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Geologic, geomorphic, and meteorological aspects of debris flows triggered by Hurricanes Frances and Ivan during September 2004 in the Southern Appalachian Mountains of Macon County, North Carolina (southeastern USA)

Abstract In September 2004, rain from the remnants of Hurricanes Frances and Ivan triggered at least 155 landslides in the Blue Ridge Mountains of North Carolina. At least 33 debris flows occurred in Macon County, causing 5 deaths, destroying 16 homes, and damaging infrastructure. We mapped debris flows and debris deposits using a light-detecting and ranging digital elevation model, remote imagery and field studies integrated in a geographic information system. Evidence of past debris flows was found at all recent debris flow sites. Orographic rainfall enhancement along topographic escarpments influenced debris flow frequency at higher elevations. A possible trigger for the Wayah and fatal Peeks Creek debris flows was a spiral rain band within Ivan that moved across the area with short duration rainfall rates of 150–230 mm/h. Intersecting bedrock structures in polydeformed metamorphic rock influence the formation of catchments within structural–geomorphic domains where debris flows originate.

Keywords Debris flows · Hurricanes · GIS · LiDAR · North Carolina

Introduction

This paper presents recent findings and conclusions on the geologic, geomorphic, and meteorological aspects of the debris flows that occurred in Macon County, North Carolina, during September 2004, and synthesizes data collected to prepare slope movement hazard maps for the county. The objectives of this paper are to document the event in Macon County, integrate the aforementioned aspects of this event to describe geologic–geomorphic domains susceptible to debris flows when tropical cyclones affect western North Carolina and to characterize rainfall distributions, rates, and durations that trigger debris flows in these domains.

In September 2004, intense rainfall from the remnants of Hurricanes Frances (September 7–8) and Ivan (September 16–17) triggered at least 155 slope movements (Fig. 1) that caused 5 deaths, destroyed at least 27 homes, and disrupted transportation corridors throughout western North Carolina (Wooten et al. 2005, 2007). In response to the destruction from these storms, the North Carolina General Assembly passed the Hurricane Recovery Act of 2005, authorizing the North Carolina Geological Survey (NCGS) to prepare county-scale slope movement hazard maps for 19 mountain counties. Macon County was selected as the pilot study area, as it was the location of the fatal Peeks Creek debris flow (Latham et al. 2005, 2006), as well as 32 other debris flows triggered by Hurricanes Frances and Ivan. The resulting Macon County slope movement hazard maps (Wooten et al. 2006) are provided in a GIS format to local government agencies to help protect public safety and guide informed decisions on land use.

Consecutive storms with heavy rainfall similar to Hurricanes Frances and Ivan in 2004 constitute dangerous scenarios for regional flooding and damaging slope movements in western North Carolina. Work by the US Geological Survey (1949), Tennessee Valley Authority (1964), and Scott (1972) established that similar weather patterns in the past had triggered regional flooding and debris flows. Back-to-back storms with heavy rainfall passed over the Blue Ridge Mountains in western North Carolina in 1916 and 1940, setting off thousands of destructive debris flows and other types of slope movements. Ongoing work by the NCGS has determined that the rainfall from the remnants of a hurricane that passed over the southeastern USA during August 10–17, 1940 triggered over 2,000 debris flows and debris slides in Watauga County alone (Witt et al. 2007a; Wieczorek et al. 2004; NCGS, unpublished data). This storm caused at least 26 fatalities in North Carolina (Wieczorek et al. 2004), of which at least 12 resulted from landslides (Witt et al. 2007a). A second storm struck southwestern North Carolina between August 28 and 31, 1940 causing fatalities from flooding and landslides in the two counties that adjoin Macon County to the east (USGS 1949). Hursh (1941) reports an August 1940 debris flow in a Macon County cornfield but does not give the date of the debris flow.

High-intensity rainfall from individual storms can also trigger debris flows, especially when antecedent moisture conditions are high. An extratropical cyclone in early November 1977 triggered over 60 debris flows near Asheville, North Carolina (Neary and Swift, 1987; Pomeroy 1991; Otteman 2001). A cloudburst with rainfall on the order of 100 mm within 1 h triggered scores of debris flows in the Great Smoky Mountains near the North Carolina–Tennessee border in September 1951 (Bogucki 1976; Clark and Ryan 1987). Witt (2005) determined that the frequency of major storms that produced debris flows in the French Broad watershed in North Carolina between 1876 and 2004 was once every 16 years.

Physiography and geomorphology

Macon County (1,347 km^2) is located within the Blue Ridge physiographic province of the Southern Appalachian Mountains (Fig. 1). The headwaters of the north-flowing Little Tennessee River originate near the southern border of the county along the eastern USA continental divide. Elevations range from 550 to 1,675 m, and the Nantahala Mountains rise abruptly west of the Little Tennessee River to an elevation of 1,663 m. The southeast part of the county includes the upper slopes of a segment of the Blue Ridge Escarpment (BRE), a geomorphic feature that extends from northeast Georgia to Virginia (Hack 1982; Clark 1993), and marks the boundary

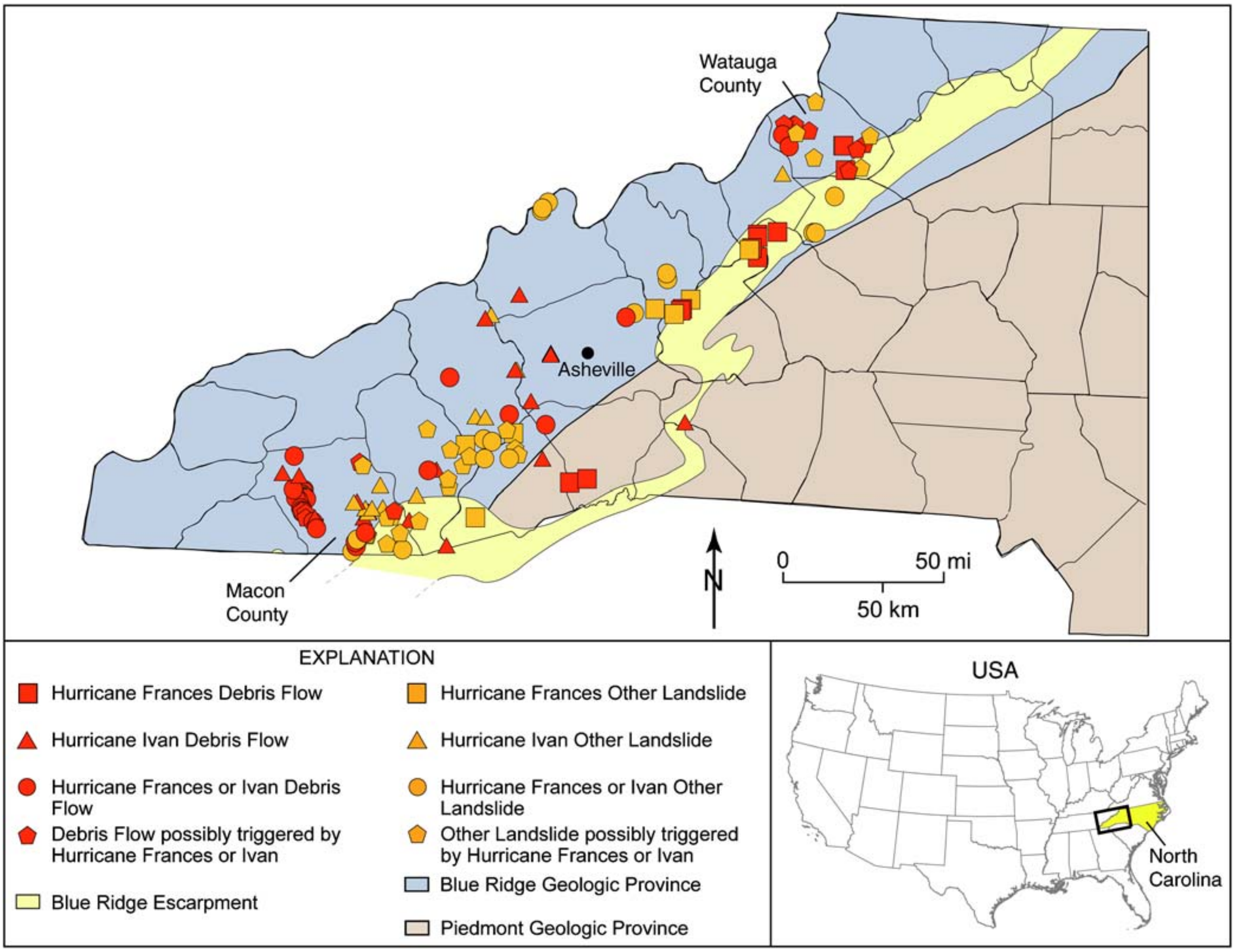


Fig. 1 Map showing the locations of slope movements attributed to Hurricanes Frances and Ivan in relation to the Blue Ridge Escarpment (*BRE*) and major geologic provinces in western North Carolina

between the mountainous Blue Ridge and the rolling foothills of the Piedmont physiographic province to the east (Figs. 1, 2).

Geologic setting

Macon County is located in the Blue Ridge Geologic Province (BRGP) of the Southern Appalachian Orogen (Figs. 1, 2). The BRGP is subdivided into the Western (WBR), Central (CBR), and Eastern Blue Ridge (EBR) tectonic subdivisions (Hatcher et al. 2005; Merschat et al. 2006; NCGS 1985). Ductile, NW-directed thrust faults separate the terranes representing Middle to Late Proterozoic and Early Paleozoic sedimentation, volcanism, and igneous intrusion overprinted by Early to Late Paleozoic, collisional, orogenic pulses. After the Mid- to Late Paleozoic Alleghenian Orogeny, the southern Appalachians experienced brittle fracturing and faulting during Mesozoic rifting and uplift. Post-Eocene uplift may be responsible for the current topographic relief (Prowell 2000). Numerous debris fan deposits (Fig. 2) indicate a long history of erosion and mass wasting in the area. Mills and Allison (1995) and Mills (1998) suggest that similar deposits elsewhere in the Blue Ridge range in age from Middle to Late Pleistocene to Early to Middle Holocene.

The WBR underlies northwest Macon County and consists of the Late Proterozoic to lower Ordovician (?) rift basin Ocoee Supergroup, comprised of middle to upper amphibolite grade metagraywacke, metaconglomerate, and schist. In thrust contact with the WBR rocks are the Cartoogechaye (Ct) and Cowrock (CRt) terranes of the CBR (Hatcher et al. 2005). The Ct and CRt consist of upper amphibolite to granulite grade, complexly interlayered metasediments, migmatitic biotite gneiss, schist, amphibolite, and minor ultramafic rocks. Further to the east, the Dahlonega Gold Belt terrane (DGBt) comprises middle to upper amphibolite grade metasediments, amphibolite, ultramafic rocks, and minor felsic metavolcanics (Hatcher et al. 2005). The Tugaloo terrane (Tt) consists mainly of upper amphibolite grade migmatitic metasediments, amphibolite, granitic intrusives, and minor ultramafic rocks (Hatcher et al. 2005).

