Report On The May 5-7, 2003 Debris Flows on Slopes Underlain by Sulfidic Bedrock of the Wehutty, Nantahala and Copper Hill Formations, Swain County, North Carolina

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In Cooperation With:

North Carolina Division of Emergency Management
Department of Crime Control and Public Safety

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Table of Contents

Report on the May 5-7, 2003 Debris Flows on Slopes Underlain by Sulfidic Bedrock of the Wehutty, Nantahala and Copper Hill Formations, Swain County, North Carolina

List of Tables and Figures

Report on the May 5-7, 2003 Debris Flows on Slopes Underlain by Sulfidic Bedrock of the Wehutty, Nantahala and Copper Hill Formations, Swain County, North Carolina

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Introduction

North Carolina Geological Survey (NCGS) staff recently collected geologic data on debris flows that were triggered by heavy rains during May 5-7, 2003 in Swain County, North Carolina. These studies are being done in cooperation with the North Carolina Division of Emergency Management, and were made possible with information provided by Swain County Emergency Management, and local residents in the areas affected by the debris flows.

Debris flows are a type of landslide characterized by a mixture of soil, rock fragments, and water that moves rapidly down slope. In this study, most of the debris flows traveled mainly along existing drainage channels. Some of these debris flows reached velocities of about 25 miles per hour (~37 feet per second), and one traveled down slope about 3,400 feet. Hazards and environmental impacts related to debris flows include the threat to public safety, damage to roads and water supply facilities, and degradation of water quality from sedimentation and potential acid runoff.

One of the purposes of this investigation is to determine if there are any rock or soil types in western North Carolina prone to slope movements (landslides). Although data collection and analyses are not yet complete on these and other slope movements that occurred during the May 5-7 timeframe, initial studies show that six major debris flows originated on slopes underlain by sulfidic rock types. Five of the six major debris flows originated on slopes underlain by sulfidic, graphitic, mica schist horizons in the Wehutty and Nantahala Formations (fig. 1). The sixth debris flow originated on a slope underlain by sulfidic mica schist, metasiltstone, and metagraywacke of the Copper Hill Formation.

Sulfidic rock contains the iron sulfide minerals pyrite (fool’s gold) and/or pyrrhotite. On freshly exposed surfaces these minerals have a brass- or gold-colored, metallic luster. Sulfidic rocks weather rapidly upon exposure in road cuts and other excavations. Pervasive orange, red-orange, and yellow staining is characteristic of weathered surfaces on sulfidic rock types. Graphite in the rocks imparts a dull metallic gray to pewter colored luster. A graphitic rock feels greasy, and the gray color can rub off on your fingers.

In all cases, the May 5-7, 2003 debris flows appear to have initiated on fill slopes along roads or on house sites built using cut-and-fill construction methods. This report is being provided at this time to advise local officials of past, and potential future problems associated with development on steep slopes underlain by these rock types.

Debris Flow Locations

During the May 5-7, 2003 flooding, four damaging debris flows originated in the sulfidic, graphitic, mica schist of the Wehutty Formation. Three of these debris flows occurred on the southeast side of Breedlove Mountain along tributaries to Charley Branch in the Glory Mountain development (fig. 3A). The fourth debris flow occurred along a tributary to Lands Creek that drains into the Bryson City reservoir (fig. 3B). Previously, on December 23, 1990 a debris flow that originated in a tributary of Lands Creek near the 2003 debris flow (fig. 3B) destroyed the chlorinator building for the Bryson City water system (fig. 7F) along with a mobile home. The 1990 debris flow also originated on slopes underlain by sulfidic, graphitic schist of the Wehutty Formation (Wooten, 1998).

One of the May 5-7, 2003 debris flows originated on a slope underlain by sulfidic, graphitic, mica schist of the Nantahala Formation. It occurred on So Hi Trail (road) located on the east side of Round Top Mountain near the Swain-Graham County line. One major, and two smaller, debris flows originated on slopes underlain by sulfidic mica schist, metasiltstone and metagraywacke of the Copper Hill Formation. These debris flows occurred in the Timber Estates development on the south side of Alarka Creek near the contact with the Wehutty Formation (fig. 3C). Latitude and longitude coordinates for all six debris flows are given in table 1.

Precipitation

Heavy rains from May 5-7, 2003 triggered the debris flows and other landslides throughout the area. The U.S. Geological Survey gaging station on the Little Tennessee River at Needmore recorded 7.37 inches of rain over the three-day period (fig. 2). Local residents, however, report as much as 15 inches of rain during the same period. Another contributing factor was the 2.09 inches of rain recorded from April 30 to May 2, 2003 that led to higher antecedent moisture conditions prior to the May 5-7 event. The May 5-7 rains resulted in a peak discharge of 9,070 cubic feet per second on the Little Tennessee River at Needmore on May 7, 2003 (fig. 2). The weather radar image shown in figure 2D indicates the regional extent of the rainfall, and that higher rainfall may have occurred east of Swain County.

Fort Payne Earthquake

Swain County residents reported that they felt shaking from the magnitude 4.6 earthquake centered at Fort Payne, Alabama on April 29, 2003. No slope movements were reported on that date in Swain County. It is possible, though unlikely; that ground shaking associated with this earthquake had a significant destabilizing influence on otherwise stable slopes in Swain County. The earthquake, however, may have had some destabilizing influence on slopes that were already marginally stable or unstable at the time of the earthquake.

The NCGS is also compiling information on earthquakes in the southeastern United States as part of hazard mitigation grant agreement HMGP-DR-1448-001.

Debris Flow Study Sites

Charley Branch Debris Flows

Figure 3A shows the location of the three debris flow tracks (labeled CB1, 4 and 5) that occurred in the Glory Mountain development around Charley Branch (CB). The tracks show the paths and distances the debris traveled down slope. The longest of the debris flow tracks is CB1 (approx. 1460 feet), followed by CB4 (approx. 1200 feet) and CB5 (approx. 960 feet). Sediment from all three debris flows was transported into Charley Branch by runoff during and after the debris flow event. Figures 4 and 5 show photographs of the various features observed around the debris flow sites during field visits in late June 2004.

At the Charley Branch location the remaining fill slopes at the apparent debris flow initiation sites were usually at a 40-50 degree slope. The original ground slope at these sites probably ranged from about 35 to 45 degrees based on measurements of adjacent natural slopes. In all cases the fills were constructed with material derived primarily from sulfidic, graphitic schist of the Wehutty Formation. Both bedding and the primary foliation in bedrock consistently dip approximately 25-35 degrees toward the southeast at this location, creating a situation where the planes of weakness in the bedrock are tilted in the down slope direction. This bedrock configuration can also have a destabilizing affect on slopes as well.

Debris flow CB1 probably caused the most damage of the three Charley Branch debris flows. It appears to have initiated in colluvium and fill used to construct a house site that was derived from sulfidic, graphitic schist and excavated nearby (figs. 4E and 4F). According to the homeowner, trees and other vegetation had been cut off the slope to improve the view from the front of the house. Removing the trees and vegetation probably contributed to the instability of the slope. The head scarp continues to erode toward the house, which is founded primarily on bedrock. Down slope the debris flow damaged another road in the development, filled in a pond, and destroyed spring boxes formerly used in the community water supply system. The homeowner reports a strong iron taste to well water at the site, which is another indicator of sulfidic rock.

