2007 Southeastern Friends of the Pleistocene Field Trip Guidebook

Investigation of the Peeks Creek Debris Flow of September 2004 and Its Relationship to Landslide Hazard Mapping in Macon County, North Carolina

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Abstract

On September 16, 2004 the remnants of Hurricane Ivan dumped heavy rain on Macon County, North Carolina, triggering a debris slide near the top of Fishhawk Mountain (figure 1) at an elevation of 4,420 ft around 10:10 PM. This slide quickly mobilized into a debris flow that traveled approximately 2.25 miles and dropped 2,000 ft colliding with the Peeks Creek community and ultimately the Cullasaja River. Along its path, calculated estimates yield a maximum velocity of 33.2 miles per hour (mph) and a conservative discharge estimate of 45,000 cubic feet per second (cfs). The resulting debris flow destroyed fifteen homes in the downstream community adjacent to Peeks Creek and killed five people.

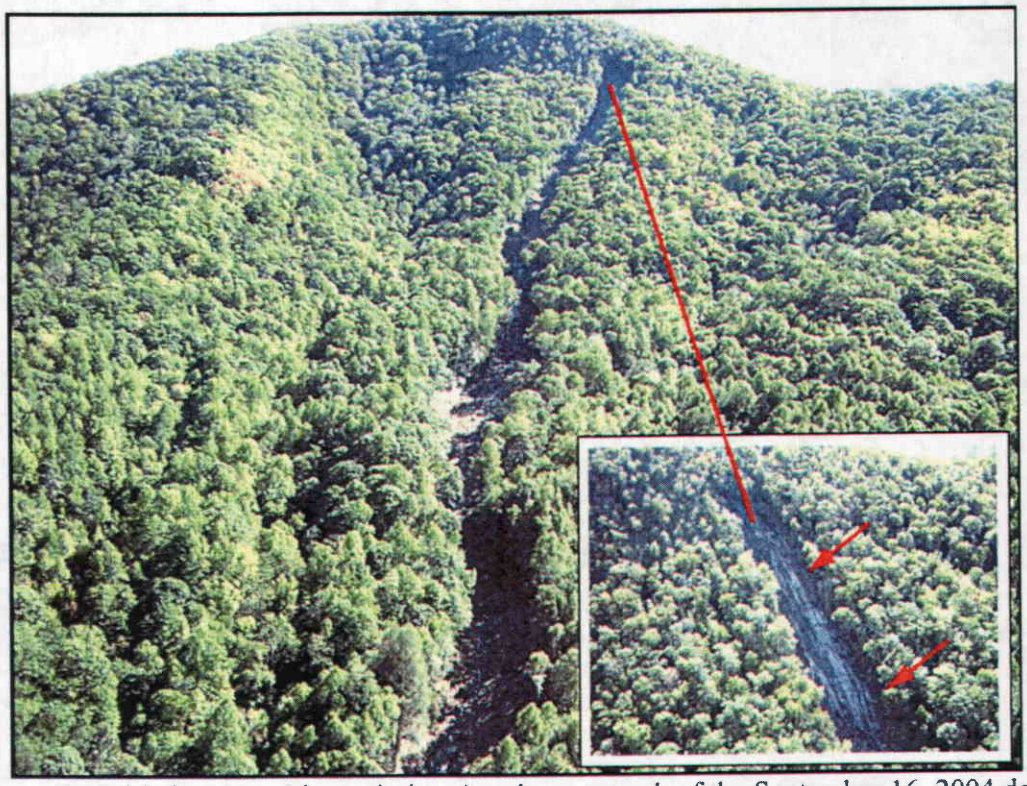


Figure 1: Initiation zone (shown in inset) and upper track of the September 16, 2004 debris flow on Fishhawk Mountain.

Western North Carolina has a history of landslides triggered by large storm events. Since 1901, there have been at least 14 recorded, landslide-producing storm or hurricane

occurrences and several of these have affected Macon County, including the Fishhawk Mountain area." T.L Clingman (1877) reported that in 1876 debris flows originated on both the northern and southern sides of Fishhawk Mountain." In the track of the recent debris flow, exposed colluvial and debris deposits indicate that prehistoric, and possibly historic, slope movements may have occurred in this same area. Hurricane Opal triggered a debris flow in the Poplar Cove area of Macon County in 1995. More recently, Hurricanes Frances and Ivan triggered numerous slope movements in Macon County in September 2004.

The stage was set in September 2004 for a slope failure of this magnitude by the back-to-back rainfalls produced by Frances and Ivan. Remnants of Frances produced rainfall totals up to 381 mm (15 inches) in portions of western North Carolina. Just eight days later, remnants of Ivan dropped up to 280 mm (11 inches) of rainfall across the same parts of the region. The soil saturation conditions in the thin (<3 m or 9.8 ft), colluvial soil sitting on top of the steeply dipping bedrock surface (35° - 55°) near the crest of Fishhawk Mountain finally exceeded their shear strength and failed initiating the debris flow. Subparallel striations on the bedrock surface in the initiation zone indicate that the failure began as a debris slide that quickly mobilized into a debris flow.

The North Carolina Geological Survey (NCGS) is investigating the causes and effects of the Peeks Creek debris flow (Latham, Wooten, and Reid, 2005). Along with this study, countywide, landslide hazards maps have been produced with funding allocated through the Hurricane Recovery Act of 2005. This map series includes maps that show where landslides have happened in the past, where shallow, translational failure are likely to initiate in the future, and downslope locations that could be affected by these failures.

Introduction

The Peeks Creek community in Macon County, North Carolina is situated in a mountain hollow along the banks of Peeks Creek near its confluence with the Cullasaja River (figure 2). A northwest to southeast trending chain of mountains ranging in elevation from 3,800 feet to 4,746 feet at the top of Fishhawk Mountain is on the southwest side of the community.

Over 30 inches of rain from the remnants of Hurricanes Frances and Ivan fell on the western portion of North Carolina in September 2004 triggering over 140 slope movements (figure 3). The Peeks Creek debris flow was triggered as the remnants of Hurricane Ivan passed over the area around 10:10 p.m. on September 16, 2004.

In the aftermath of the disaster, there were immediate concerns about the stability of other slopes in the Peeks Creek drainage basin. Since then, the NCGS has been involved in a multi-agency task force to determine the causes of the failure, address safety concerns for residents, make advisements on damage mitigation, and determine the potential for similar events to occur in Macon County. In addition, the NCGS was asked to provide on-site technical assistance as part of a cooperative multi-year, geohazards project that included creating a slope movement database for the entire state of North Carolina (figure 4). As a result of these storms, the NCGS was also charged to develop countywide landslide hazards maps for 19 western North Carolina counties.

Towards these efforts, the NCGS has gathered a variety of data including historical slope movements in Macon County (figure 5), soil and rock data, precipitation data, and general characteristics of the debris flow/debris flow track. Studies have also been completed to assess landslide susceptibility in Macon County using Stability Index Mapping (SINMAP), a Geographic Information System (GIS)-based slope stability model (Pack, Tarboton, and Goodwin, 1998) as well as to map potential areas below initiation zones that could be impacted by a debris flow/slide.

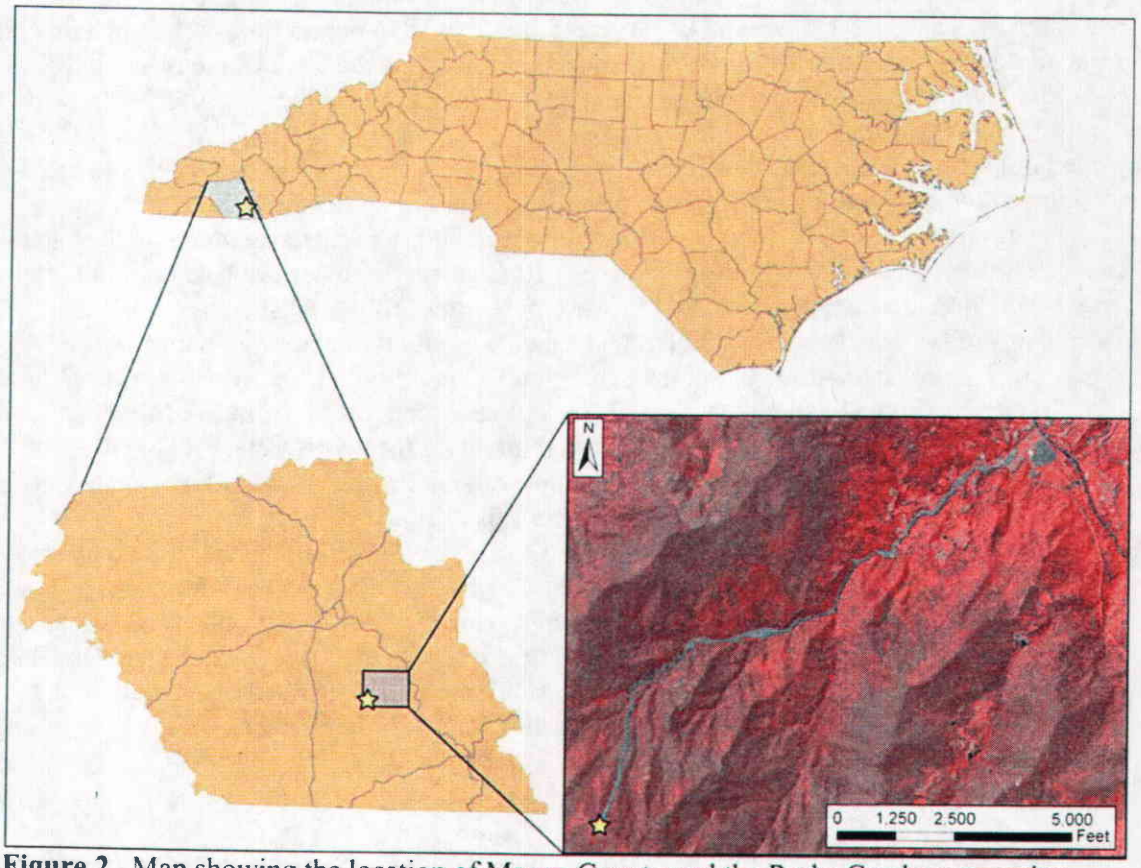


Figure 2. Map showing the location of Macon County and the Peeks Creek community. Yellow star indicates the initiation zone of the debris flow. Track is visible (linear, gray feature) on 2005 color-infrared digital ortho-quarter quadrangle shown at bottom right.

Historical Debris Flows

There are at least 14 recorded, landslide-producing hurricanes or storms that have affected western North Carolina since 1901 (Scott, 1972; Neary and Swift, 1987; Clark, 1987; Pomeroy, 1991). To date, 177 slope movements and 643 slope movement deposits have been identified in Macon County. Figure 5 shows the locations and dates of some of these slope movements.

Clingman (1877) reported several "waterspouts" descending upon Fishhawk Mountain on June 15, 1876. The one described in detail traveled down the southwest side of the mountain and, in description, resembles the September 2004 debris flow at Peeks Creek. He also tells of one on the northeast side of Fishhawk Mountain in the same watershed as the September 2004 debris flow. Any evidence of such a feature, however, is obscured by thick vegetation.

Residents of the Nickajack community just north of Peeks Creek reported having ancestors who described debris flow(s) in the area approximately 125 years ago. This would nearly correspond in time with those described by Clingman. Clark (1987) also noted a slope movement in the Burningtown area in northern Macon County. This event, described as a "waterspout," occurred on July 30, 1928.

