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Genesis and Distribution of Colluvium in Buffalo Creek Area, Marion County, West Virginia

ROBERT B. JACOBSON

Two types of colluvium are present on the Buffalo Creek landscape, an area typical of that part of the Appalachian Plateaus underlain by rocks of the Dunkard Group. Thick deposits of entrenched, diamicton, debris-flow-generated colluvium occur as long fingers in coves (zero-order drainage basins). These deposits range up to 15 m thick but most are 5 to 8 m thick. The deposits are the product of early Wisconsinan slope processes that produced colluvium at a greater rate than it could be removed by streams. Colluvial fingers are currently well drained because they are deeply dissected by gullies; natural slopes on colluvial fingers are relatively stable. The second type of colluvium is generated as modern slope failures shear bedrock and transport material downslope. Colluvium generated by this process collects up to about 2 m thickness on bedrock benches until failure conditions are reached and the material is transferred to the next lower bedrock-controlled bench. Colluvium converges on hummocky areas at heads of gullies and is eventually delivered to streams by debris flow or fluvial erosion of failure toes. Different types of modern natural slope failures occur on different surficial geologic units, indicating that surficial geologic setting has a strong influence on failure mechanisms and relative stability of natural slopes.

The Buffalo Creek area in Marion County, West Virginia (Figure 1), is typical of much of the Appalachian Plateaus underlain by rocks of the Pennsylvanian-Permian Dunkard Group. In the Buffalo Creek area there are two distinct types of colluvium: (a) thick, cove-filling diamicton deposits that are relicts of the

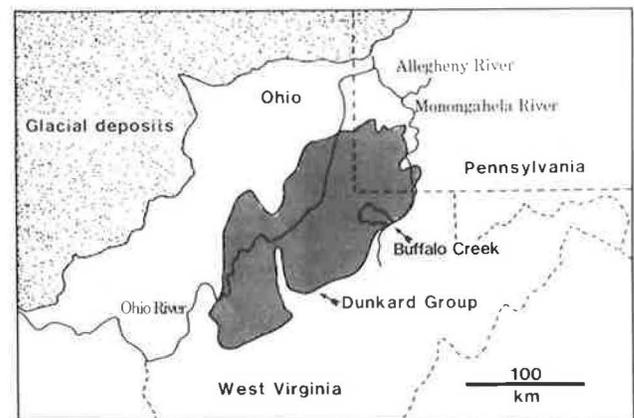


FIGURE 1 Upper Buffalo Creek study area showing outcrop area of Pennsylvania-Permian Dunkard Group and Pleistocene glacial border.

influences of a Pleistocene climate and (b) thin colluvium that is being generated and transported under present-day conditions. ("Diamicton" is used here to denote deposits with bimodal particle size distributions, in particular those with cobble-to gravel-size clasts mixed with a silty and clayey matrix.) The origin and occurrence of these two types of colluvial deposits and their influence on relative slope stability are discussed.

GEOLOGY OF BUFFALO CREEK AREA

The Buffalo Creek area is underlain by gently deformed sandstones, mudstones, and shales of the Pennsylvanian-Permian

Department of Geography and Environmental Engineering, Johns Hopkins University, Baltimore, Md. 21218. Current affiliation: U. S. Geological Survey, Mailstop 926, Reston, Va. 22092.