In summary, polyphase ductile folding, thrust faulting, metamorphism, and overprinting brittle fabrics associated with the evolution of the BRGP have resulted in the complex bedrock structure typical of the area at map, domain, and outcrop scales. The intersection of ductile structures (foliation, compositional layering, ductile shear zones, and intrusive contacts) with overprinting brittle structures (fractures, fracture systems) is reflected in the overall topography of the landscape. At outcrop scales, these structural elements form trough- or wedge-shaped bedrock foundations for colluvial catchments characteristic of debris-flow initiation zones.

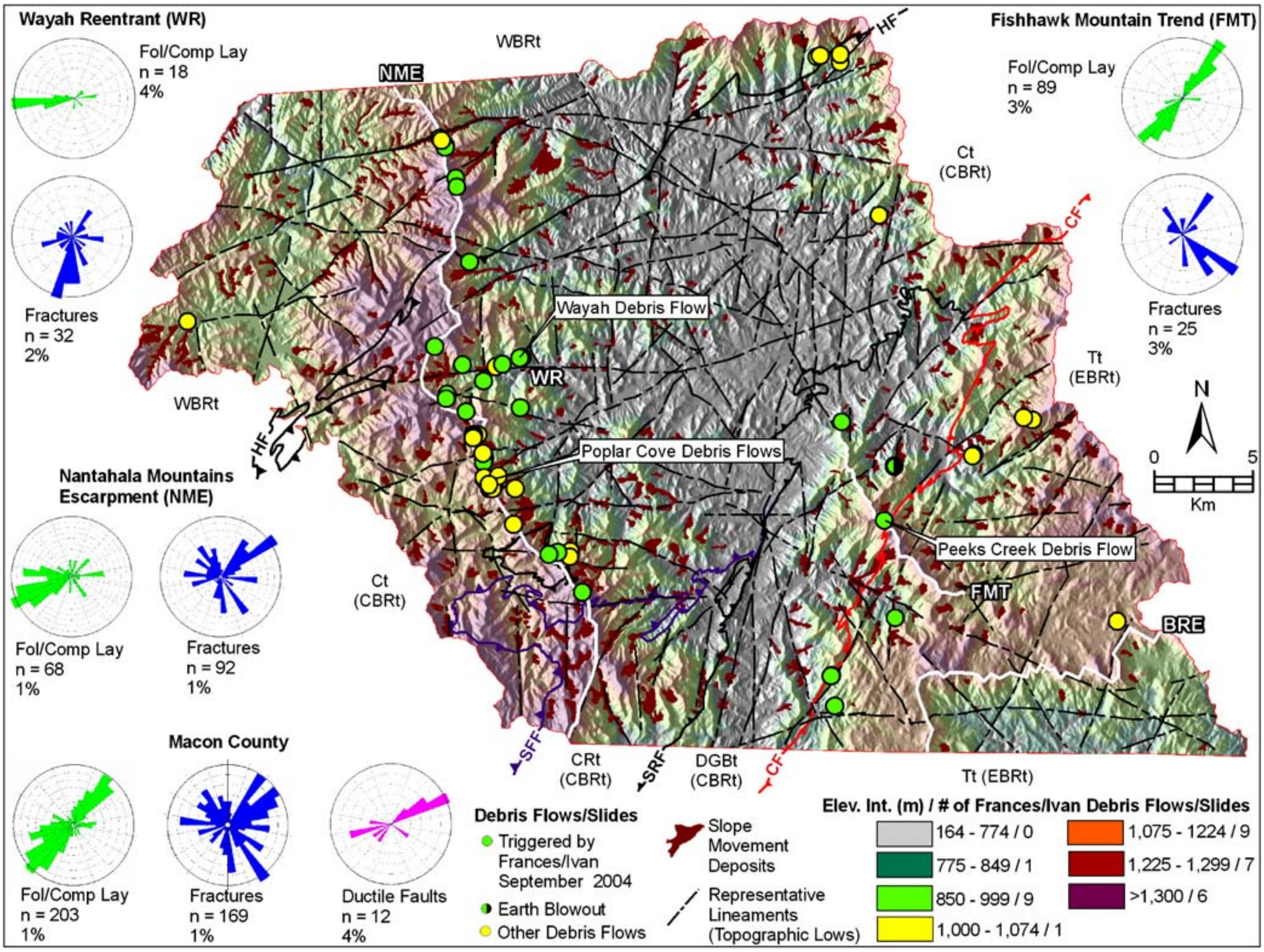


Fig. 2 Shaded relief map of Macon County showing geologic terrane boundaries, major topographic lineaments, debris flow locations, and slope movement deposits. *Rose diagrams* show the statistical distributions of the orientations of structural elements (*Fol* foliation, *Comp Lay* compositional layering) related to structural–geomorphic domains and topographic lineaments. Percentages with rose diagrams indicate increments of percent frequency for circle divisions. *NME* Nantahala Mountains escarpment, *FMT* Fishhawk Mountain trend, *BRE* Blue Ridge Escarpment, *HF* Hayesville fault, *SFF* Shope Fork fault, *SRF* Soque River fault, *CF* Chattahoochee Fault. Map base 6 m LiDAR DEM

Study methods

Several vintages of aerial photography and orthophotography (1951, 1993, 1998, 2005, 2006) used in conjunction with a 6-m pixel resolution light-detecting and ranging (LiDAR) digital elevation model (DEM) helped to target field studies, map slope movements and past debris deposits, and identify areas susceptible to debris flows. Field mapping utilized global positioning system survey methods and provided geologic, geomorphic, and topographic data on debris-flow initiation zones and characteristics of past debris-flow deposits. Debris-flow locations and mapped debris deposits shown in Fig. 2 were derived from the map of slope movements and slope movement deposits (sheet 1 of Wooten et al. 2006) prepared using ArcGIS™. Structural–geomorphic domains and major topographic lineaments shown in Fig. 2 were identified from shaded relief maps constructed from the Macon County LiDAR and 10 and 30 m USGS DEMs for the surrounding region. Slope movements were classified in general accordance with Cruden and Varnes (1996). The term earth blowout (Hack and

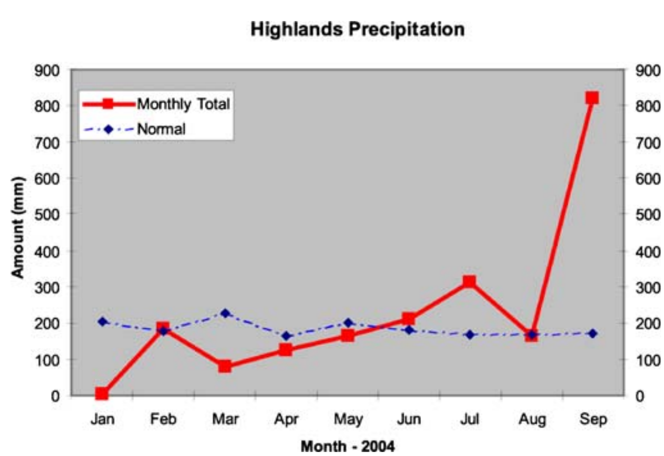


Fig. 3 Highlands monthly rainfall, January–September 2004

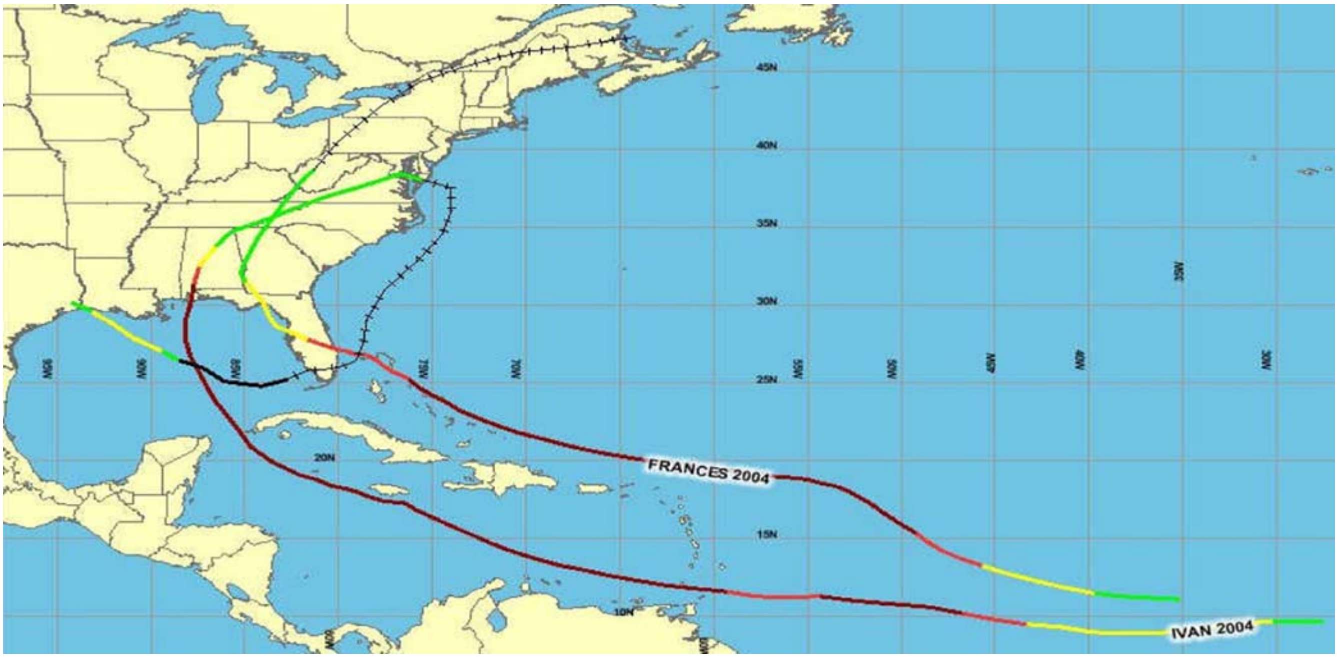


Fig. 4 Tracks of Hurricanes Frances and Ivan courtesy of NOAA Coastal Services Center

Goodlett 1960) is used for circular depressions in hillsides that apparently form when groundwater bursts forth from the slope. Soil, bedrock, landform, and ground slope data were collected at 28 Frances–Ivan debris-flow initiation zones. Soil was classified according to geologic origin and by the American Society for Testing and Materials (ASTM) D2488-02 and D4318-05 (ASTM 2002a, b). Standard geologic names for rock types were used in conjunction with the rock mass classification of Williamson (1984). Orientations of bedrock structural discontinuities (e.g., fractures, foliations, lithologic contacts) were measured at debris-flow initiation zones and at locations along debris-flow tracks.

Precipitation data from 20 station locations in the region (Figs. 3, 5, 6) and radar rainfall estimates from the National Weather Service (NWS) WSR-88D at Greer, South Carolina (KGSP), were used to develop rainfall maps for the Macon County region. Rainfall data from the US Forest Service (USFS), Coweeta Hydrologic Laboratory gages (NWS cooperative observer) at the main climate station (RG06 at 685 m), and Mooney Gap station (RG31 at 1,364 m) were also used to determine the rainfall intensity of three storms: Hurricane Opal, October 3–5, 1995; Hurricane Frances, September 6–8, 2004; and Hurricane Ivan, September 16–17, 2004. Rainfall data from Opal are included for comparison because rainfall from that storm triggered two debris flows in the Poplar Cove watershed where debris flows also occurred during Frances and Ivan. The numbers of observations and average observation intervals are given in Table 1.