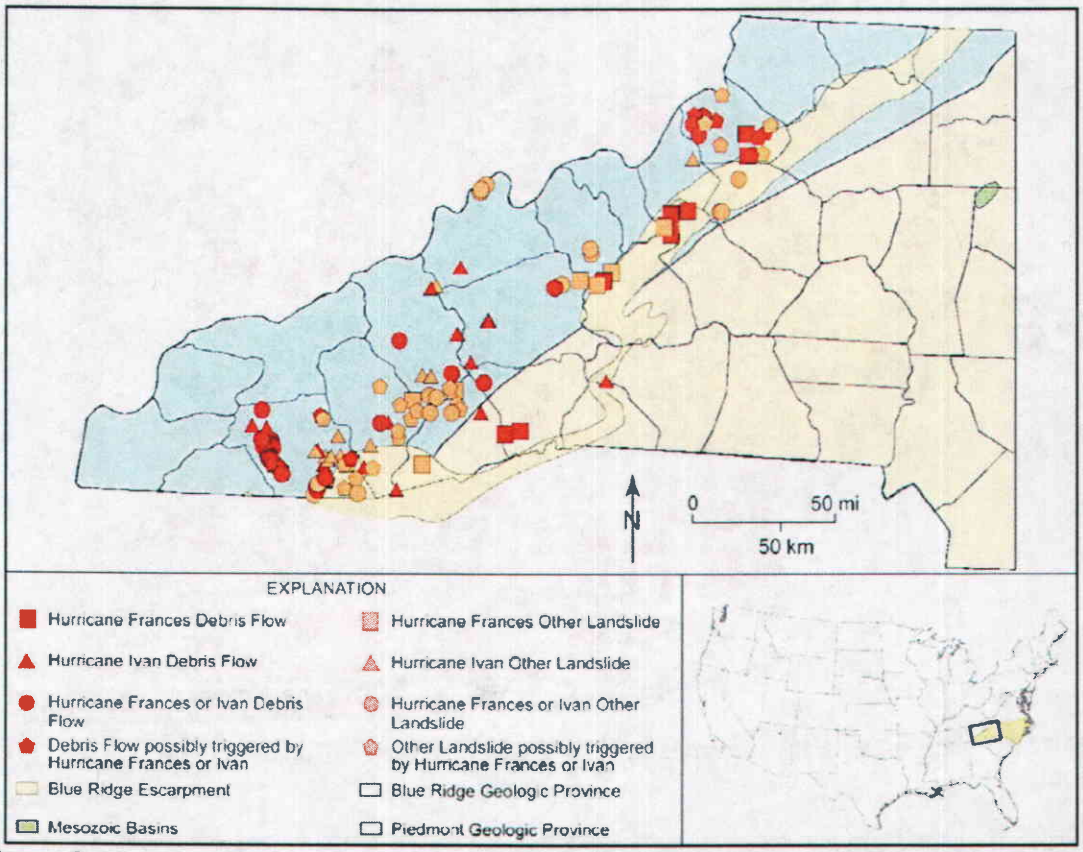


Figure 3. Map showing locations of slope movements triggered by rainfall from Hurricanes Frances and Ivan in the region. Major geologic provinces and the Blue Ridge Escarpment are shown for reference.

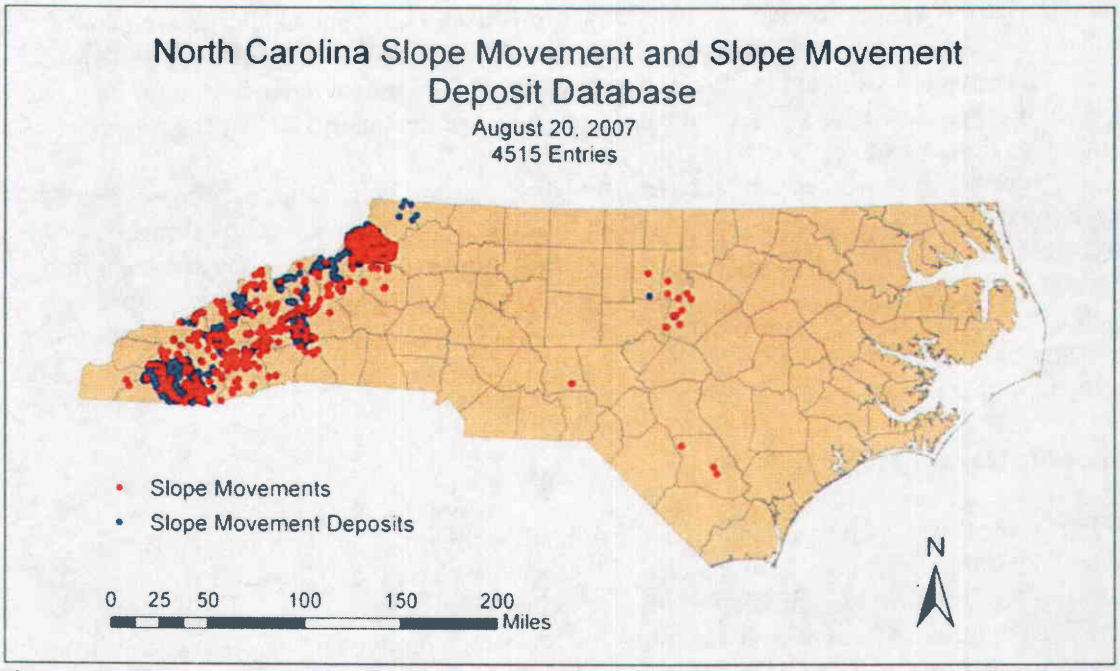


Figure 4. Slope movement – slope movement deposit database created by the NCGS (available online at http://www.cgia.cgia.state.nc.us/nconemap/).

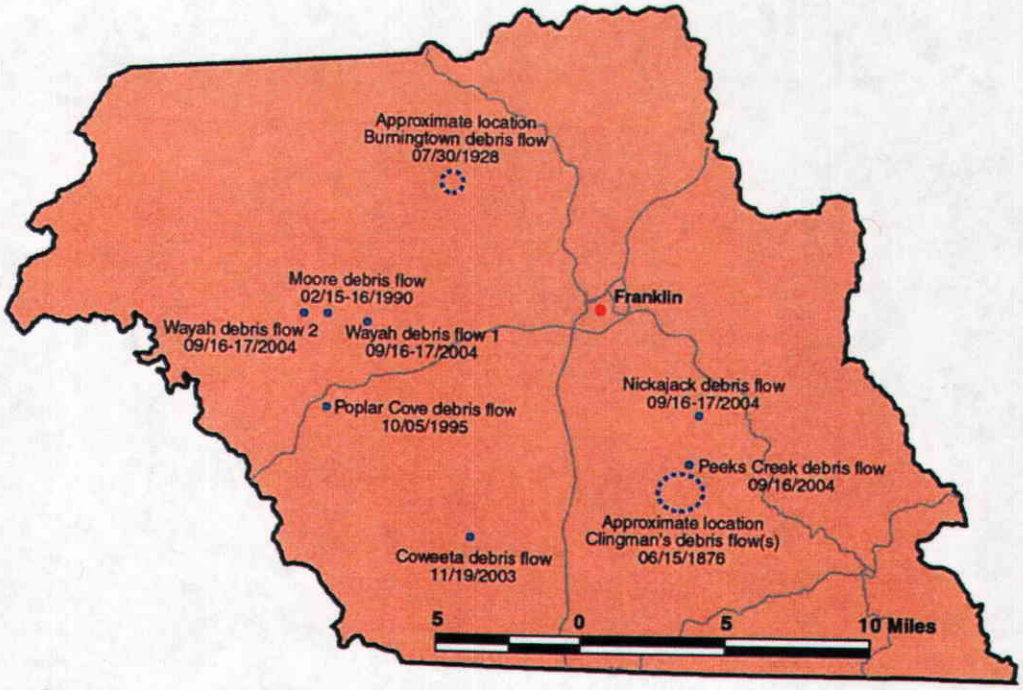


Figure 5. Map showing the locations of selected, known historic slope movements in Macon County.

On February 16, 1990, heavy rains compounded by high antecedent moisture conditions triggered a debris flow above Wayah Road in Macon County (Moore debris flow). This 1,500-foot-long slope movement damaged an unoccupied home, deposited debris on Wayah Road, and threatened to deposit sediment into Wayah Creek, a water source for the town of Franklin (USDA Forest Service, 1990). Heavy rains from Hurricane Opal triggered the Poplar Cove debris flow on October 5, 1995. This slope movement damaged multiple forest roads and deposited sediment in at least two creeks that feed into a water source for the town of Franklin (Wilkins, 1995). This same drainage was reactivated in 2004 by the remnants of Hurricanes Frances and/or Ivan.

Two debris flows triggered by the remnants of Hurricane Ivan occurred above Wayah Creek (near the town of Franklin) less than a mile apart. Both of these debris flows originated on unmodified slopes, blocked the road with debris, and deposited sediment into Wayah Creek. Wayah debris flow 1 (figure 6) destroyed a barn at the toe of the slope. A small debris flow/blowout occurred in the Nickajack community near the reported location of the historical slope movement described above. This blowout sent minor amounts of sediment onto a private road and produced minimal damage.

Landslide Hazard Mapping Program

In response to the damage caused by the remnants of Hurricanes Frances and Ivan in September 2004, The North Carolina General Assembly passed the Hurricane Recovery Act of 2005. This bill provided funding for the NCGS to begin the production of landslide hazard maps for the 19 counties listed in the bill. Macon County was selected as the pilot county for the project. The final deliverable for the county consists of three maps: Slope Movements and Slope Movement Deposits Map (where landslides have happened in the past), the Stability Index Map (where debris flows/slides are more likely to initiate in the

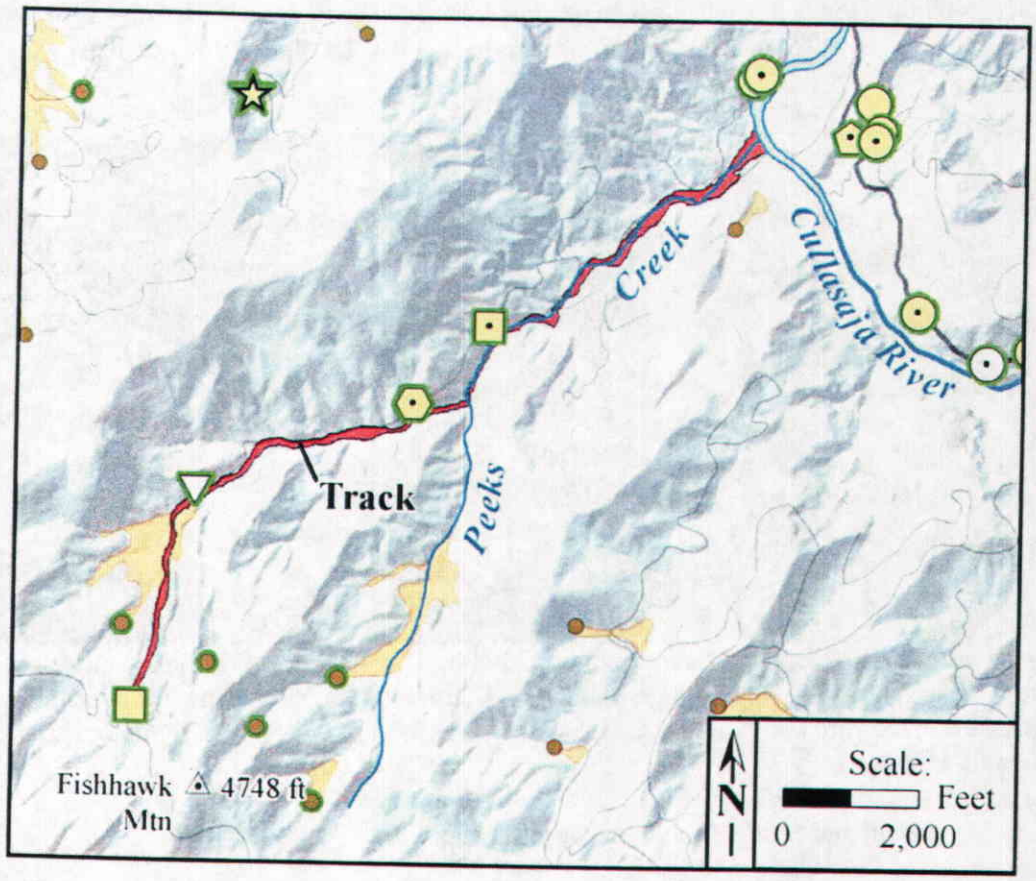
future), and the Downslope Hazards Map (where future debris flows/slides may go). See Wooten *et al* (2006) for complete maps and more specific details on how the maps were produced.

Figure 6. Wayah 1 debris flow triggered in 2004 by Hurricane Ivan (Photos courtesy of U.S. Forest Service-Coweeta Hydrologic Laboratory). Photo at left shows the initiation zone and upper portions of the track. Photo at right shows the debris flow deposit that blocked the road and destroyed a barn.

Slope Movement and Slope Movement Deposit Map

The Slope Movements and Slope Movement Deposits Map shows the locations of past slope movements (landslides). Figure 7 shows the portion of this map in the area of the Peeks Creek failure. Multiple vintages of aerial and orthrophotography in conjunction with 6-meter pixel resolution LiDAR digital elevation model (DEM) were used to identify potential failure locations. Once identified, staff members field checked the slope movements using handheld global positioning systems (GPS). The failures were classified according to Cruden and Varnes (1996), and detailed information was collected at each failure including location data, soil and/or rock properties, ground and surface water conditions and geomorphic setting. In Macon County, 56% of the slope movements initiated on modified slopes while 40% occurred on natural slopes.