Debris flow CB4 appears to have initiated in fill used to construct a house pad, although the lot is still vacant. Figure 4B shows a log exposed in the head scarp that apparently was originally incorporated within the fill material. Over time decaying woody debris in fill material can also have a destabilizing effect. Tension cracks and minor scarps were observed in other areas of the house pad fill at this location. This debris flow damaged two roads down slope and moved an old log cabin some 20 feet (?) from its original location. At the location just above Turkey Run Road, mud lines in trees indicate the top of debris flow was about 20 feet above the channel base.

Debris flow CB5 appears to have originated in material used to construct a road fill (fig. 5C). At a location about 175 feet down slope from the head scarp the debris flow followed a bend in the channel (fig. 5A-C). Mud lines preserved in the trees on either side of the channel in the bend allows the banking, or superelevation, angle of the debris flow to be determined (fig. 5 A, D). This evidence, along with the channel gradient and radius of curvature allows the velocity and discharge of the debris flow to be estimated at this point (Johnson and Rodine, 1984). Here, the velocity of the debris flow was about 25 miles per hour (~37 feet per second), with a discharge of almost 30,000 cubic feet per second. The height of the debris flow measured from the channel bottom was about 15 to 17 feet. Owing to the relatively high velocity of the debris flow, the discharge of 30,000 cubic feet per second is over three times greater than that measured for the Little Tennessee River at the Needmore gaging station on May 7, 2003 (fig. 2A).

Tension cracks (horizontal ground displacement) and scarps (vertical ground displacement) in road and house pad fills observed at locations CB2 and CB3 indicate the potential for future debris flows in the Charley Branch area (fig. 6). These tension cracks and scarps allow precipitation and runoff to infiltrate quickly into an already unstable slope that can then mobilize into a rapidly moving debris flow. Of particular concern is the water line located outboard of the tension crack at CB3. Settlement and displacement of the fill can break the water line allowing water to infiltrate into the fill and trigger a debris flow. Should debris flows originate from the house pads southeast of CB3 they may severely damage the existing house down slope.

Lands Creek Debris Flows

In the Lands Creek watershed, two debris flows, one on December 23, 1990 (LC1), and another during the May 5-7, 2003 timeframe (LC2) appear to have originated from an old logging road constructed through sulfidic, graphitic schist of the Wehutty Formation (fig. 3B). Both debris flows originated near the ridge top that marks the boundary with the Great Smoky National Park, and traveled down slope along tributaries to Lands Creek.

LC1 destroyed a mobile home and the chlorinator building for the Bryson City water system, as well as downing power lines and damaging roads (figs. 7E and 7F). The track length for LC1 is about 2,400 feet, and it deposited about 10,000 cubic yards of silt, sand and rock fragments in the lower third of the track. Estimates of the debris flow velocity and discharge made at two locations along the track yielded values of 23 miles per hour and about 18,400 cubic feet per second; and, 10 miles per hour and 13,800 cubic feet per second respectively. Older deposits observed along the LC1 track and near Lands Creek indicated prior debris flow and flooding activity in this tributary to Lands Creek.

The track length for LC2 is about 3,400 feet. LC2 deposited silt, sand, rock fragments, and woody debris along the track and also into the Bryson City reservoir (fig. 7A and 7B). Logs from the debris flow accumulated near the intake for the dam. The reservoir was drained during the May-June, 2004 timeframe, and its use as a reservoir discontinued. Because of its limited water supply capacity, Bryson City officials had already decided to discontinue use of the reservoir prior to the May 2003 debris flow.

So Hi Trail Debris Flow

The So Hi Trail (road) debris flow appears to have originated in a road fill that included sulfidic, graphitic, mica schist from the Nantahala formation (fig. 8). The debris flow may have triggered a cut slope failure as the track crossed a lower segment of So Hi Trail (fig. 8E). The entire track length is about 625 feet, and mud lines and debris were observed up to 5 feet above the channel base. No damage other than to the road was reported for the So Hi debris flow.

Alarka Creek Debris Flows

Three debris flow tracks were observed in the Timber Estates development above Alarka Creek. These slope movements originated on slopes underlain by sulfidic, mica schist, metasiltstone, and metagraywacke of the Copper Hill Formation. The largest of the Alarka debris flows appears to have initiated in a road fill on Midnight Lane (fig. 9) and has a track length over 600 feet. The debris flow moved a 60 cubic foot boulder (fig. 9E), and the top of the flow was at least 7 feet above the channel bottom in places. Two smaller debris flows occurred along Timber Estates Drive and moved down slope about 100 feet onto the floodplain of Alarka Creek. Head scarp areas of the Alarka Creek debris flows have been reseeded, and for the most part revegetated.

Public Safety

Debris flows, as well as other types of landslides, pose both primary and secondary threats to public health and safety. Primary threats include injury and death. The high velocities and high discharge rates of rapidly moving debris flows make them inherently dangerous. Not only can fast moving debris flows bury people, they can damage and destroy homes, bridges, and vehicles in their paths. For example, the victim of the fatal December 11, 2003 debris flow in Maggie Valley was trapped and buried in her home by fast moving debris (Wooten and Carter, 2003). Secondary threats to public health and safety come mainly from damage to roads and infrastructure caused by debris flows. Damage to roads and bridges can delay or prevent access by emergency vehicles. Damage to water supply facilities can temporarily cut off, or contaminate water supplies. In addition to the threat to public health and safety, the costs of property and infrastructure repairs are expense both for private citizens and communities.

Existing and Potential Environmental Impacts

Slope Stability

Other investigators have documented slope instability associated with sulfidic rocks elsewhere in the Southern Appalachians. Clark and Ryan (1987) reported an increasing severity of [debris] slides and flows in pyrite-rich rocks of the Anakeesta Formation in the Great Smoky National Park. The weathering of sulfidic rocks can decrease the stability of slopes in several ways (Bryant and others, 2003). Sulfuric acid produced by the breakdown of the iron-sulfide minerals pyrite and pyrrhotite reduces the shear strength of rock and soil. The acid accelerates the rate of rock weathering, and over time the rock fragments in a fill will behave mechanically more like soil, and less like rock. The acid also attacks the clay mineral structure in soil and decreases the cohesion, thereby reducing the shear strength of the soil component of the fill. Sulfidic materials are also susceptible to heaving due to mineral expansion as sulfide minerals oxidize when exposed to moisture. Heaving can increase the porosity and decrease the relative density of the material allowing for more infiltration and the destabilizing build-up of pore-water pressure. Graphite also reduces the shear strength of rock and soil materials.

The May 5-7, 2003 rain was a significant flooding and debris flow event; however, the region has experienced much higher rainfalls associated with hurricanes and tropical storms in the past. In 1916 and 1940 some of the hurricanes that tracked over the western North Carolina mountains dumped as much as 15-20 inches of rain in a 24-hour period (fig. 10) causing extensive flooding, landsliding, and loss of life. Should storms of this magnitude track over the mountains in the future, the impacts on developments on steep hillsides, and property down slope, will likely be severe. Tension cracks and scarps observed in fill slopes at the Charley Branch sites CB2 and CB3 suggest that these and similar sites elsewhere may develop into debris flows as a consequence of future heavy rainfalls.

Sedimentation

Debris flows lead to an increased sediment load in streams in two ways; one by depositing large volumes of remobilized sediment in pre-existing stream channels, and two, by stripping vegetation from stream banks. For the Charley Branch, Lands Creek, and Alarka debris flows, the volume of transported sediment was on the order of thousands of cubic yards for each debris flow. The silt and clay fraction of the initial runoff and dewatering of debris flows can be transported downstream some distance from the main deposits. Remnants of the main deposits in channels are easily eroded as the streams move sediment to reestablish their courses. The force of the debris flows usually strips much of the vegetation from the stream banks along the track making them more susceptible to further erosion.