Hydrometeorological conditions preceding September 2004

The first 5 months of 2004 were characterized by below-normal rainfall across Macon County and nearby portions of the southern Appalachians. Both June and July had above normal rainfall. The precipitation data from Highlands (Fig. 3, location shown in Fig. 5) illustrates the general character of the rainfall across the area. The June and July precipitation totals and departures from normal were 211 mm (+30) and 314 mm (+147), respectively. The 165-mm August total was below normal (−3 mm) but not enough to offset the effects of a third consecutive month of substantial precipitation.

Hydrometeorological conditions during September 2004

Heavy rainfall associated with the passage of the remnants of Hurricanes Frances and Ivan dominated the precipitation record during the first 3 weeks of September 2004 across the entire southern Appalachian region. Both storms developed from tropical waves that moved westward off the coast of Africa. They followed similar tracks across the Atlantic along the southern periphery of the Bermuda High into the Gulf of Mexico (Fig. 4). The tracks of both storms placed western North Carolina on the right side (relative to the northeastward storm motion) of the cyclonic circulations, resulting in significant orographic enhancement of the precipitation as south, southeast, and east winds encountered the higher terrain.

Precipitation totals from Hurricane Frances were as high as 305 to 356 mm in portions of southern Macon County (Fig. 5a). Major floods occurred in the French Broad, Swannanoa, Pigeon, and Little Tennessee River valleys (National Oceanic and Atmospheric Administration 2004) in North Carolina. Nine days later, the heavy rains associated with Ivan produced precipitation totals in Macon County ranging from 76 to 127 mm in the north to 254 to 305 mm in the south (Fig. 5b). Although both storms were weakening when they

Table 1 Table of the numbers of observations (*n*) and average observation intervals (*t* in minutes), measured at RG06 (elevation, 685 m) and RG31 (elevation, 1,364 m) at the Coweeta Hydrologic Laboratory

Hurricane	RG06		RG31	
	n	*t*	*n*	*t*
Opal (Oct. 3–5, 1995)	100	28	103	30
Frances (Sept. 6–8, 2004)	135	24	149	16
Ivan (Sept. 16–17, 2004)	160	16	137	17

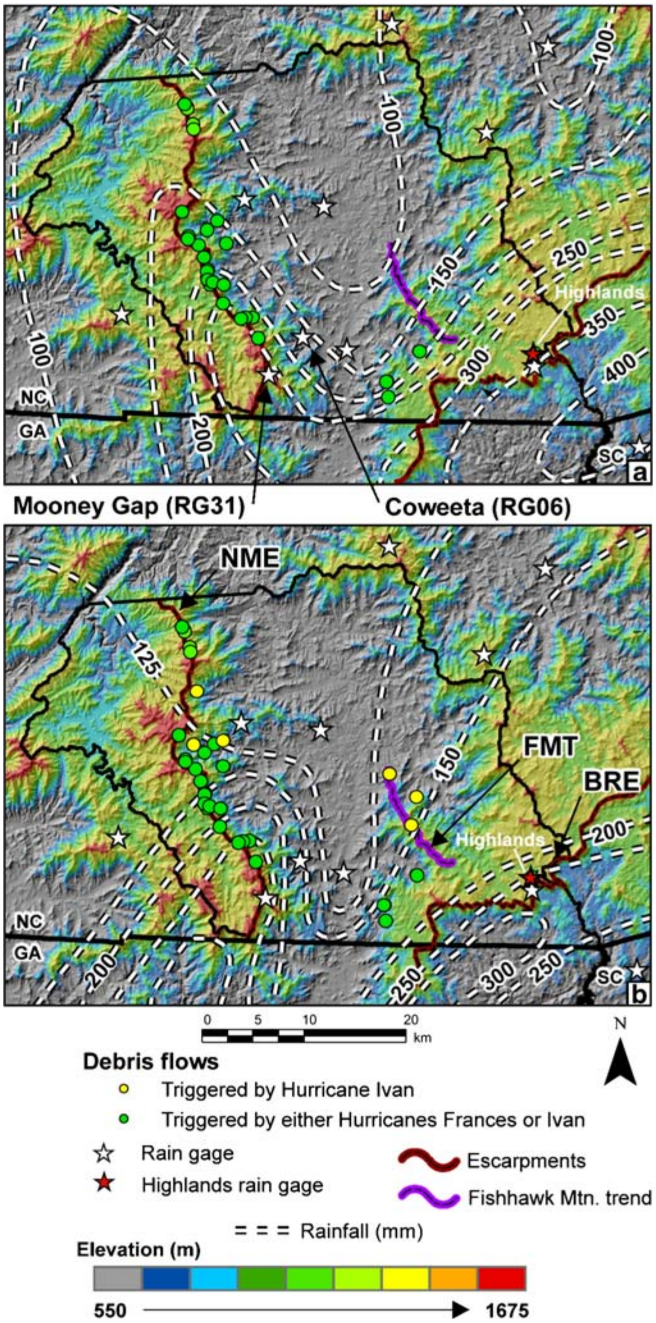


Fig. 5 **a** Map of storm total rainfall for Hurricane Frances, September 6–8, 2004 in the Macon County region, showing debris flows triggered by rainfall from Hurricanes Frances and Ivan and locations of rain gages at the Coweeta main climate station (RG06 elevation, 685 m) and Mooney Gap (RG31 elevation, 1,365 m). **b** Map of storm total rainfall for Hurricane Ivan, September 16–17, 2004 showing debris flows triggered by rainfall from Hurricanes Frances and Ivan. *GA* Georgia, *NC* North Carolina, *SC* South Carolina, *BRE* Blue Ridge Escarpment, *NME* Natahala Mountains Escarpment, *FMT* Fishhawk Mountain trend. Map base is a shaded relief 30 m US Geological Survey DEM

affected western North Carolina, strong and gusty east and southeast winds (between 18 and 27 m/s) accompanied the heavy rain.

Daily rainfall data at five locations in Macon County (Fig. 6) shows that the higher elevation stations had greater rainfall totals than the lower elevation sites. This pattern is characteristic of orographic rainfall distributions featuring enhanced precipitation on windward slopes and diminished precipitation in the lee of higher terrain.

Hydrometeorological conditions near the time of the Peeks Creek and Wayah debris flows

Hurricane Ivan was downgraded to a tropical storm over southern Alabama at 1300 Eastern Standard Time (EST) on September 16 and to a tropical depression (maximum sustained surface wind speed, 17 m/s or less) at 1900 EST on September 16. The estimated initiation time of the Peeks Creek debris flow was 2110 EST on September 16. The center of the low pressure at that time was near the northwestern tip of Georgia. The storm subsequently moved northeast following the Tennessee–North Carolina border. Brief periods of light rain spread into western North Carolina during the morning of September 16, but widespread steady rainfall in Macon County did not begin until approximately 1300 EST, about 8 h before the Peeks Creek event.

Although Ivan was weakening, basic components of the tropical cyclone structure persisted. One prominent feature was a spiral rain band that moved from northeast Georgia into western North Carolina and northwestern South Carolina after 1930 EST on September 16 (Fig. 7). The spiral rain band varied in width from about 25–50 km and included intervals of deep vertical convection in thunderstorms that produced heavy rainfall. The band crossed Macon County in a general south to north direction as it rotated around the center of low pressure. The spiral rain band produced a period of heavy rainfall between 2000 and 2100 EST with the heaviest precipitation occurring over Fishhawk Mountain, where the Peeks Creek debris flow began, at approximately 2050 EST. Radar estimates from the NWS WSR-88D at Greer, SC (KGSP), indicate that possible maximum rainfall rates as high as 147 mm/h occurred during a 15- to 20-min period, based on the reflectivity–rainfall (Z–R) relation, Z=250$R^{1.2}$ (Rosenfeld et al. 1993).

Several sources of error are inherent in measuring precipitation by radar. The lowest-level radar scan (0.5° above the horizontal) at

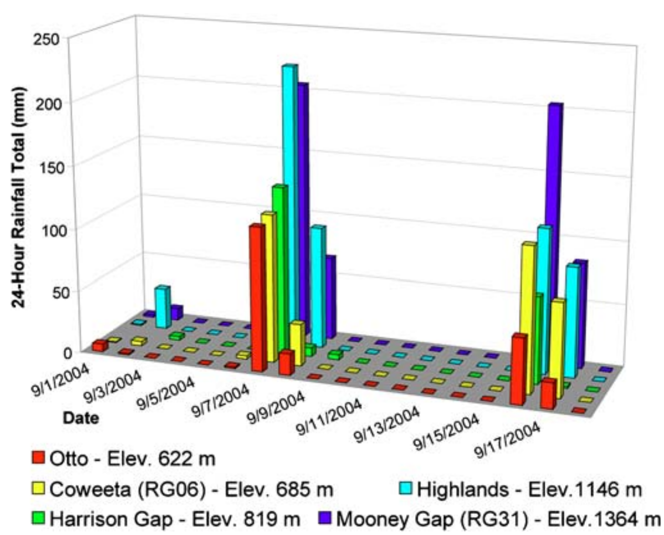


Fig. 6 Bar chart showing daily rainfall totals vs elevation for rainfall from Hurricanes Frances and Ivan measured at rain gage stations in Macon County from September 1–18, 2004. See Fig. 5 for rain gage locations

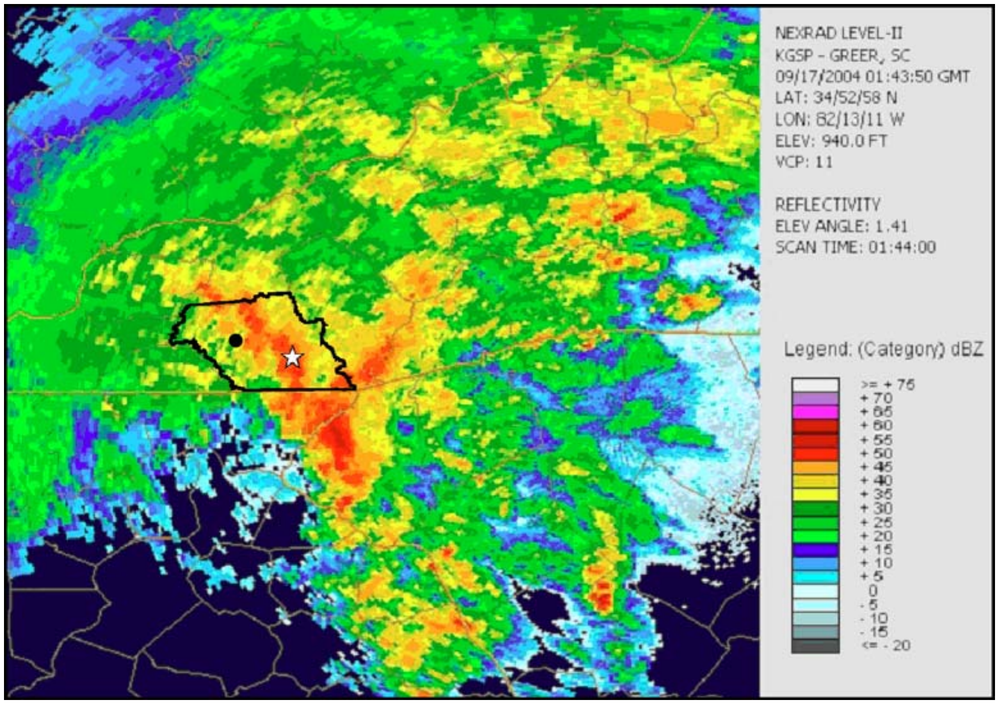


Fig. 7 KGSP WSR-88D 1.4° radar scan showing heavy precipitation in spiral rain band crossing Macon County at 2044 EST (0144 UTC). Precipitation intensity increases as reflectivity (dBZ) transitions from blue to red. The Wayah debris flow (*circle*) occurred about 2030 EST, and the Peeks Creek debris flow (*star*) occurred at about 2110 EST. Image courtesy of NOAA National Climatic Data Center

KGSP was blocked by intervening terrain resulting in a degraded reflectivity return over Macon County. The next highest scan (1.4°) placed the center of the radar beam approximately 3.2 or ~1.8 km above ground level at Fishhawk Mountain. The radar rainfall calculation does not account for below-beam effects (e.g., wind drift, drop coalescence, evaporation). Significant variations of *Z*–*R* relations within precipitation systems also limit the accuracy of the radar measurement of rainfall (Ulbrich and Lee 2002).