Slope movement deposits, prehistoric and modern accumulations of debris deposited by numerous mass wasting episodes, are also identified and located on the map. These are important because they indicate past areas of landslide activity as well as areas potentially affected by future failures. With few exceptions in Macon County the mapped deposits are below a modern landslide, or below an area modeled as a high hazard zone as discussed in the following paragraph. Slope movement deposits cover three percent of the county. For more details on the mapping process and information collected, see sheet 1 of Wooten *et al.* (2006).



Slope movement initiation zones

- Debris slide-translational
- Debris or earth flow
- Debris or earth slide-general
- Debris or earth slide-rotational
- Earth blowout
- Rock fall and creep
- Rock slide-general

- Primary / secondary road

Slope movement deposits

- Slope movement deposit apex
- Slope movement deposit

Modifiers

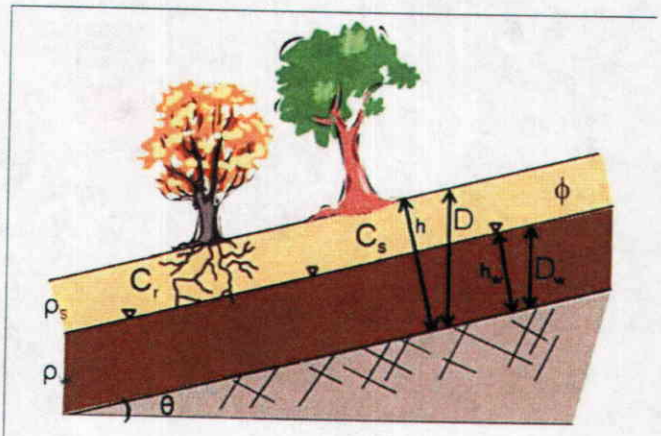
- Dot indicates slope movement initiated on modified ground
- Green halo indicates slope movement or deposit was field verified by NCGS

Figure 7. Excerpt of slope movements and slope movement deposits map of Macon County, North Carolina (sheet 1, Wooten, *et al.*, 2006) showing the area near the September 16, 2004, Peeks Creek debris flow (track shown in pink). Map base is a LiDAR hillshade DEM.

Stability Index Map

SINMAP (Pack, Tarboton, and Goodwin, 1998) is a GIS based slope stability index mapping program used to predict the potential for shallow, translational failures to occur given an established rainfall event. It uses the infinite slope model (figure 8) with wetness (pore pressures) obtained from a topographically based steady state hydrology model.

Digital elevation models (DEMs) are used to define slope and catchment areas. During a SINMAP run, the input model parameters such as cohesion, soil density, angle of internal friction, transmissivity and recharge vary using uniform probability distributions with upper and lower bounds.



$$FS = \frac{C_r + C_s + \cos^2\theta[\rho_s g(D-D_w) + (\rho_s g - \rho_w g)D_w]\tan\phi}{D\rho_s g \sin\theta\cos\theta}$$

Figure 8. Infinite slope equation used in SINMAP to determine the factor of safety.

In particular, model parameters can be calibrated to a specific area, or geographic region, based upon soil, vegetation and/or geologic data. Parameter adjustments can also be made to match those determined from observed landslides. The calibration also involves adjusting parameters so that the stability map "captures" a high proportion of observed landslides in regions with low stability index, while minimizing predicted instability in landforms where landslides have not been observed.

The output of the model is a color-coded map based on the six stability classes ranging from stable to unstable (figure 9). The model also generates statistics that accompany the stability class rankings based on calculated factors of safety. The NCGS combined some of the categories into a relative hazard ranking for debris flows/slides.Using this classfication, 11% of the county falls into the high category.For more details on parameter selection and model calibration see Witt et al. (2007) and sheet 2 of Wooten et al.(2006).

Downslope Hazard Map

The downslope hazard map shows locations potentially in the path of a debris slide/flow that initiates in one of the SINMAP high hazard zones (figure 10). ArcGIS™ was used to generate flow paths originating from the SINMAP high hazard zones. These flow paths were extended downslope until they reached a three-degree slope, the angle at which most observed debris flows tend to terminate, with a width of 65 feet, the average width of observed tracks. The flow paths were augmented with information collected about actual, observed track widths and lengths, and where known, this information was used rather than the computer generated flow path.

Mapped slope movement deposits outside of the previously described flow paths were labeled as moderate downslope hazard zones. These features were created by past mass wasting episodes, so the potential for a future event to affect these areas cannot be ruled out. However, the highest hazard on the deposits is at the apex and in the topographically lower, incised portions of the fan which have been labeled high hazard. The features can also be

problematic because they typically consist of deep, unconsolidated accumulations of clay to boulder size material that can be unstable in high, steep excavations.

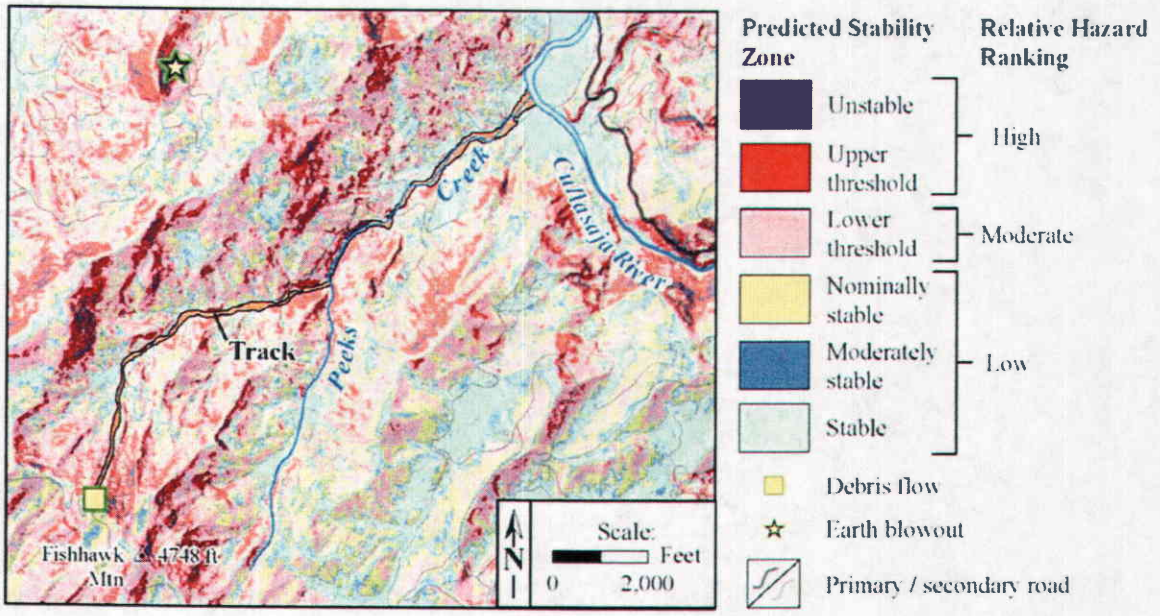


Figure 9. Excerpt of the stability index map of Macon County (sheet 2, Wooten, *et al.*, 2006) showing the relative stability zones in the vicinity of the Peeks Creek debris flow (track in orange). Map base is a hillshade LiDAR DEM.

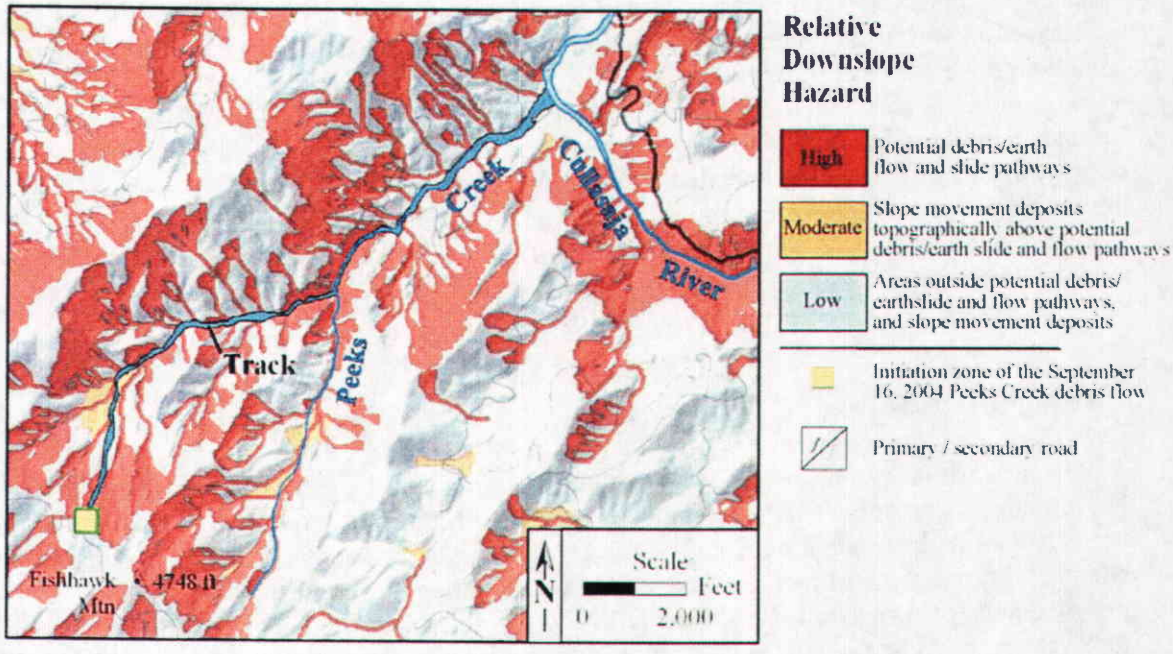


Figure 10. Excerpt of the downslope hazard map of Macon County, North Carolina for shallow translational slope movements (sheet 3, Wooten, *et al.*, 2006) showing the area in the vicinity of the September 16, 2004, Peeks Creek debris flow (track in blue). Map base is a hillshade LiDAR DEM.

Geology of the Slide and Debris Flow Area

The Peeks Creek debris flow initiated in the Middle to Late Proterozoic metagraywacke and minor biotite-muscovite schist of the Otto Formation (figure 11) (Lamb, 2001). Two tonalite-trondhjemite dikes (figure 12) cross cut the metagraywacke in the source area of the debris flow. An exfoliation fracture oriented 283-322°/35-56° NE defines the plane of failure in the headscarp. The debris flow then traveled through the biotite-muscovite schist dominated portion of the Otto Formation as well as the biotite gneiss and metagraywacke of the Tallulah Falls Formation. Multiple pegmatites are exposed along the track as well as amphibolites and minor metaconglomerates. Rock outcrops in the debris flow channel are freshly exposed (visually fresh state as defined by the Unified Rock Classification System (Williamson, 1984)). Foliation strikes northeast to southwest and dips 80-90° southeast to 40-90° northwest. Mesoscopic folds and ptygmatic veins are exposed along the whole length of the debris flow track.

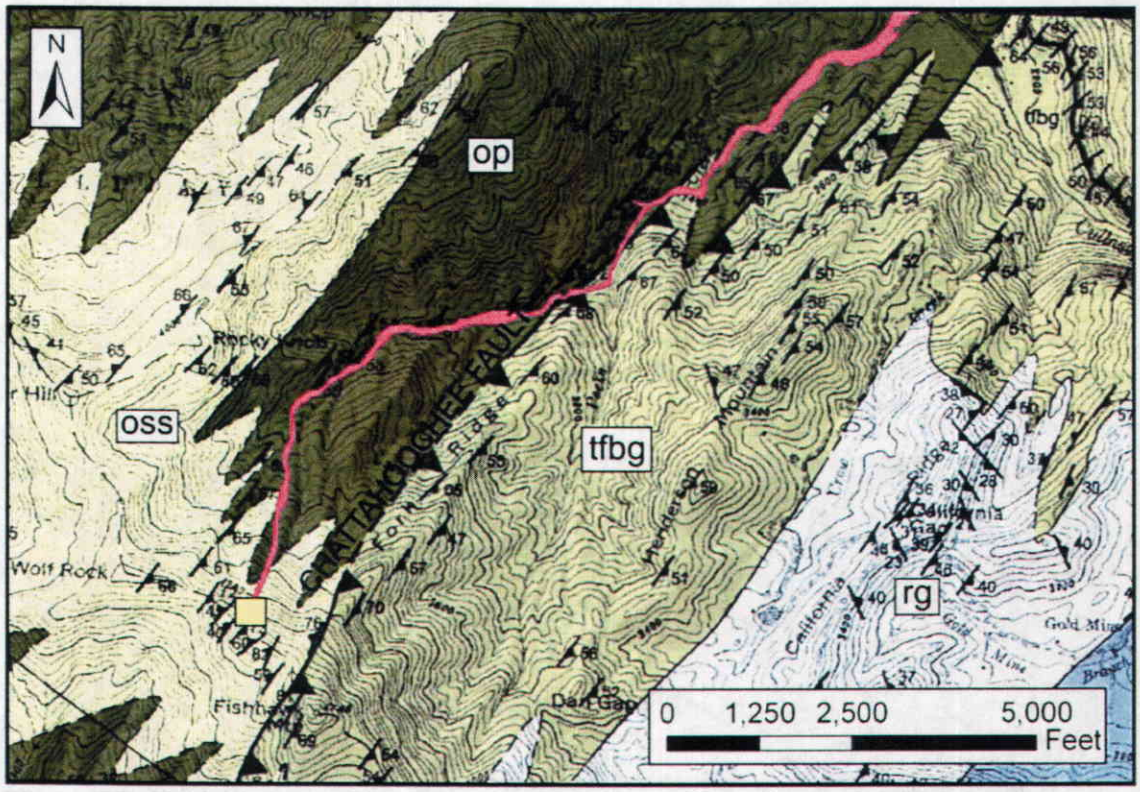


Figure 11. Geologic map of the Peeks Creek slide area (from Lamb, 2001). Initiation zone indicated by yellow square, and track is outlined in pink. **Otto Fmn.**: **op** - biotite muscovite schist with minor metagraywacke, **oss** – metagraywacke with minor schist. **Tallulah Falls Fmn.**: **tfbg** - biotite gneiss and metagraywacke. **Rabun Granodiorite**: **rg** - megacrystic granodiorite.

