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Investigation of the geologic controls on rockfall hazard potential in Tennessee

Christopher J. Vandewater

To the Graduate Council:

I am submitting herewith a thesis written by Christopher J. Vandewater entitled "Investigation of the geologic controls on rockfall hazard potential in Tennessee." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Geology.

William M. Dunne, Major Professor

We have read this thesis and recommend its acceptance:

Robert D. Hatcher Jr., Eric Drumm, Matthew Mauldon

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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INVESTIGATION OF THE GEOLOGIC CONTROLS ON ROCKFALL HAZARD POTENTIAL IN TENNESSEE

A Thesis Presented for
The Master of Science Degree
The University of Tennessee, Knoxville

Christopher J. Vandewater
May 2003

DEDICATIONS

I dedicate this work to my parents, James and Theresa, for their unconditional support, encouragement, and guidance throughout my life. For bestowing me with the opportunity to realize my dreams and achieve my goals, I am truly grateful.

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I would like to thank and acknowledge the following for their contributions to this research and helping me complete the Master of Science in Geological Sciences: Dr. William Dunne, for being a good advisor and always keeping me moving forward and for his contributions as a primary investigator on this project; Dr. Eric Drumm and Dr. Matthew Mauldon for providing me insight about how engineers think and their contributions as primary investigators on this project; Vanessa Bateman for her role as a primary investigator and the Tennessee Department of Transportation for funding this project; Dr. Robert Hatcher for being a helpful committee member with valuable knowledge of Tennessee geology; Harry Moore for his contribution and use of his computer at the TDOT Region 1 facility; Derrick Bellamy and Brett Rose for their technical contributions to this project; and Chris Heiny, Patrick Wheatley, and David Settles for their assistance during field data collection. I have enjoyed working with all of you.

ABSTRACT

Rockfall from roadcuts are a major hazard and pose problems for transportation agencies across the country. In the context of rockfall hazard management, however, no consensus exists about the role of geology in assessing rockfall hazard. This study investigates the role of geology through two approaches: (1) Eighty roadcuts in central and eastern Tennessee were evaluated with the geologic character component of the Tennessee Rockfall Hazard Rating System (RHRS), which is a revision of the geologic component of the National Highway Institute (NHI) RHRS. Scores for both RHRS's were compared to evaluate improved reproducibility, accuracy, and sensitivity of scoring for the Tennessee RHRS. (2) Collecting additional geologic attribute data beyond the RHRS system to determine if the geologic attributes correlate to rockfall type, potential abundance, and block size as identified with the RHRS. Logistic regression analysis was performed to investigate potential relationships between geologic attributes and rockfall type, block size, and rockfall mode abundance. Results indicate the revised geologic component of the RHRS is more informative and permits description of a wider spectrum of geologic conditions than the NHI version. Logistic regression analysis indicates rockfall type is predicted by lithologic variation and the number of discontinuity sets; and block size is predicted by structurally controlled rockfall, lithologic variation, mechanical layering thickness, and the number discontinuity sets. Consequently, roadcuts containing potential rockfall modes with two or more discontinuity sets, no lithologic variation, and mechanical thicknesses that exceed 1.0 m are expected to have greater geologic character scores. Additionally, nearly half of all potential rockfall modes are expected to have low block size scores.

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1. INTRODUCTION

Rockfall occurrences along roadcuts create considerable risk for human injury and property damage, posing problems for transportation agencies across the country. Negative consequences of rockfall include damage to pavement caused by the impact of falling rocks, rocks on roads that are unavoidable to motorists, road closures, and environmental impact due to collisions with vehicles transporting toxic substances (Royster, 1978; Moore, 1986; Wyllie and Norrish, 1996). Consequently, as the demand for rockfall protection increases (Flatland, 1993), transportation agencies are expected to respond with practices that minimize damage and increase driver safety.

Rockfall is produced when rock or debris is shed from a roadcut or nearby steep slope by processes such as planar sliding, wedge failure, toppling, differential weathering, and raveling onto the catchment and/or road (Norrish and Wyllie, 1996). Characterization of rockfall potential at roadcuts is a necessary step for identifying hazard level and includes attributes such as vehicular traffic patterns, roadway geometry, and rock-slope geometry (Wyllie and Norrish, 1996). However, in the context of rockfall hazard management, no consensus exists about the role of geology in assessing hazard. For example, one agency does not consider geology other than identifying a slope as a rock slope or a soil slope (Lowell and Morin, 2000), another only considers whether geologic discontinuities are oriented favorably or unfavorably to promote rockfall (Abbott *et al.*, 1998), and one has defined risk by gross rock type (GEM-15, 1996; Hadjin, 2002). Goals of this study are to investigate the role of geology through two approaches: (1) revising the geologic component of the National Highway Institute (NHI) Rockfall Hazard Rating System (RHRS) to explicitly evaluate rockfall modes and their salient characteristics; and (2) collecting additional geologic attributes beyond the RHRS system to determine if these geologic attributes correlate to rockfall type, potential rockfall mode abundance, and block size. Study results should aid agencies and future investigators in determining the optimal approach for considering the effect of geologic characteristics on rockfall hazard.

1.1. Role of Geology in Existing Rockfall Hazard Rating Systems

The Rockfall Hazard Rating System is a tool to systematically inventory and rank hazardous roadcuts. The system was originally developed by Pierson and others (1990) for the Oregon Department of Transportation (ODOT) in a study funded by Oregon, nine other states and the Federal Highway Administration (Fish and Lane, 2002) to address rockfall problems along highways in that state. However, this effort was preceded by earlier work to develop systematic inventory and ranking procedures for hazardous roadcuts dating back to the 1970's (Fish and Lane, 2002). The ODOT RHRS is based on a rock slope inventory and maintenance program developed by Wyllie (1987). Since 1990, the Federal Highway Administration has adopted and endorsed the ODOT RHRS (Pierson and Van Vickle, 1993); hereafter referred to as the National Highway Institute (NHI) RHRS.

The NHI RHRS employs a two-phase slope categorization process (Pierson and Van Vickle, 1993). The first phase is a **preliminary rating**, where slopes are assigned a rating of A, B, or C based on the estimated potential for rock to reach roadway and historical rockfall activity. A-rated slopes are most hazardous and are characterized with a **detailed rating** using the NHI RHRS that considers the following factors

- Slope Height
- Roadway Width
- Ditch Effectiveness
- Average Vehicle Risk (AVR)
- Decision Sight Distance
- Geologic Character
- Block Size/Volume of Rockfall per event
- Climate / Presence of Water
- Rockfall History

The factors affected by the geologic conditions at a roadcut are *Geologic Character* and *Block Size*. *Geologic Character* attempts to describe the roadcut by considering whether the rockfall potential is controlled structurally or by differential erosion. Block size is controlled by rock type, structural conditions such as joint length and spacing, and construction methods for the roadcut.

Since the development and implementation of the NHI RHRS (Pierson and others, 1990; Pierson and Van Vickle, 1993), more than 17 state and provincial agencies have adopted the RHRS for rockfall management. Most transportation agencies have approached roadcut geologic conditions using the RHRS without modification, but about 7 modified the RHRS, most notably Colorado (Stover, 1992), Washington (Lowell and Morin, 2000), New York (Gem-15, 1996), and Ontario, Canada (Senior, 1999).

Colorado incorporated *slope inclination* and *launching features,* which are asperities on the roadcut face that can launch a falling rock onto the road, because they felt these factors significantly contributed to rockfall hazard (Stover, 1992). In Washington, the rating system does not incorporate geology, because they wanted persons that are not geologists or geotechnical engineers to complete the rating (Lowell and Morin, 2000). New York modified the RHRS by considering risk due to two rock types, crystalline and sedimentary, based on their assumption that crystalline rocks tend to have structurally controlled rockfall, whereas sedimentary rocks tend to have rockfall controlled by differential erosion (GEM-15, 1996). Their scheme ultimately follows the NHI scheme, but new terminology was used to avoid ambiguity and some categories explicitly consider rockfall modes (GEM-15, 1996; Hadjin, 2002). Ontario's Ministry of Transportation (MTO) modifications are based on parameters related to the types of rockfall modes common in Ontario cuts. For example, in northern Ontario, raveling, toppling, and ice-jacking are the dominant rockfall behaviors because of wall-controlled blasting methods, weathering, and the fact that roadcut relief is typically less than 25 feet (Senior, 1999). Additional parameters used by Ontario include height of the water table-slope interface and looseness of the face (Senior, 1999).

2. STUDY AREA

2.1. Location and Physiography

Eighty roadcuts along primary and secondary roads in five counties in eastern and central Tennessee were evaluated with the Tennessee RHRS, and seventy-seven were also sampled to investigate the influence of geologic factors on geologic attributes of the rockfall hazard rating (Figure 1). Physiographically, this region is composed of the Blue Ridge, Valley and Ridge, the Cumberland-Allegheny Plateau, the Highland Rim, and the Nashville Basin (Bingham and Helton, 1999) (Figure 1). The Blue Ridge is underlain by mostly Early Cambrian rifted margin sedimentary and volcanic that were deposited on Grenville basement. The Valley and Ridge consists of Cambrian and Ordovician platform to Ordovician to Pennsylvanian synorogenic sedimentary rocks. All of these rocks were transported westward during the Late Mississippian-Permian Alleghanian orogeny (Hatcher *et al.*, 1989).

Nearly flat-lying Devonian-Mississippian and Pennsylvanian sedimentary rocks underlie the Cumberland Plateau and are moderately to deeply dissected, creating significant local relief. Adjacent to the Cumberland Plateau to the west, but at lower elevation is the Highland Rim, containing Ordovician to Mississippian sedimentary rocks that are moderately to deeply dissected. The Nashville Basin is a topographic low in Central Tennessee that overlays a structural dome and is surrounded by the Highland Rim where Ordovician to Mississippian sedimentary rocks gently dip away from the crest of the dome (Hardeman, 1966; Bingham and Helton, 1999).

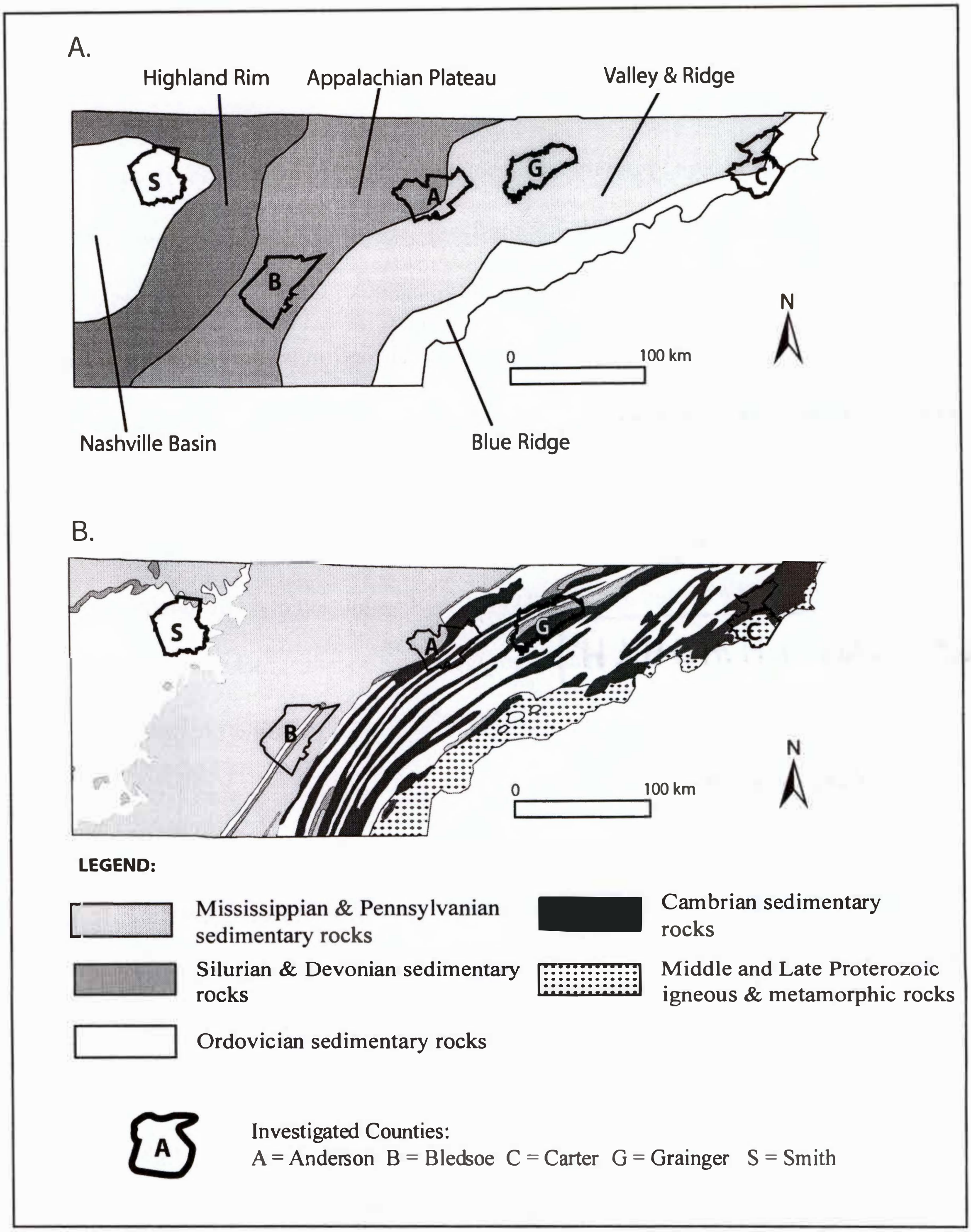

FIGURE 1. Physiographic and geologic maps of central and eastern Tennessee showing locations of investigated counties. A. Physiographic provinces map. B. Geologic map.

2.2. Geologic Setting

The five counties present contrasting geologic conditions. Lithologic variations range from crystalline rocks, such as granite, orthogneiss and paragneiss, amphibolite, and gabbro, which occur in parts of Carter County, to sedimentary rocks such as mudstones, siltstones, sandstones, and carbonates that occur in parts of Carter and Anderson, Bledsoe, Grainger, and Smith Counties. Additionally, structural variations also occur, from flat-lying bedded rocks, moderately inclined and folded bedded rocks, and foliated metamorphic and igneous rocks. Accordingly, roadcuts in the study area contain a variety of lithologies, structures such as joints and foliations, and bed thicknesses, all of which influence weathering behavior and potential rockfall modes.

2.2.1. Geology of Anderson County and Evaluated Roadcuts

The Cumberland Plateau Escarpment separates the Cumberland Plateau to the northwest and the Valley and Ridge Province to the southeast across the county (Figure 2). Significant relief in this part of the Cumberland Plateau exposes autochthonous, relatively flat-lying sedimentary rocks of the Pennsylvanian Crooked Fork Group and Slatestone Formation through Cross Mountain Formation at the highest elevations (Hardeman, 1966; Hatcher *et al.*, 1989). Joints and small-displacement mesoscopic faults are the only tectonic structures found in the rocks in this part of the Cumberland Plateau (Hatcher *et al.*, 1989). In the Valley and Ridge to the southeast, several northeast-trending thrust faults repeat the sedimentary sequence, which includes the Cambrian Rome Formation through Ordovician Chickamauga Group with isolated occurrences of Silurian Rockwood Formation, Devonian Chattanooga Shale and Mississippian Fort

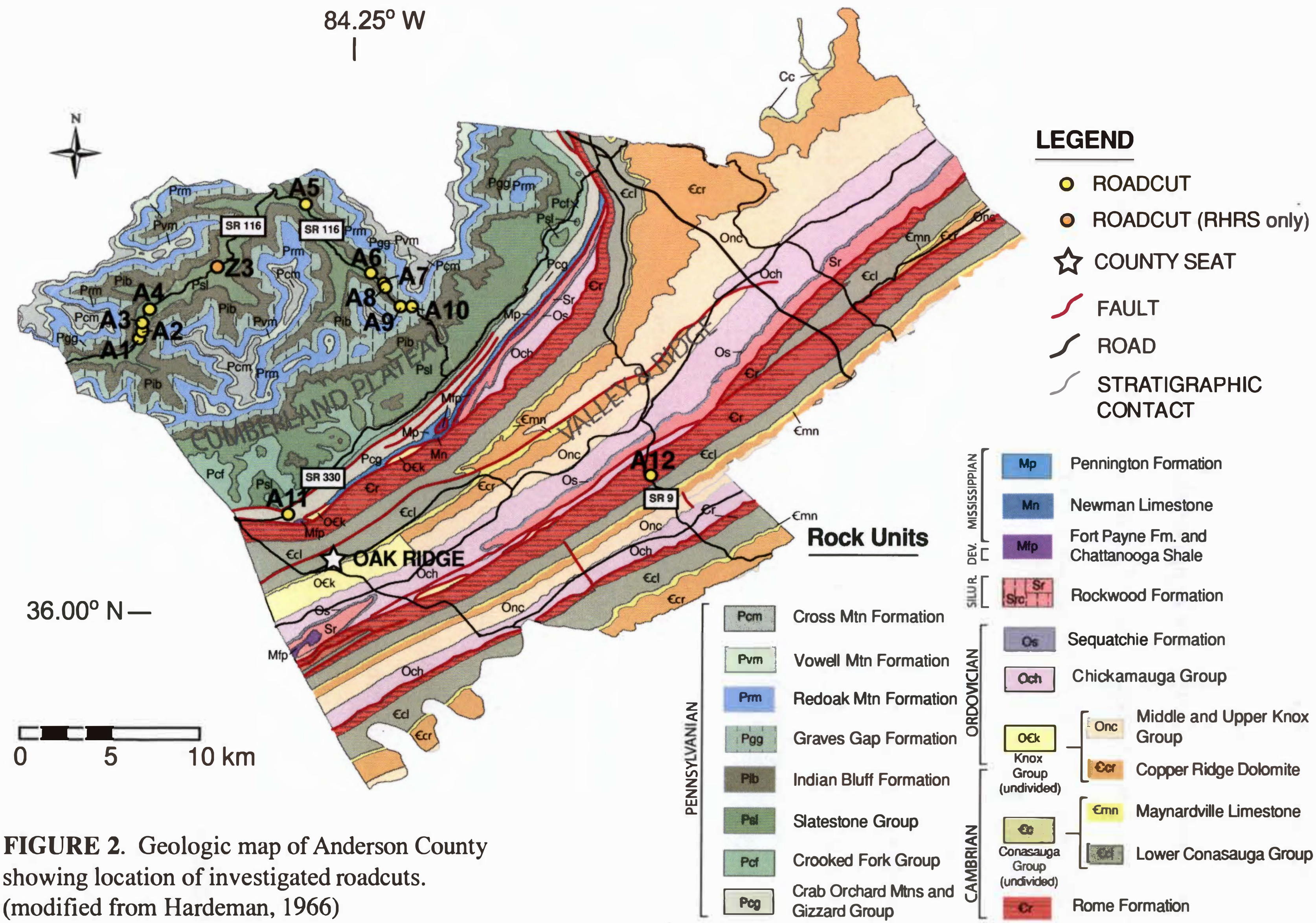

FIGURE 2. Geologic map of Anderson County showing location of investigated roadcuts. (modified from Hardeman, 1966)

Payne Formation, Newman Limestone, and Pennington Formation (Figure 2) (Swingle, 1964; Hardeman, 1966).

Twelve roadcuts in Anderson County (A1 – A12) were identified as potentially hazardous and evaluated (Figure 2, Table 1). Roadcuts A1 thro ugh A10 are located along State Road (SR) 116, which traverses the northern portions of the county in the Cumberland Plateau (Fork Mountain quadrangle, Garman and Ferguson, 1975; Duncan Flats quadrangle, Statler and Sykes, 1970). A11 and A12 are located on SR 330 and SR 9 (Clinton quadrangle, Swingle, 1964), respectively, in the southern half of the county in the Valley and Ridge.