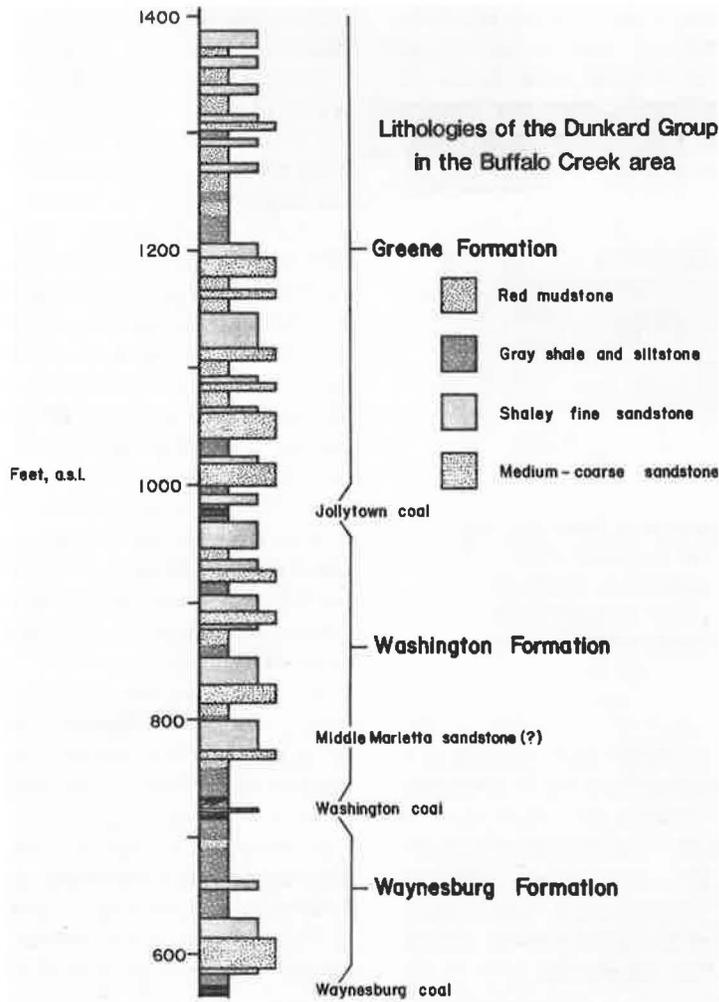


FIGURE 2 Geologic column for Buffalo Creek area from ridgetop diamond drill core log (1).

Dunkard Group. Dips range from 0 to 2 degrees. A typical geologic section from a diamond drill core log is shown in Figure 2. In the Buffalo Creek area, the lower part of the Dunkard section, including the Waynesburg Formation and the lower Washington Formation [as defined by Berryhill et al. (1)], is composed of gray siltstone and sideritic shale interbedded with thick (15 to 30 m) sandstones. The remainder of the Washington Formation above the Middle Marietta sandstone

and the entire Greene Formation are composed of repetitive cycles of interbedded sandstone and mudstone.

Red mudstones slake readily in water and have abundant fracture porosity. These two features combine to make the mudstone much weaker than superjacent and subjacent sandstones. On typical slopes in the upper Dunkard Group, juxtaposition of these strong and weak lithologies results in distinctly stepped slope profiles with 30- to 50-degree slopes on sandstone risers and 10- to 28-degree slopes on mudstone benches. Figure 3 shows a typical Greene Formation slope profile and surficial stratigraphy in a measured section exposed in a pipeline trench in Wetzel County, West Virginia.

Topography in Buffalo Creek is characterized by deeply embayed coves (or zero-order drainage basins) that form large amphitheater-like areas at heads of drainage. Ridge-to-valley relief ranges from 150 to 180 m.

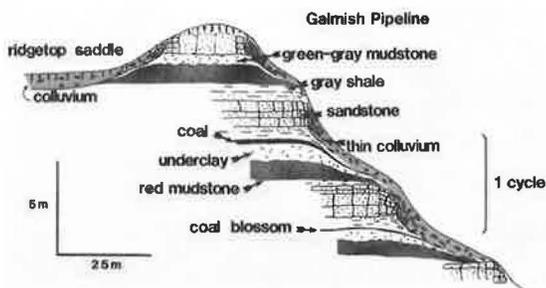


FIGURE 3 Typical hillslope stratigraphy from pipeline trench in upper Dunkard Group showing colluvial mantles on bedrock-controlled topographic benches.

SURFICIAL STRATIGRAPHY

The Buffalo Creek basin is approximately 150 km south of the Pleistocene glacial border and was flooded with slack water at least twice during the Pleistocene when glacial ice and outwash gravel dammed the north-flowing Monongahela River (2, 3).

Small isolated patches of pre-Illinoian and Illinoian lake beds can be found preserved on sandstone-protected benches on valley walls. Figure 4 shows an exposed cross section of deposits near Mannington, West Virginia, where pre-Illinoian and Illinoian clayey-silt lake sediments are overlain and underlain by thick diamicton colluvium (TDC).