Surficial deposits vary along the length of the debris flow track. The USDA Soil Survey Map of Macon County (1996) defines the soil in the headscarp as the Cleveland-Chestnut-Rock outcrop complex which is comprised of sandy loam to cobbly sandy loam approximately 17-36 inches thick. Four soil samples were collected from the initiation zone (figure 13) for gradation, Atterberg, and triaxial tests. Results of the soil tests (figure 14) indicate that these samples are non-plastic, organic silty sand with low clay contents. The

high liquid limit values for a number of the Peeks Creek samples is probably due to their high organic content.

Figure 12. One of two tonalite-trondhjemite dikes that crosscuts the foliated metagraywacke exposed in the initiation zone. The arrows show the direction of the grooves created by the rock fragments in the sliding soil mass.

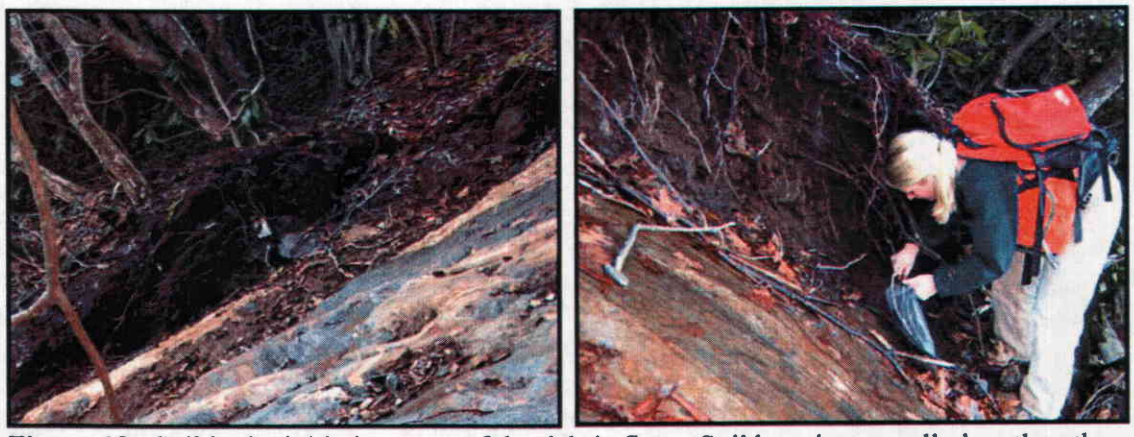


Figure 13. Soil in the initiation zone of the debris flow. Soil here is generally less than three feet thick and is in sharp contact with the steeply dipping (35-55°), underlying bedrock.

In the upper portion of the debris flow track, at least two generations of ancient debris flow and colluvial deposits are exposed. These consist of crudely imbricated, weathered boulders in a silty-sand/sandy-silt matrix. These deposits have been documented by cross sections of the upstream flow track (figures 15 and 16). The location of the K-K' cross section is shown later in the text in figure 32. In the lower third of the debris flow track, preexisting stream deposits are concentrated in the channel, and colluvium is located on the side slopes.

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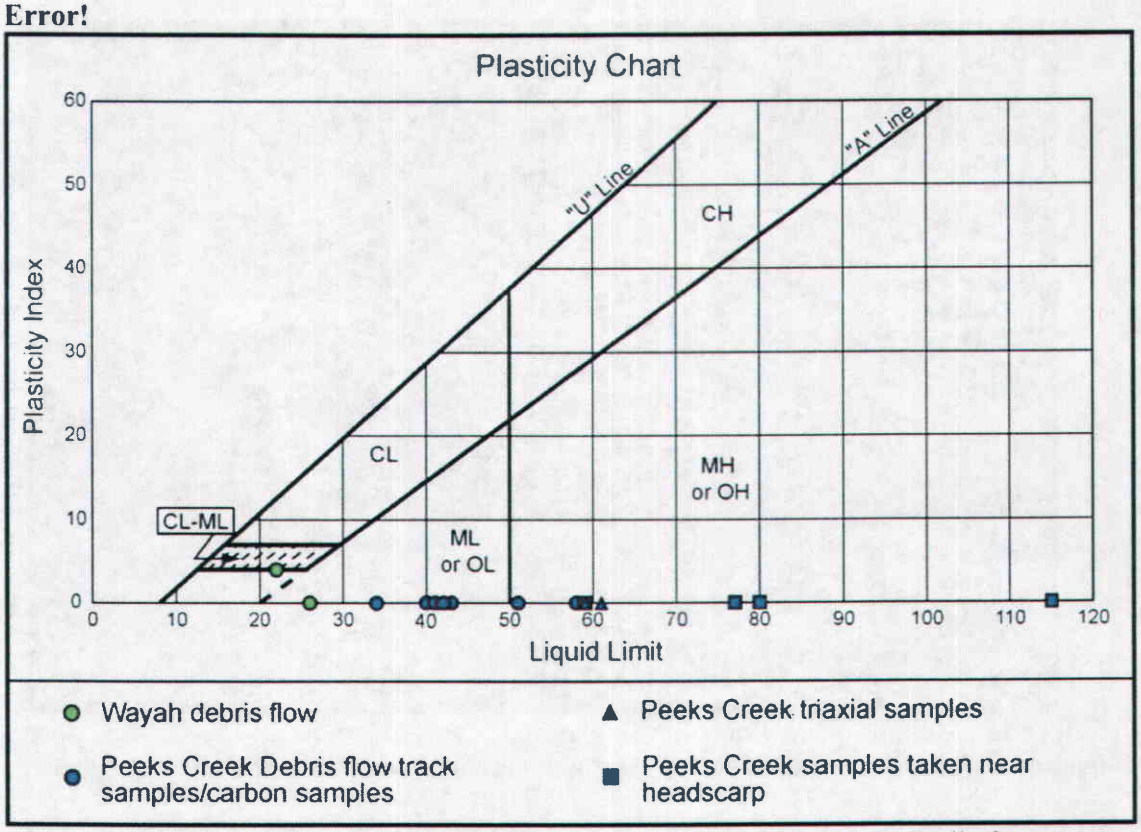

Figure 14. Test results for the fine-grained portion (passing #200 sieve) of soils from two different debris flows in Macon County. The Peeks Creek soils have no measurable plastic limit while having high to very high liquid limit values.

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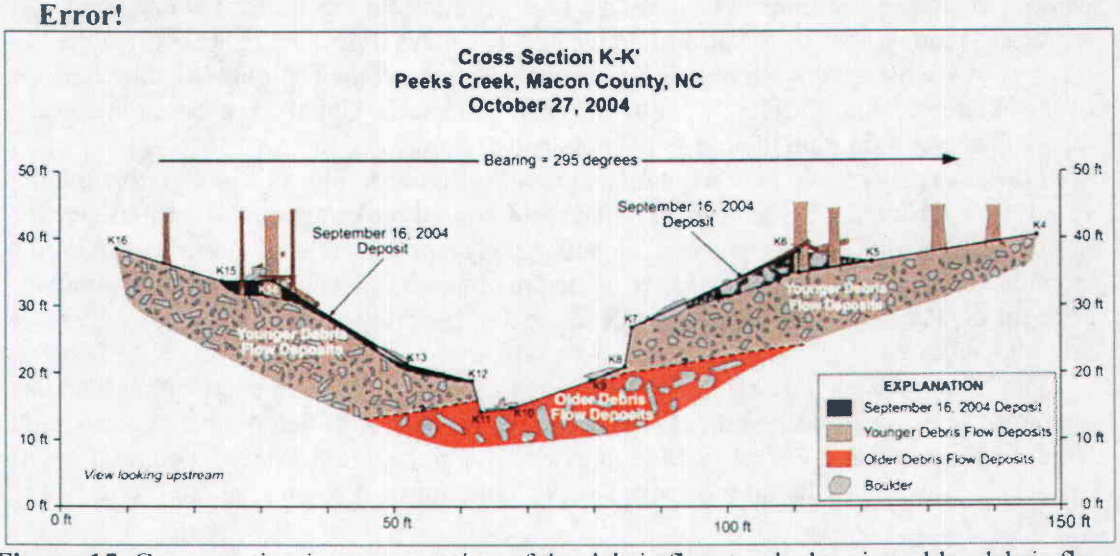


Figure 15. Cross-section in upper portion of the debris flow track showing older debris flow and colluvial deposits.

Figure 16. Multiple debris flow deposits exposed in the modern Peeks Creek debris flow track. Note crude imbrication and alignment of clasts in pre-2004 deposits in right photo.

Precipitation

It is difficult to obtain accurate measurements of precipitation associated with storm events in the mountains of western North Carolina as storms are often isolated to areas without monitoring equipment or localized heavy rainfalls are restricted to very small regions. Weather stations are also often located in valleys or low-lying areas (e.g., the forecast office for southwestern North Carolina is located at the National Weather Service office in Greer, South Carolina). Mountains can block radar signals originating in these locations thereby limiting their effectiveness and accuracy.

Elevation plays a role in precipitation amounts. Figure 17 shows a plot of precipitation versus time during the September hurricanes and rainfall measurements at various elevations throughout Macon County. The high elevation gauges recorded much higher precipitation amounts than the low elevation gauges, indicating that rainfall was higher at the initiation zone for the Peeks Creek debris flow (elevation 4,420 feet) than at the lower elevation rainfall gauges.

The National Weather Service (NWS) indicated that a spiral rain band within Ivan that contained intervals of deep vertical convection in thunderstorms that produced heavy rainfall. (figure 18) passed over Fishhawk Mountain at 9:48 p.m., approximately 20 minutes before the debris flow reportedly hit the Peeks Creek Community (Wooten *et al*, 2007).

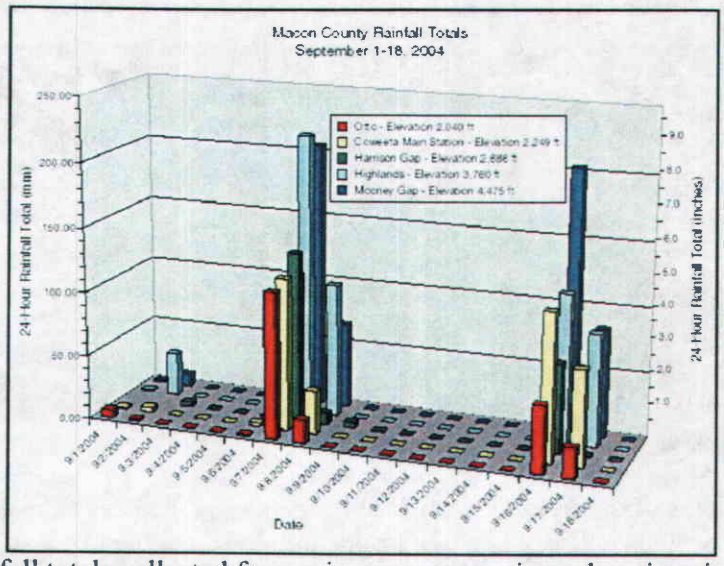


Figure 17. Rainfall totals collected from rain gauges at various elevations in Macon County over an 18-day period. Data from the U.S. Forest Service Coweeta Hydrologic Laboratory and the Integrated Flood Observation and Warning System.