2.2.2. Geology of Bledsoe County and Evaluated Roadcuts

Topographically and geologically, Bledsoe County is centered on part of the Sequatchie anticline (Figure 3). Higher elevations in the northwestern and southeastern portions of the county contain nearly flat-lying to gently southeast-dipping sedimentary rocks of the Pennsylvanian Crab Orchard Mountains Group and Rockcastle Conglomerate (Hardeman, 1966; Hatcher *et al.*, 1989). The Sequatchie anticline contains Lower Ordovician Knox Group, which forms the valley floor with overlying Middle Ordovician limestone units through Mississippian Pennington Formation rocks exposed on the two sides of the valley (Hardeman, 1966; Billingsly Gap quadrangle, Coker *et al.*, 1967; Pikeville quadrangle, Millici and Finlayson, 1967). This large fault-related fold plunges northeast and contains the trace of the Sequatchie Valley fault in the northwestern limb.

Eight roadcuts (B1 – B8) in Bledsoe County were identified as potentially

TABLE 1. Geology of potential rockfall modes at roadcuts in Anderson County.

Rock unit	Roadcut ID	Province	Lithology	Bed Orientations	Joint Set Orientations	Mechanical Layer Thickness	Roadcut Size (length, max height)	Location (decimal degree)
Slatestone Group	A1, A2, A3, A4, A5, A6	Cumberland Plateau	Medium brown, fine- to medium-grained, laminated- to thick-bedded siltstones and sandstones, and minor interbedded shale.	000/00 (A1-A5); 310/13N (A6)	021/90, 046/90 (A1); 035/90, 315/90 (A2); 030/90, 064/90, 304/90 (A3); 034/90, 070/90, 320/90 (A4); 056/90, 077/90, 334/90 (A5); (A6) none measured	<0.2 m - 1.0 m	135, 14 (A1); 20, 11 (A2); 78, 9 (A3); 49, 6 (A4); 20, 6 (A5); 44, 3 (A6)	-84.388 W, 36.137 N (A1); -84.389 W, 36.138 N (A2); -84.388 W, 36.140 N (A3); -84.384 W, 36.151 N (A4); -84.306 W, 36.203 N (A5); -84.272 W, 36.169 N (A6)
Indian Bluff Formation	A7, A8	Cumberland Plateau	Light grayish-brown, medium- to coarse-grained, thin- to medium-bedded sandstone and weathered, grayish, thin-bedded siltstone and shale.	000/00	050/90, 287/90 (A7); 299/90, 320/90 (A8)	0.2 m - 0.5 m	24, 8 (A7); 28, 5 (A8)	-84.265 W, 36.164 N (A7); -84.265 W, 36.163 N (A8)
Graves Gap Formation	A9, A10	Cumberland Plateau	Medium- to coarse-grained, well-cemented quartz sandstone	000/00	none measured	0.5 m Ĝ 1.0 m (A9); <0.2 m (A10)	60, 7 (A9); 30, 14 (A10)	-84.290 W, 36.155 N (A9); -84.252 W, 36.154 N (A10)
Crab Orchard Mountains Group	A11	Valley and Ridge	Tannish gray, fine- to medium-grained, medium to thick-bedded sandstone and interbedded dark gray-black shale.	100/60 S	none measured	0.5 m Ĝ 1.0 m (sandstone); <0.2 m (shale)	56, 18	-84.314 W, 36.048 N
Rome Formation	A12	Valley and Ridge	Grayish-tan, medium-grained, moderately well cemented with hematite cement, and interbedded greenish-tan mudstone.	052/41 SE	323/81 SW, 073/53 SE	0.2 m - 0.5 m	55, 8	-84.130 W, 36.066 N

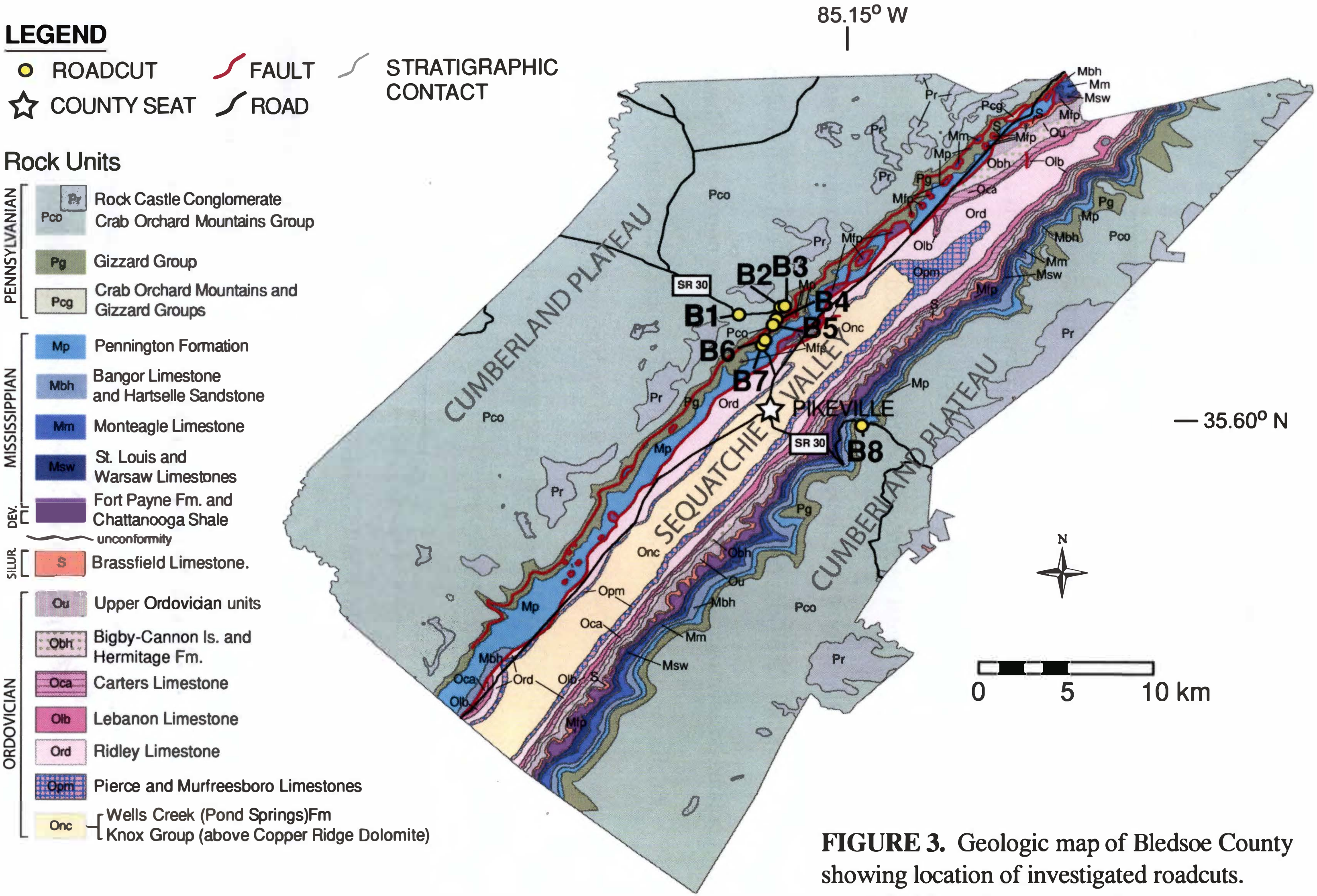

FIGURE 3. Geologic map of Bledsoe County showing location of investigated roadcuts. (modified from Hardeman, 1966)

hazardous and evaluated (Figure 3, Table 2). The roadcuts are located between mile markers 5.9 and 15.9 along State Road 30 (SR 30), which traverses the county from northwest to southeast across Sequatchie Valley.

Structurally, roadcuts B2 – B7 are located in the northwestern limb of the faulted Sequatchie anticline above a subsidiary fault (Billingsly Gap quadrangle, Coker *et al.*, 1967). Additionally, whereas B2 and B3 are manmade roadcuts, B4 is a map-scale natural rock slope named Raven Rock (Billingsly Gap quadrangle, Coker *et al.*, 1967). The rock is potentially the most hazardous feature encountered in the five counties because a large frontal portion of the slope is separating along a subvertical joints subparallel to the slope face (Figure 4). Roadcuts B6 and B7 also contain folded rocks and B7 contains an asymmetric anticline/syncline pair that verge northwest. The axial fold of the anticline trends northeast at about 069/38 SE, whereas that of the syncline trends northeast at about 065/79 SE. The common limb between the folds is only a few meters. The interlimb angle on the anticline is approximately 60° and the interlimb angle of the syncline is approximately 80° – 90°.

2.2.3. Geology of Carter County and Evaluated Roadcuts

Crystalline metamorphic and igneous rocks of the western Blue Ridge Province, and sedimentary rocks of the Appalachian fold-thrust belt in the Valley and Ridge Province, dominate the geology of the county (Figure 5). The crystalline terrane in the higher elevations of the southern half of the county consists of Precambrian pre-Grenville and Grenville-age basement rock. Late Proterozoic metamorphism produced granulite facies gneiss of the Mars Hill terrane that was later subjected to retrograde

TABLE 2. Geology of potential rockfall modes at roadcuts in Bledsoe County.

Rock unit	Roadcut ID	Province	Lithology	Bed Orientations	Joint Set Orientations	Mechanical Layer Thickness	Roadcut Size (length (m), max height (m))	Location (dec. deg.)
Vandeever Formation (Crab Orchard Mountains Group)	B1	Cumberland Plateau	Dark gray, silty shale overlain by a thin bed of more resistant tannish, silty, fine-grained sandstone at the top.	000/00	317/90, 053/90	<0.2 m	11, 3	-85.205 W, 35.649 N
Sewannee Conglomerate (Crab Orchard Mountains Group)	B2, B3, B4	Cumberland Plateau	Yellowish-tan, coarse-grained, medium-to-thick bedded, quartz-dominated sandstone with some cross beds.	224/42 NW (B2); 214/39 NW (B3); 215/38 NW (B4)	348/58 E, 304/87 NE, 065/46 SE (B2), 333/50 NE (B3), 034/62 SE, 035/38 NW, 291/83 NE (B4),	0.2 m - 1.0 m	25, 6 (B2); 29,9 (B3); 251, 31 (B4)	-85.188 W, 35.645 N (B2); -85.184 W, 35.652 N (B3); -85.184 W, 35.650 N (B4)
Upper and middle Gizzard Group	B5, B6, B7	Cumberland Plateau	grayish-yellow, thin-bedded, fine-to-medium grained siltstone and sandstone	024/30 SE (B5); 048/28 SE(B6); near horizontal - 059/29 (B7)	025/60 NW, 065/46 SE (B5); 335/80 N, 047/28 SE 54/64 NW (B6); 008/60 W, 291/90 (B7)	<0.2 m (B5); <0.2 m - 1.0 m (B6, B7)	75, 8 (B5); 27, 6 (B6); 41, 10 (B7)	-85.187 W, 35.646 N (B5); -85.191 W, 35.635 N (B6); -85.193 W, 35.635 N (B7)
Pennington Formation	B8	Cumberland Plateau	Weathered grayish-tan, medium-grained, thin-to-thick bedded sandstone with cross beds.	011/38 E	only nonsystematic fractures	0.2 m - 1.0 m	28, 5	-85.146 W, 35.592 N

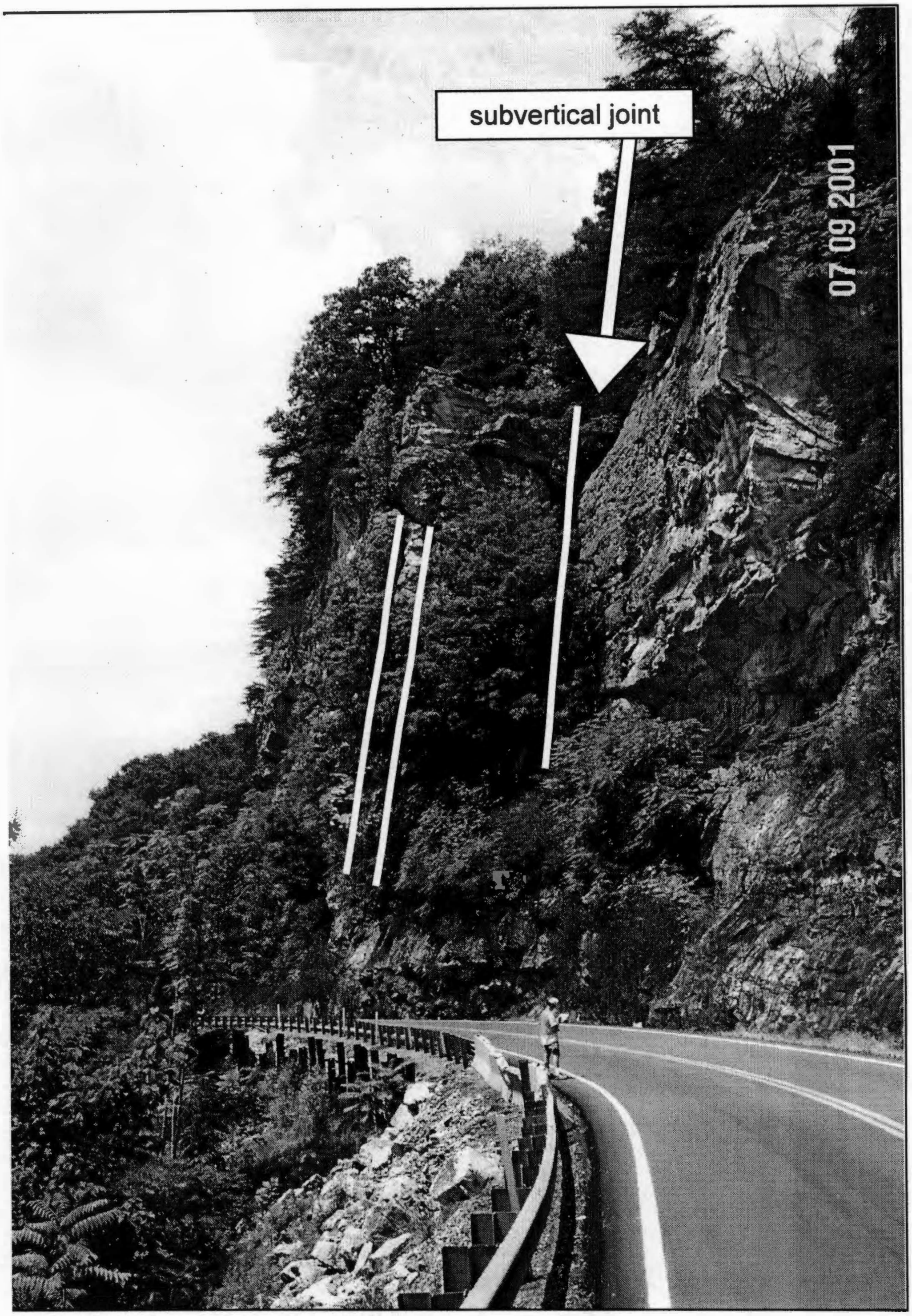

FIGURE 4. Roadcut B4 on Tennessee SR 30 showing large rock mass separating from slope face primarily along particular subvertical joint (arrow). View is to south.

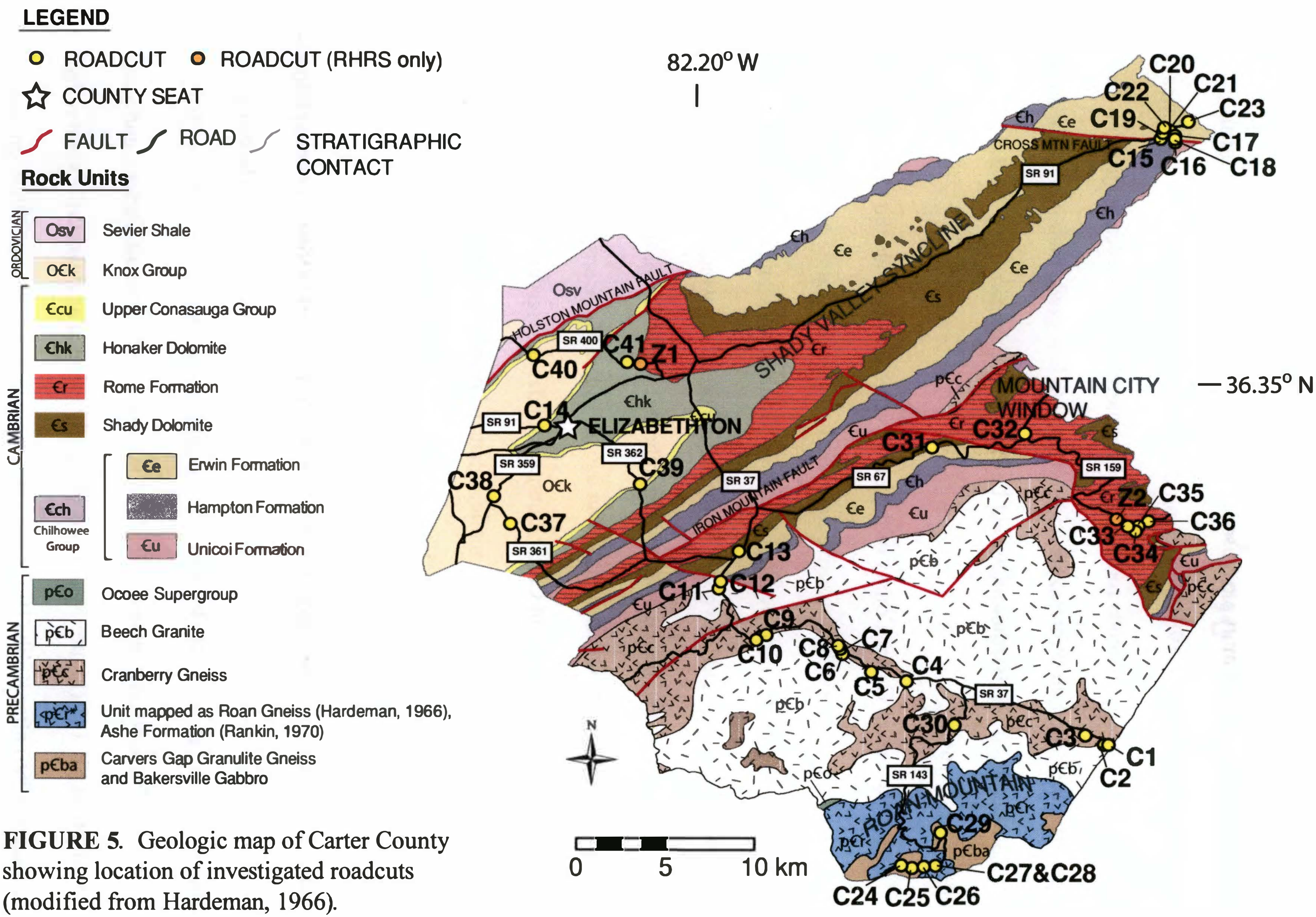

FIGURE 5. Geologic map of Carter County showing location of investigated roadcuts (modified from Hardeman, 1966).

metamorphism during Paleozoic deformation. Additionally, rocks of the Elk River Massif were subjected to multiple episodes of Paleozoic prograde metamorphism (Bartholomew and Lewis, 1984), which produced greenschist and amphibolite facies gneisses. Additionally, igneous rocks of the Crossnore plutonic-volcanic group were emplaced during the Late Proterozoic and subjected to low-grade metamorphism during Paleozoic deformation (Bartholomew and Lewis, 1984; Carrigan *et al.*, 2003; Gulley, 1985; Rankin, 1970).