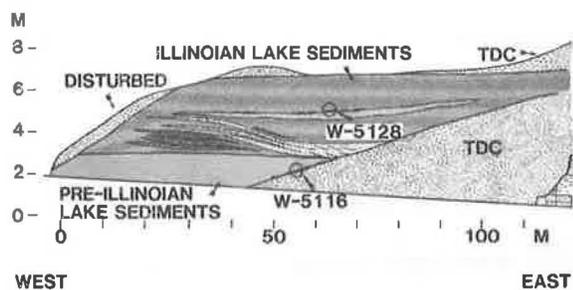


FIGURE 4 Surveyed section at Mannington, West Virginia, railroad cut showing TDC interbedded with pre-Illinoian and Illinoian lake-bed sediments. (W-prefix numbers refer to radiocarbon-dated organic samples older than 40,000 years.)

TDC consists of cobble-size sandstone clasts floating in a silty matrix. Many of the elongate clasts have rough downslope orientation. Unconformities and bedding are rare except for unusual cases from exposures on the extreme sides of deposits that have shown stacks of two to three generations of diamicton units with buried weathered soil horizons at the contacts. Most exposures of TDC show massive diamicton without internal unconformities. These observations suggest that most of the TDC that existed before the most recent pulse of TDC deposition was eroded before or during that period. Moreover, the most recent period was characterized by large debris flow events and rapid deposition rather than by smaller events and gradual deposition.

Because TDC units are found underlying pre-Illinoian lake beds as well as underlying and overlying Illinoian lake beds, it is clear that the Buffalo Creek area has experienced multiple

generations of TDC deposition during the early to late Pleistocene. However, most TDC remaining on the landscape is from the most recently deposited pulse that overlies Illinoian lake beds.

TDC occurs in coves as long fingers bounded by gullies or as small eroded patches of debris fans at cove-valley junctions. The spatial distribution of remnants indicates that TDC once filled coves and was later entrenched and eroded. Remnant TDC fingers range up to 15 m thick but most are in the range of 5 to 8 m thick. TDC and other surficial geology units are shown in a three-dimensional perspective diagram in Figure 5.

Low-angle alluvial fans prograde out from TDC-entrenching gullies and grade to terraces and active floodplain of the valley bottom alluvial complex (Figure 5). Fan deposits have a noticeably higher percentage of clasts than does TDC: 70 to 90 percent by volume in fans compared with 40 to 60 percent in TDC. There is a general trend from matrix-supported debris flow sediment at fan apexes to more fluvial, clast-supported gravel and sand at fan toes. Therefore, it is concluded that most fan sediment is delivered to fans by debris flow and the sediment is then progressively reworked by fluvial processes downslope on the fans.

Alluvial fan segments grade to alluvial deposits and terraces ranging in age from Recent to late Wisconsinan, roughly 10,000 to 18,000 years old. Because the most recent TDC deposit is crosscut by the alluvial fans, it must be older than late Wisconsinan, and because the bulk of TDC overlies Illinoian lake beds, most TDC is younger than Illinoian. Comparison of iron mineralogy, clay mineralogy, and accumulated clay in TDC weathering profiles with weathering profiles from a sequence of independently dated alluvial terraces on the Ohio River indicates that the latest pulse of TDC has been weathering since the end of the early Wisconsinan glacial advance, approximately 55,000 years before the present (3). Correlations of weathering profiles also indicate an early Wisconsinan age for 0.5- to 2-m-thick diamicton colluvium commonly found in ridgetop saddle positions (Figure 5).

The presence of TDC deposits on ridgetops where contributing slopes are very gentle and the large volume of TDC that is apparent on reconstructing entrenched deposits show that the

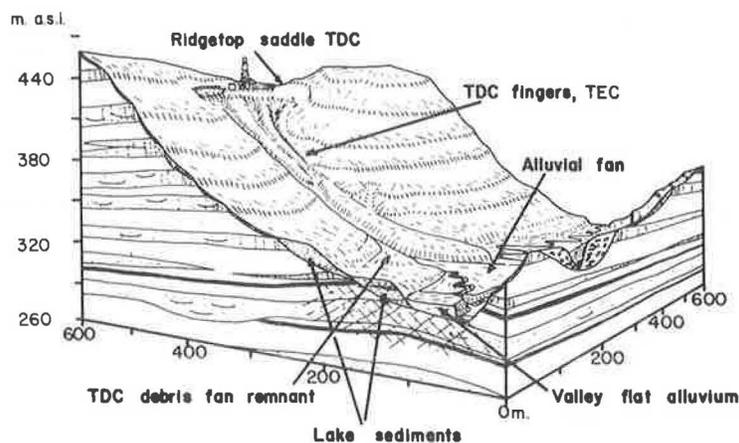


FIGURE 5 Three-dimensional perspective diagram showing morphology and stratigraphy of surficial geologic units in Buffalo Creek area.

