age proxies. Because data of clast weathering clearly pointed to a younger age for the lower deposits at the Alarka site, the soils of this site were separated in two groups. The pedons on the lower deposits (ALf1 and ALf2) were classified in the youngest group

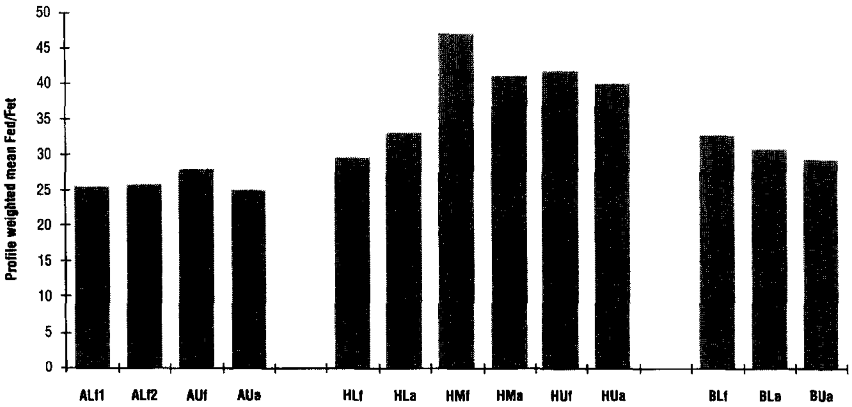

Fig. 7. Profile weighted mean Fe_d/Fe_t for the soils at the three sites. Higher values indicate more intense weathering and point to greater age.

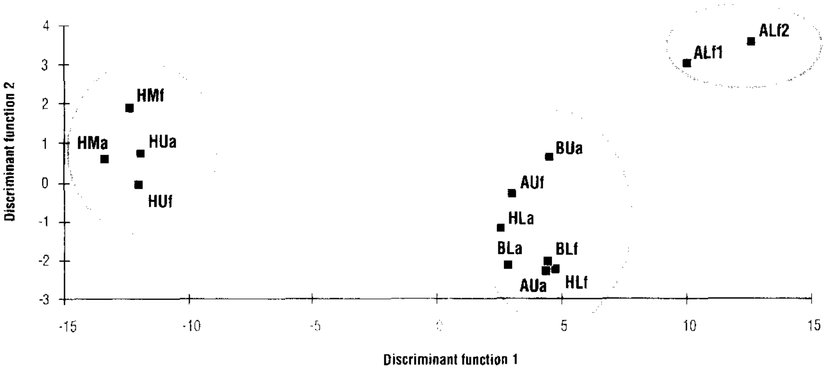

Fig. 8. Discriminant scores for the soils. Ellipses are for graphical identification of groups only. Graph shows compactness of relative-age groups (small within-group variance) and wide separation of groups (large between-group variance) achieved by discriminant functions.

(G1) and the pedons on the higher deposit (AUf and AUa) were the first members of a slightly older group (G2). Within the Hidden Valley site all relative-age indicators pointed to a younger age for the pedons on the lowest deposit (HLf, HLa), as compared to the higher pedons, and the cluster analysis systematically grouped HLf with the pedons of the Alarka site. Pedons HLf and HLa were, therefore, classified in G2. The remaining Hidden Valley pedons (HMf, HMa, HUf, HUa), located at higher positions, were assigned to a separate group (G3) representing the oldest pedons. At the Bradley site no apparent age difference occurred between deposits at different topographic levels. The Bradley pedons, classified together, were most closely associated in age with G2.

This grouping (G1, G2, G3) was described by the discriminant functions in a statistically significant manner (Wilks's lambda, T^2, $\alpha = 1\%$), indicating a physical base for the assignment of the pedons to the respective groups, and also an objective, statistical justification for it. Fig. 8 graphically illustrates the quality of the classification and shows that the discriminant functions provide a credible means of separating the three groups.

To further test the validity of the final classification, we subjected three other grouping schemes to discriminant analysis. In the first, the saprolitic soils (HMf, HMa) were assigned to a separate group. In the second, the Bradley site was classified separately, and in the third test HLf was added to G1. Separation of the new groups in the three tests was not achieved by the discriminant analysis with the statistical confidence observed in the initial run. This indicates that the statistically most appropriate grouping was chosen in the initial classification.

6. Discussion

6.1. Verification of the methods of relative-age dating

Constraints placed on techniques of relative-age dating by episodic pedogenesis are not pertinent to this study because of the large timescales of the results and because the data were classified only in broad relative-age groups. Because sites with minimal evidence for surficial erosion/deposition were selected, it can be assumed that the geomorphic evolution of the deposits was similar. Hence, the relative-ages of the soils can be extended to the deposits (i.e. parent material) within which they have formed.