Formations in Carter County of the Elk River Massif include the Cranberry Gneiss, which is comprised of massive to layered quartzofeldspathic gneiss with numerous small granitoid and pegmatitic bodies (Bartholomew and Lewis, 1984; Carrigan *et al.*, 2003), and is overlain by the Ashe Formation, which consists of metasedimentary schist, paragneiss, and amphibolite. Ion-microprobe analyses of zircons in the Cranberry Gneiss indicate an age of ~ 1190 Ma (Carrigan *et al.*, 2003).

The Mars Hill terrane in Carter County includes the Carvers Gap Granulite Gneiss (CGGG), which consists of felsic to mafic, foliated, hornblende-garnet-biotite granulite gneiss (Carrigan *et al.*, 2003; Bartholomew and Lewis, 1984; Gulley, 1985; Rankin, 1970). Bakersville Gabbro also occurs within the Mars Hill terrane of Carter County as a suite of dikes but is younger and considered genetically related to the Crossnore plutonic-volcanic group, which in Carter County, also includes the Beech Granite (Hardeman, 1966; Bryant and Reed, 1970; Rankin 1970; Bartholomew and Lewis, 1984). CGGG is restricted to the upper elevations on Roan Mountain in southernmost Carter County at C24 – C26 on SR 143 (Figure 5) and was originally mapped as Bakersville Gabbro by Hardeman (1966) after Keith (1903) and later recognized as a distinct lithologic unit within the Mars Hill terrane and subsequently renamed by Bartholomew and Lewis (1984). Structurally, the CGGG is above the Cranberry Gneiss (Carrigan *et al.*, 2003), but ion-microprobe analyses of zircons in indicate a much older age of magmatic crystallization (~1.8 Ga) than the Cranberry (Carrigan *et al.*, 2003). Gulley (1985) postulated that the CGGG is the deeper facies equivalent to the CMLG.

The northern half of the county is dominated by the Shady Valley thrust sheet, which is exposed on a large syncline that plunges southwest across the county exposing Cambrian Unicoi Formation of the Chilhowee Group through Ordovician Knox Group down plunge in Stony Creek Valley. The syncline is bound to the northwest and southeast by the Holston Mountain and Iron Mountain faults, respectively (King *et al.*, 1960; Hardeman, 1966). Numerous smaller thrust, and strike-slip faults also occur throughout the county (Hardeman, 1966; King *et al.*, 1960). The Mountain City window of Carter County, southeast of the Iron Mountain fault, primarily exposes Cambrian Shady Dolomite and Rome Formation. The youngest rock unit is Middle Ordovician Sevier Shale, which occurs northwest of the Holston Mountain fault (Figure 5) (Hardeman, 1966; King *et al.*, 1960).

Forty-three roadcuts in Carter County were identified as potentially hazardous and evaluated with the RHRS, and forty-one (C1 – C41) received subsequent geologic investigation (Figure 5, Table 3). The roadcuts are distributed along nine roads with the majority (C1 – C36) located on SR 37, SR 91, SR 143, and SR159. The rest are located on SR 359 (C37), SR 361 (C38), SR 362 (C339), and SR 400 (C40 – C41) (Figure 5).

Of particular note are roadcuts C1, C2, C3, and C35. Roadcuts C1 – C3 expose Cranberry Gneiss rocks that contain are indicative of discrete shear zones and roadcut

TABLE 3. Geology of potential rockfall modes at roadcuts in Carter County.

Rock unit	Roadcut ID	Province	Lithology	Bed/foliation orientation	Joint Set Orientations	Mechanical Layer Thickness	Roadcut Size (length, max height (m))	Location (dec. deg.)
Cranberry Gneiss	C1, C2	Western Blue Ridge, (Elk River massif)	Medium-grained, porphyroclastic biotite-quartz-feldspar mylonite with a light pinkish-gray appearance; and few compositional layers of olive green, fine-grained, friable micaceous phyllite	119/42 SW (C1); 100/32 S (C2)	008/79 E, 316/64 NE (C1); 016/88 E, 311/85 NE (C2)	<0.2 m	130, 14 (C1); 145, 14 (C2)	-82.002 W, 36.172 N (C1); -82.003 W, 36.173 N (C2)
	C3		Coarse-grained, greenish-pink, chloritized mylonite with pink feldspar porphyroblasts and lesser amounts of quartz and biotite	000/00	290/48 S, 047/32 NW, 339/37 NE, 290/90	> 1.0 m	175, 17	-82.014 W, 36.179 N
	C4		Compositional layers of milky-white, coarse-grained quartz-rich granitoid and olive green, fine-grained, friable micaceous phyllite	088/39 S	004/70 W, 300/84 SW	0.5 m Ğ 1.0 m	91, 12	-82.102 W, 36.203 N
	C5, C6, C7, C8		Light pinkish-orange, massive to weakly foliated, coarse-grained muscovite-biotite-quartz-feldspar granitoid	067/40 SE (C5), 086/34 S (C6), 076/40 S (C7), 348/40 E (C8)	290/80 S, 332/59 SW (C5); 332/26 NE, 020/55 NW (C6); 031/66 NW, 313/80 NE (C7); 301/75 SW, 028/62 NW, 045/90 (C8)	0.2 m Ğ 0.5 m (C5); >1.0 m (C6), <0.2 m Ğ 0.5 m (C7), ^{3}0.5 m (C8)	283, 8 (C5); 235, 11 (C6); 53, 9 (C7); 162, 17 (C8)	-82.119 W, 36.209 N (C5); -82.132 W, 36.217 N (C6); -82.133 W, 36.219 N (C7); -82.134 W, 36.220 N (C8)

TABLE 3. *continued.*

Rock unit	Roadcut ID	Province	Lithology	Bed/foliation orientation	Joint Set Orientations	Mechanical Layer Thickness	Roadcut Size (length, max height (m))	Location (dec. deg.)
Cranberry Gneiss	C9		Light gray, massive, coarse-grained, quartz-rich granitoid with minor biotite	massive	054/68 SE	massive	96, 9	-82.173 W, 36.226 N
	C10		Dark olive brown, aphanitic, mafic-looking dike and very light gray, massive, fine-grained, phaneritic quartz-feldspar granitoid	massive	massive, none measured	massive	140, 9	-82.176 W, 36.224 N
	C30		Highly weathered to decomposing migmatitic gneiss with light colored layers composed of coarse-grained, quartz-feldspar granitoid banded with fine grained, dark gray layers of more intermediate composition	317/35 NE	none measured	<0.2 m	30, 3	-82.076 W, 36.181 N
Beech Granite	C11,	Western Blue Ridge (Crossnore plutonic-volcanic complex)	Bluish-gray, massive, coarse-grained, biotite-feldspar-quartz granitoid with a thick (> 1.0m), dark gray, fine-grained, mafic-looking compositional layer in the lower portion of the roadcut	015/40 E to mostly massive	massive, none measured	> 1.0 m to massive	76, 12	-82.194 W, 36.250 N
	C12		Dark-olive gray, aphanitic, strongly jointed, metabasalt	massive	322/53 SW, 039/46 NW	massive	107, 12	-82.194 W, 36.251 N

TABLE 3. *continued.*

Rock unit	Roadcut ID	Province	Lithology	Bed/foliation orientation	Joint Set Orientations	Mechanical Layer Thickness	Roadcut Size (length, max height (m))	Location (dec. deg.)
Carver's Gap Granulite Gneiss	C24, C25, C26	Western Blue Ridge, (Mars Hill terrane)	Foliated medium-fine grained, dark gray gneiss with a rusty mottled appearance due to weathered garnet; and medium grained, massive and foliatd amphibolite that contains roughly equal amounts of plagioclase and amphibole in hand	064/43 NW, 320/42 NE (C24); 059/39 NW (C25); 279/59 N (C26)	055/63 SE, 331/84 SW, 282/64 NW (C24); none measured (C25); 003/51 E, 094/77 S (C26)	< 0.2 m Ğ 0.5 m (C24); <0.2 m (C25); >1.0 m (C26)	91,9 (C24); 109, 6 (C25); 31,9 (C26)	-82.103 W, 36.112 N (C24); -82.100 W, 36.110 N (C25); -82.093 W, 36.111 N (C26)
Bakersville Gabbro	C27, C28	Western Blue Ridge, (Mars Hill terrane)	Massive, phaneritic, coarse-grained, dark-gray black plagioclase-amphibole gabbro	massive	352/80 W, 084/70 S, 304/18 NE (C27); none measured (C28)	massive	96, 12 (C27); 52, 9 (C28)	-82.088 W, 36.113 N (C27); -82.088 W, 36.113 N (C28)
	C29		gray felsic quartzo-feldspathic granitic gneiss with quartz-dominant compositional layers; and dark-colored, coarse-grained, quartz-rich gabbroid	massive	328/68 SW	massive	104, 12	-82.086 W, 36.129 N
Shady Dolomite	C13, C31	Western Blue Ridge (Shady Valley syncline)	Medium-gray, fine-grained, thick- to massively bedded dolomite interbedded with thin layers of pastel pinkish and yellowish shale.	219/50 NW (C13); 088/39 S (C33)	162/88 SW, 95/43 S (C13); none measured (C33)	>1.0 m (C13); 0.2 m - 1.0 m (C33)	183, 85 (C13); 191, 13 (C31)	-82.185 W, 36.264 N (C13); -82.089 W, 36.318 N (C31)

TABLE 3. *continued.*

Rock unit	Roadcut ID	Province	Lithology	Bed/foliation orientation	Joint Set Orientations	Mechanical Layer Thickness	Roadcut Size (length, max height (m))	Location (dec. deg.)
Erwin Sandstone	C15, C16, C17, C18, C19, C20	Western Blue Ridge (Shady Valley syncline)	Gray, mostly thin bedded quartz arenite; heavily jointed	near horizontal (C15, C16, C17, C18); 152/32 SW (C19), 028/12 SE (C20)	312/78 NE, 060/61 NW (C15); 308/90, 070/76 SE, 356/78 E (C16); 012/80 E, 074/80 SE, 358/90 (C18); 056/78 SE, 323/90, 297/90 (C19); 328/78 SW, 083/90 (C20); none measured (C17)	< 0.2 m (C15, C16, C17, C18, C20); 0.2 m - 1.0 m (C19)	280, 6 (C15); 55, 6 (C16); 30,6 (C17); 111,6 (C18); 87, 6 (C19); 113, 6 (C20)	-81.976 W, 36.471 N (C15); -81.968 W, 36.470 N (C16); -81.969 W, 36.471 N (C17); -81.970 W, 36.473 N (C18); -81.972 W, 36.473 N (C19); -81.974 W, 36.475 N (C20);
Hesse Sandstone	C21, C22, C23	Western Blue Ridge (Shady Valley syncline)	Bluish-gray, massively-bedded, well cemented quartzite with cross beds; weathers to a tannish gray color	near horizontal (C21, C22, C23);	223/90, 340/86 SW (C21); 050/66 SE, 340/60 SW, 314/90, and 082/76 S (C22); 064/67 SE (C23)	0.2 m - >1.0 m (C21, C22, C23)	226, 6 (C21); 152, 6 (C22); 50, 3 (C23)	-81.975 W, 36.476 N (C21); -81.969 W, 36.475 N (C22);

TABLE 3. *continued.*

Rock unit	Roadcut ID	Province	Lithology	Bed/foliation orientation	Joint Set Orientations	Mechanical Layer Thickness	Roadcut Size (length, max height (m))	Location (dec. deg.)
Rome Formation	C32, C33, C34, C35, C36	Mountain City Window	Dark maroonish gray, thir to medium-bedded, fine- to medium-grained siltstone and sandstone with some shaly interbeds	062/62 SE, 059/26 SE (C32); 044/78 SE (C33); 016/86 SE (C34); 038/44 SE, 032/58 SE, 000/00, 213/71 NW (C35); 180/6[illegible] W, 037/75 SE (C36); 228/14 (C37)	none measured (C32); 328/35 SW (C33); 280/76 N, 029/74 NW (C34); 039/83 SE, 045/41 NW, 298/80 NE, 328/72 SW (C35); 291/49 SW, 270/64 N, 310/40 NE (C36);	0.5 m - 1.0 m (C32); 0.2m - 1.0 m (C33); <0.2 m (C34); <0.2 m - 0.5 (C35); 0.2m - 0.5m (C36);	198, 6 (C32); 62, 11 (C33); 61,7 (C34); 84,6 (C35); 70, 6 (C36)	-82.043 W, 36.325 N (C32); -81.993 W, 36.278 N (C33); -81.990 W, 36.277 N (C34); -81.989 W, 36.278 N (C35); -81.982 W, 36.281 N (C36);
Maynardville Limestone (Conasauga Group)	C14, C39, C40	Western Blue Ridge (Shady Valley syncline)	Light to dark gray, thin- to medium-bedded, fine- to medium-grained, ribboned, cherty limestone	220/76 NW (C14); 060/08 SE (C39), 057/23 SE (C40)	320/72 SW, 285/30 S (C14); 058/87 NW (C39); none measured (C40)	<0.2 m - 0.5 m (C14); 0.2 m - 1.0m (C39); <0.2 m (C40)	98, 6 (C14); 69, 3 (C39); 63, 11 (C40)	-82.280 W, 36.326 N (C14); -82.236 W, 36.303 N (C39); -82.282 W, 36.362 N (C40)
Honaker Dolomite Conasauga Group)	C41	Western Blue Ridge (Shady Valley syncline)	Bluish-gray, thinly- to medium bedded, fine-grained dolomite with secondary calcite veins	013/47 E	057/44 SE, 272/90	0.2 m - 0.5 m	88, 17	-82.240 W, 36.358 N
Knox Group	C37, C38	Western Blue Ridge (Shady Valley syncline)	Light gray, massively bedded, fine-grained dolomite	228/14 NW (C37); 117/37 SW (C38)	none measured	>1.0 m	88, 5 (C37); 141, 34 (C38)	-82.303 W, 36.293 N (C37); -82.296 W, 36.281 N (C38)

C35 contains a well-exposed anticline in the Rome Formation that has an axial trend of approximately 035°, an interlimb angle of about 50°, and is obliquely cut by SR 159, which is oriented at approximately 100°.

2.2.4. Geology of Grainger County and Evaluated Roadcuts

The Valley and Ridge Province dominates the topography and geology of Grainger County. Northeast-trending folds and thrust faults transect the county and repeat the sedimentary sequence (Hardeman, 1966) (Figure 6). The oldest exposed unit is the Rome Formation, which crops out in the northern and central portions of the county in the hanging walls of large thrust faults. The youngest rocks are exposed along the slopes of the most significant geographic feature in the county, Clinch Mountain, which is underlain by a footwall syncline beneath the Saltville fault, and includes from older to younger, Silurian Clinch Sandstone, Chattanooga Shale, and Grainger Formation, and Newman Limestone (Hardeman, 1966). Other stratigraphic units occurring in the county include members of the Knox and Chickamauga Groups.

Four roadcuts in Grainger County (G1 – G4) were identified as potentially hazardous and evaluated (figure 6, Table 4). The roadcuts are located near each other along SR 32 (U.S. 25E) (Howard Quarter quadrangle, Harris and Mixon, 1970).

2.2.5. Geology of Smith County and Evaluated Roadcuts

Physiographically, Smith County in Middle Tennessee is located on the Highland Rim in the central and eastern areas of the county and the Nashville Basin in the westernmost areas of the county (Figure 7) and contains nearly flat-lying sedimentary

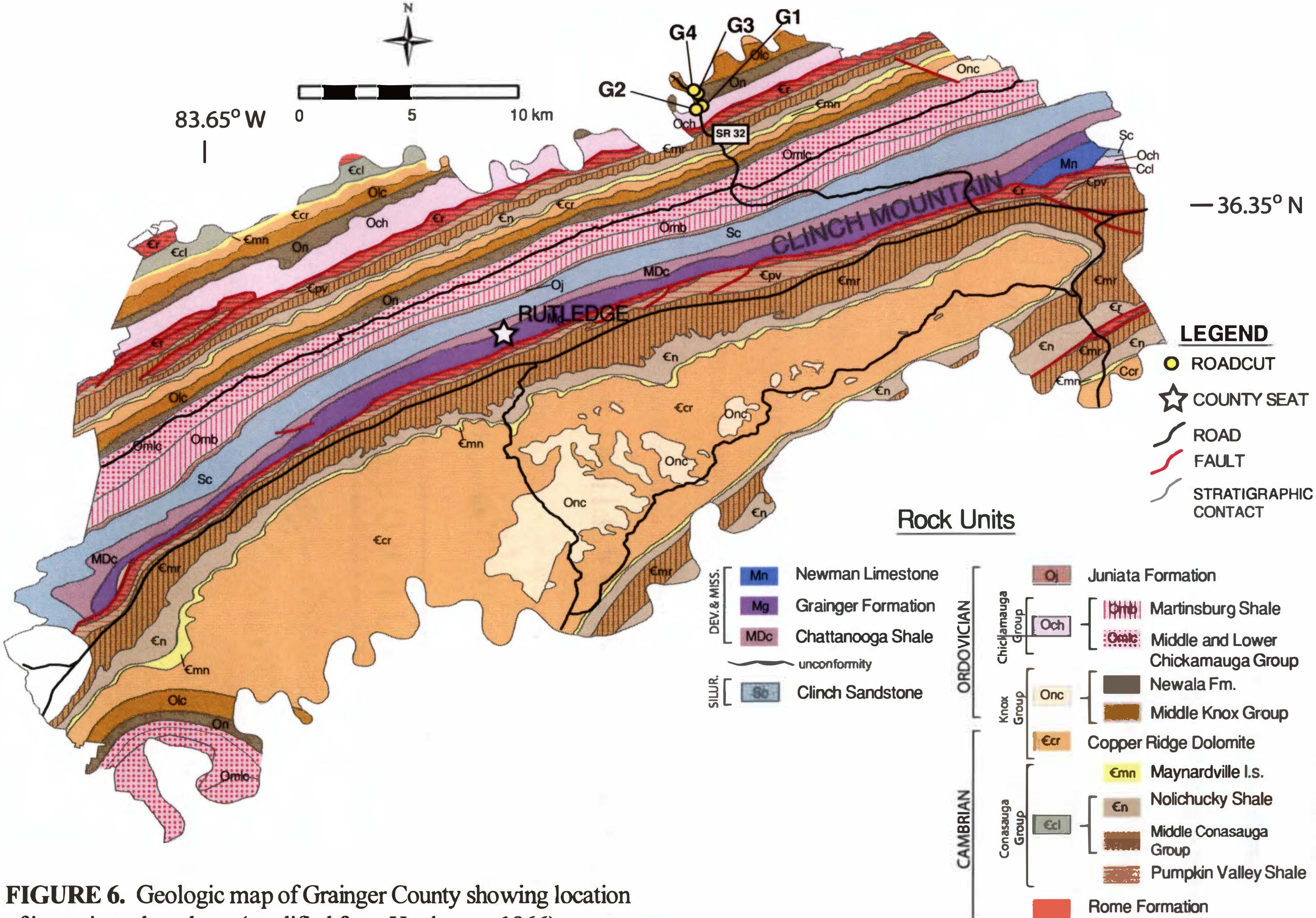

FIGURE 6. Geologic map of Grainger County showing location of investigated roadcuts (modified from Hardeman, 1966).

TABLE 4. Geology of potential rockfall modes at roadcuts in Grainger County.