Buffalo Creek landscape was extensively destabilized during the early Wisconsin. Upland erosion was sufficient to strip hill-slope residual weathering profiles and form thick colluvial deposits as production of colluvium overwhelmed the transport capacity of streams. In contrast, the late Wisconsin climate produced geomorphic processes that favored fluvial dissection of TDC. Dissection has continued to this day, leaving TDC as long fingers with 8- to 18-degree longitudinal slopes and 30- to 50-degree gully side slopes.

It should be emphasized that the spatial sequence of TDC and alluvial fan deposits described earlier is found consistently throughout this landscape (3). Moreover, soil cores reveal that TDC soil profiles are consistently weathered to an extent commensurate with an early Wisconsin age.

Hill-slope area not occupied by cove-filling or ridgetop saddle TDC is covered by thin colluvium and weathered bedrock (TC/R). Figure 6 shows typical stratigraphic relations on upper Dunkard Group (upper Washington and Greene formations) TC/R hillslopes as exposed in a trench in the Buffalo Creek area. Diamictic colluvium, ranging up to 2 m thick, overlies sheared mudstone in the center of the bench and tapers to feather edges over weathered sandstone at the upper and lower ends. Shear zones and conspicuous slickensides occur at or slightly below the colluvium contact and are found on all slopes on this landscape. Movement along these zones shears mudstone and mixes in weathered sandstone to create diamictic colluvium. These observations indicate that failure in mudstone is an integral part of the process by which colluvium is created and transported on these slopes.

Weathering profiles in the TC/R complex are weakly developed. Weathered sandstone may have up to 15 cm of true residual soil over fractured and partly weathered rock. Weathering profiles in bench colluvium have cambic B horizons (weak structural development with little accumulation of clay and sesquioxides) or lack B-horizon development altogether, indicating that periods of stability are short, around several thousands of years or less.

PRESENT-DAY SLOPE PROCESSES

Slope failures on natural slopes in the Buffalo Creek area were studied by detailed mapping at 1:8000 scale in nine small

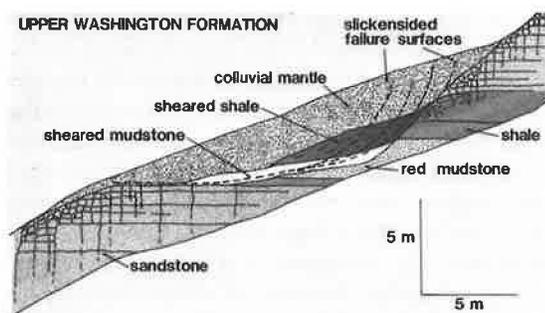


FIGURE 6 Surveyed section in trenched slope failure, upper Washington Formation, Buffalo Creek area. Rotational failure occurs in mudstone section underneath accumulating colluvial mantle.

drainage basins totaling 29.2 km². These data reveal that location, type, and density of natural slope failures are strongly influenced by surficial geology of the area. Comparison of slope-failure spatial density on the two types of colluvial units can give an indication of relative stability. However, because slope-failure temporal frequency is not considered, spatial density must be interpreted with caution.

A total of 716 slope failures was inventoried. Of that total, 561, or 78.4 percent, occurred in TC/R. Dividing TC/R failures by the area occupied by TC/R gives failure density of 28.6 failures/km², equal to 11 975 m³/km². Among TC/R failures, 68.6 percent of the total number and 83.5 percent of the inventoried volume were rotational failures on mudstone benches like that shown in Figure 6. This amounts to 65.2 percent of the total volume of all failures regardless of surficial lithology; hence the majority of the mappable failure volume on this landscape is produced on mudstone benches.

Figure 6 shows how size and location of mudstone bench rotational failures are controlled by mudstone bedrock thickness and sandstone layer spacing; failures begin below upper sandstone layers and toe out above the next lower sandstone. Mean surface slope for mudstone bench failures is 19.8 degrees ($N = 254$; $SD = 5.5$ degrees).