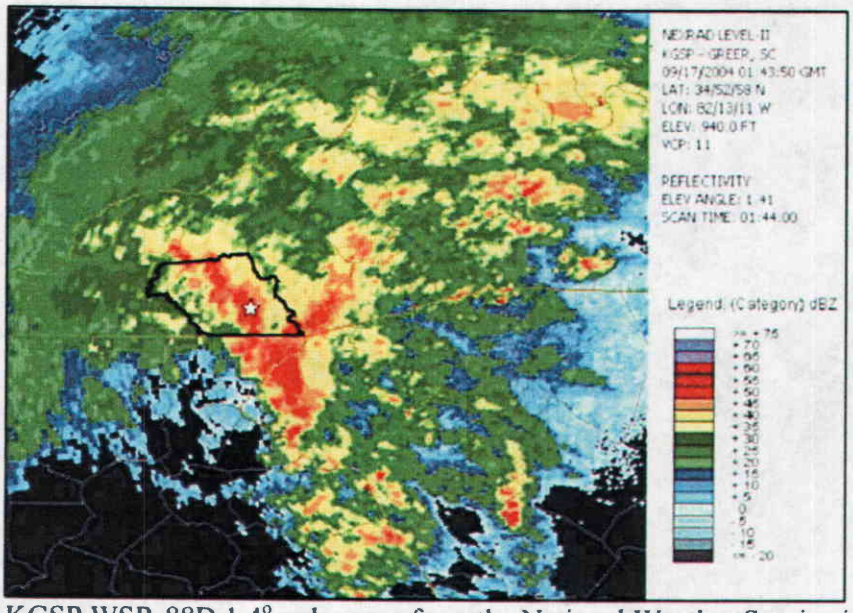


Figure 18. KGSP WSR-88D 1.4° radar scan from the National Weather Service in Greer, SC showing heavy precipitation in spiral rain band crossing Macon County at 9:44 p.m. Precipitation intensity increases as reflectivity (dBZ) transitions from blue to red. The Peeks Creek debris flow indicated by the white star occurred at about 10:10 p.m. (from Wooten *et al.*, 2007).

Peeks Creek Community before the Debris Flow

The residents of the Peeks Creek community describe the floodplain surrounding the creek as a "garden spot" before the September 2004 event. Many residents had built homes immediately adjacent to the Creek as shown by the photos of their front yards in figure 19.

(a) (b)

Figure 19. Photos of the creek side yards of residences in the Peeks Creek community prior to the September 2004 debris flow. The bridge in (b) crosses the Creek. (Photos courtesy of Marilyn Jones)

In figures 20 and 21 the residences of Wayne and Marilyn Jones (the brick house) and their neighbors (Larry and Nan Morris) are shown prior to the flood. Both houses were situated in the flood plain.

Figure 20. The Jones' residence adjacent to Peeks Creek. This photo was taken from Peeks Creek Road next to the creek. (Photo courtesy of Marilyn Jones)

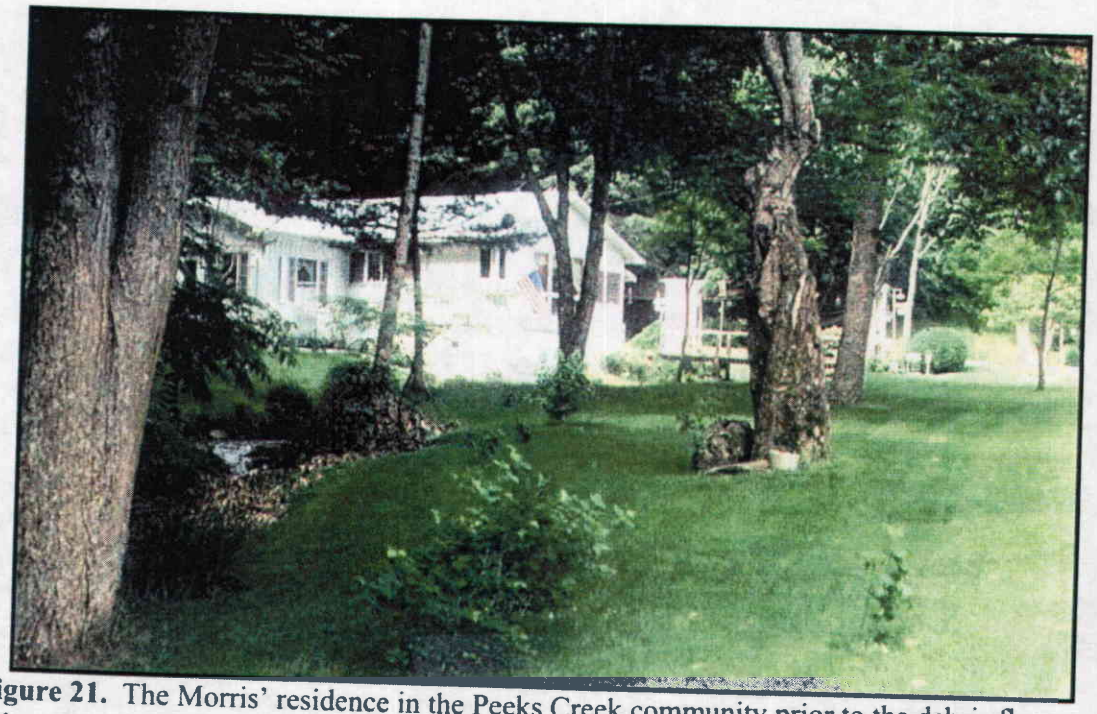


Figure 21. The Morris' residence in the Peeks Creek community prior to the debris flow. (Photo courtesy of Marilyn Jones)

The September 16, 2004 Debris Flow

The Peeks Creek debris flow most likely began as a debris slide. Parallel scratch marks caused by rock fragments in the colluvial soil moving over the bedrock surface indicate that movement was in one direction as opposed to the turbulent motion associated with a debris flow (figure 12). The initial debris slide was approximately 75 feet wide, 350 feet long, and about 3 feet thick (figure 22, point 1 in figure 23). It quickly began to mobilize into a debris flow as water was added to the system. Erratic impact marks observed on bedrock in the debris flow track indicate that the material transformed into a debris flow and/or hyperconcentrated streamflow. The existence of a superelevation angle across a channel bend at section K-K' approximately 1,700 feet below the headscarp confirms that the transformation to flow had already occurred at that point.

Near the top of the track, the debris flow cut through at least two generations of pre-existing debris flow and colluvial deposits (point 2 on figure 23). These are identified by crudely imbricated, weathered boulders in an oxidized sandy-silt/silty sand matrix (figure 16). In this area the track is approximately 100 feet wide and 25 feet deep. Carbon-14 dating has been performed on several samples taken along the debris flow track. Interpretation of these results is pending.

Approximately one third of the way down, the track gradient flattens into a relatively broad (approximately 250 feet wide) area where both deposition and erosion of material occurred (point 3 on figure 23). Imbricated boulders (figure 24), some up to seven feet long, line the channel and have rerouted the flow of Peeks Creek into two channels.

Downstream from the broad, flat area is a 0.6-mile, steeper, more incised portion of the track that ends just upstream of the Peeks Creek community (point 4 on figure 23). The upper boundary of this section is near the confluence of the North Fork of Peeks Creek with the main Peeks Creek channel. There are two side slope failures (figure 25) in this section that originated from Fishhawk Mountain Road on the north side of the stream channel. The

upstream failure appears to have been related to poor drainage along the road (point 5 on figure 23). Tension cracks and scarps continue to develop along this portion of the roadway. The downstream failure began as an embankment failure that quickly scoured the steep bedrock surface that leads down to the creek (point 6 on figure 23). It is possible that both these embankment failures created temporary debris dams along Peeks Creek before the main debris flow occurred, however any evidence for this was destroyed by the main debris flow. At the end of this section, the channel takes a nearly right angle turn to the north just before entering the Peeks Creek community. As the material in the debris flow rounded the bend, the woody debris was skimmed off the top and slammed into the house shown in figure 26. The house was pushed several feet off its foundation. Fortunately the woman inside did not sustain any major injuries. Major damage to homes began below this section and continued along the last quarter of the track.

Figure 22. Looking uphill at the head scarp created by the debris slide. Arrow points to patch of colluvium not removed by the initial slide. Note person, circled in red, for scale.

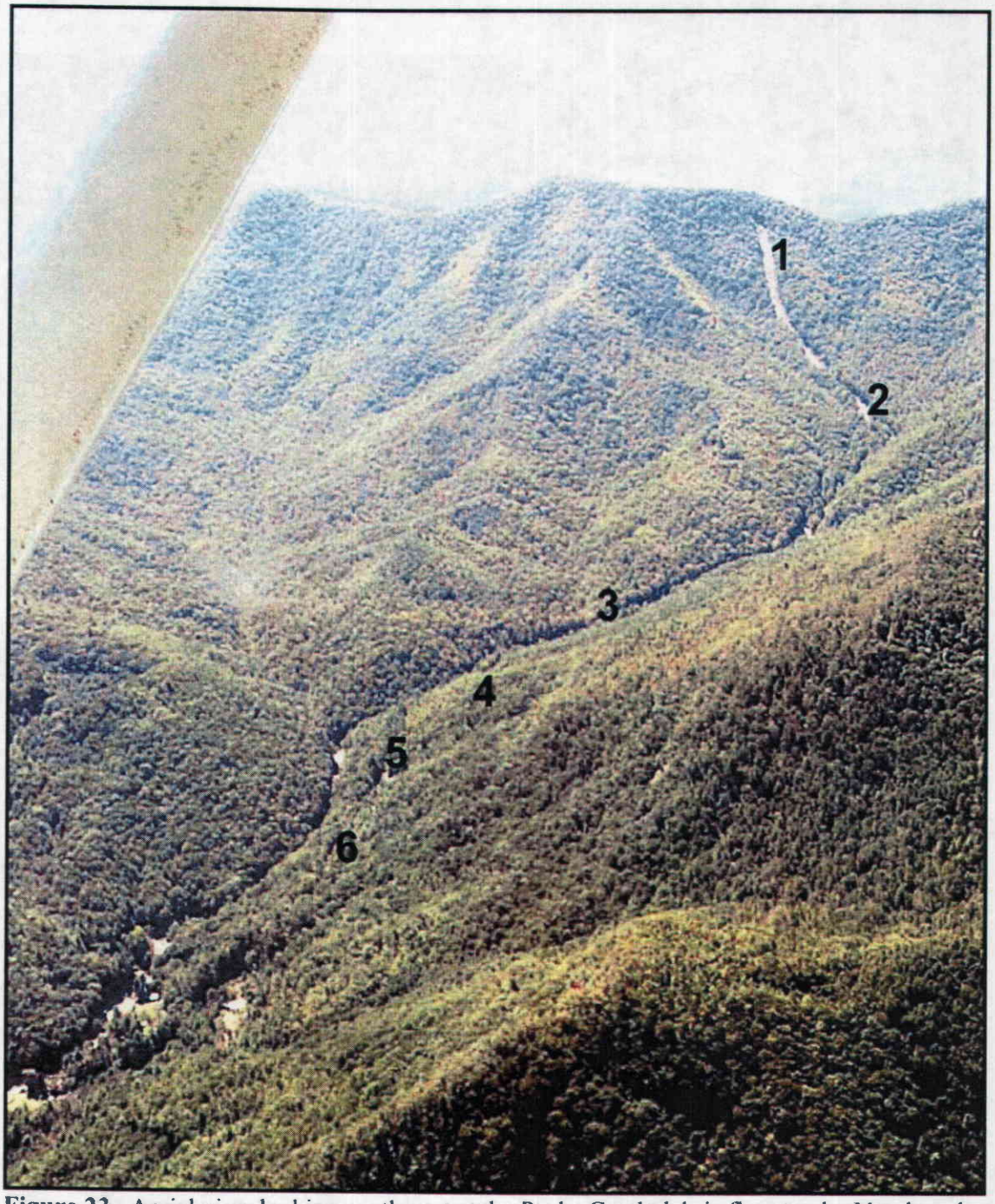


Figure 23. Aerial view looking southwest at the Peeks Creek debris flow track. Numbered points refer to locations described in the text. Photo from Macon County News & Shopping Guide, September 23, 2004 issue

Figure 24. Imbricated boulders with woody debris deposited on top. Note people (circled in red) in each photo for scale.

Figure 25. Embankment failures along Fishhawk Mountain Road upslope of the steep, incised portion of Peeks Creek. Photo at left is looking upslope from Peeks Creek at one of the failures. The red line indicates the location of Fishhawk Mountain Road. Photo on right is looking downslope from Fishhawk Mountain Road toward Peeks Creek at the second side slope failure. The red line indicates the edge of the road.

Figure 26. Base of the steep incised section of the channel in the lower portion of the debris flow track just upstream of the Peeks Creek community. The house in the left center was pushed several feet off its foundation by the woody debris (located about 500 feet below section H-H' in figure 32).