Rock unit	Roadcut ID	Province	Lithology	Bed Orientations	Joint Set Orientations	Mechanical Layer Thickness	Roadcut Size (length, max height)	Location
Chickamauga Group	G1, G2	Valley and Ridge	Medium-gray, medium-to-coarse grained, cherty limestone	048/41 SE (G1); 047/30 SE (G2)	081/55 N (G1); 083/63 N (G2)	0.5 m Ğ 1.0 m	183, 21 (G1); 94, 18 (G2)	-83.451 W, 36.395 N (G1); -83.451 W, 36.395 N (G2)
Mascot Dolomite (Knox Group)	G3	Valley and Ridge	Light gray (fresh) to very light gray, and blackish (weathered) dolomite with a fine-grained crystalline texture and secondary calcite	070/022 SE	063/045 NW	0.5 m Ǧ 1.0 m	199, 24	-83.452 W, 36.395 N
Kingsport Formation (Knox Group)	G4	Valley and Ridge	Most of the roadcut is thick-bedded, light-gray calcareous grainstone with dark gray-black chert nodules that weathers to very light gray and grades stratigraphically upward at the southern end of the roadcut into units that resemble Mascot Dolomite.	054/024 SE	only nonsystematic fractures	0.5 m - >1.0 m	122, 24	-83.455 W, 36.396 N

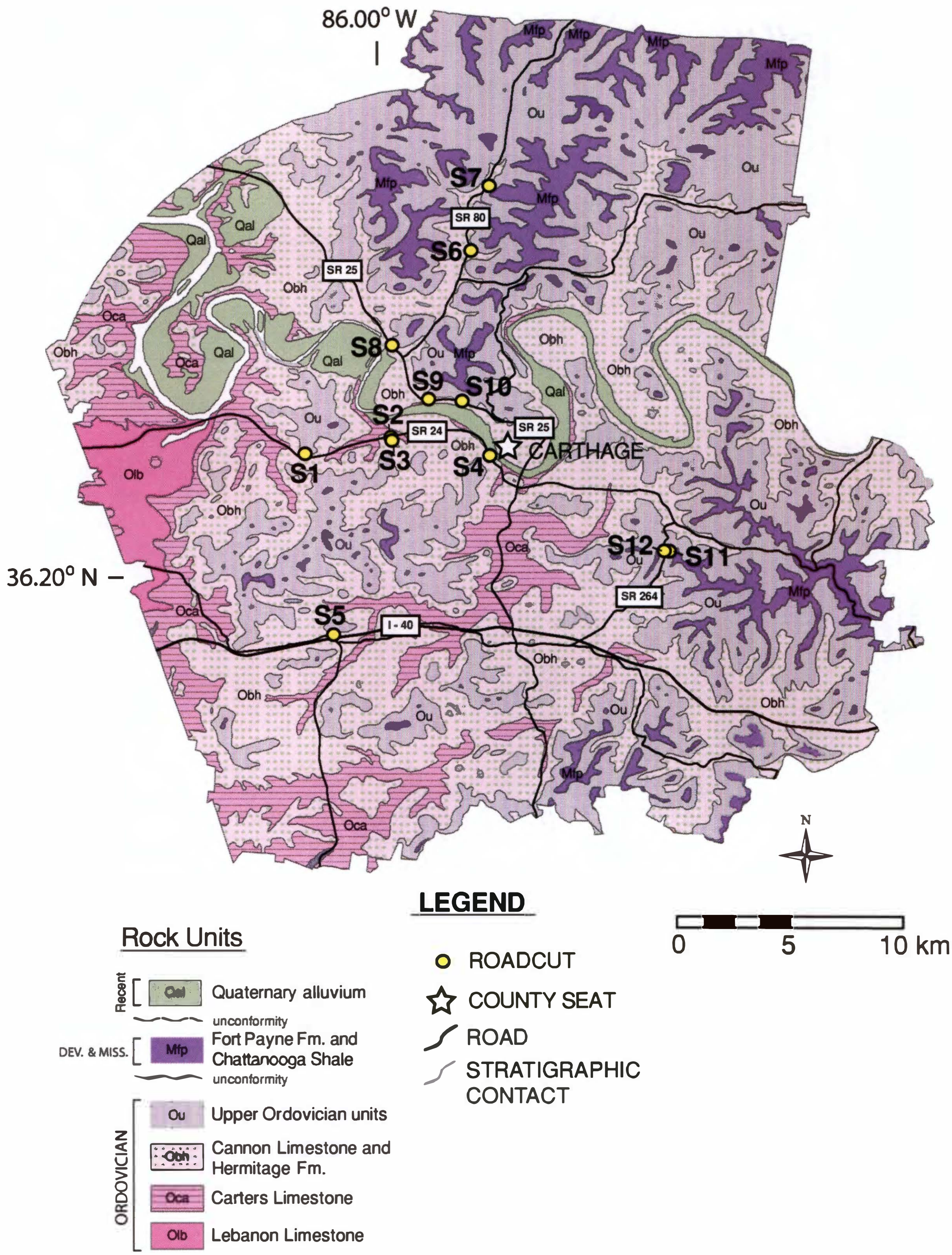

FIGURE 7. Geologic map of Smith County showing location of investigated roadcuts (modfied from Hardeman, 1966).

rocks that are deeply to moderately dissected by streams, creating relief in the county. The Middle Ordovician Lebanon Limestone is the oldest stratigraphic unit, exposed at the lower elevations along the Cumberland River in the western part of the county, while the Chattanooga Shale and Fort Payne Formation are the youngest units. They unconformably overlie Upper Ordovician units and occur on hilltops, particularly in the northern and eastern parts of the county (Figure 7) (Hardeman, 1966).

Twelve roadcuts in Smith County (S1 – S12) were identified as potentially hazardous and evaluated (Figure 7, Table 5). The roadcuts are located along state roads 24, 25, 80, 264, and a westbound offramp interchange of Interstate 40 (Gordonsville quadrangle, Wilson, 1976).

Of particular note are roadcuts S4 and S9, which is a large, naturally occurring bluff carved by the Cumberland River and is over 900 m long. The lower 30 m expose Cannon Limestone overlain by Upper Ordovician Leipers-Catheys Formation limestone (Gordonsville quadrangle, Wilson, 1976). Additionally, S9 is of interest because it contains several closely spaced joint sets and nonsystematic fractures and has experienced a significant amount of rockfall over the past several years that has caused the face of the roadcut to significantly recede.

TABLE 5. Geology of potential rockfall modes at roadcuts in Smith County.

Rock unit	Roadcut ID's	Province	Lithology	Bed Orientations	Joint Set Orientations	Mechanical Layer Thickness	Roadcut Size (length (m), max height(m))	Location (decimal degree)
Cannon Limestone	S1	Eastern Highland Rim	Medium gray, grain-supported, fossiliferous, medium bedded limestone	000/00	only nonsystematic joints present	<0.2 m - 0.5 m	71, 4	-86.031 W, 36.247 E
	S2, S3	Eastern Highland Rim	Medium gray, mud-supported, fine-grained, thinly bedded limestone interbedded with gray mudstone.	000/00	304/90, 035/90 (S2); 035/90, 055/90, 304/90 (S3)	<0.2 m	157, 9 (S2); 101, 9 (S3)	-85.995 W, 36.256 N (S2); -85.995 W, 36.256 N (S3)
	S4 (lower 30 m)	Eastern Highland Rim	Dark gray, fine-to-medium grained, and thinly-to-thickly bedded limestone.	000/00	inaccessible, none measured	<0.2 m - 1.0 m	913, 24	-85.959 W, 36.253 N
	S5	Eastern Highland Rim	Dark gray, very coarse, grain-supported, fossiliferous limestone	000/00	292/90, 050/90	<0.2 m	104, 8	-85.959 W, 36.253 N
	S6, S7	Eastern Highland Rim	Medium gray, fine-grained, mud supported, and mottled (S6) limestone	000/00	S6 inaccessible, none measured; 300/90, 030/90 (S7)	<0.2 m - 0.5 m	149, 20 (S6); 200, 4 (S7)	-85.965 W, 36.332 N (S6); -85.958 W, 36.358 N (S7)
Leipers-Catheys Formation	S8, S9	Eastern Highland Rim	Dark gray, medium-bedded, fine- to medium-grained, fossiliferous limestone with granule size phosphate nodules, and interbedded with thin shale layers.	000/00	314/90, 004/90 (S8); 285/90, 055/90 (S9)	0.2 m - 0.5 m (S8); 0.2 m - 1.0 m (S9)	438, 26 (S8); 447, 34 (S9)	-86.998W, 36.294 N (S8); -85.982 W, 36.270 N (S9)
	S10	Eastern Highland Rim	Thin-bedded, fine- to medium-grained, silty limestone interbedded with gray silty mudstone	000/00	290/90, 027/90	<0.2 m	481, 19	-85.968 W, 36.269 N
	S11, S12	Eastern Highland Rim	Medium gray, thin bedded, fine-to-medium grain, fossiliferous limestone	000/00	340/82 E, 054/84 SE (S11); 315/72 SW, 058/90 (S12)	<0.2 m	39, 9 (S11); 55, 9 (S12)	-85.887 W, 36.212 N (S11); -85.887 W, 36.212 N (S12)

3. METHODOLOGY OF RHRS REVISION

3.1. Geological Revisions to NHI RHRS

The Geologic Character category in the NHI RHRS (Pierson and Van Vickle, 1993) evaluates the geologic conditions contributing to rockfall hazard potential at a roadcut. However, the NHI approach does not suitably describe geologic conditions because it does not explicitly incorporate rockfall modes and uses ambiguous terminology. Consequently, the NHI RHRS produces scores that are not useful because little geologic knowledge of the roadcut is gained and because the RHRS terminology can be interpreted differently among different raters, limiting the reproducibility for scoring with the system.

The *Geologic Character* category in the NHI RHRS (Pierson and Van Vickle, 1993) considers two cases (Figure 8). 'Case 1' is structurally controlled rockfall where the key factors are discontinuity size, discontinuity orientation, and rock friction. 'Case 2' is differential erosion rockfall where the factors are differential erosion features and differential erosion rates. The cases are mutually exclusive because a rater only records the score for the rockfall condition with the greater hazard.

'Case 1' is scored for two factors, *structural condition* and *rock friction* (Figure 8). Structural condition attempts to describe the relative orientation and length of joints in the roadcut (Pierson and Van Vickle, 1993). Discontinuous joints are defined as less than 10 ft in length, whereas continuous joints are defined as greater than 10 ft in length. Rock friction describes the surface smoothness of the joints. Clay-filled and slickensided joints are assigned highest hazard because they requires less shear stress to exceed the coefficient of friction and cause movement along the joint surface and a slickensided

GEOLOGIC CHARACTERISTICS		VALUES OF HAZARD ASSESSMENT			
		Low Hazard → High Hazard			
CASE 1	**Structural Condition**	Discontinuous joints, favorable orientation	Discontinuous joints, random orientation	Discontinuous joints, adverse orientation	Continuous joints, adverse orientation
	Rock Friction	Rough, irregular	Undulating	Planar	Clay infilling, or slickensided
CASE 2	**Structural Condition**	Few differential erosion features	Occasional differential erosion features	Many differential erosion features	Major differential erosion features
	Difference in erosion rates	Small difference	Moderate difference	Large difference	Extreme difference

FIGURE 8. NHI Geologic Character rating scheme. Case 1 is for structurally related rockfall and Case 2 is for weathering-related rockfall.

surface indicates previous movement along that surface.

'Case 2' is scored for two categories, *Structural Condition* and *Difference in Erosion Rates* (Figure 8). Structural Condition describes the surficial weathering features of a roadcut, whereas Difference in Erosion Rates describes the formation rate of surficial weathering features (Pierson and Van Vickle, 1993).

Examination of the scoring factors for the NHI *Geologic Character* category prompted the need to develop a modified approach to deal with issues of terminology, field application, and assessment capability. Issues that were identified include:

(1) Use of "structural condition" for both structural and nonstructural rockfall creates confusion.

(2) Use of "random" for intermediate orientation hazard condition is problematic because random could include potentially very hazardous orientations, and does not encompass the case of parallel surfaces at an intermediate-risk orientation.

(3) Use of "joints" is incorrect, as bedding surfaces, faults, and cleavage may provide failure surfaces for structural cases.

(4) Use of "continuous" and "discontinuous" to describe discontinuity size is confusing because a discontinuity is not continuous by definition.

(5) Use of "favorable" for the low-orientation hazard condition is an ambiguous term, which means favorably stable in this case, but could be misinterpreted as favorably disposed to rockfall.

(6) Differential erosion is really in most cases differential weathering.

(7) The NHI RHRS does not take advantage of well-established geotechnical

terms (Turner and Schuster, 1996) and known rockfall modes (e.g. plane, wedge, topple, etc.)

(8) The system does not consider raveling explicitly even though it may be a prominent rockfall type, as Ontario's MTO (Senior, 1999) and New York (GEM-15, 1996; Hadjin, 2002) recognized.

(9) The current system does not assess the abundance or degree to which a potential rockfall mode is present in a rock slope. This factor often controls the volume of rock that may be shed to the road.

(10) Only the most hazardous condition is considered when a better assessment of risk is to consider all rockfall modes in a rock-slope that could deliver rock to the road.

Based on these issues, the NHI RHRS was revised for use in the study areas to incorporate rockfall modes explicitly including raveling; to use measurable attributes that are applicable to particular rockfall modes including abundance; to cumulatively sum the ratings where more than one rockfall mode is present; and to eliminate ambiguous terminology.

3.2. Tennessee Geologic Character Scoring System

The Tennessee system evaluates five rockfall modes: plane, wedge, topple, differential weathering, and raveling, using appropriate combinations of six characteristics (Figures 9 and 10). The modified RHRS was compared to the NHI RHRS by scoring roadcuts using both systems. The comparisons of these scores and their implications are discussed later. After all roadcuts in the study area received a RHRS

ROCKFALL MODES	CHARACTERISTICS					
	Abundance	Block Size	Inclination	Friction	Relief	Block Shape
Planar	X	X	X	X		
Wedge	X	X	X	X		
Topple	X	X	X			
Differential Weathering	X	X			X	
Raveling	X	X				X

FIGURE 9. Rockfall modes and characteristics of the Tennessee Geologic Character rating scheme. **X** indicates inclusion of rated criteria for a rockfall mode.

A.

Planar Rockfall				
Abundance	<10%	10-20%	20-30%	>30%
Score	**3**	**9**	**27**	**81**
Block Size	<1 ft (< 0.3 m)	1 to 3 ft (0.3 Ğ 0.9 m)	3 to 6 ft (0.9 Ğ 1.8 m)	>6 ft (>1.8 m)
Score	**3**	**9**	**27**	**81**
Steepness	0 - 20¼	20-40¼	40-60¼	>60¼
Score	**2**	**5**	**14**	**41**
Friction (micro/macro)	Rough/Undulating	Smooth/Undulating	Rough/Planar	Smooth/Planar
Score	**2**	**5**	**14**	**41**

B.

Wedge Rockfall				
Abundance	<10%	10-20%	20-30%	>30%
Score	**3**	**9**	**27**	**81**
Block Size	<1 ft (< 0.3 m)	1 to 3 ft (0.3 Ğ 0.9 m)	3 to 6 ft (0.9 Ğ 1.8 m)	>6 ft (>1.8 m)
Score	**3**	**9**	**27**	**81**
Steepness	0 - 20¼	20-40¼	40-60¼	>60¼
Score	**2**	**5**	**14**	**41**
Friction (micro/macro)	Rough/Undulating	Smooth/Undulating	Rough/Planar	Smooth/Planar
Score	**2**	**5**	**14**	**41**

C.

Topple Rockfall				
Abundance	<10%	10-20%	20-30%	>30%
Score	**5**	**14**	**41**	**122**
Block Size	<1 ft (< 0.3 m)	1 to 3 ft (0.3 Ğ 0.9 m)	3 to 6 ft (0.9 Ğ 1.8 m)	>6 ft (>1.8 m)
Score	**5**	**14**	**41**	**122**

D.

Differential Weathering Rockfall				
Abundance	<10%	10-20%	20-30%	>30%
Score	**3**	**9**	**27**	**81**
Block Size	<1 ft (< 0.3 m)	1 to 3 ft (0.3 Ğ 0.9 m)	3 to 6 ft (0.9 Ğ 1.8 m)	>6 ft (>1.8 m)
Score	**3**	**9**	**27**	**81**
Relief	<1ft	1 to 3 ft	3 to 6 ft	>6 ft
Score	**3**	**9**	**27**	**81**

E.

Raveling Rockfall				
Abundance	<10%	10-20%	20-30%	>30%
Score	**3**	**9**	**27**	**81**
Block Size	<1 ft (< 0.3 m)	1 to 3 ft (0.3 Ğ 0.9 m)	3 to 6 ft (0.9 Ğ 1.8 m)	>6 ft (>1.8 m)
Score	**3**	**9**	**27**	**81**
Shape	Tabular	Blocky	Round	-
Score	**3**	**9**	**27**	-

FIGURE 10. Scoring schemes for the Tennessee RHRS Geologic Character. **A.** Planar rockfall; **B.** Wedge rockfall; **C.** Topple rockfall; **D.** Differential Weathering rockfall; **E.** Raveling rockfall.

rating (Appendix 6-A), each was revisited to collect data about additional geologic attributes to provide a basis for statistically investigating whether the occurrence of these attributes correlate to structural- or weathering-related rockfall modes, block size, and mode abundance.

Attributes common to all rockfall modes are the relative *abundance* of the rockfall mode and *block size.* The relative abundance of a rockfall mode controls the volume of a roadcut or slope face that is susceptible to rockfall and is expressed as a percentage of the total slope face surface area (Figure 11). In the NHI RHRS, *block size* is treated separately from *Geologic Characteristics*, but is incorporated into the Tennessee version because block size is an attribute of all potential rockfall modes.

Attributes unique to planar and wedge rockfall are *steepness* of the failure plane(s) and wedge intersection, respectively, and the micro- and macro*friction* profiles of the failure plane(s). As rockfall hazard potential increases with steepness frictional resistance provided by the sliding surface topographically controls whether the rock mass will fail. Friction is evaluated in profile for both the micro- and macroscale parallel to the likely movement direction of the rock mass (Figure 12.). The microfriction is rough or smooth, and the macrofriction is planar or undulating. The macroscale topography is assumed to have the greatest affect on the friction because more energy is required to overcome large-scale asperities and slip over the macroscale asperities likely results in failure of the rock mass, whereas slip over the microscale asperities only requires localized movement (Barton, 1973).

Since topple rockfall requires a surface(s) dipping steeply into and sub-parallel to a slope face (Norrish and Wyllie, 1996), steepness is not considered. Additionally, even

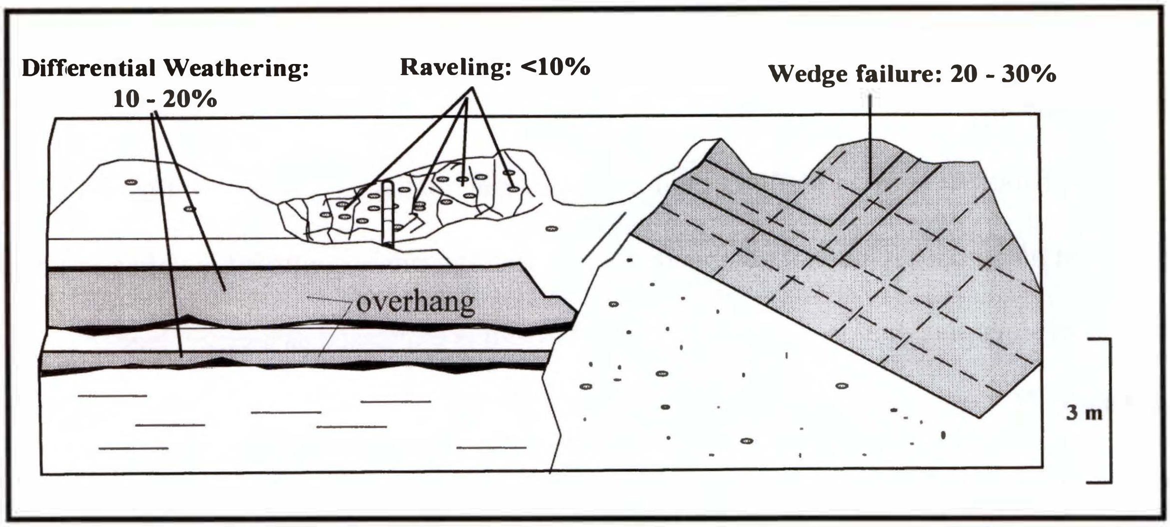

FIGURE 11. Schematic examples of relative abundance at a roadcut.