Observations from the trench exposure shown in Figure 6 and from other trenched failures indicate that stability of TC/R mudstone benches is controlled by several factors. A basal slickensides shear surface starts in colluvium or weathered sandstone at the upslope end of the failure and passes downward through shale and mudstone in a near-circular arc. Older shear surfaces are often present above the basal shear surface and are often encrusted with iron and manganese oxides. About midway through the failure mass the basal shear surface flattens out, converges with the older shear surfaces, and passes to the ground surface. When a failure initiates in this setting, intact mudstone and colluvium are sheared in the circular portion of the failure surface and peak strengths of these materials are mobilized. In the flattened portion of the failure surface, where mudstone and colluvium have been previously sheared, residual or near-residual strengths are mobilized. In addition, where the failure surface intersects the root zone, typically from 0 to 1 m deep, roots can be expected to add a component of cohesive strength. Typical effective-strength values for these components were gathered from reports of geotechnical tests on similar materials in the region and are summarized in Table 1.

Using the strength values in Table 1 as representative estimates for the Buffalo Creek area and with the shear-surface geometry shown in Figure 6, Janbu static equilibrium slope-stability analyses indicate that this general class of failures requires pore pressures from a piezometric surface at least 27 cm above the ground surface in order to approach failure for the 19.8-degree mean slope condition [more details are given elsewhere (3)]. These calculations are consistent with field observations during periods of prolonged rainfall when artesian spouts of water up to 15 cm high have been seen issuing from root holes and faunal burrows. Excess pore pressures can develop in TC/R because the massive colluvium is much less permeable than underlying sheared and fractured mudstone and sandstone.

TABLE 1 TYPICAL EFFECTIVE-SHEAR-STRENGTH PARAMETER VALUES FOR HILL-SLOPE MATERIALS IN BUFFALO CREEK AREA

Component	$\bar{\phi}$ (degrees)	\bar{c} (kN/m ²)	Test	Source
Peak mudstone	18.0	10	Direct shear	Hamel and Adams (4)
Residual mudstone	13.0	0	Direct shear	Hamel and Adams (4)
Colluvium	31.5	0	Triax, CU	ASCS (5)
Tree roots	0	4.3	Extension device	GSA (6)

Note: ASCS = Agricultural Stabilization and Conservation Service; GSA = Geological Society of America.

Rotational TC/R failures tend to equilibrate at a postfailure angle of approximately 15 degrees. Each site then evolves back to failure conditions as colluvium from upslope accumulates in the failure scar. The rate of accumulation is ultimately controlled by the rate of sandstone weathering. As colluvium accumulates and loads the bench, threshold pore-water pressure values decline until the occurrence of a meteorological event of sufficient magnitude causes failure. In this manner production and accumulation of colluvium drive a cascading system of slope failures that transports colluvium downslope. Colluvium eventually converges and accumulates on benches above TDC gullies, just above the beginning of integrated drainage channels. These are common failure sites and tend to have hummocky microtopography suggestive of frequent movement. When these benches fail, colluvium is dumped directly into gullies by debris flows or fluvial erosion of failure toes. In general, colluvium generated and transported by TC/R failures completely bypasses TDC without influencing TDC stability.

The remaining 31.4 percent of TC/R failures is composed of shallow planar slides on sandstone slopes. In terms of volume, TC/R planar failures account for only 16.5 percent of the TC/R volume and 12.9 percent of total inventoried failure volume. Sandstone planar failures occur on a mean slope of 33.7 degrees ($N = 157$; $SD = 6.1$ degrees).

Slope failures on TDC compose 21.6 percent of the total inventory and 39.6 percent of the total volume. Failure density is 23.1 failures/km², equal to 9818 m³/km². These failure density data show that TDC is somewhat more stable than TC/R under natural conditions. Planar slides on TDC gully side slopes make up 81.9 percent of TDC failures, and all appear to be the result of oversteepening by lateral stream erosion. Mean failure slope for these planar failures is 42.3 degrees ($N = 110$; $SD = 7.7$ degrees).