The occurrence of rainfall rates at least as high as the radar estimates are realistic in view of rain gage measurements made nearby (Fig. 8). The Mooney Gap station (RG31, ~16 km southwest of Fishhawk Mountain) measured short duration rainfall rates of approximately 90 to 230 mm/h at 1- to 3-min intervals between 2023 and 2031 EST, coincident with the approximate time reported for the Wayah debris flow, ~16 km north–northwest of RG31. The same spiral rain band that produced the high rainfall rates shown in Table 2 crossed Fishhawk Mountain 15 to 20 min later. This time frame also corresponds with the latter part of the 4.65-h period of 25 mm/h cumulative rainfall shown in Fig. 9.

Distribution and characteristics of the September 2004 debris flows

Field studies during 2004–2006 identified or confirmed 171 recent (i.e., identified by field studies, or in 1951 and later imagery) slope movements in Macon County:

– 121 (71%) of the 171 recent slope movements initiated as shallow translational slope failures (i.e., debris–earth slides–debris flows).
– 48 (28%) were attributed to rainfall from the remnants of Frances and Ivan;
– 33 (69%) of the 48 Frances and Ivan slope movements were debris flows (including one earth blowout) that occurred on relatively undisturbed, forested slopes.
– 15 (31%) of the 48 Frances and Ivan slope movements occurred on slopes modified by human activity such as excavations and embankments.
– Field studies identified preexisting debris deposits at all of the 62 relatively recent debris-flow sites (including 28 field-verified Hurricane Frances–Ivan debris flows), indicating that prior, and in many cases multiple, debris flow events had occurred. The total area of mapped debris deposits in the county is ~45 km^2 or ~3.3% of the land area (Fig. 2).
– All 33 debris flows attributed to Hurricanes Frances and Ivan initiated an above-elevation of 775 m; the greatest number occurred between elevations 1,200 and 1,300 m (Fig. 10). Six of the 11 debris flows initiating below 1,075 m occurred in the Wayah reentrant (Fig. 2).

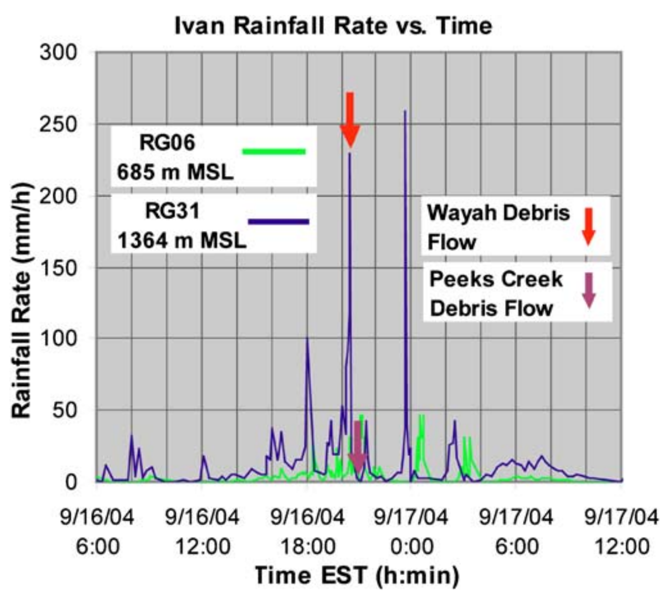


Fig. 8 Chart showing rainfall rate vs time for Ivan at the main climate station (RG06 elevation, 685 m) and Mooney Gap (RG31 elevation, 1,364 m) at the Coweeta Hydrologic Laboratory. *Arrows* indicate the approximate times of the Wayah and Peeks Creek debris flows

Table 2 Table of times, durations, and rainfall rates measured at Mooney Gap (RG31 elevation, 1,364 m) on September 16, 2004 at the Coweeta Hydrologic Laboratory that were produced by the same spiral rain band that crossed Fishhawk Mountain 15–20 min later, just before the initiation of the Peeks Creek debris flow

Rainfall rates–Mooney Gap (RG31)		
Time (EST)	Duration (min)	Rate (mm/h)
2023	5	91
2026	3	117
2028	2	152
2030	2	122
2031	1	227
2037	6	20

At the 28 sites investigated, thin, 0.5- to 2.4-m-thick (1 m average) colluvial soil in sharp contact with bedrock (stained weathering state) is characteristic of soil–bedrock relationships observed in lateral and head scarps. Sporadic bedrock outcrop occurs in the vicinity of most initiation zones. Locally, residual soil derived from completely decomposed bedrock is in transitional contact with partly decomposed bedrock. Soil types range from nonplastic to low plasticity, organic sandy silt to silty sand with gravel and cobbles, and typically vary within individual catchments. Low plasticity and high liquid limit test values characterize the soil samples taken from initiation zones of the Peeks Creek and Wayah debris flows (Fig. 11). Ground slopes adjacent to debris flow initiation zones average 36° and range from 28 to 44°.

Ground slopes at all debris-flow initiation zones generally conform to the orientation of exfoliation (dilation) fracture surfaces in near-surface bedrock. Exfoliation fractures typically form basal surfaces of catchments. Steep to moderately dipping foliations and/or fractures form the lateral bounding surfaces and, in some cases, head scarps of these bedrock-controlled catchments. We observed groundwater seepage along bedrock fractures and at soil–bedrock contacts at several of the debris-flow initiation zones. Minimal root penetration into bedrock was observed along scarps, indicating that roots were confined primarily to the soil zone. Vegetation is generally a mixed conifer–hardwood forest, with an understory of mountain laurel (*Kalmia latifolia*) and rhododendron (*Rhodedendron catawbiense*) present at several sites.

Structural–geomorphic domains

We used bedrock structure and geomorphology to delineate structural–geomorphic domains and subdomains associated with recent debris-flow activity (Figs. 2 and 12) to develop a basis whereby rainfall distributions, rates, and durations that trigger debris flows in these domains can be related to the geologic framework. The domains are the Nantahala Mountains Escarpment (NME), which includes the Wayah reentrant and Poplar Cove subdomains, and the Fishhawk Mountain trend (FMT). In general, the domains are steep, highly dissected, erosional features with abrupt elevation changes and are highlighted by areas modeled as having a high susceptibility to debris flows on a stability index map for Macon County (sheet 2 of Wooten et al. 2006). The stability index map base for Fig. 12 was generated using Stability Index Mapping software developed by Pack et al. (1998) for use in ArcView 3.x™ (and recently in ArcGIS 9.x™). Information on model selection, parameterization, and calibration for the stability index map is given in Wooten et al. (2006) and Witt et al. (2007a, b).

Stream dissection and the formation of colluvial catchments (i.e., debris-flow initiation zones) within these domains are influenced by intersecting lineaments related to brittle and ductile bedrock structures oblique to the overall trends of the domains (Fig. 2). Other researchers in the nearby Blue Ridge and Piedmont have also recognized relationships between landforms, lithology, structure, and topographic lineaments (Acker and Hatcher 1970; Garihan et al. 1988; Clark 1993; Hatcher 1993; and Hatcher et al. 2005). Structural relationships are described in more detail for representative examples of debris flows in each domain.

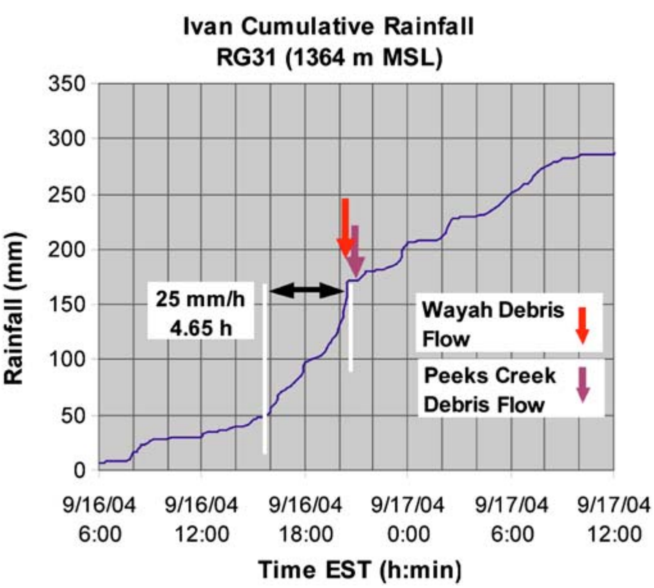


Fig. 9 Graph showing cumulative rainfall vs time for Ivan at the Mooney Gap station (RG31 elevation, 1,364 m) at the Coweeta Hydrologic Laboratory. *Arrows* indicate the approximate times of the Wayah and Peeks Creek debris flows relative to the 4.65-h peak cumulative rainfall rate of 25 mm/h that immediately preceded the debris flows

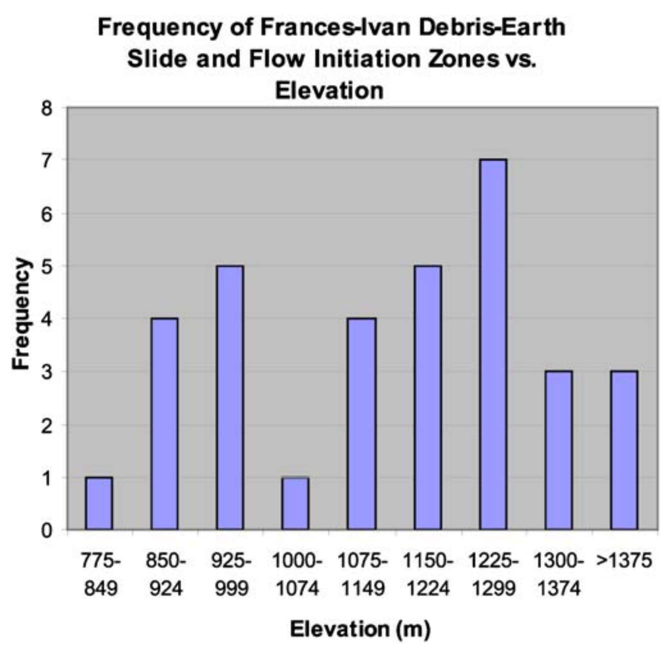


Fig. 10 Bar chart showing frequency of debris-earth slides and flows vs initiation zone elevation. Elevations in Macon County range from 550 to 1,675 m