It cannot be ascertained whether the source materials of the different debris flows had the same degree of weathering and soil formation at time zero. As a result, it is conceivable that some of the characteristics of the pedons on the debris flow deposits partly reflect the composition of the source material. The degree of weathering of the clasts in the deposits, however, is unlikely to have been influenced by preweathering of the source material upslope. During transportation in debris flows, clasts interact with each other, with the matrix, and with obstacles on the surface and in the path of the flow. Weathered clasts in the source material are destroyed by these interactions during transportation and only fresh clasts are incorporated in deposits (Mills, 1983; Graham et al., 1989). The similarity of the results for the other proxies to those of clast weathering indicates that these other proxies, too, were minimally influenced by inheritance from the source material. Time has been, therefore, the chief factor in the determination of differences in pedogenetic development at the study sites and the results are indeed indicative of the relative ages of the pedons.

The lack of systematic variation between pedons on the toe vs. apex of the deposits also points to the effectiveness of the relative-age dating methods, and to the appropriateness of the chosen variables. Although subtle morphologic differences occur between pedons on toe and apex positions, relative-age indicators should theoretically show little difference between soils on a single geomorphic surface.

Pedons developed in saprolite have systematically the highest values (highest relative age) and are assigned to separate clusters. Because it can be expected that, in small areas with uniform geomorphic conditions, such as the Hidden Valley site, saprolite is older than debris flow deposits, the high values for these saprolitic pedons can be seen as an additional verification of the method.

6.2. *Relative ages of the deposits*

The results point to a greater age and a larger within-site variation for the Hidden Valley site than for the other two sites. If this inference is correct, it indicates either a greater difference in age of the deposits at the Hidden Valley site or, as soils become older, more variation is introduced in the development. Acceptance of the latter option is consistent with the concept of chaotic pedogenesis (Phillips, 1993). Absolute dating of the deposits might resolve this contention. At the Hidden Valley site greater vertical separation also occurs between the deposits than at the other sites. Mills and Allison (1995a,b)) observed similar correspondence between high vertical separation and large differences in relative-age proxies.

In spite of the generally large between-site variation, each of the three sites has a deposit that is similar in age to deposits at the other sites. This similarity in age may result from an inadequate resolution of the applied relative-age dating methods. If real, the similarity indicates, however, that an external factor, operative across all three sites, accounts for the debris flows. In the tectonically stable Southern Blue Ridge this external control was most likely provided by extreme precipitation events.

The two youngest deposits occur at the Alarka site. Deposits of comparable age were not observed at the other two sites. It is not likely that deposits of that age have been present at those other sites; they cannot be covered and would have been exposed to less erosion than the older deposits. The absence at the Hidden Valley and Bradley sites, therefore, implies that large-scale factors alone cannot explain the occurrence of debris flows in the region. Local, intrinsic factors must also affect the timing of debris flow activity.

6.3. *Implications for landscape stability*

This research, as well as studies by others (Mills, 1981, 1983; Whittecar and Ryter, 1992), shows that the higher debris flow deposits are at least slightly older than lower deposits in the same valley. Similar topographic relationships for alluvial aprons have been explained by the progressive growth of aprons where mountain streams enter lowland valleys. Because the aprons are more resistant than the host valleys, the river in the host valley is displaced laterally to the opposite site of the valley and the focus of deposition shifts away from the mountain front (Hack, 1960, 1965).

An alternative explanation, for debris flow deposits, invokes climatic change. The most unstable slopes in an area fail soon after conditions become conducive to debris flow formation but when the environment is still relatively dry. More stable slopes fail later, when conditions for debris flow formation are optimal, and only when thoroughly saturated by precipitation. The resulting flows are fluid, mobile and travel to lower elevations. They reach these lower elevations via stream channels along the sides of the existing, older, deposits. This hypothesis assumes that the difference in age between the debris flow deposits is less than the time required for slopes to achieve instability. In any case, the observation that the locus of deposition shifts over time demonstrates that mapping older debris flow deposits may not be synonymous with delineating sites of future debris flow activity.

7. Conclusions

Debris flow deposits commonly occur in small, low-order stream valleys throughout the Little Tennessee River basin. Analyses of clast weathering, indices of soil development, and an iron species ratio generated consistent relative ages for the soils and sediments of these debris flows. The combination of qualitative and quantitative approaches produced a physically justifiable and statistically significant relative-age classification for the debris flow deposits. The methods provide a reliable means of relative-age dating of debris flow deposits in a warm to temperate, humid environment.

The general difference in age of sites within relative proximity of each other shows that intrinsic factors affect the formation of debris flows locally. Extrinsic factors, probably weather events, triggered debris flows at approximately the same time at various locations in the study area. Additional insights in age relationships of debris flow deposits in the Southern Appalachians can establish when the extrinsic conditions were most favorable for the formation of debris flows. Because precise absolute dates of debris flows are not readily obtainable, further relative-age studies are warranted.

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