Acid Drainage

The potential for acid drainage from the sulfidic rock types found in North Carolina, including Swain County, has long been recognized (see, for example, Schaeffer and Clawson, 1996). There are indicators at the Charley Branch and So Hi Trail sites that there may be acid drainage associated with areas of disturbed sulfidic rock. Iron bacteria can oxidize the iron released from the sulfide minerals and actually elevate the levels of acid production (Byerly, 1996). The bright orange growth observed in leachate from debris at the CB5 locality at Charley Branch indicates the presence of these bacteria (fig. 4D). Acid drainage can also accelerate the corrosion rate of metal culverts (Bryant and others, 2003). The heavy iron oxide coating and corrosion observed in a galvanized culvert at the So Hi Trail site (fig. 8C) indicates the presence of acid drainage.

The degree of any water quality degradation from acid drainage depends strongly on the pH of the drainage and no pH measurements of surface water were made during this study. Both Byerly (1996) and Schaeffer and Clawson (1996) report on successful methods to neutralize acid runoff using limestone and lime in road embankments constructed with acid-producing sulfidic rock.

Locations of Sulfidic Rock Units

Typically, sulfidic rock types are dark colored, graphitic mica schists, phyllites and metasiltstones; however concentrated sulfide minerals can also occur in lighter colored mica schists, metasandstones, and metagraywackes. Discrete, sulfide-rich stratigraphic horizons can also occur within formations generally characterized by the presence of sulfidic rock types (e.g., the Nantahala, Wehutty, Anakeesta, and Copper Hill Formations; and, the Horse Branch Member of the Ammons Formation) (see, for example, Mohr, 1975). In other words, although sulfidic rocks are common in these formations, not all rock types within them are sulfidic.

The 1985 geologic map of North Carolina (NCGS, 1985) also shows the general locations of rock types that are known to contain sulfide minerals. The 1985 map can be found at the web address:
http://gis.enr.state.nc.us/sid/bin/index.plx?client=zGeologic_Maps&site=9AM.

The geologic map of southwestern North Carolina and adjoining parts of Tennessee and Georgia (Wiener and Merschat, 1992) shows the location of formations likely to contain abundant sulfide minerals. An excerpt from this map is shown in figure 1. The entire map can be found at the web address:
http://gis.enr.state.nc.us/sid/bin/index.plx?client=zOtherGeology&site=9AM.

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Glossary of Selected Geological Terms

colluvium – Any loose, heterogeneous, and unconsolidated mass of soil and rock particles deposited by rainwash, sheetwash, or slow, continuous down slope creep. Colluvium usually contains angular to subrounded rock particles and usually collects at the base of gentle slopes or hillsides.

feldspar – A group of abundant rock-forming minerals of the general formula $MAl(Al,Si)_3O_8$, where M = K, Na, Ca, Ba, Rb, Sr, or Fe. Feldspars are the most widespread of any mineral group and occur in all kinds and types of rocks.

garnet – A group of minerals of the formula $A_3B_2(SiO_4)_3$, where A = Ca, Mg, Fe, Mn, and B = Al, Fe, Mn, V, and Cr. Garnet occurs in igneous rocks, but is most common in metamorphic rocks.

graphite – A naturally occurring crystalline form of carbon (*adj* **graphitic**).

metaconglomerate – A metamorphosed sedimentary rock (conglomerate) originally composed of mainly sand- and gravel-sized grains, with the gravel having a diameter greater than 4.0 mm.

metagraywacke – A field term for a metamorphosed, dark, clayey, impure sandstone. A metagraywacke consists mainly of sand-sized feldspar and quartz, and lesser amounts of the mica minerals muscovite, and biotite.

metasandstone – A metamorphosed sedimentary rock (sandstone) originally composed of mainly sand-sized grains of quartz and feldspar (having a diameter between 0.06 mm an 4.0 mm).

metasiltstone – A metamorphosed sedimentary rock (siltstone) originally composed of mainly silt-sized mineral grains (having a diameter between 0.004 mm and 0.06 mm). Silt-sized grains are smaller than sand, but larger than clay. The metamorphic minerals biotite and muscovite (micas), abundant in metasiltstone, recrystallized from the clay component of the original sedimentary rock.

mica – A flaky, scaly, or platy group of minerals with the general formula: $(Mg,Fe,Li,Al)_{2-3}(Al,Si)_4O_{10}(OH,F)_2$. Micas are common rock-forming constituents of igneous, metamorphic, and sedimentary rocks. Biotite is a black colored mica, and muscovite is a white or silver colored mica.

phyllite – A metamorphic rock, intermediate in grade between slate and mica schist, usually formed by the metamorphism of a fine grained sedimentary rock like shale. The mica grains in phyllite are smaller than the mica grains in schist.

pyrite – A common pale brass yellow to bronze-colored, iron sulfide mineral (fool's gold) with the formula: FeS_2. (adj. **pyritic**).

pyrrhotite – A common, red-brown to bronze-colored, iron sulfide mineral with the formula: FeS. It is darker-colored and softer than pyrite, and forms at higher metamorphic grades.

quartz – An important rock-forming mineral with the formula SiO_2. It is, next to feldspar, the most common mineral found in most rocks in the Earth's crust.

schist – A strongly and finely foliated metamorphic rock that can be readily split into thin flakes or slabs (e.g., **mica schist** is a strongly foliated rock dominated by the mica minerals biotite and muscovite). In this study the schists formed mainly by the metamorphism of fine-grained sedimentary rocks like shale.

sulfidic – A term used to describe rocks that contain the iron sulfide minerals pyrite and pyrrhotite.

Feature Name	County	7.5-Minute Quadrangle	Latitude (DMS)	Longitude (DMS)	Latitude (DD)	Longitude (DD)
Charley Branch 1	Swain	Wesser	35^{o}20’22.02”	-83^{o}32’54.85”	35.33945^{o}	-83.54857^{o}
Charley Branch 2	Swain	Wesser	35^{o}20’32.47”	-83^{o}33’06.80”	35.34236^{o}	-83.55189^{o}
Charley Branch 3	Swain	Wesser	35^{o}20’31.35”	-83^{o}33’03.81”	35.34204^{o}	-83.55106^{o}
Charley Branch 4	Swain	Wesser	35^{o}20’26.13”	-83^{o}33’19.34”	35.34059^{o}	-83.55537^{o}
Charley Branch 5	Swain	Wesser	35^{o}20’17.90”	-83^{o}33’24.53”	35.33531^{o}	-83.55681^{o}
Lands Creek 1	Swain	Bryson City	35^{o}27’55.80”	-83^{o}28’27.12”	35.46550^{o}	-83.47420^{o}
Lands Creek 2	Swain	Bryson City	35^{o}28’12.36”	-83^{o}28’35.64”	35.47010^{o}	-83.47657^{o}
Midnight Trail	Swain	Alarka	35^{o}21’14.73”	-83^{o}25’57.50”	35.35409^{o}	-83.43264^{o}
Alarka Creek	Swain	Alarka	35^{o}21’35.49”	-83^{o}25’58.87”	35.35708^{o}	-83.43302^{o}
Timber Estates	Swain	Alarka	35^{o}21’24.70”	-83^{o}25’25.47”	35.35686^{o}	-83.42374^{o}
So Hi Trail	Swain	Noland Creek	35^{o}23’08.99”	-83^{o}34’58.32”	35.38583^{o}	-83.58287^{o}

Table 1. Coordinates in degrees, minutes, seconds (DMS) and decimal degrees (DD) for all debris flows and potential debris flow initiation zones discussed in report.