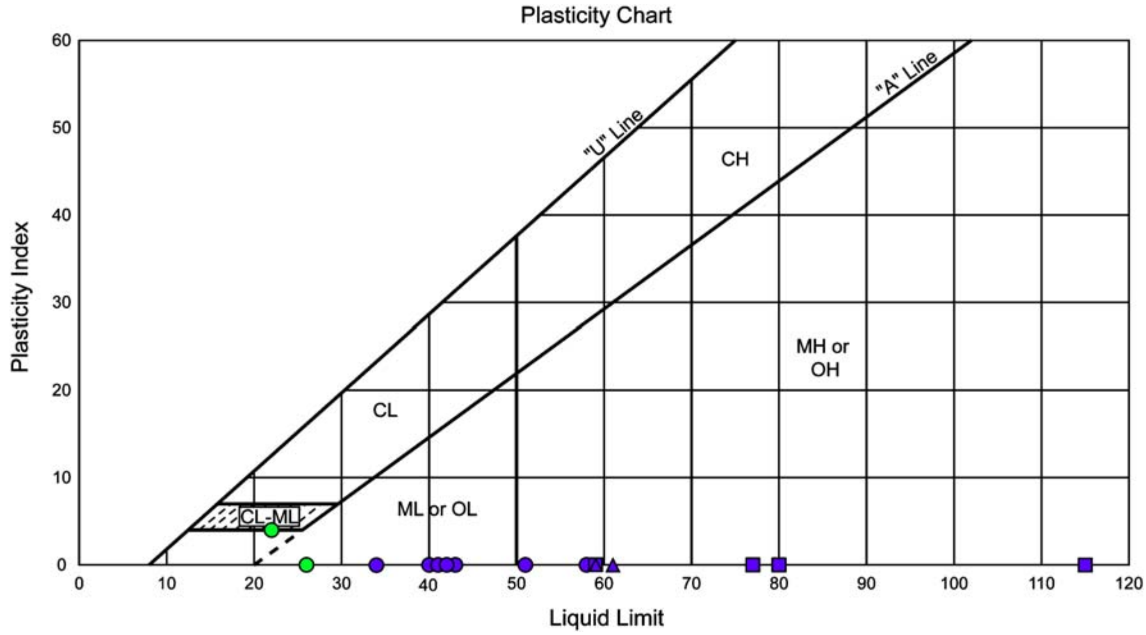
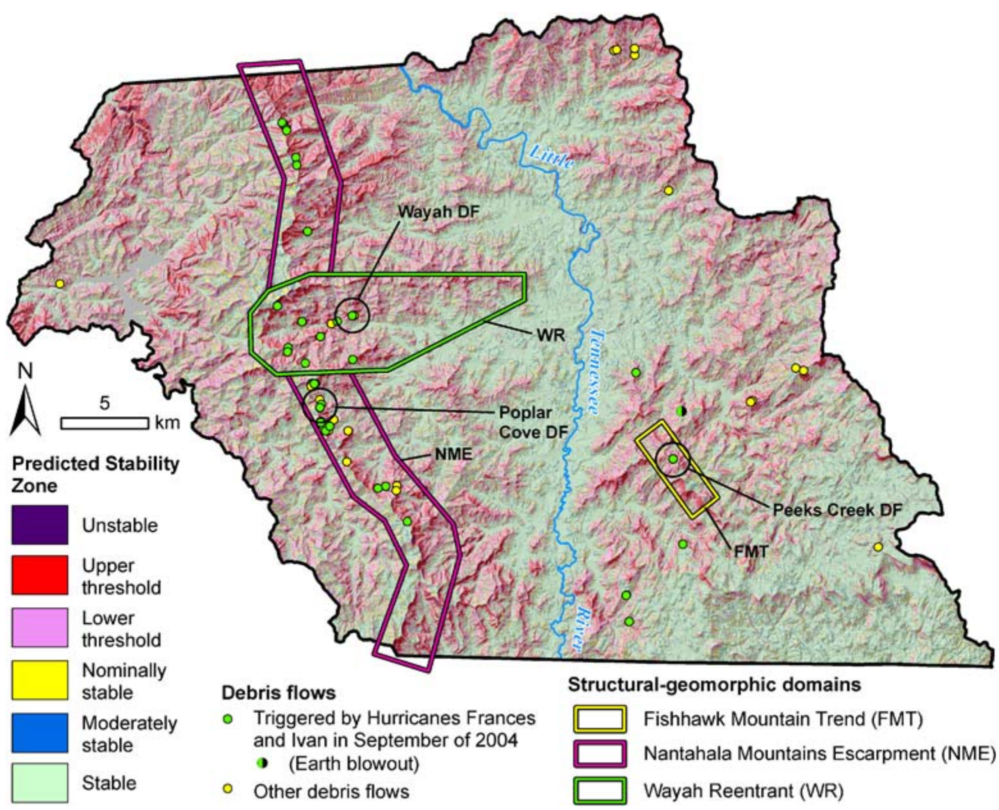


Fig. 11 Chart showing Atterberg limits (ASTM 2002b) for soil samples taken from the initiation zones of the September 16, 2004 Wayah debris flow (*green circles*) and September 16, 2004 Peeks Creek (*blue squares* and *blue triangles*) debris flows. Samples from past debris flow deposits (*blue circles*) exposed in the track of the Peeks Creek debris flow are shown for comparison. All samples shown on the chart are coarse grained soils (>50% retained on no. 200 sieve)

The majority (25 of 33) of Frances–Ivan-related debris flows occurred in reentrants of various scales along the steep eastern flanks of the 25 km-long NME (Figs. 2, 12). Headward erosion along east-flowing tributaries to the Little Tennessee River has resulted in east-facing slopes being generally steeper than those that drain west. The origin of the NME is unknown; however, the NE to NW trends of its different segments parallel numerous topographic lineaments with orientations similar to measured bedrock fractures (Fig. 2). The overall NNW trend of the NME cuts across the northeast and east–west strike of bedrock units; therefore, its

Fig. 12 Structural–geomorphic domains in relationship to debris flow locations for Macon County. Map base is a shaded relief 6 m LiDAR DEM overlain by a stability index map (modified from sheet 2 of Wooten et al. 2006). Unstable (*purple*) and upper threshold (*red*) stability zones portrayed on the map highlight the topographic features of the structural–geomorphic domains discussed in the text



origin post-dates the Early- to Mid-Paleozoic ductile deformation reflected in the map patterns of geologic terranes (Fig. 2).

The highest frequencies of Frances–Ivan debris flows occur in the Wayah reentrant (9) and Poplar Cove (7) subdomains of the NME (Figs. 2, 12). Metasedimentary and metaigneous rocks of the Cartoogechaye terrane underlie both areas. Reentrants along the NNW-trending NME are likely controlled by NE- and WNW- to ENE-trending lineaments related to bedrock structures intersecting the NME (Fig. 2). The Wayah reentrant is the largest reentrant in the NME in Macon County. Bedrock units that strike E–W control the orientation of the Wayah reentrant and the similar linear trend of Wayah Creek. Catchments and tributary drainages to Wayah Creek trend parallel to NS- and NW-striking fracture systems. In the Poplar Cove area and elsewhere along the NME, bedrock units strike mostly NE, nearly orthogonal to the trend of the NME (Fig. 2).

The Peeks Creek debris flow initiated on a NE-facing slope of Fishhawk Mountain. At 1,447 m, Fishhawk Mountain is the highest among a range of peaks referred to as the Fishhawk Mountain Trend (FMT). The NNW trend of these peaks is subparallel to that of the NME 19 km to the west (Figs. 2, 12). NE-trending lineaments that correspond to layering, foliations, and ductile shear zones within metasedimentary and metaigneous rocks are oblique to the NNW trend of the FMT.

Wayah debris flow

Residents present within 50 m of the Wayah debris-flow path reported that the failure occurred during Hurricane Ivan at about 2030 EST, on September 16, 2004. This time coincides with the 13-min period of high intensity rainfall (90 to 229 mm/h) at Mooney Gap, 15 km to the southeast (Table 2, Fig. 8). The debris flow initiated on south-facing 40–45° slopes at elevation 914 m within the Wayah reentrant (Figs. 2, 12). The 640 m-long track terminated in the floodplain of Wayah Creek (Fig. 13) at an elevation of 700 m, destroying a barn. Exposures along the track and in incised debris-fan deposits at the toe of the slope indicate that at least four previous debris-flow events pre-date the September 2004 debris flow (Fig. 14).

Colluvial soil is in sharp contact with bedrock, in contrast with the more gradual transition from residual soil to parent bedrock also observed in the initiation zone. NNW striking, a high-angle E-dipping fractures intersect low-angle exfoliation fractures subparallel to the ground surface to form a wedge-shaped colluvial

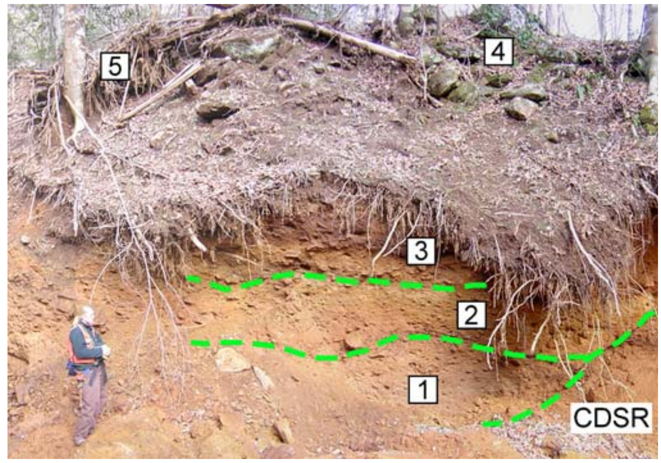


Fig. 14 Multiple debris flow deposits exposed in the scoured channel of the September 16, 2004 (Ivan) Wayah debris flow (see Fig. 13). Numbered deposits show relative ages of debris deposits, *1* oldest and *5* youngest (large woody debris from the September 16, 2004 debris flow). A cut-and-fill structure is preserved where unit 1 eroded into CDSR (completely decomposed bedrock)

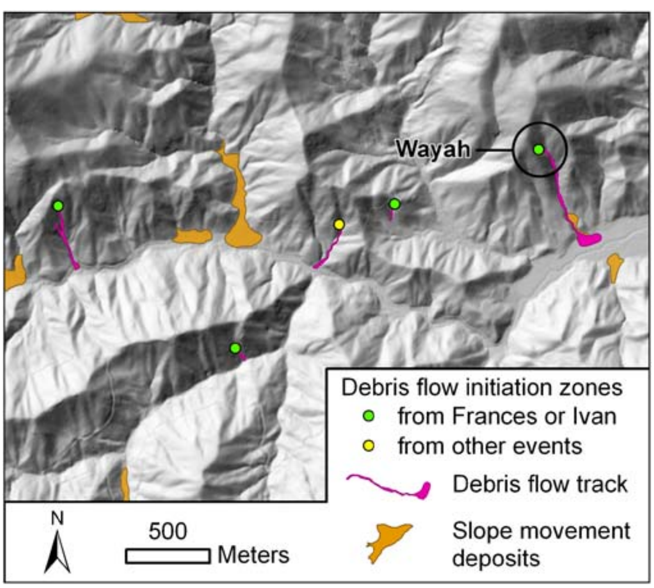


Fig. 13 Location map for the September 16, 2004 (Ivan) Wayah debris flow and other debris flows in the area. Map base is a shaded relief 6 m LiDAR DEM