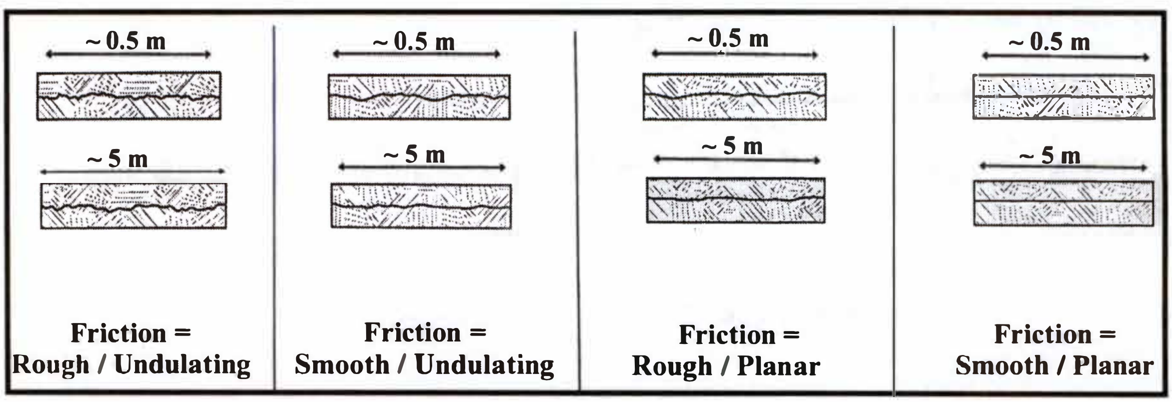

FIGURE 12. Visual scoring aid for friction. Terms indicate micro- and macro- friction profiles (modified from Barton, 1973).

though some interlayer slip may occur, friction is not considered for topple.

Amount of relief is an attribute unique to differential weathering, and represents the extent that a rock mass overhangs the material directly underneath. *Block shape* is an important attribute for raveling due to the greater potential for spherical blocks to roll, which increases the ability for a rock to land in the road. Therefore block shapes are described in order of increasing hazard as tabular, blocky, or round.

To compare hazard ratings for roadcuts scored by both the NHI and the Tennessee systems, both systems used 943 total points with a maximum of 300 from geology. This equivalence is achieved by capping the maximum geology score at 300 for the Tennessee system even though scores from multiple active rockfall modes are cumulatively scored. Interestingly, only one of the 80 A-rated roadcuts in the study area yielded a score of 300 or greater, so this capping value is not a significant truncation to scores of the Tennessee system.

To score characteristics, the NHI RHRS uses four categories that are each an exponent of 3 (Pearson and Van Vickle, 1993). An exponent value of 1 is assigned for the lowest hazard category ($3^1 = 3$ points) and 4 for the highest hazard category ($3^4 = 81$ points), and values of 2 and 3 for the intermediate hazard categories, respectively. The premise for exponential scoring is that roadcuts with hazardous characteristics have scores that are easily distinguished from lower hazard roadcuts.

Following the NHI approach, each characteristic in the Tennessee system was scored using four categories (Figure 10). The only exception is shape scoring for raveling because the use of a fourth category was found to overemphasize hazard for this mode that typically sheds small blocks. With this reduction for raveling, each of the other four potential rockfall modes can yield scores of up to 244 (Figure 10). For topple, which has two scorable characteristics; each characteristic has a maximum score of 122. For differential weathering, with three scorable characteristics, maximum characteristic score is 81. For planar and wedge rockfall with four scorable characteristics, *abundance* and *block size* have maximum scores of 81. Due to the uncertainty for quantifying *friction* (Barton, 1973), this factor is combined with *steepness*, and they are reduced to 41 points each.

4. METHODOLOGY FOR RELATING GEOLOGIC ATTRIBUTES TO RHRS GEOLOGIC CHARACTERISTICS

4.1. Geologic Attributes

Slope geometry, lithologic data, and discontinuity about 134 identified potential rockfall modes at 77 roadcuts were collected. Because the use of a logistic regression technique requires the format (Hosmer and Lemeshow, 1989), categorical values were used for many geologic attributes (Table 6). Slope orientation data were collected because it is expected that north-facing roadcuts could have high abundances of potential differential weathering-related rockfall. Lithologic attributes were chosen for quantitative reasons as well as qualitative reasons. Quantitatively, rock type, grain size, fissility/cleavage, and layer thickness could affect block size. Secondary lithologic attributes, such as the lithologies that preferentially weather to create overhangs, were also collected to investigate whether lithologic variation affects rockfall mode and abundance. Orientation of bedding surfaces or foliation was collected not explicitly analyzed unless the features are potential failure surfaces. Regarding discontinuity data, the presence of non-systematic fractures and blast fractures was noted because of the possibility that their interaction with systematic discontinuities may influence mode abundance. Discontinuity geometric data were chosen following recommendations of the ISRM (International Society for Rock Mechanics) Suggested Methods (Barton, 1978) and collected to investigate their expected association with rockfall mode, mode abundance, and block size.

Most data values are self explanatory, but a few require comment (Table 6). For differential weathering, the negative relief lithology was distinguished from the

TABLE 6. Geologic attributes collected.

Attribute	Values
SLOPE ORIENTATION AND FAILURE MODE INFORMATION	
Attribute	**Values**
Slope Trend	azimuth value using right-hand-rule
SlopeFaceOrientation	slope trend + 90
Slope Facing Direction	N, NE, E, SE, S, SW, W, NW
Failure Type	structural, weathering
Failure Mode	Planar, Wedge, Topple, Differential Weathering, Raveling
ModeAbundance	from Tennessee RHRS
BlockSize	from Tennessee RHRS
Overhang Relief	from Tennessee RHRS
Steepness	from Tennessee RHRS
Friction	from Tennessee RHRS
LITHOLOGY OF POTENTIAL ROCKFALL	
Attribute	**Values**
Rock Formation	observed from geologic map of Tennessee
Rock Type	based on field description; clastic sedimentary, carbonate sedimentary, crystalline
Grain Size	< .004mm (clay), .004mm - .039mm (silt), .040mm - 2.0mm (sand), 2.0mm - 4.0mm (granule), 4.0mm - 64mm (pebble)
Primary Mineralogy	assessed from field description
Degree of Weathering	fresh; weathered; highly weathered; decomposed
Fissility/Cleavage	yes, no
Degree of Fracturing	unfractured, fractured, highly fractured
Thickness	< 0.2m, 0.2m - 0.5m, 0.5m - 1.0m, >1.0m
UNDERCUT LITHOLOGY FOR DIFFERENTIAL WEATHERING	
Attribute	**Values**
Transition to Overhang	sharp, gradual
Rock Type	based on field description; clastic sedimentary, carbonate sedimentary, crystalline
Grain Size	< .004mm (clay), .004mm - .039mm (silt), .040mm - 2.0mm (sand), 2.0mm - 4.0mm (granule), 4.0mm - 64mm (pebble)
Mineralogy	assessed from field description
Degree of Weathering	fresh; weathered; highly weathered; decomposed
Fissility/Cleavage	yes, no
Degree of Fracturing	unfractured, fractured, highly fractured
Thickness	< 0.2m, 0.2m - 0.5m, 0.5m - 1.0m, >1.0m
BEDDING/FOLIATION ORIENTATION OF PRIMARY LITHOLOGY	
Attribute	**Values**
Strike	measured azimuth value using right-hand-rule
Dip	measured azimuth value using right-hand-rule
Dip Direction	N, NE, E, SE, S, SW, W, NW
DISCONTINUITY DATA	
Attribute	**Values**
Presence of Non-systematic Fractures	yes, no
Presence of Fractures	yes, no
Presence of Fracture Infilling	yes, no
Fracture Infilling Material	observed
Type	systematic joint, non-systematic fracture, bedding, fault
Strike	measured azimuth value using right-hand-rule
Dip	measured azimuth value using right-hand-rule
Dip Diection	N, NE, E, SE, S, SW, W, NW
Representative Length	< 5m, 5m - 10m, 10m - 20m, > 20m
Representative Spacing	< 0.5m, 0.5m - 1.0m, 1.0m - 2.0m, > 2.0m

overhanging lithology of the rock mass that might fail. Layer thickness was not actual bedding thickness in sedimentary rocks, but rather mechanical layering thickness between upper and lower bounding discontinuities of a set of beds with the same lithology. Also, well-defined foliation surfaces and compositional layering interfaces form such discontinuities in metamorphic rocks. Discontinuity attributes were recorded for each potentially active discontinuity surface, or sets of surfaces at a roadcut.

4.2. Logistic Regression: Method Overview

Whereas linear regression analysis attempts to determine the linear relationship between two or more variables where the dependent variable is *continuous* (Ott and Longnecker, 2001), logistic regression analysis attempts to determine the log-linear relationship between two or more variables where the dependent variable is *binary* (Hosmer and Lemeshow, 1989; Allison, 1999; Stokes *et al.*, 2000). Logistic regression analysis is used because *Abundance* and *Block Size* categories in the Tennessee RHRS and rockfall mode are categorical data that are treated in a binary fashion. To facilitate a binary approach, *Abundance* is treated as either greater than or less than 20%, *Block Size* is either greater or less than 0.3 m in longest dimension, and rockfall type is either structural- or weathering-related.

Logistic regression, is a log-linear type of regression analysis where the dependent 'outcome' variable is restricted to two-values, coded 1 and 0, which respectively represent the occurrence or nonoccurrence of an outcome event, and is predicted by one or more independent 'explanatory' variables. The analysis produces the coefficients of a prediction model formula with their standard errors of estimate and significance levels, and odds ratios with their 95% confidence intervals (Allison, 1999; Stokes *et al.*, 2000). The model formula predicts the probability of the occurrence as a function of the independent variables and circumvents the shortfalls of linear regression with the use of odds ratios. Odds of an event is the probability of the event divided by the probability of the nonevent.

Logistic regression is often used in the social sciences (Cleary and Angel, 1984; Wang *et al.,* 1995; Studenmund, 1997), and is now being applied to fields such as landslide hazard assessment (Apt *et al.*, 2002; Dai and Lee, 2001;), hydrology (Bent and Archfield, 2002; Zain, 2001), and resource exploration (Harris and Pan, 1999; Sahoo and Pandalai, 1999). The logistic regression equation is log-linear and has the form (Allison, 1999):

$$[1] \quad \ln[p/(1-p)] = a + BX + \text{error}_B, \text{ where}$$

$$[2] \quad p/(1-p) = \text{odds of event, and}$$

where ln is the natural logarithm, p is the probability that the 'outcome' event Y occurs ($p(Y=1)$), $\ln[p/(1-p)]$ is the log odds, a is the intercept coefficient, B is the coefficient of the independent 'explanatory' variable parameter, X, and error_B is the standard error of B (Figure 13). The method uses the independent variable values and the probabilities of the dependent variable to find the values for the coefficients. Additionally, the logistic distribution constrains the estimated probabilities of the dependant variable to lie in the range (0,1).

For example, say that the dependent variable, Y, is *Block Size*, and that the independent variable, X, is *rockfall type*. *Block Size* is coded as: $Y = 1$ where block sizes are greater than 0.3 m, and $Y = 0$ where block sizes are less than 0.3 m. *Rockfall type* is

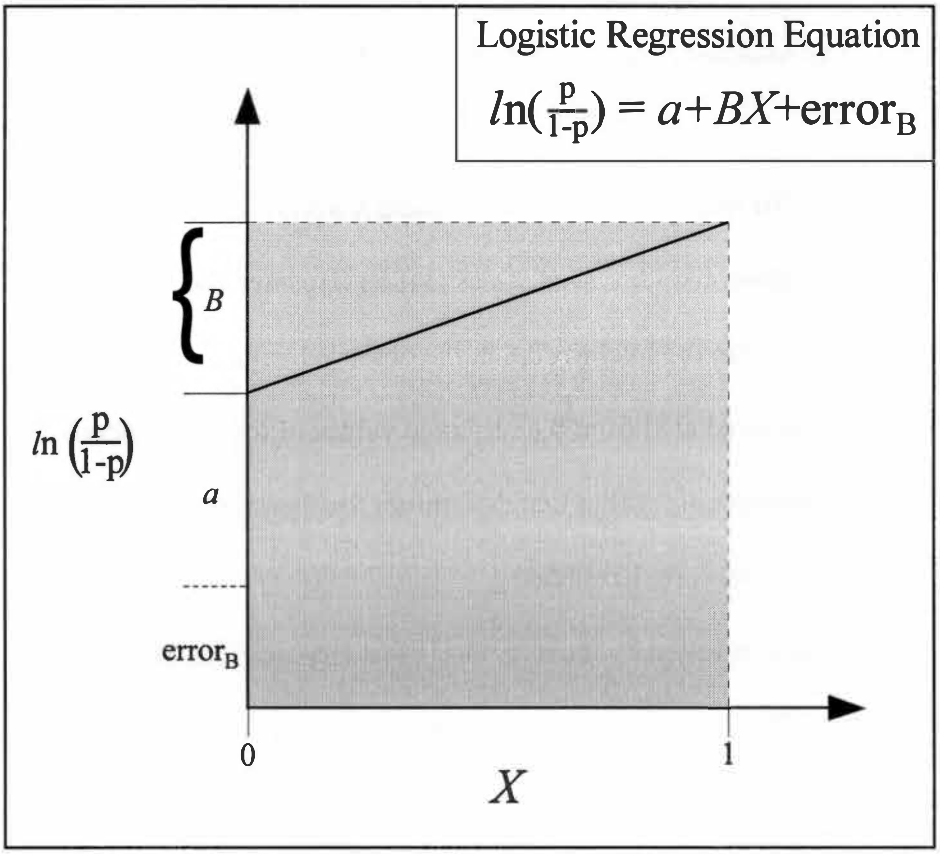

FIGURE 13. The logistic regression equation. Graph shows the relationship between the log odds of Y and the independent explanatory variable, X, in the logistic regression equation.

coded as: $X = 1$ where rockfall is weathering controlled, and $X = 0$ where rockfall is structurally controlled. The modeled outcome probability is *Block Size* greater than 0.3m ($p(Y=1)$).

Model parameter coefficients, *B*'s, of the independent variables and their standard errors are calculated by maximum-likelihood estimates (MLE) (Hosmer and Lemeshow, 1989). MLE attempts to maximize the likelihood that the observed values of the dependent variable, Y, may be predicted from the observed values of the independent variable(s), X, by using an iterative algorithm that determines the direction and amount of change in the coefficients for increasing likelihood.

Coefficient significance is tested by the hypothesis that a coefficient, *B*, of an independent variable is zero (H: $B = 0$) and is indicated by the significance probability value (p_w*-value*) determined from the Wald statistic with the form:

$$\text{Wald} = [\text{estimated } B/\text{error}_B]^2$$

which has a chi-square distribution with 1 degree of freedom. Large Wald values have small associated p_w*-values* (Allison, 1999). The hypothesis, H: $B = 0$, is rejected when p_w*-values* are smaller than the predetermined significance level (i.e. < .05%), indicating that the independent variable is statistically significant. Independent variables do not have a statistically significant relationship with the outcome variable and are eliminated from consideration when their effect is not statistically significant based on the Wald statistic.

Unlike linear regression where the slope coefficient (*B*) is the rate of change in *Y* with changes in *X*, the slope coefficient in logistic regression is interpreted as the rate of change in the log-odds of *Y* as *X* changes (Figure 13). However, a more intuitive interpretation of the coefficient utilizes the odds ratio (Hosmer and Lemeshow, 1989; Allison, 1999; Stokes *et al.*, 2000), which is determined as follows:

Given:

$$p = \text{prob}\ (Y = 1), \text{ then}$$

$$p = \text{prob}\ (Y{=}1 \mid X{=}0)*\text{prob}\ (X{=}0) + \text{prob}\ (Y{=}1 \mid X{=}1)*\text{prob}\ (X{=}1)$$

$$odds = p/(1\text{-}p)$$

The graph in Figure 13 shows that the coefficient, B, is equal to the change in log odds as follows:

$$\ln(odds \mid X{=}1) - \ln(odds \mid X{=}0) = \ln\left(\frac{odds \mid X=1}{odds \mid X=0}\right) = B$$

Multiplying the log odds by e yields the odds ratio:

$$[3] \qquad \text{odds ratio} = \frac{odds \mid X=1}{odds \mid X=0} = e^{B}$$

The odds ratio is equal to e^B. If coefficient $B > 0$, then $e^B > 1$ and $(odds \mid X{=}1) > (odds \mid X{=}0)$. If coefficient $B = 0$, then $e^B = 1$ and $(odds \mid X{=}1) = (odds \mid X{=}0)$. If coefficient $B < 0$, then $e^B < 1$ and $(odds \mid X{=}1) < (odds \mid X{=}0)$. For example, if coefficient $B = 1.6$, then its odds ratio is equal to $e^{1.6}$, which is 5, meaning that when the independent variable, X, increases one unit, the odds that the $Y = 1$ increases by a factor of 5. Odds ratios equal to 1 mean that there is a 50/50 chance that the event will occur with a change in the independent variable. Odds ratios less than 1 indicate lower odds that the event will occur with a change in the independent variable. Statistical significance of an independent variable can be ascertained by the 95% confidence interval of e^B. When the 95% confidence interval for e^B includes the value 1.0, it indicates that a change in value of X from 0 to 1 does *not* produce a statistically significant change in the odds for Y. In such a case, that variable X is not considered a useful predictor in the logistic model. However, when the 95% confidence interval for e^B *does not* include the value of 1.0, it indicates that a change in value of X from 0 to 1 produces a statistically significant change in the odds for Y, and therefore that variable is considered a useful predictor in the logistic model.

Unlike linear regression, logistic regression lacks an equivalent measure to the R^2 statistic, which is the proportion of the variance in the dependent variable that is explained by the variance in the independent variables. Therefore, evaluation of model parameters is accomplished by considering: (1) the likelihood ratio chi-square statistic to determine if the overall model is statistically significant by testing the global null hypothesis that the coefficients of all independent variables are collectively equal to zero; (2) the Hosmer-Lemeshow goodness-of-fit statistic to test the global null hypothesis that the model fits the data and rejecting the hypothesis if the model does not fit the data; and (3) the *c*-statistic, which measures the logistic equation discriminatory power. The *c*-statistic varies from .5 (predictions are no better than chance) to 1.0 (predictions are always correct) and *c* is the percent of all possible pairs of cases in which the model assigns a higher probability to a correct case than to an incorrect case (Hosmer and Lemeshow, 1989).

4.3. Data Models

For this study, the SAS software was used to perform stepwise logistic regression with the following dependent variables: (1) Rockfall type, (2) Block Size greater than

0.3 m, and Abundance greater than 20%, (Table 7). The dependent variable that measures the gross rockfall type is ROCKFALL and is equal to 1 if the rockfall type is weathering and 0 if structural. Weathering-related rockfall types are differential weathering and raveling, and structural-related rockfall types are planar, wedge, and topple. The dependent variable that measures block size is BLOCK_SIZE and is equal to 1 if the block size length is greater than 0.3 m and 0 otherwise. The dependent variable that measures rockfall mode abundance is ABUNDANCE and is equal to 1 if the mode abundance is greater than 20% and 0 otherwise.