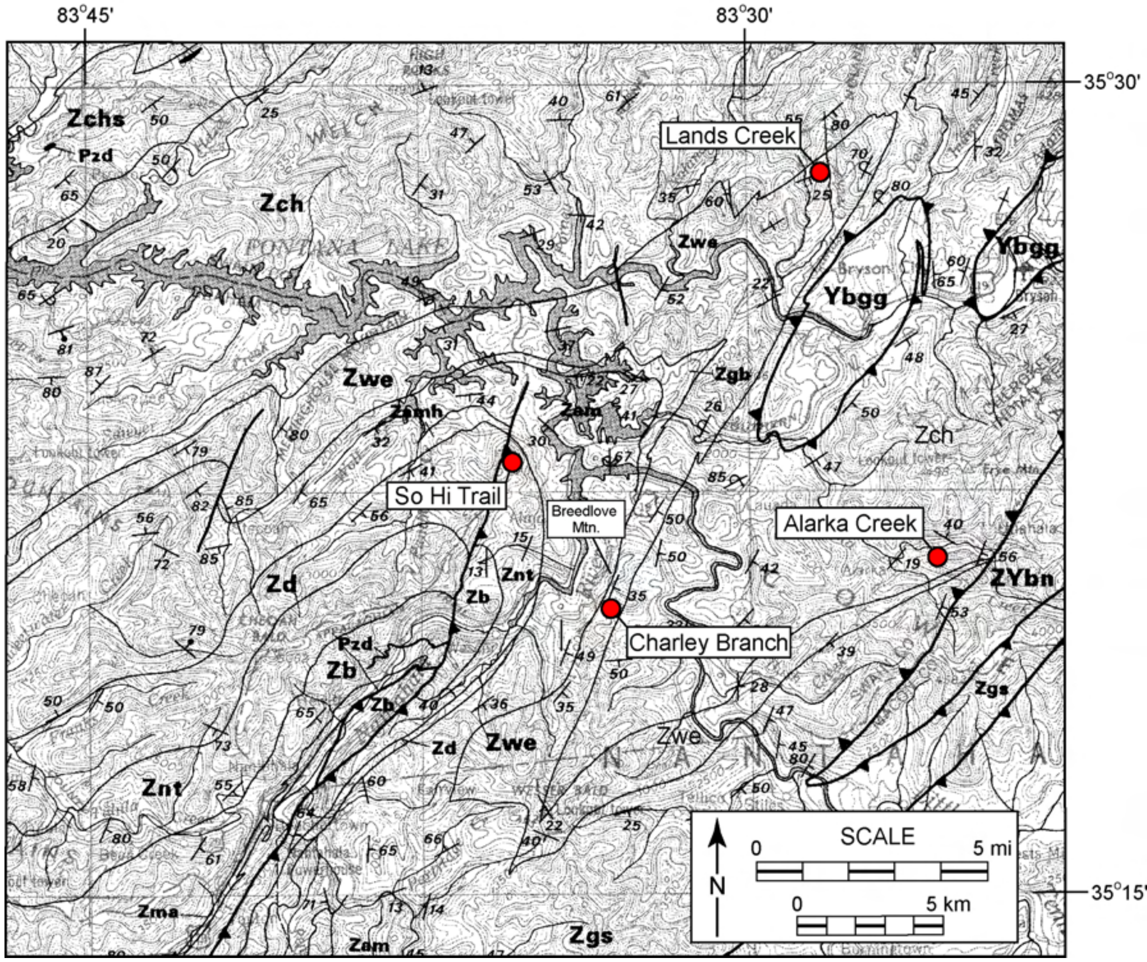
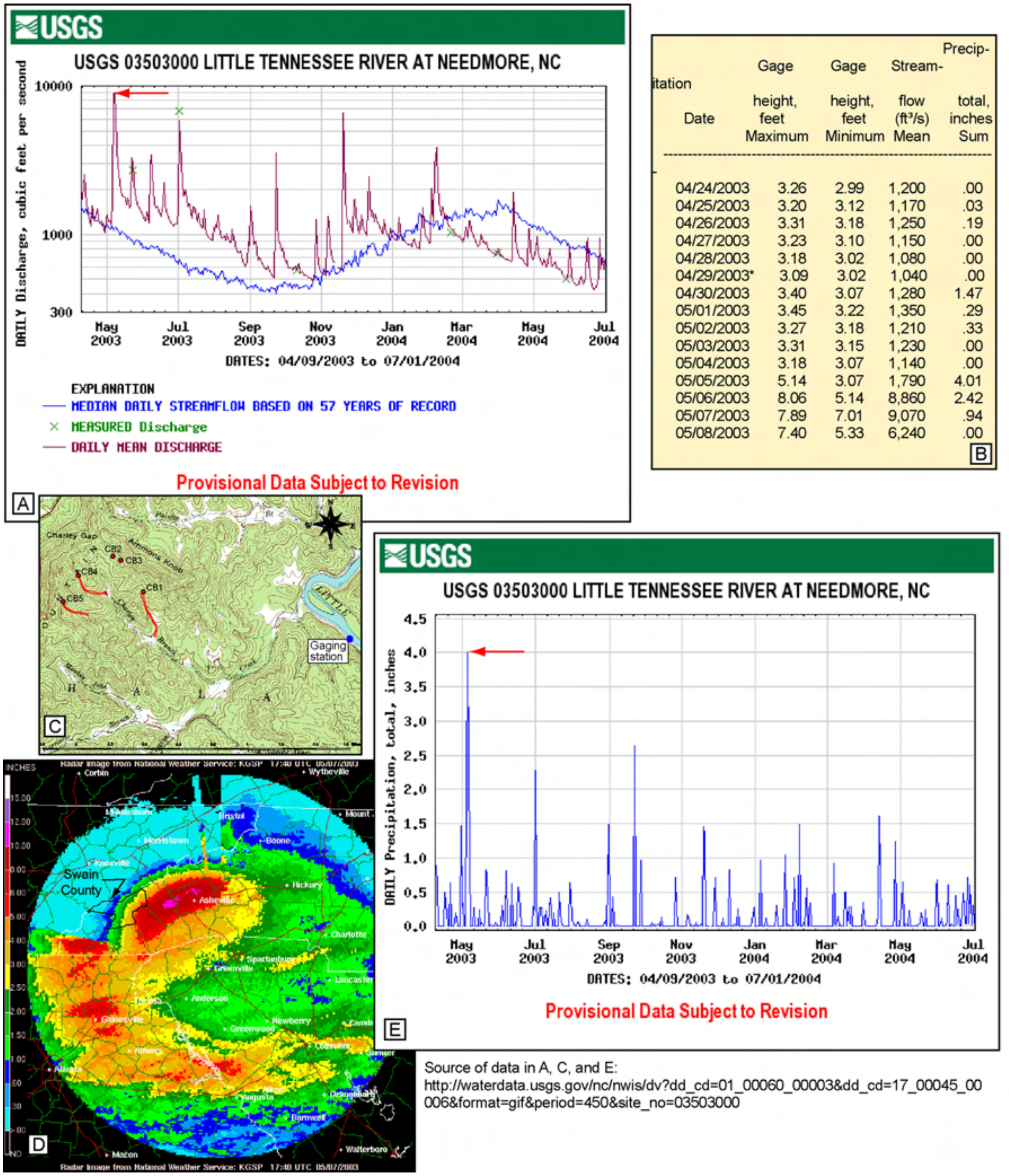


Figure 1. Location of debris flow study sites. Locations of the debris flow study sites are shown on a geologic map excerpted from Wiener and Merschat (1992). Most sites studied have multiple debris flows: Alarka Creek - 3 debris flows; Charley Branch - 3 debris flows; Lands Creek - 2 debris flows; and So Hi Trail - 1 debris flow. Geologic formations shown on the map relevant to this study that characteristically contain sulfidic, graphitic schist and pyllite bedrock units are the Wehutty (Zwe) and the Nantahala (Znt) Formations. Localized sulfidic, graphitic schist units also occur in the Copperhill Formation (Zch). The Horse Branch Member of the Hot House Formation (Zamh) characteristically contains dark-gray graphitic and sulfidic mica schist and metasiltstone.