Peeks Creek Community after the Debris Flow

The Peeks Creek community was devastated by the debris flow. Several homes were pushed off their foundations. Figure 27 shows the Jones' residence displaced 30-40 feet downstream and debris that accumulated on the upstream side. Just before the debris flow, Mr. Jones was leaving for work and started down the road in his truck but stopped and returned to his house. He and his wife heard the flow coming down the valley and scrambled up the bank just before their house was destroyed (personal communication with Marilyn Jones, 2006). The debris flow moved another small house nearly 500 feet downstream where it collided with the Morris residence (figure 28). A woman inside the house at the time survived the ordeal with no major injuries (Lewicki, 2004).

Figure 27. Jones residence destroyed by debris flow (Photo courtesy of Marilyn Jones).

Figure 28. Two views of smaller house that moved 500 feet before colliding with the Morris' residence. Photo on left shows the valley before construction of the temporary road shown in the photo at right.

Other homes were completely destroyed. In all, five people were killed, and two others sustained serious injuries. Fifteen homes were destroyed, and most, if not all, of this property damage was not covered by insurance. Aerial photos of the Jones residence and the location of three of the fatalities are shown in figures 29 and 30. The home with the three fatalities was completely destroyed by the debris flow.

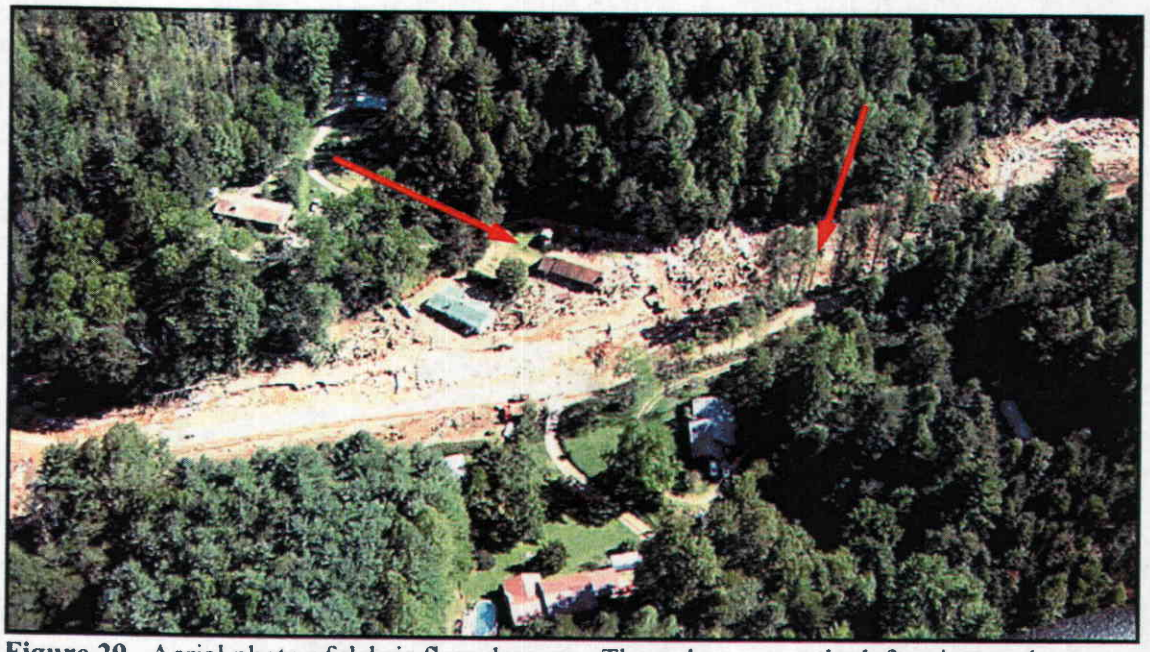


Figure 29. Aerial photo of debris flow damage. The red arrow on the left points to the Jones' residence, and the red arrow on the right points to the location of the three fatalities.

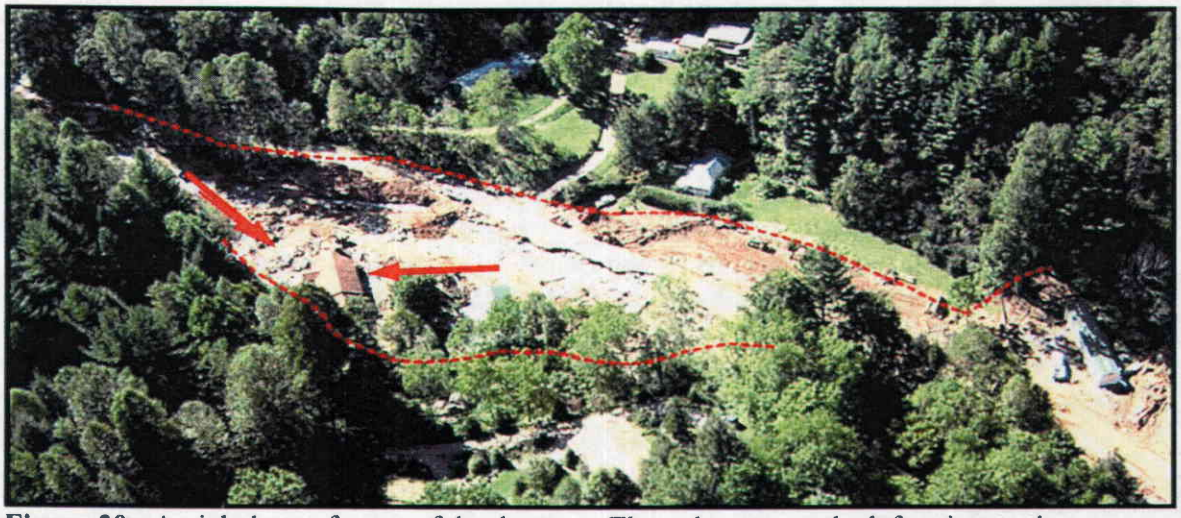


Figure 30: Aerial photo of some of the damage. The red arrow on the left points to the location of the 3 fatalities, and the red arrow on the right points to the Jones' residence. The red line indicates the boundary of the debris flow track. The main road was destroyed and the Creek cut a new channel.

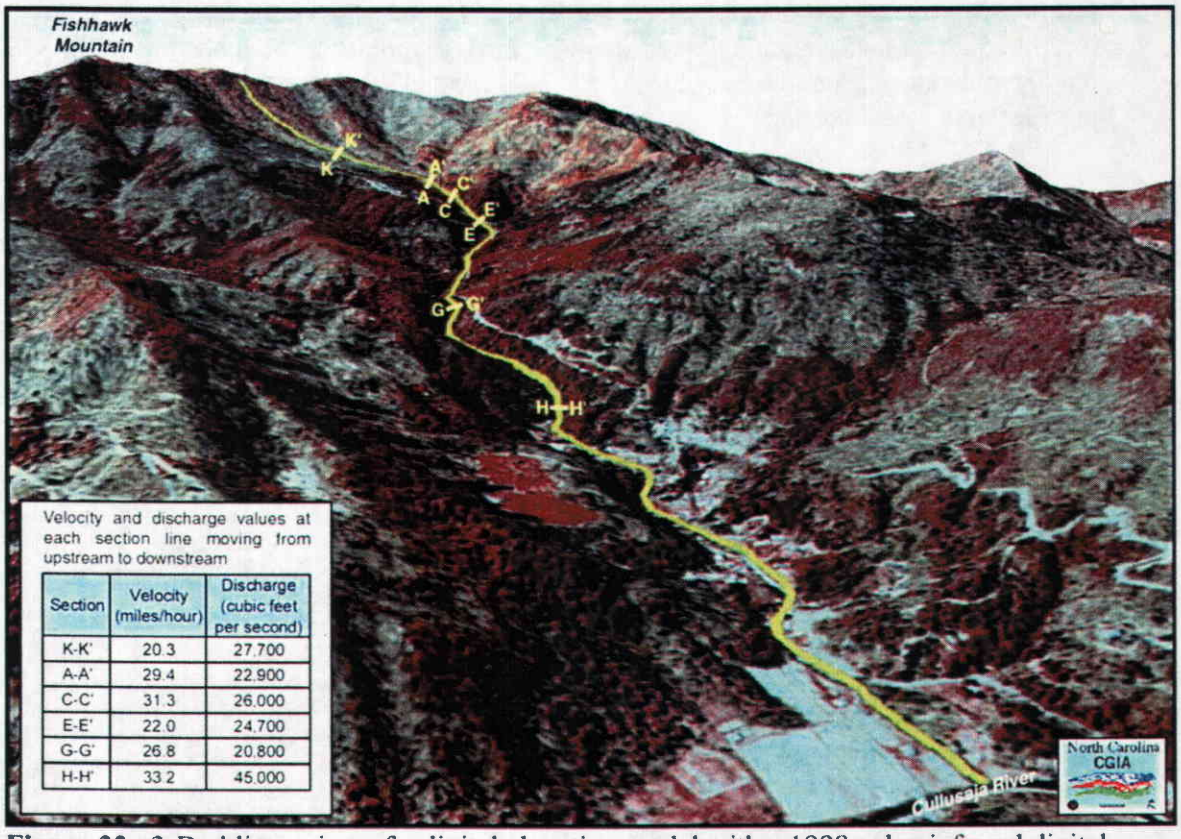
Not all of the houses in the Peeks Creek Community were destroyed. Several of the homes suffered only minimal damage. An aerial photo of the valley just downstream from the above images (figures 29 and 30) is shown in figure 31. The white house shown in the inset had a few mud splatters on it but was not damaged. The arrow points to its location in the air photo. Setbacks from the Creek could have reduced damage and possibly saved lives. The house with the green roof in the bottom right of the photograph is where some partial remains were reportedly found.

Figure 31: Aerial photo of lower part of valley showing house in floodplain that experienced only minor damage from the debris flow. This shows the value of setbacks.

Just beyond the Peeks Creek community, Peeks Creek intersects the Cullasaja River. Near this location, deposits were limited to thin layers of sand adjacent to the Creek.

Velocity and Discharge Calculations

Estimates of velocity and discharge were calculated at six points along the debris flow track in order to gain a better understanding of why the debris flow was so destructive. According to Chen (1987), debris flows resemble hyperconcentrated stream flow and will bank as they travel around a curve in the channel. An estimate of velocity can be calculated given the radius of curvature of the stream channel, the superelevation angle of the material as it rounds the curve, the stream gradient, and acceleration due to gravity. If velocity is known, discharge can be calculated by multiplying the velocity times the cross-sectional area of the channel at that location (Fetter, 1994). Figure 32 shows the locations of the cross sections measured to calculate velocity and discharge and a table with the estimated values.



Velocity and discharge values at each section line moving from upstream to downstream

Section	Velocity (miles/hour)	Discharge (cubic feet per second)
K-K'	20.3	27,700
A-A'	29.4	22,900
C-C'	31.3	26,000
E-E'	22.0	24,700
G-G'	26.8	20,800
H-H'	33.2	45,000

Figure 32. 3-D oblique view of a digital elevation model with a 1998 color-infrared digital orthophoto quarter quadrangle (DOQQ) superimposed. Shown are the locations of six cross sections measured by NCGS along the debris flow track to compute velocity and discharge estimates shown in inset table. Debris flow track is shown in yellow.

Velocity and discharge values vary along the debris flow track from the initiation zone down to the Peeks Creek community (figure 33). The minimum velocity calculated is 20.3 mph at section K-K', and the maximum velocity calculated is 33.2 mph at section H-H'. The minimum discharge calculated is 20,800 cfs at section G-G', and a conservative value for maximum discharge is 45,000 cfs at section H-H'. In comparison, the Pigeon River caused

extensive flood damage in the Canton area in Haywood County just west of Asheville during Hurricane Frances. Discharge on this river was 19,800 cfs at Canton on September 8, 2004 (USGS, 2004).