For each model, independent variables and interactions were selected based on physical/geological reasons to test for correlation with the dependent variable. In stepwise logistic regression, the model is built by adding independent variables in steps. Each step consists of two parts: first, the Wald statistic of an independent variable is tested for significance at the 0.05 significance level and if the Wald statistic p_w-value is less than 0.05 then the variable is entered into the logistic model equation, otherwise the variable is eliminated from consideration. Second, if a variable enters the logistic model, then the Wald statistic is retested for significance to determine if the variable should stay in the logistic model, taking into account the other variables. If the variable is not significant after the second step, then it is removed from the model equation and eliminated from consideration (Hosmer and Lemeshow, 1989).

In each model, independent variables are categorical or ordinal and therefore must be entered as dummy variables, meaning that one categorical value for that variable becomes the reference category. Dummy coding makes comparisons to the one categorical value that becomes the reference (Kleinbaum *et al.*, 1998). For example, for

TABLE 7. Variables and interactions for logistic regression models.

	ROCKFALL MODEL	BLOCK SIZE MODEL	ABUNDANCE MODEL
DEPENDENT VARIABLE, *Y*	ROCKFALL	BLOCKSIZE	ABUNDANCE
MODELED CATEGORY (p(*Y* =1))	weathering	block size > 1ft	abundance > 20%
INDEPENDENT VARIABLES, *X*	Slope Aspect Rock Type Lithologic Variation Number of Discontinuity Sets	Failure Type Mechanical Layering Thickness Lithologic variation Fissility/Cleavage Rock Type Number of Discontinuity Sets	Fissility/Cleavage Lithologic Variation Slope Aspect Rock Type Mechanical Layering Thickness Presence of Water Number of Discontinuity Sets
INTERACTION TERMS * indicates interaction between two variables.	Rock Type* Lithologic Variation	Failure Type * Rock Type Mechanical Layer Thickness*Number of Discontinuity Sets	Slope Aspect* Presence of Water Lithologic Variation*Rock Type

the categorical variable *Slope Aspect*, a set of dummy variables is created called East, West, and North, leaving South as the reference value. If a roadcut faces east it is coded 1 on a variable called "East" and 0 on "West" and "North". If the resulting *B* coefficient for "East" is significant and yields an odds ratio, of say 2, it means that a roadcut facing east causes the odds of the dependent variable to be two times greater compared to a roadcut facing South, which is the reference value. A significant *B* coefficient for an independent variable value means that value has a significantly different effect on the outcome variable from the reference value (Allison, 1999).

Dummy coding is also applied to the interactions between independent variables. The interaction between two independent variables entered as a set of dummy variables involves multiple interaction terms for the different combinations of values. Determination of significance of the effect on the dependent variable by an interaction between two independent variables is the same as for a single independent variable.

5. RESULTS

5.1. Comparison of Tennessee RHRS Scores to NHI Scores for Geologic Character

Roadcuts were scored using both the Tennessee RHRS and the NHI Geologic Character schemes. Both systems yield the same score at roadcuts where differential weathering is the only mode. Yet, the average geologic character score for the Tennessee system is 84 whereas the average NHI geologic character/block size score is 66 (Figure 14). Overall, the Tennessee system scores can be higher for two reasons. One reason is that in the Tennessee system, the scores are cumulative for all potential rockfall modes at a roadcut, whereas the NHI RHRS only uses the highest-case score. Of the 80 roadcuts, 50 have multiple rockfall modes with differential weathering and raveling being most common (Figure 14 and 15). Another reason is the high percentage of roadcuts that have raveling, which is not scored with the NHI RHRS does not allow the scoring of raveling. Abundance is another factor that is not evaluated in the NHI RHRS. However, abundance causes a relative decrease for some Tennessee scores versus NHI scores for two reasons. First, where multiple rockfall modes are present, the scores for each individual mode tend to be lower for the Tennessee than NHI scores because the relative abundance of each mode tends to be smaller where multiple rockfall modes are present. Second, NHI scores tend to be higher than the Tennessee scores where only structural modes are present and in *low abundance*, which occurs at five roadcuts.

5.2. Results of Logistic Regression: ROCKFALL Dependent Variable

Logistic Regression analysis did not yield meaningful significant results relationships between geologic attributes and ABUNDANCE, so this section and the next section

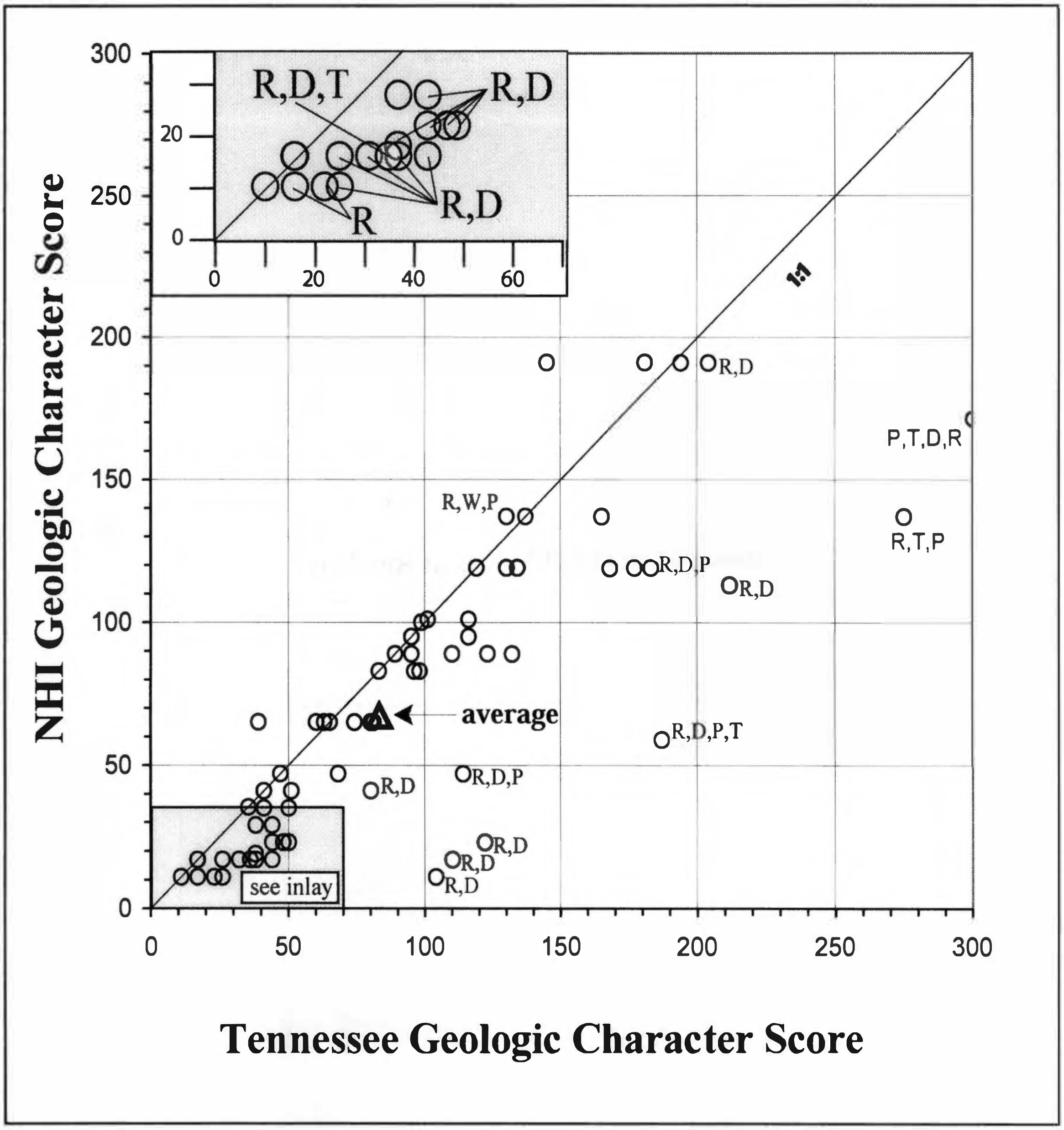

FIGURE 14. Comparison of Tennessee Geologic Character scores vs. NHI Geologic Character and Block Size scores. Note: Points without lettering indicate only a single rockfall mode at that roadcut; P = planar; Wedge = wedge; T = topple; D = differential weathering; R = raveling. Some points represent identcal scores for multiple rockfall modes.

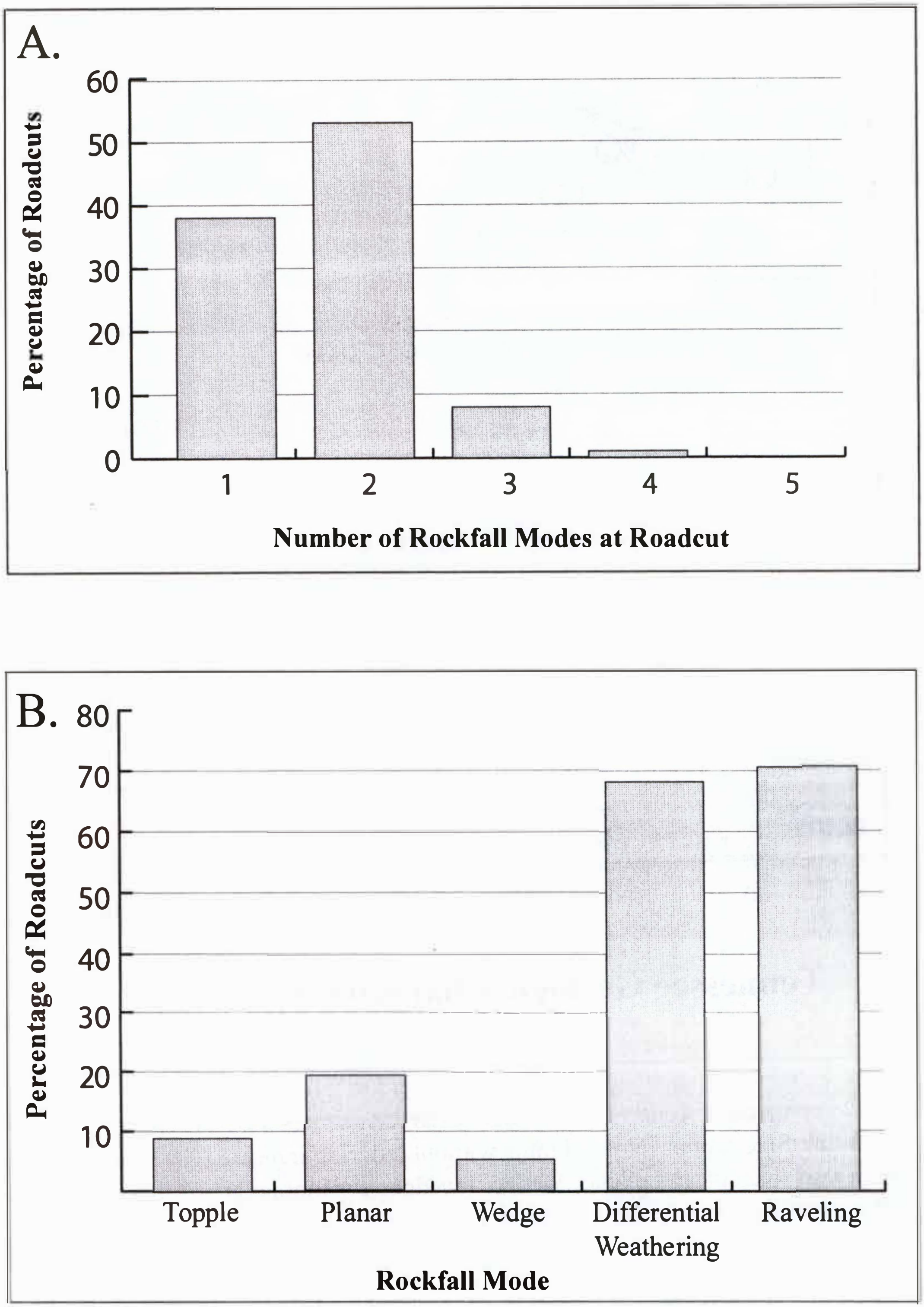

FIGURE 15. Distribution and frequency of rockfall modes at roadcuts. **A.** Percentage of number of rockfall modes at a roadcut. **B.** Percentage of rockfall modes at roadcuts. Note: Multiple rockfall modes can be present at a roadcut and therefore, percentages do not sum to 100%.

focuses on the relationships found for ROCKFALL and BLOCK_SIZE. The results from ROCKFALL logistic regression analysis (Table 8) indicate that rockfall type is influenced by the occurrence of lithologic variation and by the number of discontinuity sets. The coefficient for the Lithologic Variation variable has a Wald statistic of 6.7, which is significant at the 0.05 level (95% confidence). According to the odds ratio, lithologic variation increases the odds of weathering-related rockfall by a factor of 5.8. The coefficient on the Number of Discontinuity Sets variable has Wald statistics of 11.7 for zero sets, 5.6 for one set, and 5.3 for two sets that are significant at the 0.05 level. Odds for weathering rockfall are: 9.7 times greater when no discontinuity sets are present as opposed to three or more discontinuity sets; 6.0 times greater when there is one discontinuity set as opposed to three or more; and 4.0 times greater when there are two discontinuity sets as opposed to three or more. Slope Aspect, Rock Type, and their interaction are not statistically significant predictors of rockfall type and are not included in the model. The overall model is significant at the 0.05 level according to the Likelihood chi-square statistic and predicts 78.8% of the responses correctly. The goodness of fit statistic indicates that the logistic log-linear model fits the data.

5.3. Results of Logistic Regression: BLOCK_SIZE Dependent Variable

The results from the BLOCK_SIZE logistic regression analysis (Table 8) indicate that block sizes are influenced by rockfall type, lithologic variation, mechanical thickness, and number of discontinuity sets. The coefficient for the Rockfall Type variable has a Wald statistic of 15.5, which is significant at the 0.05 level. The odds for block sizes larger than 0.3 m in longest dimension are 19.3 times greater for structural- related

TABLE 8. Logistic regression results. A. Results for the ROCKFALL dependent variable. B. Results for the BLOCKSIZE dependent variable.

A. ROCKFALL Dependent Variable.

Dependent Variable = ROCKFALL **Modeled category = Weathering**							
Variable	**Reference Value**	***B***	**Error *B***	**Wald Statistic**	**Wald p_w -value**	**Odds Ratio**	**95% C.I.**
Lithologic Variation: yes	no	1.8	0.7	6.7	0.01	5.8	1.5, 22.0
Number of Discontinuity Sets: 0	>2 sets	2.3	0.7	11.8	<0.01	9.7	2.6, 35.4
Number of Discontinuity Sets: 1	>2 sets	1.8	0.8	5.6	0.02	6.0	1.4, 26.4
Number of Discontinuity Sets: 2	>2 sets	1.4	0.6	5.3	0.02	4.0	1.2, 13.3
Likelihood Chi-Square [df] [p-value]					25.7	[4]	[<0.01]
Hosmer Lemeshow Goodness of Fit [df] [p-value]					0.91	[5]	[0.97]
c -statistic						0.788	

B. BLOCKSIZE Dependent Variable.

Dependent Variable = BLOCKSIZE **Modeled category = Block size > 0.3 m**							
Variable	**Reference Value**	***B***	**Error *B***	**Wald Statistic**	**Wald p_w -value**	**Odds Ratio**	**95% C.I.**
Failure Type: structural	weathering	2.6	0.6	15.4	<0.01	19.3	4.4, 84.5
Lithologic Variation: yes	no	1.72	0.52	11.0	<0.01	5.6	2.0, 15.4
Number of Discontinuity Sets: 2	>2 sets	-1.5	0.7	5.2	0.02	0.22	0.06, 0.8
Mechanical Thickness: < 0.2m	> 1.0m	-2.0	0.7	8.0	<0.01	0.13	0.03, 0.5
Likelihood Chi-Square [df] [p-value]					48.8	[8]	[<.01]
Hosmer Lemeshow Goodness of Fit [df] [p-value]					6.7	[8]	[0.57]
c -statistic						0.824	

than for weathering-related rockfall. The coefficient for the Lithologic Variation variable has Wald statistics of 11.0, which is significant at the 0.05 level. The odds for block sizes larger than 0.3 m in longest dimension are 5.5 times greater when there is a lithologic variation is present than when absent. The coefficient for the Mechanical Thickness < 0.2m variable has a Wald statistic of 7.9, which is significant at the 0.05 level. The odds for block sizes larger than 0.3 m in longest dimension are 7.7 times less when the mechanical thickness is less than 0.2 m than where the mechanical thickness is greater than 1.0 m. The coefficient for the Number of Discontinuity Sets variable has a Wald statistic of 5.2 for two sets, which is significant at the 0.05 level. The odds for block sizes larger than 0.3 m in longest dimension are 4.5 times less when there are two sets than where there are three or more. The variables: Fissility/Cleavage, Rock Type, and the Thickness × Number of Discontinuity Rockfall Type × Rock Type interactions are not statistically significant predictors of block size and were not included in the model. Overall the model is significant at the .05 level according to the Likelihood chi-square statistic, and the goodness of fit statistic indicates that the logistic model fits the data. The model has a *c*-statistic of 0.824.

6. DISCUSSION

6.1. Tennessee RHRS

The Geologic Character of the Tennessee RHRS allows for the description of a wider spectrum of geologic conditions at roadcuts than the NHI RHRS. Geologic scoring with the Tennessee RHRS is more reproducible than the NHI RHRS because it avoids incorrect and ambiguous terminology by explicitly identifying potential rockfall modes. As demonstrated by the greater geologic character scores where raveling is present (Figure 5), the Tennessee RHRS captures the significance of raveling with respect to the production of rockfall material without overemphasizing its role as a potential failure mode. Though raveling occurs at 70% of the roadcuts in the study area (Figure 6), the hazard potential stemming from raveling may be small compared to other rockfall modes because block sizes for raveling are typically small. However, because negative consequences due to raveling can be significant if small blocks are shed from large heights and the blocks roll or launch onto the roadway, characterization of raveling is necessary for effective rockfall management.

The cumulative scoring of potential rockfall modes in the Tennessee RHRS yields greater total Geologic Character scores compared to the NHI RHRS. One possible implication could be a concern that the score increase would overemphasize the role of Geologic Character in hazard scoring, but the following points counterbalance this concern. First, although the importance of an accurate geologic evaluation is the focus here, the Tennessee system also evaluates traffic volume and roadway conditions with the same proportion of possible score as the NHI RHRS. For example, a roadcut could score very high on Geologic Character, but if catchment is sufficient to minimize rockfall impacting the roadway, the overall score will not be large despite the Geologic Character score.

Second, considering all potential rockfall modes, not just the most hazardous condition, gives insight to the structural and weathering condition of a roadcut, which is critical because the most hazardous condition may not be the one that produces a significant rockfall. Similarly, the possibility also exists that rockfall by one mode can trigger rockfall by another mode. Therefore, recognition of all modes more completely defines the portion of a roadcut that is prone to failure.

Third, scoring all potential rockfall modes at a roadcut provides an indication of likely successful remediation techniques (Wyllie and Norrish, 1996). Furthermore, by evaluating all potential rockfall modes at a roadcut, the need to separate the roadcut into segments where different modes are present is obviated, thereby reducing the data collection complexity and clarifying the positioning of remediation strategies. Lastly, the 300-point cap for the Geologic Character score prevents overemphasis of geology on the total score and only occured once for 80 roadcuts. Therefore, it does not significantly truncate geologic scoring. Overall, the methodology of scoring all rockfall modes captures useful information omitted by the single-case methodology in the NHI RHRS, and does not overemphasize the role of geology in hazard potential. This strategy also facilitates more insightful management decisions about remediation prioritization compared to the NHI RHRS.