Date	Gage height, feet Maximum	Gage height, feet Minimum	Streamflow (ft^3/s) Mean	Precipitation total, inches Sum
04/24/2003	3.26	2.99	1,200	.00
04/25/2003	3.20	3.12	1,170	.03
04/26/2003	3.31	3.18	1,250	.19
04/27/2003	3.23	3.10	1,150	.00
04/28/2003	3.18	3.02	1,080	.00
04/29/2003*	3.09	3.02	1,040	.00
04/30/2003	3.40	3.07	1,280	1.47
05/01/2003	3.45	3.22	1,350	.29
05/02/2003	3.27	3.18	1,210	.33
05/03/2003	3.31	3.15	1,230	.00
05/04/2003	3.18	3.07	1,140	.00
05/05/2003	5.14	3.07	1,790	4.01
05/06/2003	8.06	5.14	8,860	2.42
05/07/2003	7.89	7.01	9,070	.94
05/08/2003	7.40	5.33	6,240	.00

Source of data in A, C, and E:
http://waterdata.usgs.gov/nc/nwis/dv?dd_cd=01_00060_00003&dd_cd=17_00045_00006&format=gif&period=450&site_no=03503000

Figure 2. Precipitation and stream discharge associated with the May 5-7, 2003 flooding. A. Stream hydrograph data for the Little Tennessee River at Needmore, NC for late April 2003 through early July 2004. Note that the highest discharge occurred during the May 2003 event (indicated by arrow). B. Summary table of data. Total rainfall recorded for the May 5-7 event was 7.37 inches. C. Location of the USGS gage at Needmore with respect to the Charley Branch area. Gaging station is indicated by blue dot. D. May 7, 2003 radar image showing precipitation estimates for the regionally extensive May storm event. This image indicates that Swain County received anywhere from approximately 0.30-inches of rain in western portions of the county, and up to approximately 6 inches along the eastern county line. E. Plot of precipitation at the Little Tennessee River at Needmore, NC. Again, note spike (indicated by arrow) in precipitation amount during early May 2003.

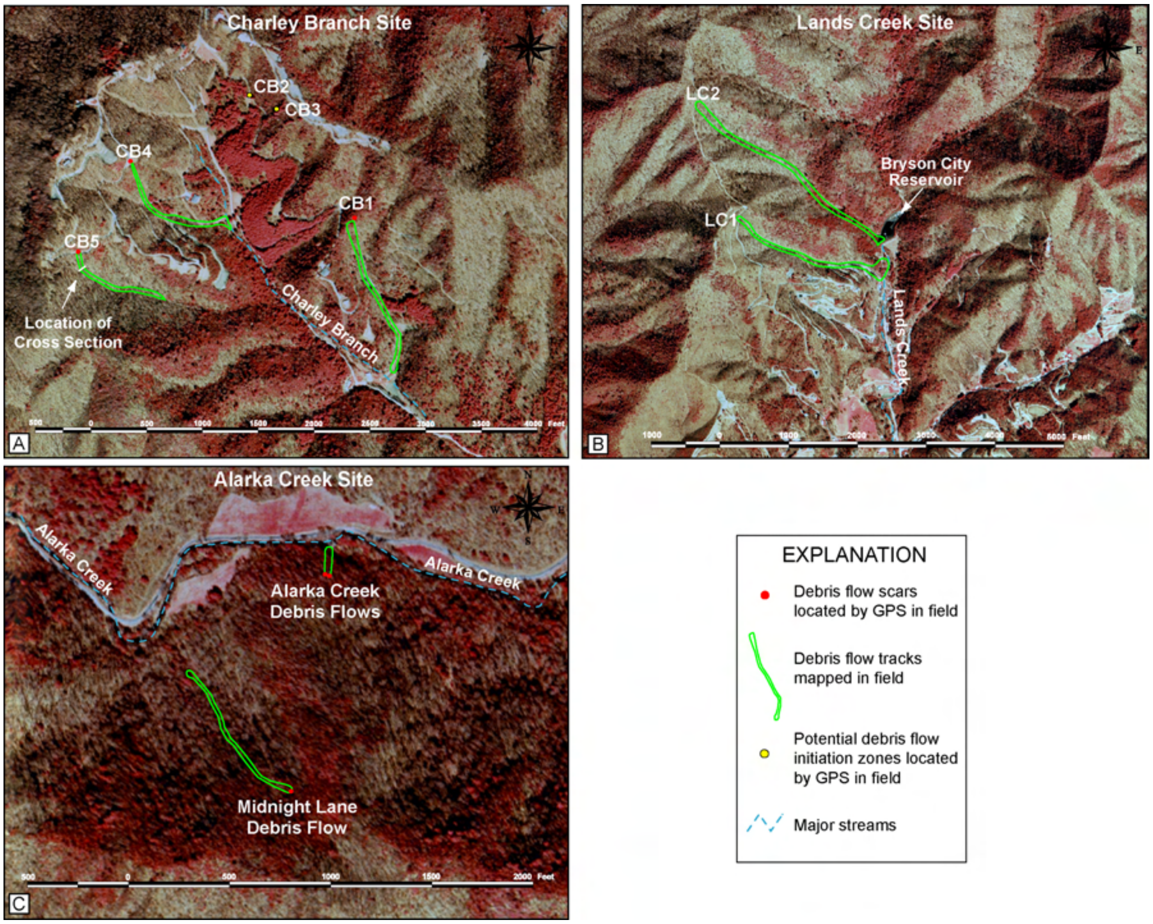


Figure 3. Color infrared aerial photographs of the Charley Branch, Lands Creek, and Alarka Creek areas excerpted from the 1998 digital ortho-quarter quads (DOQQs). A. Color infrared photograph of the Charley Branch area. All debris flows at this location occurred during the May 5-7, 2003 storm event. B. Color infrared photograph of the Lands Creek area. The Bryson City Reservoir is in the middle of the photograph. The Lands Creek I debris flow (LC1) occurred December 12, 1990, and the Lands Creek II debris flow (LC2) occurred during the May 5-7, 2003 storm event. C. Color infrared photograph of the Alarka Creek area. All debris flows at this location occurred during the May 5-7, 2003 storm event. The aerial photograph was taken prior to construction of Midnight Lane and Timber Estates Drive.