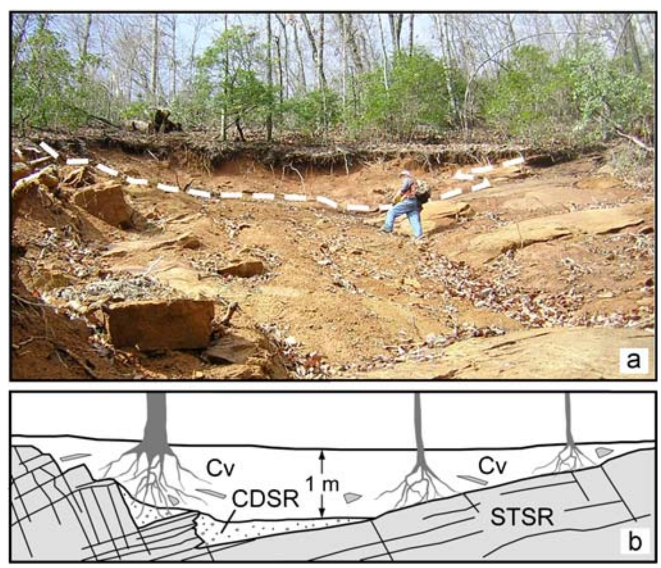


Fig. 15 **a** Photograph of the September 16, 2004 (Ivan) Wayah debris flow initiation zone. *White-dashed* approximates the base of the colluvial wedge exposed in the head scarp. **b** Schematic cross section through the debris flow initiation zone showing the wedge-shaped colluvial catchment (view looking up slope). *Cv* Colluvial soil, *CDSR* completely decomposed bedrock, and *STSR* stained bedrock. High-angle fractures dip east and low-angle exfoliation fractures dip southwest, creating a bedrock-controlled wedge. North-dipping metamorphic foliation and compositional layering are in the plane of the section. View looking up slope (north)

catchment (Fig. 15). Aligned with the Wayah reentrant, foliation, and compositional layering in the granulite grade, garnet, quartzo–feldspathic gneiss, and interlayered garnet, amphibole gneiss strike ENE, and dip 55–85° north (Eckert 1984; Lesure and Force 1993).

Poplar Cove debris flows

The Poplar Cove subdomain of the NME is significant because seven Hurricane Frances–Ivan debris flows occurred there in 2004, and two debris flows occurred there when the remnants of Hurricane Opal passed over the area during October 3–5, 1995 (USFS, personal communication). The NCGS investigated the Opal debris flows in 1998, and Fig. 16 shows the two debris flows that merged into a single track. Storm total rainfall for Opal recorded at Mooney Gap (RG31) was 274 mm over 52 h, with short duration, peak rainfall rates of 213 and 137 mm/h at 0029 and 0038 EST, respectively, on October 5, 1995.

A Francis–Ivan debris-flow scar (Fig. 17) exposes intensely foliated to mylonitic felsic and mafic gneiss with mylonitic foliation and compositional layering dipping NW (oblique to the slip surface). Steep N-striking, closely spaced exfoliation fractures dip east (down slope), forming the main slip surface. A 1 m-thick tonalite–trondhjemite dike intrudes the country rock in a steep NE-striking, SE-dipping ductile shear zone. The intersection of the dike and the exfoliation fracture forms a wedge-shaped catchment. Approximately 10 km southwest of the Poplar Cove area, Hatcher et al. (1978) also recognized several ductile shear zones. The NE strike of these zones follow several lineaments (Fig. 2) that project NE into the area of the Poplar Cove debris flows. Elsewhere, such shear zones are found in several Frances–Ivan debris-flow initiation zones, including Peeks Creek. These observations suggest that the ductile shear zones may be factors in the development of catchments related by enhancing rock weathering and bedrock-controlled groundwater flow in the shallow subsurface.

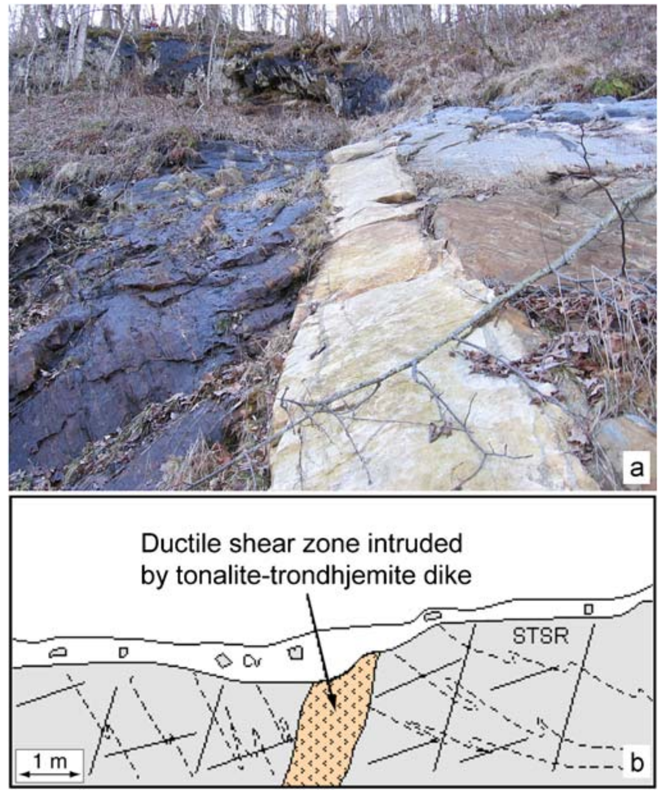


Fig. 17 **a** Photograph of the September 2004 (Hurricanes Frances–Ivan) Poplar Cove debris flow initiation zone. **b** Schematic cross-section through the debris flow initiation zone. *Cv* Colluvial soil and *STSR* stained bedrock. Slip plane is an east-dipping exfoliation fracture surface. Compositional layering–foliation in mylonitic gneiss dips northwest (*dashed lines* in schematic); ductile shear zone fractured and intruded by unfoliated tonalite–trondhjemite dike strikes northeast (*out of the photo*) and dips southeast. These structural features and steeply dipping, N–S striking fractures (*observed at top of photo in the head scarp*) create a bedrock-controlled wedge. View looking up slope (west)

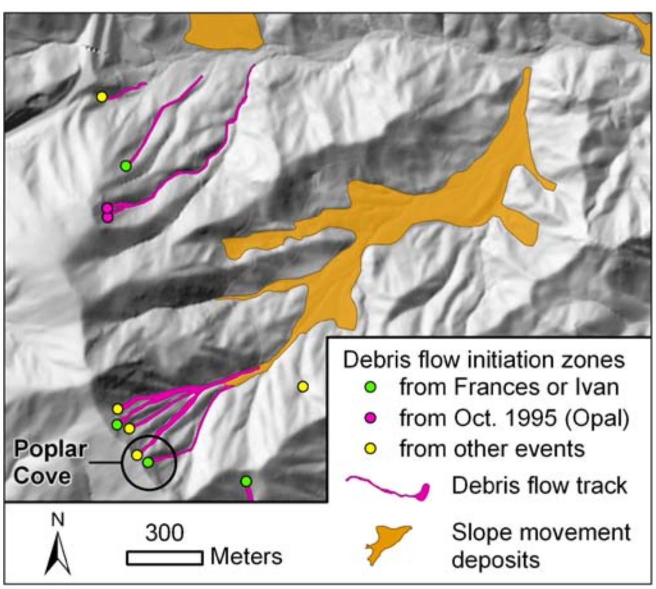


Fig. 16 Location map for the October 1995 (*Opal*) debris flow and the September 2004 (Hurricanes Frances–Ivan) debris flows in the Poplar Cove area. Map base is a shaded relief 6 m LiDAR DEM

Peeks Creek debris flow

Residents in the Peeks Creek community reported that the debris flow occurred during Hurricane Ivan on September 16, 2004 at about 2110 EST. The debris flow traveled 3.6 km down slope to the Cullasaja River, leaving 5 dead, 2 victims seriously injured, and 16 homes destroyed (Figs. 18, 19). Calculated estimates of peak velocity (14.8 m/s) and discharge (1,275 to 1,980 m^3/s) explain why the debris flow was so destructive (Latham et al. 2005 and 2006).

The Peeks Creek debris flow began at an elevation of 1,347 m on the NE side of the Fishhawk Mountain within the FMT (Fig. 12). The NNW trend of the FMT parallels numerous other topographic lineaments that likely relate to NNW-striking fracture zones (Fig. 2). Fishhawk Mountain occurs along a segment of the FMT that is finely dissected by NE-trending lineaments that likely parallel layering, foliations, fractures, and ductile shear zones proximal to the Chattahoochee fault (Lamb 2001), a ductile thrust fault that forms the boundary between the Dahlonega Gold Belt and Tugaloo terranes (Fig. 2).

The debris flow initiated on 33–55° slopes within a shallow, trough-shaped colluvial catchment, leaving a 125-m-long and 30 m-wide bedrock scar (Fig. 19a,b). Exfoliation fractures dip 35 to 53° NE

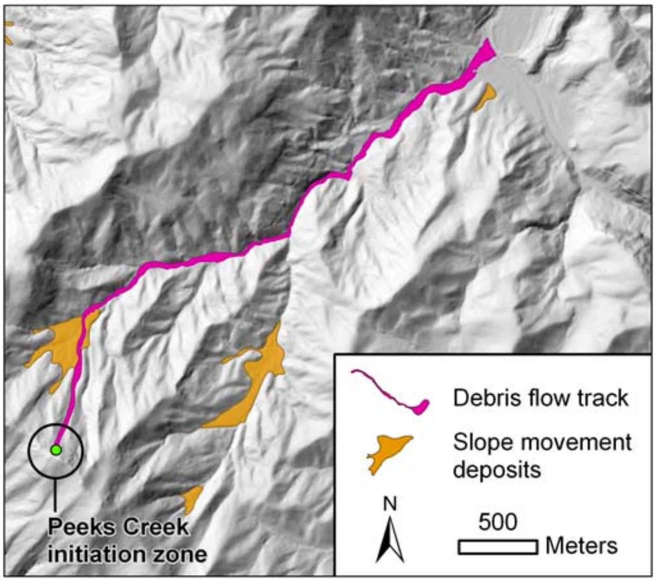


Fig. 18 Location map for the September 16, 2004 (Ivan) Peeks Creek debris flow. Map base is a shaded relief 6 m LiDAR DEM

and control the general slope of the ground surface. Colluvial soil (0.3- to 1.2-m-thick) ranges from matrix-supported silty sand to sandy silt with organics and is locally clast-supported by gravel- to cobble-sized subangular rock fragments. Foliation and compositional layering in the isoclinally folded, interlayered sequence of migmatitic, biotite–muscovite schist, and metagraywacke strike NE and dip 70° east. These fabrics form lateral bedrock walls within the larger catchment (Fig. 19b). Two steep, SE-dipping tonalite–trondhjemite dikes intrude and cross-cut the metasedimentary bedrock. Groundwater seepage was frequently observed along the exposed soil–bedrock contact and along the intersections between exfoliation fractures and high-angle NW-striking tectonic fractures (Fig. 19b). Deposits exposed along the length of the track indicate that at least two debris flows occurred before the September 2004 event. Clingman (1877) reported "water spouts" on the SW and NE sides of Fishhawk Mountain in 1876 that, from his description, were likely debris flows.