Compared to the NHI RHRS, the contribution of individual rockfall modes to the Geologic Character score is appropriately lower in the Tennessee system when the mode is less abundant. The advantage of this result is that the use of abundance as a geologic characteristic in the Tennessee RHRS differentiates roadcuts that would score identically in the NHI RHRS, which does not evaluate abundance. Additionally, the use of abundance overcomes a potential problem for the NHI RHRS. The potential problem is that the most hazardous condition, as identified by the NHI RHRS, may only occupy a small portion of the roadcut and is less abundant than another "less hazardous" condition that is not recorded for the NHI system. Yet, the so-called "less hazardous" mode while it lacks the risk at the particular spot of the "more hazardous" mode, it may have equivalent or greater cumulative risk because it is present on such a greater portion of the roadcut. Therefore, the use of abundance in the Tennessee RHRS acts as a sensitivity indicator to the overall role of potential rockfall mode.

6.2. Logistic Regression for ROCKFALL

The logistic regression results for the ROCKFALL dependent variable (Table 6) indicate that both lithologic variation and number of discontinuities are significant predictors of rockfall type. Intuitively, lithologic variation should affect rockfall type because lithologic variation promotes differential weathering. Similarly, as the number of discontinuity sets increases, structural conditions are created that promote planar, wedge, and topple rockfall, and the odds of differential weathering and raveling decrease. It was expected that a northerly slope aspect would increase the odds of weathering rockfall because north-facing roadcuts receive less direct sunlight and are more susceptible to freeze-thaw cycles. However, the results do not indicate any such relationship.

6.3. Logistic Regression for BLOCK_SIZE

The logistic regression results for the BLOCK_SIZE dependent variable (Table 6) indicate that rockfall type, number of discontinuities, mechanical thickness, and lithologic variation are significant predictors of block sizes larger than 0.3 m. Structural rockfall is strongly influential on block sizes larger than 0.3 m, but the odds are also interpreted such that weathering rockfall is influential on block sizes smaller than 0.3 m, which is likely due to raveling, which typically has blocks smaller than 0.3 m, as much as structural rockfall typically involving block sizes greater than 0.3 m. Lithologic variation also favors larger block size because roadcuts with such variation have nearly 5.5 times greater odds to produce large blocks, which is interpreted to mean that the presence of a lithology appropriate for undercutting favors the creation of overhangs greater than 0.3 m.

Rock units with mechanical layer thicknesses smaller than 0.2 m have 7.7 times lower odds than those with thicknesses greater than 1.0 m to produce large block sizes. This statistic is interpreted to indicate that as intuitively expected, rock units with thinner mechanical layers have greater odds for producing small blocks, whereas rock units with thicker mechanical layers have greater odds for producing large blocks.

Interestingly, rockfall modes with *greater* than two discontinuity sets are more likely to produce block sizes greater than 0.3 m than those with two discontinuity sets. It is reasonable to expect that more discontinuity sets would favor a multiplicity of bounding surfaces favors *smaller* block sizes. However, the opposite relationship exists and is interpreted to relate to the occurrence of structural failure modes, which by definition (Norrish and Wyllie, 1996) are most efficient with three or more sets of discontinuities.

6.4 Implications

Results of the logistic regression analyses highlight geological attributes of roadcuts that increase potential rockfall hazard rating scores for the Tennessee RHRS. Identifying geologic conditions that increase the potential rockfall hazard helps agencies to make decisions about rockfall mitigation and roadcut remediation.

The presence of lithologic variations increases the odds of potential weathering-related rockfall, and the average score for potential rockfall modes that contain rocks with lithologic variation is 48. However, the average geologic character score for potential rockfall modes that contain rocks without lithologic variation is 54 (+12.5%) and includes an overwhelming majority of the structural-related rockfall modes (24 of 27.). Furthermore, the average geologic character score for structural rockfall modes is 84 as compared to 43 for weathering-related rockfall modes.

Additionally, as the number of discontinuity sets increases, the odds of structural-related rockfall increase, which is consistent with the observation that all occurrences of structural rockfall modes contain at least two discontinuity sets. Similarly, the odds of block sizes greater than 0.3 m are greatest with the existence of more than two discontinuity sets. Plus, potential structural rockfall modes have an average block size score of 26, which translates approximately to the third hazard category (3-6 ft).

Therefore, if a roadcut contains rocks without lithologic variation and two or more discontinuity sets, a greater geologic character score is expected because of the increased odds of large intact rock blocks shed by structural rockfall modes. This expectation is even greater where mechanical thicknesses exceed 1.0 m because of the increased odds of block sizes greater than 0.3 m.

Although the presence of lithologic variation increases the odds for block sizes greater than 0.3 m, the average block size score for rockfall modes with rocks containing lithologic variation is only 10, whereas the average block size score for rockfall modes that contain rocks without lithologic variation is 13. The higher average score for the lack of variation is due to greater frequency of block size scores of 81 points (6 of 86, vs. 1 of 47). Additionally, 53% of rockfall modes with lithologic variation have block size scores greater than 3, whereas 47% of modes without lithologic variation have block size scores greater than 3. Both percentages are about 50% whether or not a lithologic variation exists, so nearly one-half of all rated rockfall modes can be expected to have block size scores of 3. However, if a rockfall mode is associated with lithologic variation, slightly greater scores for block size are favored, but rarely the highest hazard score.

7. CONCLUSIONS

The Geologic Character category utilized in the Tennessee RHRS describes a wider spectrum of geologic conditions occurring at roadcuts than the NHI version and produces higher average scores because the Tennessee RHRS:

- avoids ambiguous terminology
- explicitly identifies potential rockfall modes including raveling
- accumulates hazard scores of all potential modes at a roadcut.

Additionally, results of logistic regression analyses indicate:

- Lithologic variation and number of discontinuity sets are significant predictors of rockfall type because the occurrence of lithologic variation promotes differential weathering and a greater number of discontinuity sets increases the odds of structural rockfall modes.
- Block sizes greater than 0.3 m. are predicted by structural rockfall modes, the presence of more than two discontinuity sets, lithologic variation, and mechanical layering thicknesses greater than 1.0 m.

With respect to the Tennessee RHRS, roadcuts containing rocks without lithologic variation and two or more discontinuity sets are expected to have greater a geologic character score because of the increased odds of large intact rock blocks shed by structural rockfall modes. This expectation is even greater where mechanical thicknesses exceed 1.0 m because of the increased odds of block sizes greater than 0.3 m. Additionally, nearly half of all rockfall modes are expected to have block size scores of only 3. However, where rockfall modes contain lithologic variation, expectation of slightly greater scores for block size is favored.

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APPENDICES

Appendix 1

Tennessee's Rockfall Hazard Rating System User's Manual

TABLE OF CONTENTS

1. INTRODUCTION

The Tennessee Rockfall Hazard Rating System (RHRS) is a tool used to identify roadcuts that are potentially hazardous due to rockfall risk, and is part of Tennessee's Rockfall Management System (Bateman, 2001). This Appendix describes the process for selecting potentially hazardous roadcuts (Sections II and III), and the basis for scoring each of the characteristics at a potentially hazardous roadcut with the Tennessee RHRS (Section IV). The scoring for certain characteristics (ditch effectiveness, geologic characteristics, presence of water on cut, and rockfall history) in the Tennessee RHRS is modified from the National Highway Institute (NHI) RHRS (1993), so the basis for these changes is described along with the new scoring approaches in Section IV.

2. TENNESSEE'S RHRS METHOD: SLOPE IDENTIFICATION

As used here, a hazardous roadcut is a roadcut or rock slope that has potential for rockfall events to reach the roadway. The process of identifying potentially hazardous roadcuts on Tennessee state roads begins with a virtual drive-through using TRIMS - the Tennessee Roadway Information Management System. TRIMS is an integrated roadway management tool that incorporates video-logging of all state routes with photographs captured at one-hundredth-of-a-mile increments (Figure A-1.1). Potentially hazardous roadcuts are identified during the virtual drive-through, and the corresponding log miles are recorded. Other roadway information for each roadcut, such as average daily traffic and speed limit, is recorded and used if the roadcut subsequently is rated at the detail level.

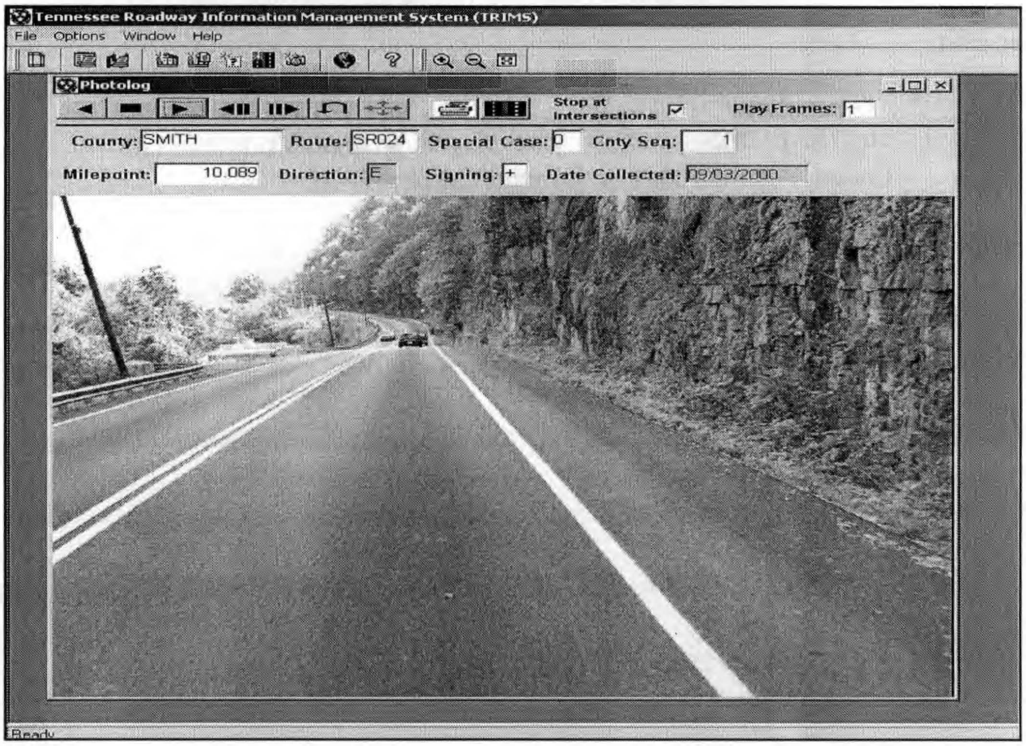

Figure A-1.1. Example TRIMS user screen.

3. TENNESSEE RHRS METHOD: PRELIMINARY RATINGS

After identifying potentially hazardous cuts using TRIMS, the roadcuts are visited, evaluated and assigned preliminary ratings according to the following NHI guidelines (NHI, 1993).

A Slopes have a moderate-to-high potential for rocks to reach roadway and/or high historical rockfall activity.

B Slopes have a low-to-moderate potential for rocks to reach roadway and/or moderate historical rockfall activity.

C Slopes have a negligible-to-low potential for rocks to reach roadway and/or low historical rockfall activity.

When evaluating the potential for rocks to reach the roadway, the following are considered:

1. Impact marks on the road.
2. Ditch effectiveness, including width and shape of catchment
3. Estimated size and amount of material per event.
4. Presence of launching features.

A motorist's decision site distance should be considered if the potential for rocks to reach the roadway is moderate. A limited decision site distance with moderate potential for rocks to reach the roadway is considered hazardous, and the roadcut should be assigned a preliminary rating of A.

When evaluating the historical rockfall activity, the following are considered:

1. Frequency and presence of rockfall on roadway as determined from maintenance records.

2. Frequency of removal of rock debris from catchment/roadway as determined from maintenance records.

3. Amount of material in the catchment (particularly in the absence of maintenance reports)

4. Number of impact marks in the road (particularly in the absence of maintenance reports)

4. TENNESSEE RHRS METHOD: DETAILED RATING SYSTEM.

The purpose of the detailed rating system is to numerically differentiate the potential risk at identified roadcuts (NHI, 1993). As a result, roadcuts can be sorted and prioritized for maintenance/remediation based on their scores. Only roadcuts receiving a preliminary rating of *A* receive the detailed rating. The primary method of data collection for the Tennessee RHRS detailed ratings is via personal digital assistants

(PDA's) (Bellamy, 2002); with paper forms used as back up method.

Most categories and the scoring system of the Tennessee RHRS detailed ratings are in the NHI (1993) RHRS. However, several categories were modified to provide geologic characteristics, and to improve repeatability and consistency among raters. Consequently, the detailed rating system has the following categories:

- Slope height
- Ditch effectiveness
- Average Vehicle Risk (AVR)
- Roadway width
- Percent of Decision Site Distance (%DSD)
- Geologic characteristics
- Presence of water on slope
- Rockfall history

Like the NHI RHRS, each factor in the Tennessee detailed rating is assigned a score that increases exponentially with degree of hazard and then all categories are summed to yield an overall score. The exponential scoring of each category benchmark, from 3 to 81 points, is calculated on the basis of 3^x where $x = 1$ (low risk) to 4 (high risk).

It should be noted however, that directly measurable categories allow for scores within the continuum of 1 to 100 points. Those scores are calculated with the 3^x equation and using exponential formulas to determine the value of the exponent, x. Exponential formulas are discussed later under their respective headings. Furthermore, since some categories in the Tennessee detailed rating are modified from the NHI version, their respective scores are weighted to maintain consistency with the NHI RHRS and are also discussed later. The detailed description of each of the categories in the Tennessee RHRS Detailed Rating is below.

4.1. Slope Height.

The Tennessee RHRS allows slope height to be determined in two ways, by visually estimating or by measuring. Raters may find that, through experience, their ability to visually estimate the height of a roadcut produces reliable estimates compared to measured values, and therefore prefer estimation as the method to determine slope height. Estimation of height should be done to the nearest ten feet, and until the rater is comfortable with the reliability of his/her estimation, it should be done in conjunction with measurement so that the two results can be compared.

Measurement. To determine the height of a roadcut the following steps are carried out following NHI recommended methods (NHI, 1993):

a) Measure vertical angles from near and far shoulders (edges of pavement) to top of roadcut (see Figure 1), using a clinometer.

b) Measure width of roadway between shoulders using a measuring wheel

c) Calculate height of road cut using the equation (NHI, 1993) (Figure A-1.2.).

$$\text{Total Slope Height} = \frac{(X) * \sin\alpha * \sin\beta}{\sin(\alpha - \beta)} + H.I.$$

Where: X = Horizontal distance between α between β
α = Angle measured from near shoulder
β = Angle measured from far shoulder
$H.I.$ = height of clinometer above pavement

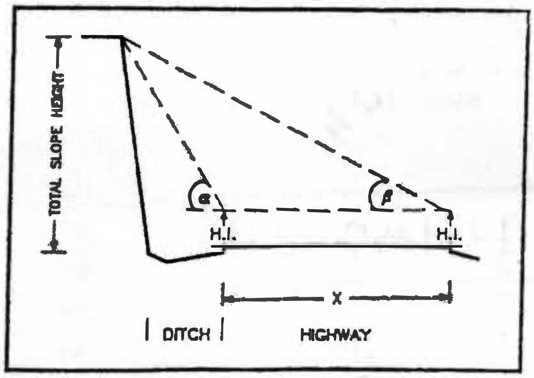

Figure A-1.2. Diagram showing roadcut slope height measurement locations (modified from NHI, 1993).

Scoring. Following NHI guidelines, scoring is calculated with the following exponential equation or scoring chart shown in Table A-1.1 (NHI, 1993):

$$3^x \text{ where } x = \frac{Slope\ Height(ft)}{25}$$

Table A-1.1 Slope Height scoring table (NHI, 1993).

Slope Height Scoring Table							
Height (ft)	**Score**		**Height (ft)**	**Score**		**Height (ft)**	**Score**
9	1		**68**	20		**87**	46
10 - 20	2		**69**	21		**88**	48
21-28	3		**70**	22		**89**	50
29-34	4		**71**	23		**90**	52
35-38	5		**72**	24		**91**	55
39-42	6		**73**	25		**92**	57
43-45	7		**74**	26		**93-94**	60
46-48	8		**75**	27		**95**	62
49-51	9		**76**	28		**96**	65
52-53	10		**77**	29		**97**	71
54-55	11		**78**	31		**98**	74
56-57	12		**79**	32		**99**	78
58-59	13		**80**	34		**100**	81
60	14		**81**	35		**101**	85
61-62	15		**82**	37		**102**	88
63	16		**83**	38		**103**	92
64-65	17		**84**	40		**104**	97
66	18		**85**	42		**105**	100
67	19		**86**	44			

4.2. Ditch Effectiveness.

The NHI (1993) Ditch Effectiveness category is a subjective evaluation of site conditions that prevent rock from reaching the roadway. In the Tennessee RHRS, this category was modified to increase objectivity by evaluating ditch effectiveness as a function of the TDOT recommended design catchment width the slope of catchment area, and the presence of launching features.

Measurement. The following steps are carried out:

a) Measure actual catchment width with a tape, and record value for comparison with the TDOT design width.

b) Determine whether catchment slope has a 6:1 or greater width to depth ratio and record as "yes" or "no".

c) Any catchment with 6:1 or greater ratio is considered less hazardous, while a ratio less than 6:1, including a flat catchment, is considered more hazardous.

d) Note the presence of any launching features that could allow a falling rock to launch and bypass the catchment.

Scoring.

a) Obtain the recommended design catchment width for a new road cut with the measured slope height using the TDOT Design Catchment Width Table (Table A-1.2.), which is based on rockfall simulations using Colorado's Rockfall Simulation Program 4.0 (CRSP). The design widths are presented for both vertical and inclined slopes for a particular height of a new roadcut.

b) Evaluate actual catchment width as a percentage of the recommended catchment width for a new road cut. Then, using the Ditch Effectiveness Criteria Scoring Table (Table A-1.3.), identify the correct column for the calculated percentage and select the appropriate row on the basis of catchment slope and launching features.

Table A-1.2. TDOT recommended design catchment width for new slopes.

Design Catchment Width (feet)		
Slope Height (feet)	Recommended Catchment Width, Vertical Slope (feet)	Recommended Catchment Width, Inclined Slope (feet)
0-40	18	18
40-50	18	24
50-60	24	30
60-70	28	34
70-80	32	38
80-100	36	42
100-125	36	42
125-175	40	48
>175	52	60

Table A-1.3. Ditch Effectiveness scoring table.

Ditch Effectiveness Criteria				
Percent of Design Catchment Width from Table	>90%	70% - 90%	50% - 70%	<50%
Score with 6:1 or greater catchment slope	3	9	27	81
Score w/ Poor Catchment Slope **OR** Launch Features	9	27	81	81
Score w/ Poor Catchment Slope **AND** Launch Features	27	81	81	81

4.3. Average Vehicle Risk (AVR)

Measurement. The average vehicle risk (AVR) is determined by the average daily traffic (ADT) data (provided from TRIMS), the measured slope length, and posted speed limit (NHI, 1993):

$$AVR = \frac{ADT\,(cars\,/\,day) * SlopeLength\,(miles)}{24\,(hours\,/\,day) * Posted\ Speed\ Limit\,(mph)} \times 100\%$$

Scoring. The score is determined by the following exponential formula or comparing the calculated AVR to the values in Table A-1.4. (NHI, 1993):

$$3^x, \text{ where } x = \frac{\%\,Time}{25}$$

Table A-1.4. Average Vehicle Risk scoring table (NHI, 1993).