Figure 4. Photographs of debris flows CB1, CB4, and CB5 in the Charley Branch area. A. View looking upslope at apparent source area for CB4 from just above Rhododendron Road. Turkey Run Road crosses the channel just above the pile of debris in the left central portion of the photograph. Arrow points to apparent initiation point. B. Photograph of the left flank of CB4 near the source area. Note mudline on tree approximately 2 feet above the scarp and the log sticking out of the debris. C. Middle portion of debris flow channel at CB4 just upslope of Turkey Run Road. Mudline on tree (shown by arrow) indicates material was moving through the channel approximately 20 feet above the base of the channel. D. Terminus of the main debris flow deposit downslope from CB5. Debris dam is approximately 4-5 feet high. Note orange colored iron oxide in the stream channel. This color is probably the result of iron oxidizing bacteria and may indicate acidic runoff from sulfidic rock in the debris. E. Rock outcrop just upslope of the apparent initiation point of debris flow at CB1. Gray rock towards the base of the outcrop is graphitic schist. Red-brown to orange staining on upper portion of outcrop indicates the sulfidic nature of the rock. F. Right flank of headscarp located at CB1. Fill material added to slope is micaceous, low plasticity silt with gravel and cobbles of schist. G. View from the source area of the debris flow at CB1. Material in the foreground is displaced fill material. Debris flow crossed the road in multiple locations before destroying the pump house for the neighborhood water system and filling in a pond.

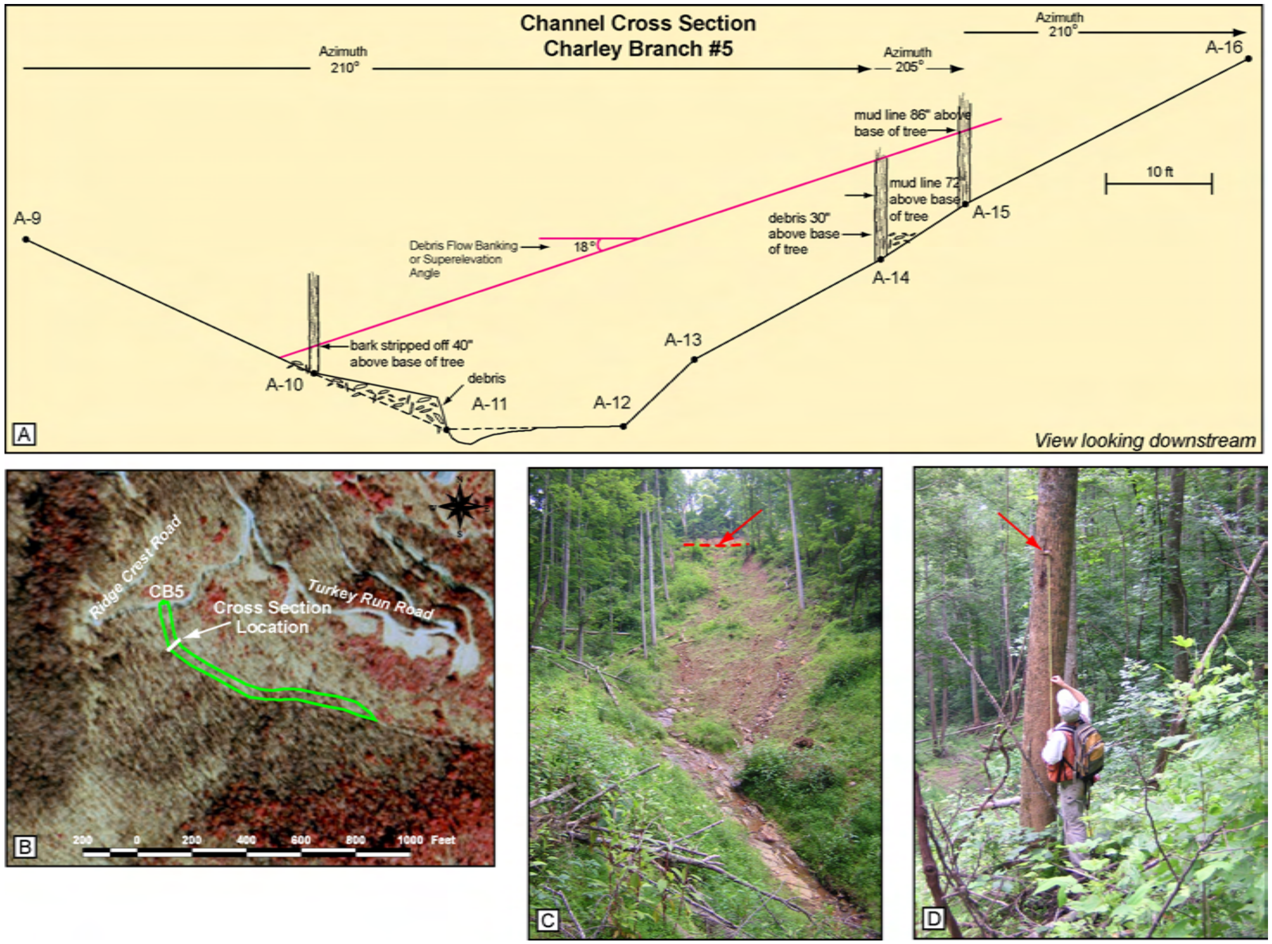


Figure 5. Cross section and photographs of debris flow CB5 in the Charley Branch area. A. Cross section through a bend in the debris flow channel located at CB5. The velocity of material in the channel was approximated using the superelevation angle of material around the bend, channel gradient, and radius of curvature. The velocity for the May debris flow was approximately 25 miles per hour (37 feet per second) with a discharge of almost 30,000 cubic feet per second of material. B. Map showing the location of the cross section within the debris flow channel at CB5. C. View looking up the debris flow track to the apparent initiation area (indicated by arrow) from the cross section location. D. Tree at station A-15 on the cross section. Note mud up the tree as well as piece of wood wedged into the side of the tree, approximately 7 feet above the ground surface indicating high flow at this location.

Figure 6. Photographs of scarps and tensions cracks in slopes at Charley Branch sites CB2 and CB3. A. Scarp developing along the embankment of the building pad at CB2. B. Tension crack that has developed along the road to the lower building pad at CB3. This crack is approximately 18 inches deep, 6 -7 inches wide, and 60 feet long (up to the water line). C. View looking at the water line to be connected to houses. The water line falls in line with the tension crack(s) developed along the road embankment. Note leaning trees on slope below.