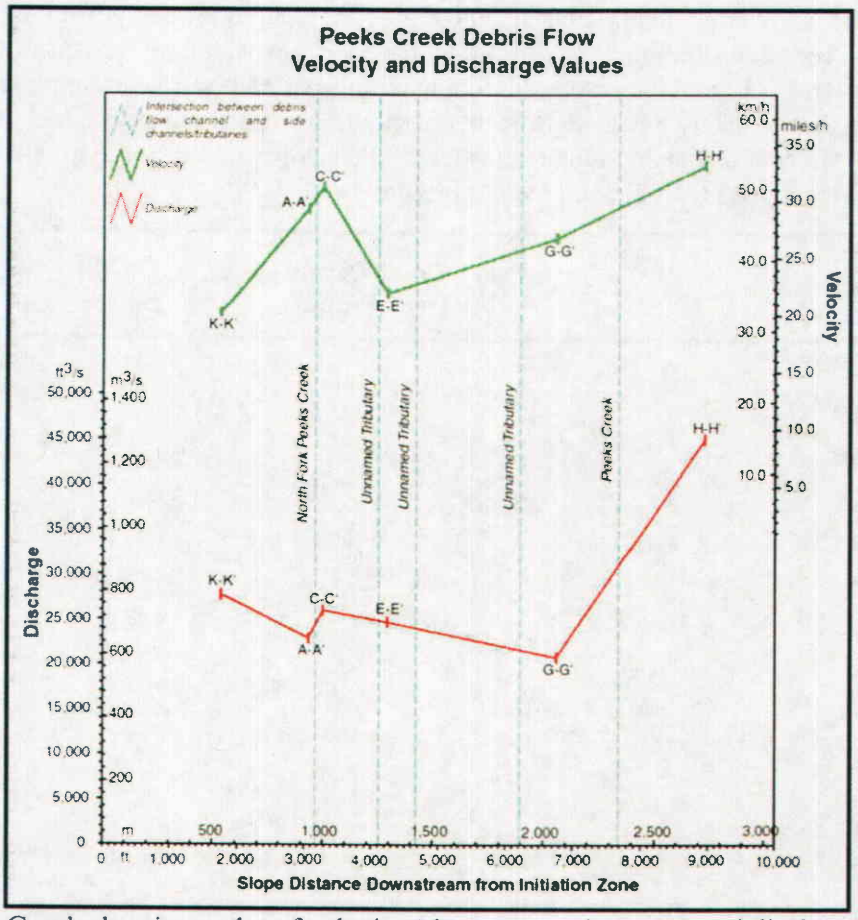


Figure 33. Graph showing a plot of velocity (shown at top in green) and discharge (shown at bottom in red) versus slope distance from the initiation zone. Locations of section lines are shown on each line. Blue dashed lines indicate the locations of side channels that may have contributed significant flow to the debris flow.

Fluctuations in velocity can be attributed to variations in the stream channel gradient as well as to contributions of flow from side channels. The debris flow will decelerate along a lower gradient reach and deposit more material. Contribution from side channels could increase the velocity by increasing the flow and reducing the viscosity of the material, depending on the volume of flow in side channels. The main debris flow may have temporarily dammed some side channels, limiting their influence on the velocity of the material. The velocity at section K-K' (20.3 mph) is probably lower due to the relatively smaller amount of water present and its proximity to the initiation zone (i.e., it is just beginning to accelerate). The velocity decreases at E-E' to 22.0 mph, probably from a change in stream gradient, as the channel gradient flattens just upstream from this section line (figure 34). It most likely continued to decrease as evidenced by deposition in this flatter portion of the channel until just upstream of section G-G' (velocity here is 26.8 mph) where the debris flow transitioned into a narrower portion of the channel.

Discharge depends on the calculated cross sectional area of the debris flow and velocity. More scour will take place with higher velocity flow that can increase the cross sectional area. The depth to competent bedrock also dictates the amount of channel scour. Discharge is lowest at section A-A' (22,900 cfs) probably due to a flattening of the channel gradient (figure 34). Discharge increased at section C-C' (26,000 cfs) probably from the North Fork of Peeks Creek contribution. It continues to decrease downslope (minimum value of 20,800 cfs at section G-G') and then increases to a maximum of 45,000 cfs at section H-H' (figure 33). This is most likely due to significant contribution from the main channel of Peeks Creek, the steeper channel gradient, and steeper side slopes that produce greater amounts of runoff that increases the volume of water present.

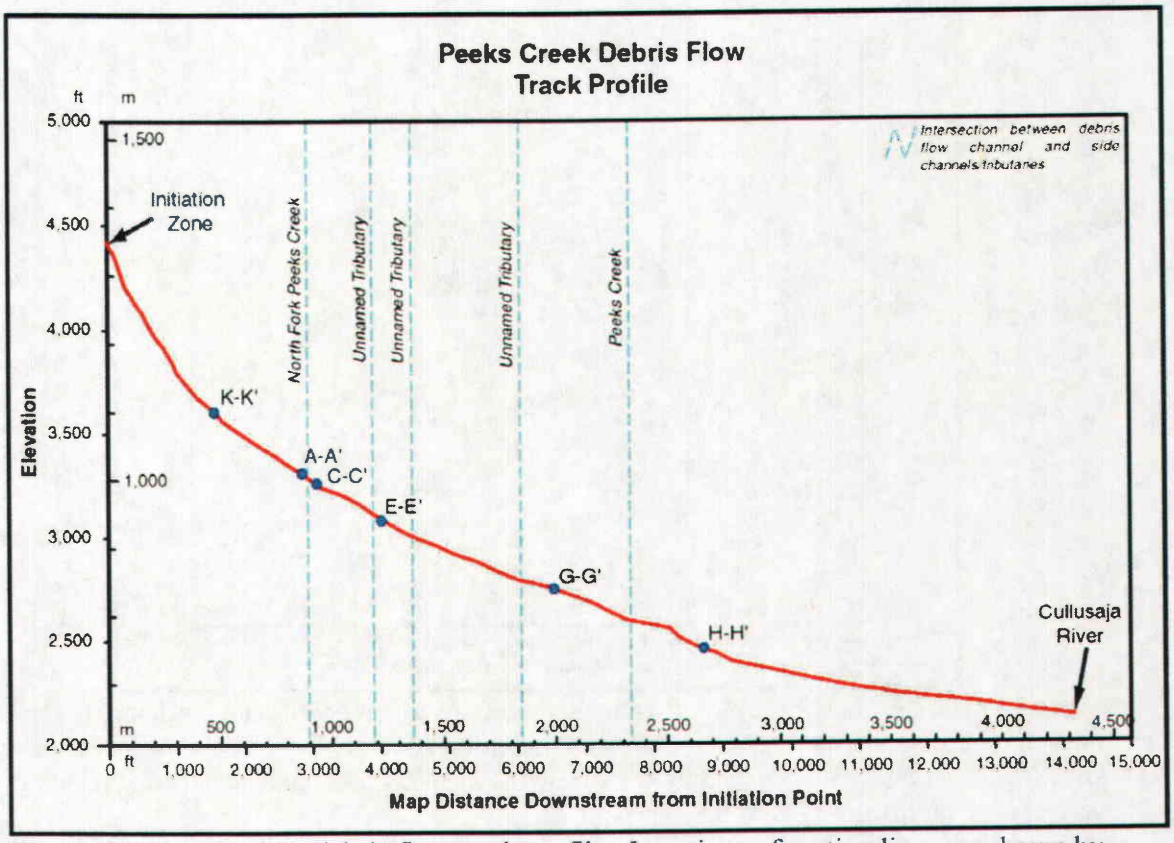


Figure 34. Graph of the debris flow track profile. Locations of section lines are shown by blue dots. Blue dashed lines indicate the locations of side channels that may have contributed significant flow to the debris flow. This could account for the fluctuations in velocity and discharge estimates. Vertical exaggeration used to show subtle changes in the channel gradient.

Conclusions

Although why this particular slope failed at this particular time may never be known, much ground has been gained in understanding what happened and characterizing the nature of this debris flow. There has been a history of slope movements in Macon County and even in the Peeks Creek watershed. Heavy rains from the remnants of Hurricanes Ivan combined with high antecedent moisture conditions triggered the 2.25-mile debris flow that started a few hundred feet below the peak of Fishhawk Mountain. The debris flow exposed pre-existing debris flow deposits and in many places scoured the channel down to bedrock before

entering the Peeks Creek community killing five people and destroying fifteen homes. Initial estimates of maximum velocity and discharge are 33.2 mph and 45,000 cfs, respectively. Studies will continue at Peeks Creek to further assess the potential for future catastrophic slope failures within the Peeks Creek watershed.

Acknowledgements

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Field Trip Stops

Directions to Stop #1

From the Cullasaja Exxon located on the southwest side of Hwy 64, go east on Hwy 64 0.3 miles and turn right onto Peaceful Cove Road. Go 0.1 miles and turn left on River Road. Go 1.7 miles on River Road and turn right on Peeks Creek Road. Go 0.1 miles on PC road to stop #1 shown on Figure 35.

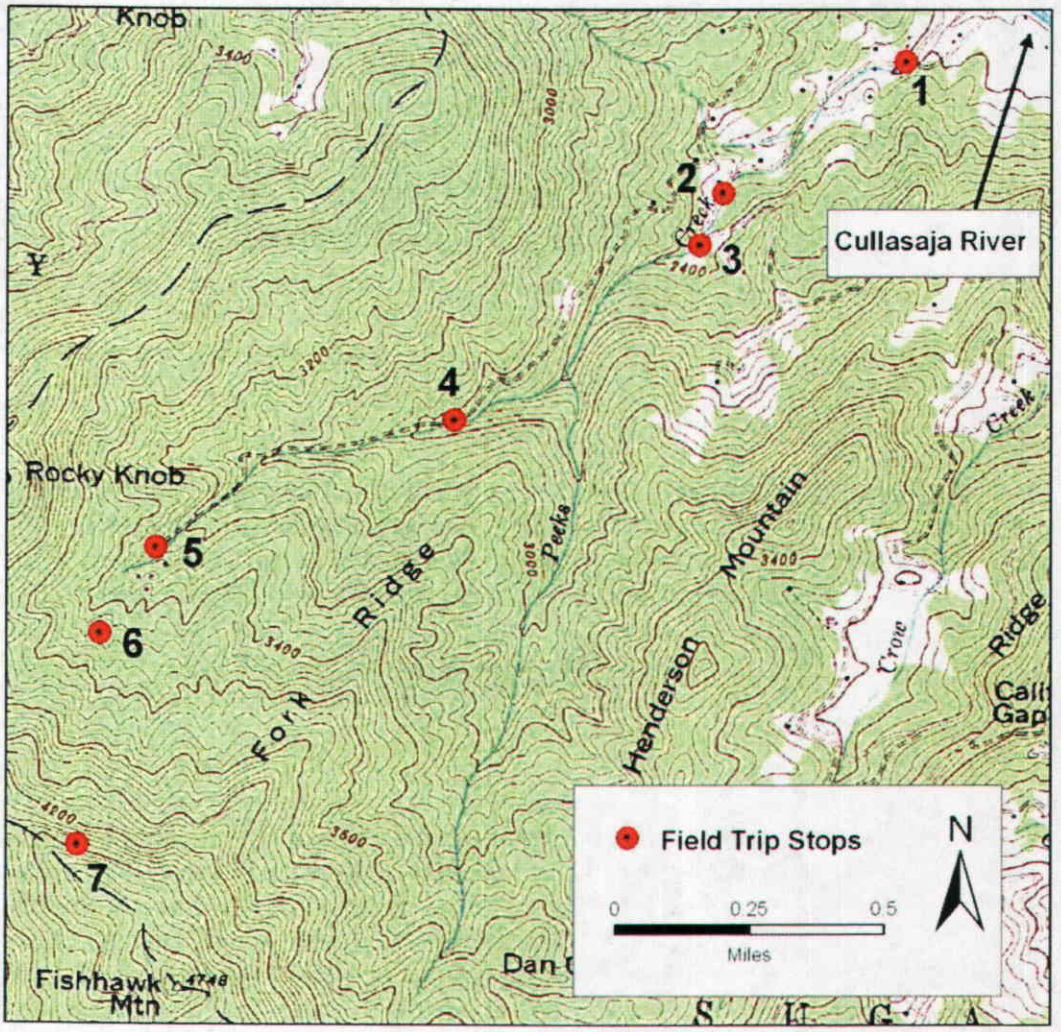

Figure 35. Location of field trip stops.

Stop 1

At this location, the Peeks Creek valley opens up onto the wide flood plain of the Cullasaja River (figure 36). This stop gives one a feel for the layout of the valley. A short walking tour of the lower valley will be given here.

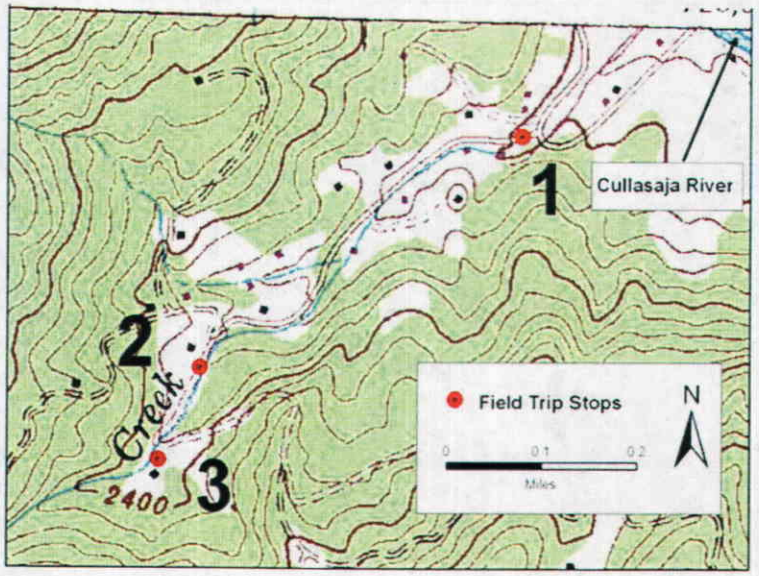

Figure 36. Close-up of topographic map of Peeks Creek valley with stops.