Simple infinite slope-failure models using typical effective Mohr-Coulomb strength parameters for colluvium and tree roots as noted in Table 1 show that slopes as steep as those found on colluvial finger side slopes should only exist under conditions of zero pore-water pressure and fully mobilized root strength. The infinite slope model for planar failures shows that a dry equilibrium slope can exist up to approximately 40 degrees. Without root strength, dry slopes should stand at the internal angle of friction, around 31.5 degrees; wet slopes, with the water table at the surface, should equilibrate near 17 degrees and wet slopes with root strength would equilibrate near 28 degrees. These simple calculations show that observed stability of natural TDC gully side slopes at inclinations exceeding 43 degrees is dependent on both tree root strength and free drainage resulting from deep dissection.

Erosion and failure of alluvial fans, valley-bottom alluvium, and old lacustrine deposits were not explicitly studied. Depositional slopes of the first two units are very stable and failures occur mainly by toppling of cut banks where lateral stream-channel migration causes local oversteepening. Remnants of old lacustrine deposits underlie only a small fraction of the Buffalo Creek area, and under natural conditions these deposits are stable because of equilibration to extreme wet conditions during the Pleistocene (3).

SUMMARY AND DISCUSSION

Landscape history of the Buffalo Creek area provides a model for the distribution of surficial lithologies. TDC deposits, relicts from Pleistocene-age climatic influences, exist as entrenched fingers in coves and as eroded patches of debris fans at cove-valley junctions. Late Wisconsinan to Recent entrenchment of TDC created gravelly alluvial fans that are inset against TDC and prograde onto valley bottoms.

Colluvium is being created under present-day conditions by slope failures that shear up bedrock and move colluvium downslope from bench to bench. Colluvium converges on bedrock-controlled benches just above entrenched gullies. Hummocky topography in these areas suggests that they are relatively active parts of the landscape. Failures in the hummocky areas ultimately deliver colluvium to the gullies and the rest of the fluvial system.

The genesis and spatial distribution of colluvium in the Buffalo Creek area have many similarities with other areas in the Ohio River Valley, but there are also some important differences. Slopes adjacent to major river valleys are exemplified in a study of colluvium in McMechen, West Virginia by Gray and Gardner (7, pp. 29–32). In the McMechen area two similar processes generate colluvium: on slopes where drainage basins have been carved, colluvium accumulates in coves; on slopes with straight contours, colluvium cascades downslope from bench to bench to accumulate at the base. Because the McMechen area is in a relatively young, gorgelike section of the Ohio River [near the former divide between the preglacial Teays and Pittsburgh rivers (2)], slopes are uncommonly steep and surface drainage has not been developed along long sections of the valley walls. Under these conditions it appears that colluvium is being produced faster than it can be removed by streams.

In contrast, the Buffalo Creek area has been eroding steadily for a longer time and is not close to the bluffs of a major river. Hence, the topography has developed with deeply embayed coves and continuously curving convex and concave contours;

surface drainage is well developed in these small drainage basins. As a result, TC/R failures converge into coves and deliver colluvium to stream channels rather than accumulating at the foot of slopes. The modern (Holocene and Recent) balance between production of colluvium on slopes and removal by streams does not allow colluvium to accumulate in thick deposits.

In the McMechen area, the late Wisconsinan age of the thick, foot-slope colluvium (7) indicates that these steep valley-wall slopes were extensively destabilized by the late Wisconsinan climate. In contrast, the Buffalo Creek area experienced major accumulation of debris-flow-generated colluvium in early Wisconsinan time when colluvium was generated faster than streams could export it from small basins. Fluvial dissection and alluvial fan deposition occurred in this area in the late Wisconsinan.

Present-day, natural slope-failure mechanisms are strongly influenced by surficial geologic setting. Most failures occur as rotational, colluvium-generating failures on mudstone benches. Failure susceptibility of these rotational failures increases as colluvium collects on mudstone benches; the mean failure slope requires moderate artesian pore-water pressure to reach failure, an event that is not uncommon under modern conditions. A smaller proportion of failures occurs as planar failures on weathered sandstone risers.

Planar failures on TDC gully side slopes are equilibrated to fully mobilized root strength and negligible pore-water pressures. Dry conditions prevail on these slopes because deep dissection encourages rapid drainage and low groundwater tables. Sorting of failure mechanism, location, and density according to surficial geologic setting indicates that different surficial geologic units have important differences in relative stability.

The results of this study may help in geotechnical engineering problems in Dunkard Group and similar landscapes by

providing a predictive model for the spatial distribution of surficial geologic materials and by showing the relative stability of these materials in their natural setting.

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