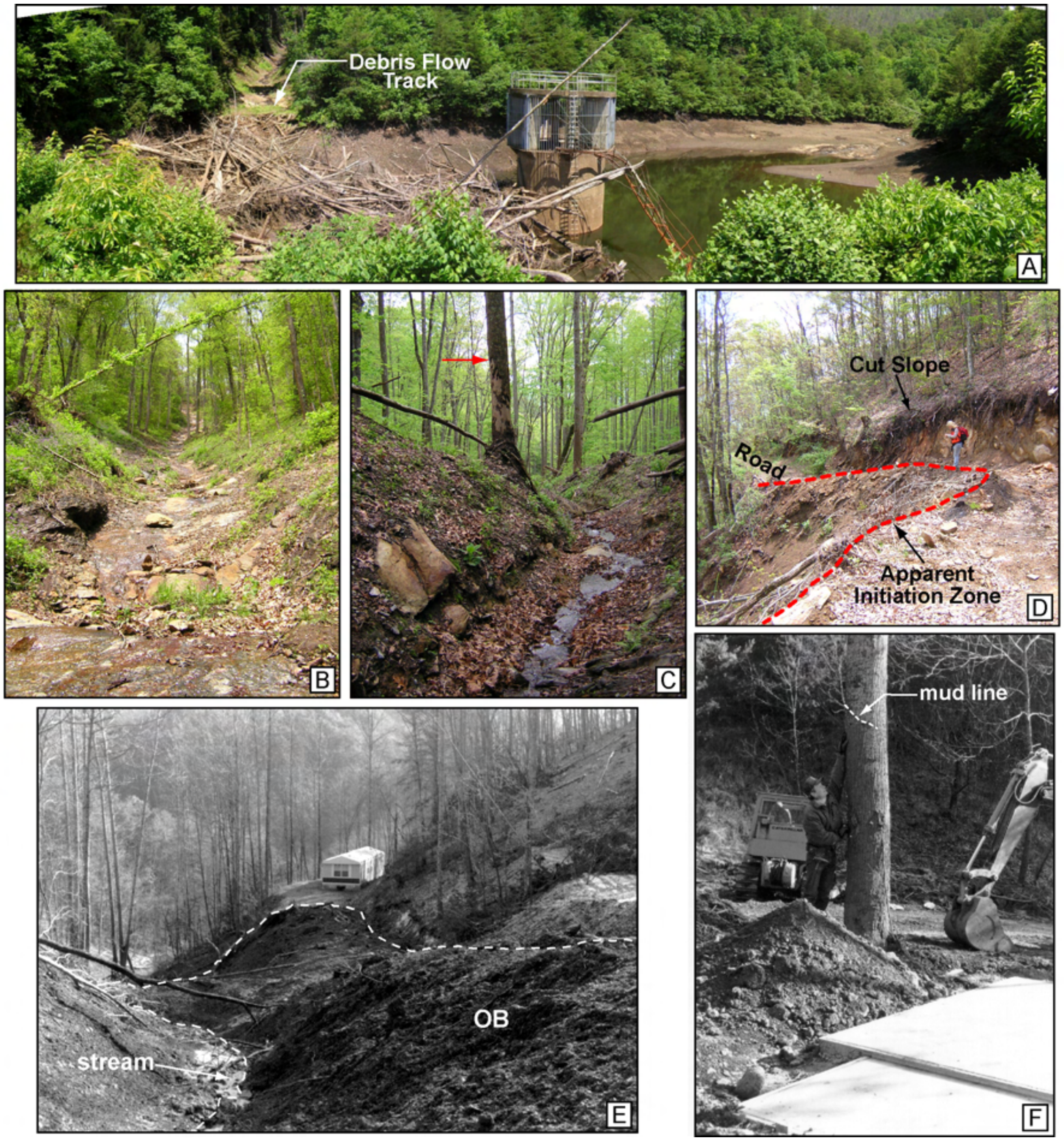


Figure 7. Photographs of the Lands Cree I (LC1) and Lands Creek II (LC2) debris flows. A. June 17, 2003 photograph of the Lands Creek II (LC2) debris flow track taken from the dam. Material from the debris flow was deposited into the now drained Bryson City Reservoir. B. Photograph of the upper part of the LC2 debris flow channel toward the apparent initiation zone. C. Bark removed from tree in the mid-section of the LC2 debris flow track. Height is approximately 15 feet above the base of the channel. D. Photograph of the initiation zone for the LC2 debris flow. Failure appears to be in the road embankment. E. Photograph of part of the December 23, 1991 debris flow deposit taken on January 23, 1991. Here the 1990 debris flow overbank deposit (OB) overlies an older (pre-1952) overbank deposit along the outside bend of the stream channel. The 1990 deposit blocks the access road to a mobile home, and downed utility lines. F. January 23, 1991 photograph of the lower depositional area of the Lands Creek I debris flow. The dashed line shows the height of the mud line on a tree near the destroyed chlorinator buildings for the Bryson City municipal water system. Most of the December 23, 1990 deposit had already been removed. Foundation slabs for the new chlorinator buildings are visible in the foreground. Here the December 23, 1990 debris flow deposit overlies older (pre-1952) debris fan deposits of previous flood and debris flow events originating in this tributary to Lands Creek.