Discussion

Not knowing whether it was Hurricane Frances or Ivan that triggered many of the 33 debris flows that occurred during the two storms complicates the interpretation of the effects of rainfall rate and duration on debris-flow initiation. Furthermore, rainfall from Frances 9 days before Ivan resulted in high antecedent moisture conditions for the Wayah and Peeks Creek debris flows, subsequently initiated by rainfall from Ivan. The peak rainfall rates related to the Wayah and Peeks Creek debris flows of 150 to 230 mm/h at 1- to 3-min intervals (Table 2) are higher but of significantly shorter duration than the 25–100 mm/h rates for

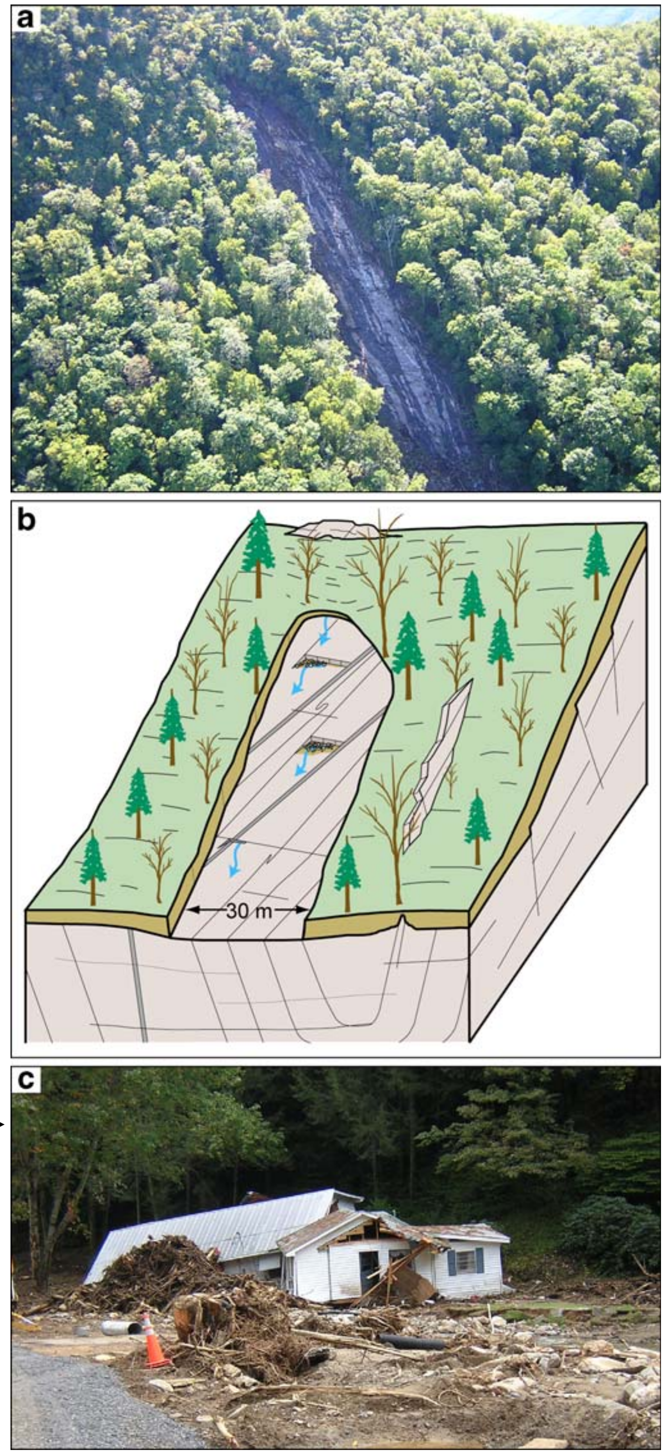


Fig. 19 **a** September 19, 2004 photograph of the September 16, 2004 (Ivan) ▶ Peeks Creek debris flow initiation zone (view looking southwest). *Dark areas* on the bedrock surface are from shallow groundwater discharge along the soil-bedrock contact and bedrock fractures. Length of the bedrock scar is approximately 125 m. **b** 3D 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 form the slip surface between soil and bedrock. *Blue arrows* indicate areas of observed seepage. *Dark gray* features are unfoliated tonalite–trondhjemite dikes. **c** Homes damaged by the Peeks Creek debris flow. The debris flow carried the house on the *right* into the *lower house*. Upstream is to the *right*

several consecutive hours that triggered 629 debris flows in Madison County, VA, in June 1995 (Wieczorek et al. 2000).

The average rate of 25 mm/h for the 4.65-h period of peak cumulative rainfall during Ivan (Fig. 9) falls at the lower end of the range of rainfall rate given by Wieczorek et al. (2000) for the 1995 Virginia storm. This difference is not surprising given that the 1995 Virginia storm triggered nearly 600 more debris flows than initiated by Frances and Ivan in Macon County. Wieczorek et al. (2004) reported that 254 mm of rain within 6 h (42 mm/h average) triggered 763 debris flows in August 1940 in the Deep Gap area of Watauga County, NC. Neary and Swift (1987) concluded that rainfall rates on the order of 90–100 mm/h (188 mm storm total) initiated debris flows in the Bent Creek area near Asheville, NC, during a November 3–5, 1977 storm, but they do not report durations associated with these rates. The peak rainfall rate at Mooney Gap (RG31) during Opal in 1995 was 214 mm/h with duration of 9 min or less; however, the temporal relationship between this peak and 1995 Poplar Cove debris flows is unknown.

Estimates of the recurrence intervals of debris flows and frequencies of debris-flow events in the Southern Appalachians are inherently scale-dependent. Although the ages of the debris deposits mapped in Macon County (Fig. 2) are not known, our field studies identified preexisting debris deposits at all of the 62 relatively recent debris flow sites investigated. Kochel (1987) describes debris flows from the 1969 event in Nelson County, VA, that affected areas with preexisting Holocene and pre-Holocene debris fan deposits. Kochel (1990) also reports that, in the nearby Great Smoky Mountains, characteristic recurrence intervals for debris flows on specific fans are on the order of 400 to 1,600 years. Our work indicates that, in recent times, debris flows can recur within years in small watersheds (2–10 km^2) located in structural–geomorphic domains prone to debris flows. Debris-flow events summarized by Clark (1987) and Witt (2005) demonstrate that the frequency of major debris-flow events in the region is on the order of every two to three decades.

In relationship to elevation, the highest frequency of Frances–Ivan debris flows occurred between elevations 1,200 and 1,300 m (Fig. 10), with the highest concentration of the debris flows within NME structural–geomorphic domain. This debris-flow distribution combined with the generally higher rainfall amounts measured at higher elevations suggests that orographic enhancement of rainfall contributed to the increased numbers of debris flows at higher elevations. Six of the 11 debris flows that initiated below 1,075 m occurred in the Wayah reentrant, a subdomain of NME. The topography of the Wayah reentrant may have enhanced rainfall both at higher and lower elevations, resulting in a cluster of debris flow below 1,075 m. Bedrock structure and enhanced weathering may result in the overall increase in debris-flow susceptibility within this major E–W trending structural domain. The Wayah reentrant may be a small-scale analog of the Elk Creek reentrant in Watauga County discussed below.

The high frequency of August 1940 debris flows along the BRE in Watauga County (Wieczorek et al. 2004) also illustrates that certain structural–geomorphic domains are regional landscape features prone to debris-flow activity. The BRE, like the smaller scale NME in Macon County, is a steep erosional feature with abrupt elevation changes that favor orographic enhancement of rainfall, especially when they are windward slopes. Additionally, the Elk Creek reentrant in the BRE (Deep Gap area), where over 600 debris flows occurred in August 1940, is where WNW-trending ductile faults (Bryant and Reed 1970) and other WNW-trending topographic lineaments intersect the NE-trending BRE (NCGS unpublished data).

Our observations support the concept of bedrock structural control on individual catchment formation and shallow groundwater flow in bedrock fracture systems. Although his work focused on the influence of bedrock on the orientations of first-order streams in the Coweeta area, Grant (1988) concluded that intersecting lenticular dilation (exfoliation) fractures and downslope-striking tectonic fractures can create small depressions in bedrock surfaces. Water accumulates in such depressions, enhancing weathering and in situ soil formation, and eventually leads to a debris avalanche (flow) initiated by excess hydrostatic pressure from water-transmitting bedrock fracture systems during peak rainfall conditions.

Conclusions

Rainfall rates of 150 to 230 mm/h for 15- to 20-min durations can trigger debris flows in structural–geomorphic domains in the region that are prone to debris flows, especially when antecedent moisture conditions are high, as was the case for the back-to-back storms of September 2004. Historically, the scenario of successive storms within 6 to 20 days of each other has occurred three times between 1916 and 2004 in the region, yielding an average frequency of once every 29 years. Six documented events produced debris flows in Macon County between 1876 and 2004 (once every 23 years), with the 33 debris flows of September 2004 being the largest number of debris flows reported for a single event. Within the Poplar Cove subdomain of the NME, debris flows occurred in 1995 and 2004, and in the Fishhawk Mountain area (FMT), debris flows were reported in 1876 and 2004.

Prehistoric (and possibly historic) debris deposits identified at 62 recent debris flow locations (28 are Frances–Ivan sites) demonstrate repeated occurrence of debris flows in the region. Although the recurrence of debris flows within individual catchments may be on the order of hundreds or thousands of years, the recurrence of debris flows within small watersheds (~1–10 km^2) in the region can be on the order of years or decades.

Bedrock structure at three spatial scales influences the development of landscapes prone to debris flows. Brittle bedrock structures that trend N–S, NW–SE, and E–W exert a strong influence on the origin and configuration on the ~100 km^2 Nantahala Mountains Escarpment (NME) and the ~8 km^2 Fishhawk Mountain trend (FMT) structural–geomorphic domains. Topographic lineaments coincident with orientations of ductile and brittle structures influence the formation of reentrants in the NME and FMT, forming watersheds on the order of ~1–10 km^2 where debris flows occur. At outcrop scales, intersecting ductile and brittle bedrock structures influence the development of bedrock-controlled colluvial catchments and shallow groundwater flow within the small-scale watersheds.

The orographic effects of structural–geomorphic domains can enhance both storm rainfall totals and rainfall rates, each of which generally increases with elevation. This effect, combined with intersecting bedrock structures that favor the development of colluvial catchments, enhances the debris-flow susceptibility of the NME and the FMT in Macon County and, on a regional scale, the BRE, especially when such features are windward slopes during cyclonic tropical weather systems that track to their west.