Go 0.5 miles up Peeks Creek Road

Stop 2

At this location, evidence of the debris flow can be seen on the side of the road (figures 37 and 38) where imbricated boulders lie on dimensional lumber. The devastation of the upper valley is clearly visible here. The channel of the stream was heavily modified and incised by the debris flow. Stream restoration efforts may eventually obscure this situation.

Go 0.1 miles to where the road leaves the stream and valley.

Stop 3

The farthest house located upstream in the Peeks Creek Community (shown previously in figure 25), and the first to be damaged by the debris flow, belonged to Mrs. Treadwell. Mrs. Treadwell, 88 years old, lived alone with her cat. She reported hearing a large violent gust of air that she claims knocked her house off its foundations, followed by the debris flow (personal communication, 2006). She had received a call from her sister at 10:05 p.m. the night of the debris flow, which was unusual because she generally was in bed by 8:00 p.m. and did not take calls after that. Her sister in Oklahoma was watching the weather on television and seeing that an unusually violent storm was occurring in the Peeks Creek area, called to check on Mrs. Treadwell. While she was on the phone with her sister, her bedroom was destroyed. Her telephone was in the living room. If her sister had not called it is quite likely that Mrs. Treadwell would not have survived.

Figure 37. Imbricated boulder from an older debris flow deposit with lumber and other debris (shown by arrow) from the September 16, 2004 debris flow.

Figure 38. Close-up of 2"x 4" wedged between imbricated boulders of an older debris flow deposit exposed along the lower reach of Peeks Creek..

Unfortunately, no photos of the stream next to Mrs. Treadwell's house could be located. All of her photos were in her bedroom and were destroyed by the debris flow. She reported the stream next to her house as being "quite lovely" with 2 small waterfalls. Figure 39 shows the current condition of her streamside.

Go 0.2 miles back down Peeks Creek Road; turn left on Fishhawk Mountain road. Go 1.3 miles on Fishhawk Road.

Figure 39. Peeks Creek next to the Treadwell property after the debris flow.

Stop 4

The wide, devastated channel (figure 40) of a Peeks Creek tributary is at this stop. Velocity of the debris flow decreased in this low gradient reach of the track depositing mud, boulders and large woody debris. Clast-supported, imbricated cobbles within the channel are interpreted to be post-debris flow, high water deposits. Below this area, the channel narrows considerably before opening up at the top of the Peeks Creek community. This land is owned by the U.S. Forest Service (USFS).

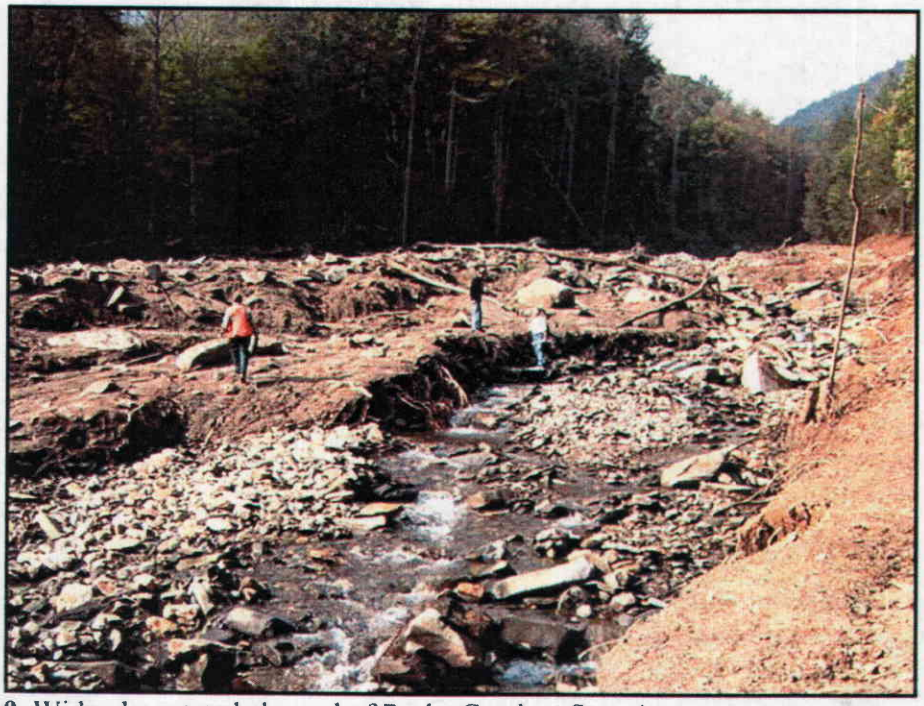

Figure 40. Wide, devastated channel of Peeks Creek at Stop 4.

Go 0.5 miles upstream up the USFS road.

Stops 5 and 6

A culvert and bridge crosses the stream near Stop 5. From here, a short hike upstream shows the nature of the track up to the initiation zone. A short distance up the channel, the stream can be observed flowing over older debris flow deposits as opposed to bedrock (figure 41). Three distinct debris deposits can be observed here (Stop 6): the September 2004 event and two older deposits that are relatively aged as "younger" and "older" at this time. Age dating has been performed on these deposits.

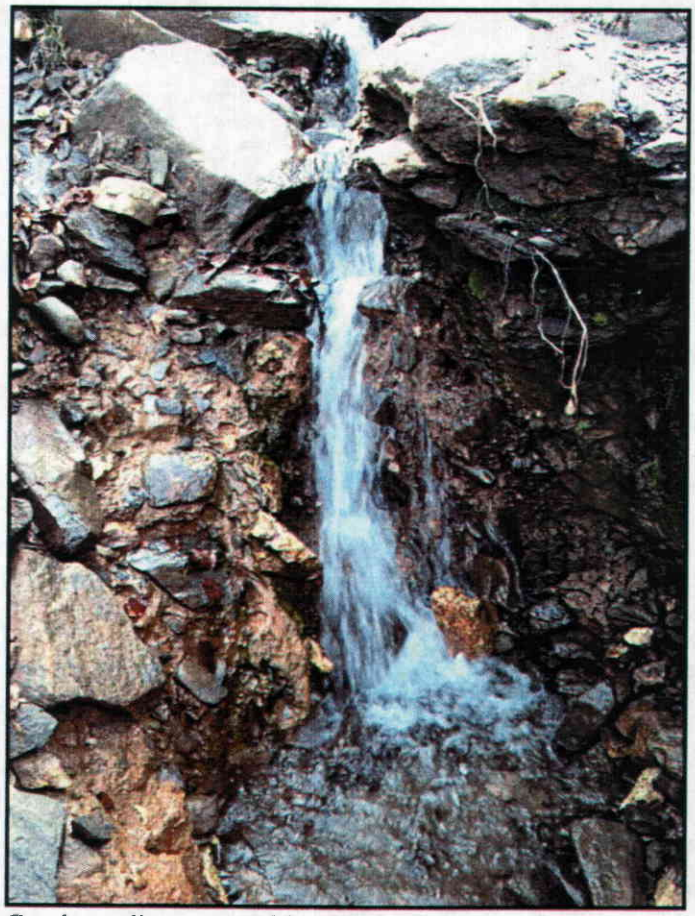

Figure 41. Peeks Creek eroding away older debris flow deposits.

In the area between stops 5 and 6, the track gradient flattens into a relatively broad area where older debris flows have deposited material.

Stop 7

The extreme uphill part of the debris flow track ends at the headscarp where a debris slide initiated the debris flow. Before the slope failure, this area was heavily forested and no bare rock slope was exposed. The footing on the bedrock scar is quite slippery and climbing the rock is not recommended (figure 42).

Figure 42. Ken Gillon of the NCGS working his way up the side of the scar.

On the left side of the scar (if looking down from the top) is a nearly vertical foliation plane hidden in the trees (figure 43). The prominent horizontal fracture in the photo is an exfoliation plane; a similar type structure does not exist on the right side of the headscarp. The assumption is that slabs of rock were released along these factures and created an exposed bedrock catchment. Over time the catchment accumulates soil and vegetation until an extreme rainfall event triggers a failure. The ~100 ft-wide by ~400 ft-long area that failed during Ivan is only a portion a larger colluvial catchment below the peak of Fishhawk Mountain (figures 1 and 44).

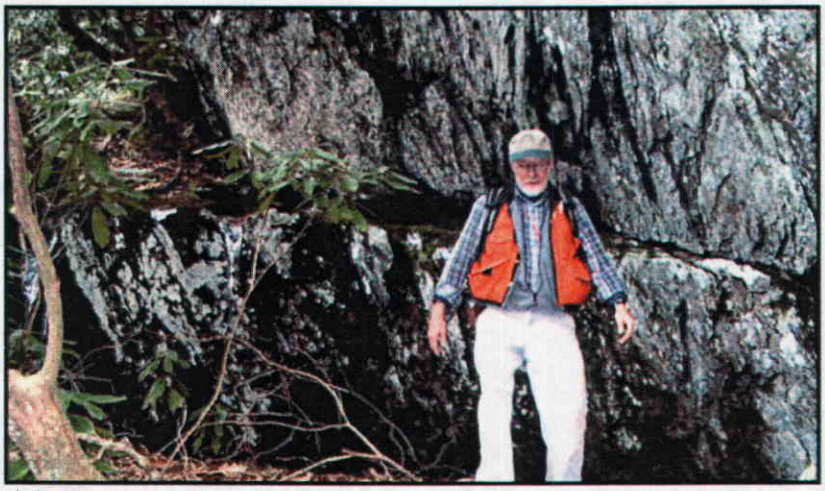

Figure 43. Rick Wooten of the NCGS in front of the steeply dipping foliation planes located off to the left flank of the scar and obscured by vegetation (see figure 44). The gently dipping discontinuity along the cliff face is an exfoliation fracture.

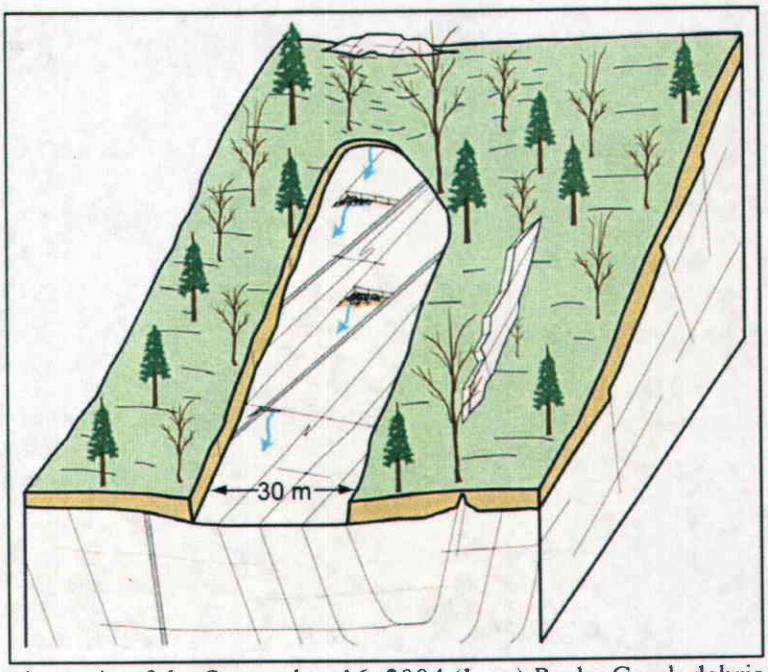

Figure 44. 3-D schematic of the September 16, 2004 (Ivan) Peeks Creek debris flow initiation zone within a large-scale colluvial catchment. Foliation and compositional layering in isoclinally folded bedrock strikes NE, subparallel to the long dimension of the scar. High-angle tectonic fractures strike NW, nearly orthogonal to foliation and compositional layering. Exfoliation fractures dip downslope 35°-53°and formed the slip surface between soil and bedrock. Blue arrows indicate areas of observed seepage. Dark grey bedrock features are thin (1 m thick) NE-striking, unfoliated tonalite-trondhjemite dikes.