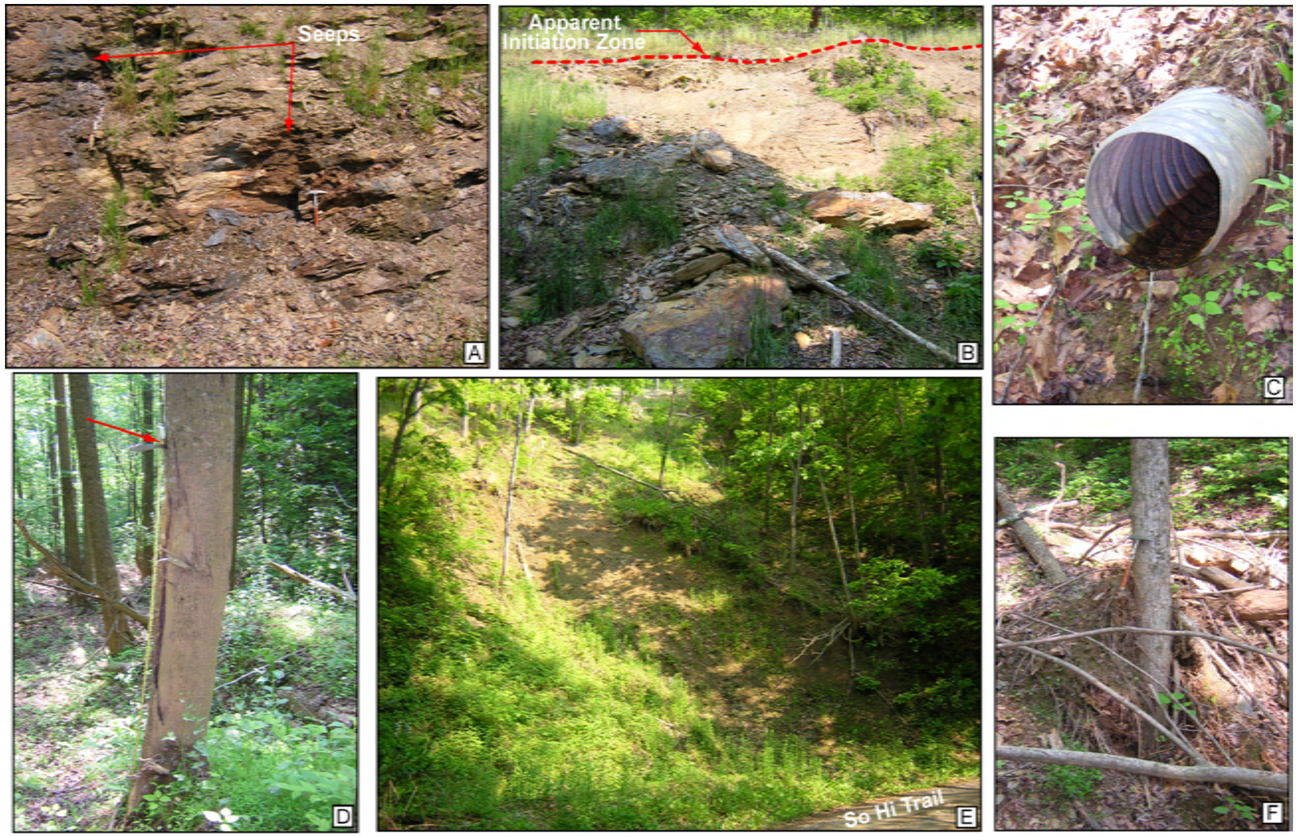


Figure 8. Photographs of the So Hi Trail debris flow and acid drainage. A. Photograph of road cut on upper leg of So Hi Trail. Outcrop is stained state to partially decomposed sulfidic graphitic schist located upslope of the embankment failure where the debris flow apparently started. Bedrock seeps were observed at this location (indicated by arrow). B. Photograph of the apparent head scarp where the debris flow started. Material here is embankment fill composed of moderately plastic silt with pieces of schist present. Large boulders present on the slope were most likely placed there when excavation was done for road construction. C. Corroded culvert just downslope of lower leg of So Hi trail. Although the culvert looks relatively new, considerable staining has occurred where water consistently flows. This staining is most likely due to runoff from the sulfidic rock upslope. D. Mudline on a tree approximately 35 feet below lower leg of So Hi Trail. Height of mudline is 5 feet. E. Debris flow (cut slope failure) scar between lower leg of So Hi Trail and an abandoned dirt wheel track. Water was observed seeping from material. F. Photograph of tree in lower third of the debris flow track (below lower leg of So Hi Trail) with debris stacked against it. Note hammer for scale.

Figure 9. Photographs of the Midnight Lane debris flow in the Alarka Creek area. A. Photograph taken of the highly fractured sulfidic, garnet, biotite, muscovite schist and metagraywacke present in the stream channel. Here, closely spaced fractures have created planes of weakness in the material forming a low spot in the outcrop. Groundwater seepage along the bedrock low may have had a destabilizing effect on the fill. Location of outcrop can be seen in Photograph B. B. Photograph from the outcrop location toward the apparent source area and head scarp. The segment of Midnight Lane at the apparent initiation zone was destroyed in the debris flow and has since been reconstructed. C. Photograph of a portion of the debris flow deposit approximately two thirds of the way downslope. Location can be seen in Photograph D. D. Photograph taken from Starry Lane, the terminus of the debris flow, looking upslope at the apparent source area. Note the debris that has collected on the upslope side of most of the trees. E. Large boulder (~60 cubic feet) lodged against a tree in the debris flow deposit. Bark has been removed from tree approximately 7 feet above the ground surface. Tree location can be seen in Photograph D.

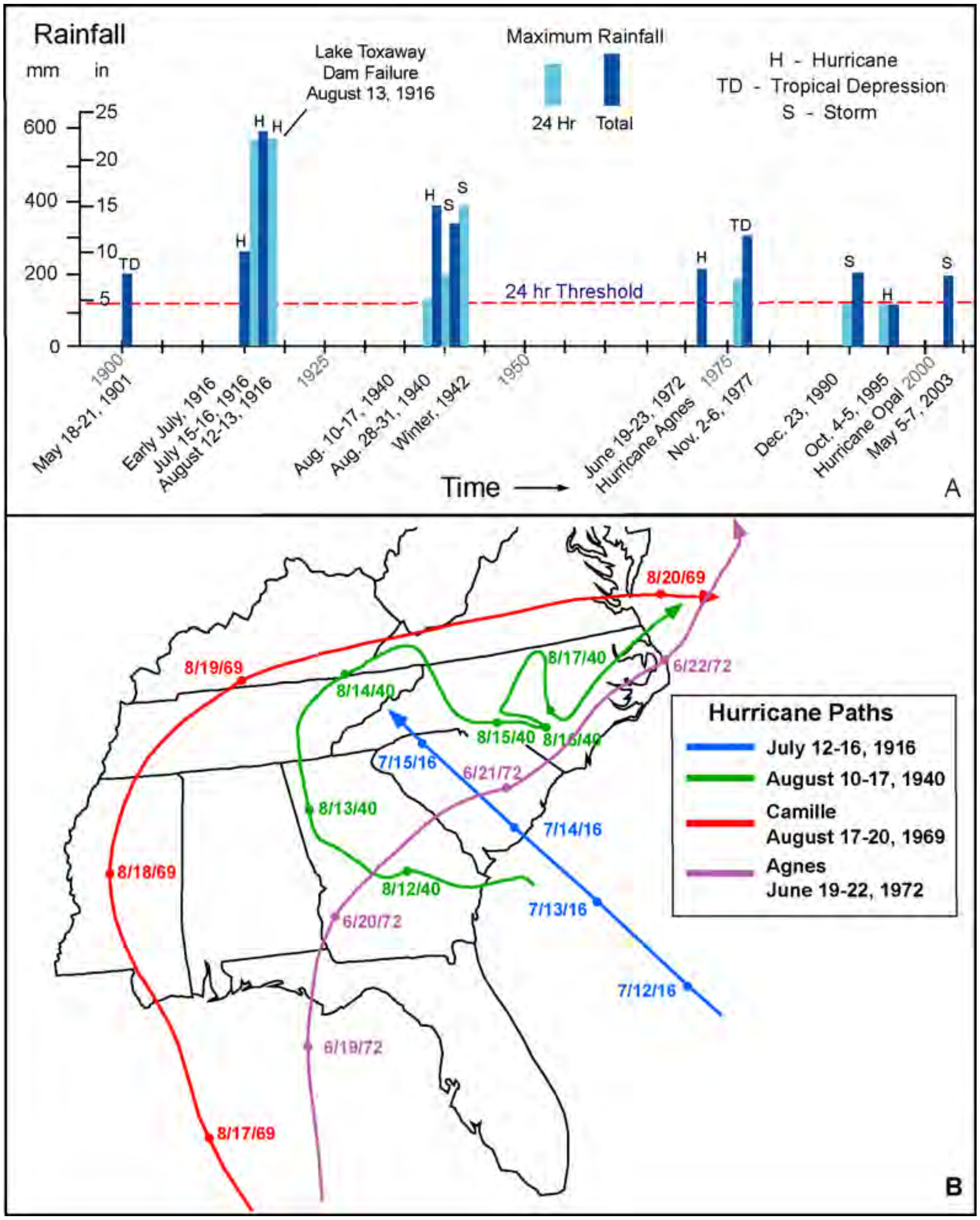


Figure 10. A. Chart showing rainfall amounts that triggered debris flow events in western North Carolina. The hurricanes and storms of July-August, 1916, and August 1940 set off hundreds of debris flows. The Lake Toxaway dam, in Transylvania County, failed after two and possibly three hurricanes tracked over the Southern Appalachians within six weeks in July-August, 1916. The rainfall total of 7.4 inches for the May 5-7, 2003 event is the value recorded at the U.S.G.S. gaging station at Needmore on the Little Tennessee River (fig. 2). Rainfall totals associated with this storm may have exceeded 7.4 inches elsewhere in western N.C. The 24-hour threshold line shows the minimum 24-hour rainfall needed to trigger widespread debris flows in the Southern Appalachians as estimated by Eschner and Patric (1982). B. Paths of 20th century hurricanes that caused widespread flooding and major debris flow events in the Southern Appalachians. Major debris flow events occurred in western North Carolina in 1916 and 1940 with loss of life and widespread damage. Heavy rains along with the slow rate of movement of the mid-August 1940 hurricane set off hundreds of debris flows. In 1972, Hurricane Agnes initiated debris flows and debris slides in western North Carolina although the path was to the east. Hurricane Camille triggered hundreds of debris flows in the Blue Ridge Mountains of Virginia causing extensive damage and loss of life in 1969. Map adapted from Scott (1972) and Bailey and others (1975).