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References

Acker LL, Hatcher RD Jr (1970) Relationships between structure and topography in northwest South Carolina. Geologic notes, Division of Geology, State Development Board, Columbia, SC 14(2):35–48

American Society for Testing and Materials (2002a) Standard practice for description and identification of soils (visual–manual procedure) Designation D2488–02. In: Annual book of ASTM standards, v. 04.08, soil and rock, building stones, geotextiles. American Society for Testing and Materials, Philadelphia

American Society for Testing and Materials (2002b) Standard test methods for liquid limit, plastic limit, and plasticity index of soils designation D4318–05. In: Annual book of ASTM standards, v. 04.08, Soil and rock, building stones, geotextiles. American Society for Testing and Materials, Philadelphia

Bogucki DJ (1976) Debris slides in the Mt. LeConte area, Great Smoky Mountains National Park, U.S.A. Geogr Ann (58A):179–191

Bryant B, Reed JC Jr (1970) Geology of the Grandfather Mountain window and vicinity, North Carolina and Tennessee. US Geological Survey Professional Paper 615

Clark GM (1987) Debris slide and debris flow historical events in the Appalachians south of the glacial border. In: Costa JE, Wieczorek GF (eds) Debris flows, avalanches: process, recognition, and mitigation. Geol Soc Am Rev Eng Geol 7:125–138

Clark GM (1993) Quaternary geology and geomorphology of part of the Inner Piedmont of the southern Appalachians in the Columbus Promontory upland area, southwestern North Carolina and northwestern South Carolina. In: Davis TL, Hatcher RD Jr (eds) Studies of Inner Piedmont geology with a focus on the Columbus Promontory. Carolina Geol Soc Field Trip Guidebook, pp 67–84

Clark GM, Ryan PT (1987) Debris slides and debris flows on Anakeesta Ridge, Great Smoky Mountains National Park, Tennessee. US Geological Survey Circulation 1008

Clingman TL (1877) Water Spouts. In: Nichols J (ed) Selections from the speeches and writings of the Honourable Thomas L. Clingman of North Carolina with additions and explanatory notes. Raleigh, NC, pp 68–77

Cruden DM, Varnes DJ (1996) Landslide types and processes. In: Turner AK, Schuster RL (eds) Landslides investigation and mitigation, special report 247, Transportation Research Board. National Research Council, Washington, pp 36–75

Eckert JO Jr (1984) Stratigraphy, structure, and metamorphism of the east half of the Wayah Bald quadrangle, North Carolina: evidence for Paleozoic granulite facies metamorphism in the southern Appalachians. MS thesis, University of South Carolina

Garihan JM, Ranson WA, Preddy MS, Hallman TD (1988) Brittle faults, lineaments, and cataclastic rock in the Slater, Zirconia, and part of the Saluda 71/2-minute quadrangles, northern Greenville County, South Carolina, and adjacent Henderson and Polk Counties, North Carolina: In: Secor D T (ed) Southeastern geological excursions: Geological Society of America Southeastern Section Guidebook, pp 266–312

Grant WH (1988) Debris avalanches and the origin of first-order streams. In: Swank WT, Crossley DA Jr (eds) Ecological studies, v. 66: forest hydrology and ecology at Coweeta. Springer, New York, pp 103–110

Hack JT (1982) Physiographic divisions and differential uplift in the Piedmont and Blue Ridge. US Geological Survey Professional Paper 1265

Hack JT, Goodlett JC (1960) Geomorphology and forest ecology of a mountain region in the Central Appalachians. US Geological Survey Professional Paper 347

Hatcher RD Jr (1993) Perspective on tectonics of the Inner Piedmont, southern Appalachians. In: Davis TL, Hatcher RD Jr (eds) Studies of Inner Piedmont geology with a focus on the Columbus Promontory: Carolina Geological Society field trip guidebook, pp 1–16

Hatcher RD Jr, Mershat CE, Milici RC, Wiener LS (1978) Field trip 1—a structural transect in the southern Appalachians, Tennessee and North Carolina. In: Field trips in the Southern Appalachians. Tennessee Division of Geology Report of Investigation 37: 5–52

Hatcher RD Jr, Merschat AJ, Thigpen JR (2005) Blue Ridge primer. In: Hatcher RD Jr, Merschat AJ (eds) Blue Ridge geology geotraverse east of the Great Smoky Mountains Park, western North Carolina: Carolina Geological Society field trip guidebook, pp 1–24

Hursh CR (1941) The geomorphic aspects of mudflows as a type of accelerated erosion in the Southern Appalachian. American Geophysics Union Reports and Papers, General Assembly, pp 253–254

Kochel RC (1987) Holocene debris flows in central Virginia. In: Costa JE, Wieczorek GF (eds) Debris flows, avalanches: process, recognition, and mitigation. Geol Soc Am Rev Eng Geol 7:139–155

Kochel RC (1990) Humid fans of the Appalachian Mountains. In: Rachocki AH, Church M (eds) Alluvial Fans: A field approach. Wiley, New York, pp 109–129

Lamb DD (2001) Geology of the Scaly Mountain quadrangle, emphasizing the structures, timing and emplacement mechanisms for the Rabun granodiorite, eastern Blue Ridge, southwestern North Carolina. MS thesis, University of Tennessee

Latham RS, Wooten RM, Reid JC (2005) Preliminary findings on the September 16, 2004 debris flow at Peeks Creek, Macon County, North Carolina. In: Proceedings of the 56th Highway Geology Symposium, Wilmington, NC, 4–6 May 2005, pp 277–290

Latham RS, Wooten RM, Witt AC, Brame S (2006) Investigation of the Peeks Creek debris flow of September 2004, Macon County, North Carolina. 14th Annual David S. Snipes/ Clemson Hydrogeology Symposium Field Trip Guidebook, Clemson University

Lesure FG, Force ER (1993) Preliminary geology and geochemistry of rocks and saprolite in part of the Franklin quadrangle, North Carolina. US Geological Survey Map MF-2223, scale 1:24,000

Merschat AJ, Stahr DW III, Hatcher RD Jr, Cyphers SR (2006) Detailed geologic mapping in the Great Balsam and Cowee Mountains, central and eastern Blue Ridge, western North Carolina. Geol Soc Am 38:166

Mills HH (1998) Surficial deposits and landforms on the south and west piedmont slopes of Roan Mountain, Mitchell County, North Carolina. In: Southeastern Friends of the Pleistocene 1998 Field Trip Guidebook, pp 9–34

Mills HH, Allison JB (1995) Weathering rinds and the evolution of Piedmont slopes in the southern Blue Ridge Mountains. J Geol 103:379–394

National Oceanic and Atmospheric Administration (2004) Storm data. National Climatic Data Center 46:9

Neary DG, Swift LW Jr (1987) Rainfall thresholds for triggering a debris avalanching event in the southern Appalachian Mountains. In: Costa JE, Wieczorek GF (eds) Debris flows, avalanches: process, recognition, and mitigation. Geol Soc Am Rev Eng Geol 7:81–92

North Carolina Geological Survey (1985) Geologic map of North Carolina, scale 1:500,000 (out of print). http://www.gis.enr.state.nc.us/sid/bin/index.plx?client=zGeologic_Maps&site=9AM

Otteman R (2001) Using GIS to model debris flow susceptibility for the Bent Creek Experimental Forest near Asheville, North Carolina. M.S. thesis, East Carolina University, Greenville, NC

Pack RT, Tarboton DG, Goodwin CN (1998) Terrain stability mapping with SINMAP, technical description and users guide for version 1.00, 4114–0, Terratech Consulting Ltd, Salmon Arm, British Columbia

Pomeroy JS (1991) Map showing late 1977 debris avalanches southwest of Asheville, western North Carolina. U.S. Geological Survey Open File Report 91–334, map scale 1:24,000

Prowell DC (2000) The last Appalachian orogeny: evidence for Cenozoic tectonism and uplift of mountains in the eastern United States. Geol Soc Am 32(2):A–67 Southeast Section abstracts with programs

Rosenfeld D, Wolff DB, Atlas D (1993) General probability-matched relations between radar reflectivity and rain rate. J Appl Meteor 32:50–72

Scott RC Jr (1972) Geomorphic significance of debris avalanching in the Appalachian Blue Ridge Mountains. PhD thesis, University of Georgia, Athens, Georgia

Tennessee Valley Authority (1964) Floods on the French Broad River, Davidson River, King Creek, Nicholson Creek in the vicinity of Brevard, NC. Report no. 0-6373, TVA Division of Water Control Planning, Knoxville, TN

Ulbrich CW, Lee LG (2002) Rainfall characteristics associated with the remnants of Tropical Storm Helene in upstate South Carolina. Weather Forecasting 17:1257–1267

US Geological Survey (1949) Floods of August 1940 in the Southeastern States. US Geological Survey Water Supply Paper 1066

Wieczorek GF, Morgan BA, Campbell RH (2000) Debris flow hazards in the Blue Ridge of Central Virginia. Environ Eng Geosci VI(1):3–23

Wieczorek GF, Mossa GS, Morgan BA (2004) Regional debris flow distribution and preliminary risk assessment from severe storm events in the Appalachian Blue Ridge Province, USA. Landslides 1:53–59

Williamson DA (1984) Unified rock classification system. Bull Assoc Eng Geol XXI: 253–254

Witt AC (2005) A brief history of debris flow occurrence in the French Broad River Watershed, western North Carolina. N C Geogr 13:58–82

Witt AC, Smith MS, Latham RS, Douglas TJ, Gillon KA, Fuemmeler SJ, Bauer JB, Wooten RM (2007a) Life, death and landslides: the August 13–14, 1940 storm event in Watauga County, North Carolina. Geol Soc Am 39(2):76 Southeast Section Abstracts with programs

Witt AC, Wooten RM, Latham RS, Fuemmeler SJ, Gillon KA, Douglas TJ, Bauer JB (2007b) A comparative study of two GIS slope stability models for use in the N.C. landslide hazard mapping program. In: Schaefer VR, Schuster RL, Turner AK (eds) Conference presentations 1st North American landslide conference, Vail Colorado. Assoc Eng Env Geol Special Publication 23:387–400

Wooten RM, Reid JC, Latham RS, Medina MA, Bechtel R, Clark TW (2005) An overview of the North Carolina Geological Survey's geologic hazards program—phase I: In: Proceedings of the 56th Highway Geology Symposium, Wilmington, NC, 4–6 May 2005, pp 291–307

Wooten RM, Latham RS, Witt AC, Fuemmeler SJ, Gillon KA, Douglas TJ, Bauer JB (2006) Slope movement hazard maps of Macon County, North Carolina, N.C. Geological Survey Geologic Hazards Map Series 1, 3 sheets, map scale 1:48,000

Wooten RM, Latham RS, Witt AC, Gillon KA, Douglas TJ, Fuemmeler SJ, Bauer JB, Reid JC (2007) Landslide hazards and landslide hazard mapping in North Carolina: In: Schaefer VR, Schuster RL, Turner AK (eds) Conference presentations 1st North American landslide conference, Vail Colorado. Assoc Eng Environ Geol Special Publication 23:458–471

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