Average Vehicle Risk Scoring Table							
AVR %	**Score**		**AVR %**	**Score**		**AVR %**	**Score**
9	1		**68**	20		**87**	46
10 - 20	2		**69**	21		**88**	48
21-28	3		**70**	22		**89**	50
29-34	4		**71**	23		**90**	52
35-38	5		**72**	24		**91**	55
39-42	6		**73**	25		**92**	57
43-45	7		**74**	26		**93-94**	60
46-48	8		**75**	27		**95**	62
49-51	9		**76**	28		**96**	65
52-53	10		**77**	29		**97**	71
54-55	11		**78**	31		**98**	74
56-57	12		**79**	32		**99**	78
58-59	13		**80**	34		**100**	81
60	14		**81**	35		**101**	85
61-62	15		**82**	37		**102**	88
63	16		**83**	38		**103**	92
64-65	17		**84**	40		**104**	97
66	18		**85**	42		**105**	100
67	19		**86**	44		-	-

4.4. Roadway Width

Measurement. The roadway width is measured from edge of pavement to edge of pavement perpendicular to the longitudinal direction of the road. If the width varies along a roadcut, it is measured at the narrowest width.

Scoring. The score is obtained by the following exponential formula or by comparing measured width to the values in the Table A-1.5. (NHI, 1993):

$$3^x, \text{ where } x = \frac{52 - \textit{Roadway Width}(\textit{ft.})}{8}$$

Table A-1.5. Roadway Width scoring table (NHI, 1993).

Roadway Width Scoring Table				
Width	**Score**		**Width**	**Score**
18	100		**35**	10
19	93		**36**	9
20	81		**37**	8
21	71		**38**	7
22	62		**39**	6
23	54		**40**	5
24	47		**41**	5
25	41		**42**	4
26	36		**43**	3
27	31		**44**	3
28	27		**45**	3
29	24		**46**	2
30	21		**47**	2
31	18		**48**	2
32	16		**49**	2
33	14		**50**	1
34	12		-	-

4.5. Percent Decision Sight Distance (DSD)

The decision sight distance (DSD) is the maximum road length that a driver has to identify and avoid a rockfall hazard.

Measurement.

The DSD is measured along the edge of pavement in the direction of oncoming traffic. It is the distance from the roadcut to where a 6" object disappears from view at a height of 3.5 ft above the ground. Where both directions of traffic are likely to be affected by rock in the road, the distance is measured in both directions and the shorter distance is recorded. The measured distance is recalculated as a percent of the recommended AASHTO (1994) distance for that speed limit. The recommended AASHTO distances are shown in Table A-1.6.

Table A-1.6. AASHTO recommended decision sight distances.

Posted Speed Limit (mph)	Decision Sight Distance (ft)
25	375
30	450
35	525
40	600
45	675
50	750
55	875
60	1,000
65	1,050

Table A-1.7. Percent Decision Sight Distance scoring table (NHI, 1993)

%DSD Scoring Table								
%DSD	**Score**		**%DSD**	**Score**		**%DSD**	**Score**
36	100		**53**	40		**69-70**	16
37	96		**54**	38		**71**	15
38	90		**55**	36		**72**	14
39	86		**56**	34		**73-74**	13
40	81		**57**	32		**75**	12
41	77		**58**	30		**76-77**	11
42	73		**59**	29		**78-79**	10
43	69		**60**	27		**80-81**	9
44	65		**61**	26		**82-83**	8
45	62		**62**	24		**84-85**	7
46	58		**63**	23		**86-88**	6
47	55		**64**	22		**89-92**	5
48	52		**65**	21		**93-97**	4
49	49		**66**	19		**98-103**	3
50	47		**67**	18		**104-112**	2
51	44		**68**	17		**113**	1
52	42		-	-		-	-

<u>Scoring.</u> The score is determined by the following exponential formula or by comparing the measured %DSD to the values in Table A-1.7. (NHI, 1993):

$$3^x, \text{ where } x = \frac{120 - \%DSD}{20}$$

4.6. Geologic Characteristics

The Tennessee DOT's characterization of geology is significantly modified from the NHI (1993) characterization. The Tennessee RHRS characterizes all active potential failure modes at a roadcut, scores each failure mode, and sums the scores rather than selecting based on highest score, as is done in the NHI RHRS. The NHI scheme distinguishes structurally controlled rockfall (Geologic Character Case 1) from weathering controlled rockfall (Geologic Character Case 2) (NHI, 1993). The Tennessee RHRS subdivides the above cases into specific failure modes. Structurally controlled failure modes are planar slide, wedge slide, and topple failure, while the weathering controlled failure modes are differential weathering, and raveling. All relevant modes are recorded as part of the hazard inventory.

Characteristics pertinent to all failure modes are the relative *abundance* of the failure zone as a percentage of the total cut surface area, and *block size*. Characteristics unique to planar and wedge failure are *steepness* of failure plane(s) and the micro- and macro-*friction* profiles of the failure plane(s). The a*mount of relief* is a characteristic unique to differential weathering, and block *shape* is unique to raveling.

The scores for different failure modes are additive up to a maximum score of 300 points. The upper limiting value is used because the NHI (1993) RHRS allowed a maximum score of 300 for the combination of the Case1/Case2 geology score and the Block Size score. Thus, the Tennessee RHRS has the same maximum contribution from geology to the total rockfall hazard score as compared to the original NHI RHRS despite summing the scores of the different operative failure modes. It should be noted that the cap has little effect on the scoring; the maximum was reached on only one occasion during Phase I of Tennessee's Rockfall hazard inventory.

Since potential planar and wedge failures are characterized by four criteria in the Tennessee detailed system, as opposed to three criteria in the NHI system (Case 1 with Block Size), the scores for the *steepness* and *friction* categories are each weighted approximately half of the 3^x value (rounded to the nearest integer) to retain the same weighting as the NHI system (Case 1 with Block Size). Similarly, scores for topple *abundance* and *block size* are weighted approximately one-and-a-half times the 3^x value, because steepness and friction are not considered for topple, so that total potential score matches the NHI system (Case 1 with Block Size).

For the raveling mode, the scores for *shape* are capped at 27 points because only three options exist for block shape (tabular = 3, blocky = 9, round = 27), and using the lower three bin scores (not 81) prevents large scores that would overestimate the hazard due to raveling, particularly when it usually yields blocks less than 1 foot in linear dimension.

Measurement Methods and Scoring

Abundance Measurement. The relative abundance of a failure mode is determined by visual inspection and is expressed as a percentage of the total slope-face surface area, where the rock face is susceptible to the failure mode. Visual scoring aids were developed to help raters become more comfortable with the assessment of abundance percentage (see Figure A-1.3). The aids show the relative area percentage of black dots, which represent active failure zones, versus a white background. Additionally, photo-scoring aids are also being compiled as representative abundances of failure zones are encountered in the field.

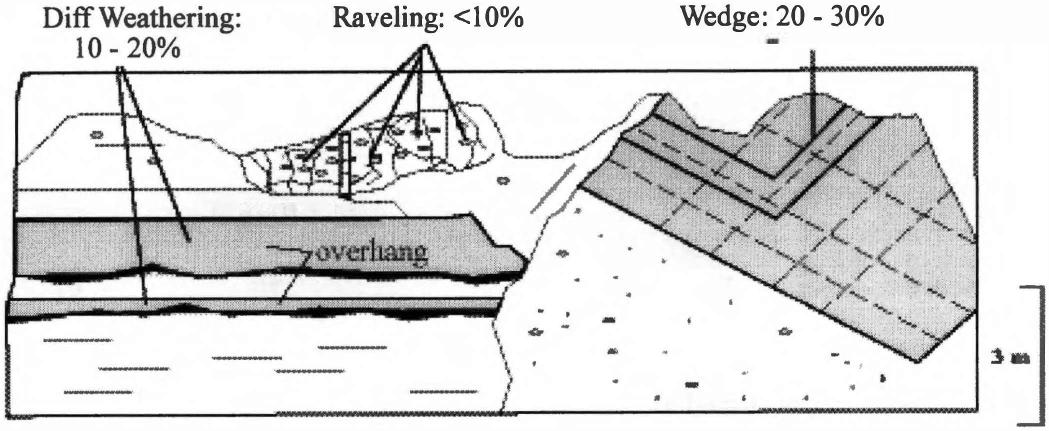

Figure A-1.3. Schematic examples of abundance at a roadcut.

Abundance Scoring. The measured relative abundance of rocks susceptible to a failure mode is scored as:

Abundance	<10%	10-20%	20-30%	>30%
Score	**3**	**9**	**27**	**81**

For topple, *abundance* is scored as:

Abundance	<10%	10-20%	20-30%	>30%
Score	**5**	**14**	**41**	**122**

Block Size Measurement. The block size of a failure mode is determined by visually inspecting rock blocks that have shed from the cut and/or have the potential to shed. A representative block is selected and the longest dimension measured. Given that blocks typically break apart when they fall and impact the ground, the size of blocks to be shed should be given preference over the size of shed blocks when they are not the same.

Block Size Scoring. The measured longest dimension of the representative block size is scored as:

Block Size	<1 ft (< 0.3 m)	1 ft - 3 ft (0.3 – 0.9 m)	3 ft - 6 ft (0.9 – 1.8 m)	>6 ft (>1.8 m)
Score	**3**	**9**	**27**	**81**

For topple, block size is scored as:

Block Size	<1 ft (< 0.3 m)	1 ft - 3 ft (0.3 – 0.9 m)	3 ft - 6 ft (0.9 – 1.8 m)	>6 ft (>1.8 m)
Score	**5**	**14**	**41**	**122**

Steepness Measurement. The steepness of a failure plane susceptible to planar failure or the line of intersection from planes forming a potential wedge failure is estimated or measured using a clinometer and recorded in degrees from horizontal.

Steepness Scoring. The benchmark scores for steepness of potential failure planes or the lines of intersection from planes forming potential wedge failures were determined by calculating $3^x/2$ for x = 1 to 4, then rounding to the nearest integer, and scored as:

Steepness	0 - 20°	20-40°	40-60°	>60°
Score	**2**	**5**	**14**	**41**

Friction Measurement. The micro- and macro-friction of a surface susceptible to planar failure or wedge failure is measured by visual inspection with the aid of friction profiles modified from Barton (1973) (Figure A-1.4).

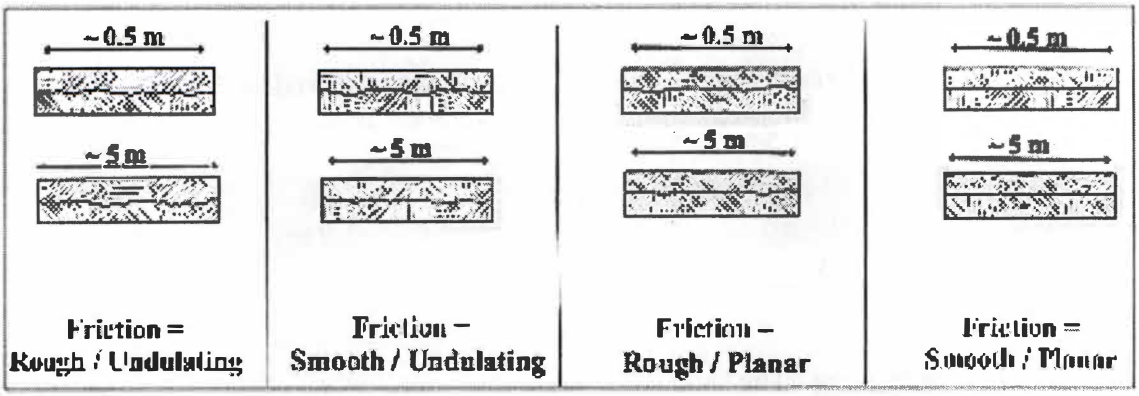

Figure A-1.4. Visual scoring aid for Friction showing micro- and macrofriction profiles.

Evaluation of the surface (s) is made relative to the sliding direction. The macro-friction is identified as planar or undulating (non-planar), and the micro-friction is identified as rough or smooth. It is assumed that the macro term has the greatest affect on the friction.

Friction Scoring. The benchmark scores for the friction of potential failure surfaces were determined by calculating $3^x/2$ for x = 1 to 4, then rounding to the nearest integer and scored as:

Friction (micro/macro)	Rough/Undulating	Smooth/Undulating	Rough/Planar	Smooth/Planar
Score	**2**	**5**	**14**	**41**

Relief Measurement. The amount of relief created by an overhang due to differential weathering is measured at the greatest distance across the base of the overhang, perpendicular to the slope face. Where multiple overhangs occur, a representative overhang is chosen and measured. Where overhangs are inaccessible, the distance must be visually estimated.

Relief Scoring. The amount of relief of an overhang is scored as:

Relief	<1 ft (< 0.3 m)	1 ft - 3 ft (0.3 – 0.9 m)	3 ft - 6 ft (0.9 – 1.8 m)	>6 ft (>1.8 m)
Score	**3**	**9**	**27**	**81**

Shape Measurement. The shape of a block susceptible to raveling is visually identified as tabular, blocky, or round. A tabular rock has one dimension significantly shorter than the other two with a flat appearance. A blocky rock has equant dimensions predominantly and has the appearance of a cube or shoebox. A round rock is spheroidal in shape and has the potential to roll.

Shape Scoring. The shape of a block susceptible to raveling is scored as:

Shape	Tabular	Blocky	Round	-
Score	**3**	**9**	**27**	**-**

4.7. Presence of Water on Cut

This category is modified from the NHI (1993) category of Climate and Presence of Water on Slope. Climate was removed from the analyses because the climate in Tennessee does not vary enough to warrant its use in the RHRS. Instead the presence of water on a cut was modified to describe the flow of the water on the cut. It should be noted however, the flow of water on a cut can be affected by periods of heavy precipitation, recent precipitation, and prolonged drought conditions.

Measurement. Visual examination of the entire cut is necessary to identify water. If water is not present and signs of seeping water, such as concentrated areas of vegetation on the cut face are lacking, the presence of water is considered to be *none*. Areas of concentrated vegetation and/or wet rock surfaces without noticeable percolating water indicate *seeping*. Noticeably dripping or trickling water from the rock face up to an amount similar to that of a running faucet or hose is *flowing*. A large amount of water pouring from the cut is *gushing*. Figure A-1.5 is a visual aid used to assess the presence of water on a roadcut based on the benchmark categories, with the exception of *none*.

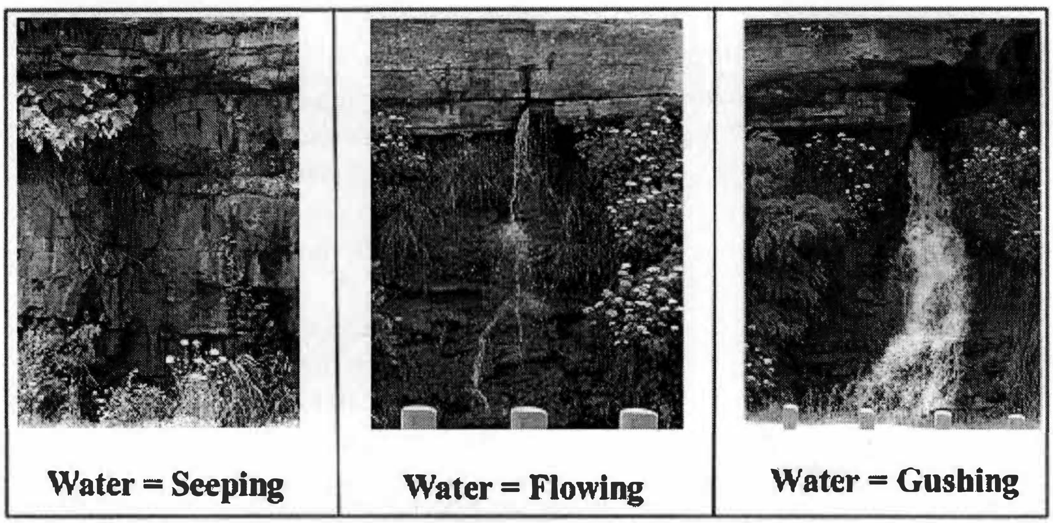

Figure A-1.5. Visual scoring aid for Presence of Water on Cut.

<u>*Scoring.*</u> The presence of water on cut is scored as:

Water	None	Seeping	Flowing	Gushing
Score	**3**	**9**	**27**	**81**

4.8. Rockfall History

This category is slightly modified from the NHI (1993) category primarily due to the limited availability of maintenance records regarding rockfall history and clean out, but the scoring benchmarks are unchanged.

Measurement and Scoring. Maintenance records are the best source of information about rockfall history. However, guidance is necessary for estimation of rockfall history if maintenance records are unavailable. When absent, rockfall history is best assessed by the amount of material in the catchment, number of impact marks in the road caused by falling rocks, the presence of rocks in the road, and is scored as:

Table A-1.8. Rockfall History scoring criteria.

Rockfall Benchmark	Frequency of Occurrence (From maintenance records)	Field Judgment (If no maintenance records exist)	Score
Few	1 or less per year	No impact marks in the road, no rocks in the road, few rocks in ditch	**3**
Several	2 per year	No impact marks in the road, no rocks in the road, many rocks in catchment	**9**
Many	3-4 per year	Few impact marks or few rocks in road, many rocks in catchment	**27**
Constant	5 or more per year	Many impact marks and/or many rocks in the road, many rocks in catchment	**81**

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Appendix 2

Tennessee RHRS Sampling Protocol

Purpose: This protocol outlines procedures pertaining to: (1) hazardous roadcut identification, selection, and data collection using TRIMS, (2) safety precautions and field assessment procedure during preliminary ratings for the Tennessee RHRS, and (3) safety precautions, field investigation, and data collection during the detailed ratings for the Tennessee RHRS. These procedures are intended to increase user safety and generate reproducibility of results by different users for the Tennessee RHRS scores.

Identifying and Selecting Roadcuts to Rate using TRIMS

A hazardous roadcut is a manmade roadcut or steep natural rock slope adjacent to a road that has the potential to produce rockfall onto a roadway or has a history of producing rockfall onto a roadway. The process for identifying hazardous roadcuts begins by selecting a county or counties to investigate. Once a county or counties is selected, the user virtually drives the roads using the TRIMS photo-catalog at a TDOT facility, which requires coordination with TDOT to select a day(s) to use an available computer. Sometimes, coordinating times is not easy because of computer availability, and therefore it is desirable to virtually drive roads for multiple counties during a single visit to TDOT.

Once a county is selected, the following steps are used to identify potentially hazardous roadcuts, their location, and roadway information at those locations.

Spreadsheet software, and a laptop computer or personal digital assistant is useful for recording the information gathered during this process.

Step 1. Identify all primary and secondary roads within the county using an official Tennessee highway map and compile a list of the roads.

Step 2. For each primary and secondary road within a county, virtually drive the length of the road in the county at 1/100th mile increments, beginning at logmile 0.0, sequence 1. Repeat for each sequence if necessary. If a potentially hazardous roadcut is identified during the virtual drive along a road, pause TRIMS and record the following:

a. State road number

b. Logmile to nearest hundredth of a mile

c. County sequence

d. Reference to the centerline: left or right

e. Average Daily Traffic (ADT) count of automobiles

f. Comments regarding the amount of road shoulder, horizontal and vertical curves in the road, potential places to park a vehicle, and places off the road for persons to stand.

g. Additional comments useful for future reference, such as roadcut size, amount of vegetation, etc.

Repeat for all identified roadcuts.

Step 3. When finished, exit TRIMS and shutdown computer, if necessary.

Preliminary Hazard Ratings

After potentially hazardous roadcuts are identified and their location information is collected using TRIMS, the next steps are to collect historical rockfall information about the roadcuts, visit the roadcuts, and assign preliminary ratings to determine which roadcuts should receive detailed ratings.

Maintenance Records Research Component

One person is required to gather available maintenance records for potentially hazardous roadcuts from the local TDOT office that oversees roadway maintenance in a given county. Call the TDOT office, explain the nature of the call and inquire about the availability of maintenance records. Often actual records do not exist, although useful information may be obtained by speaking with TDOT workers knowledgeable about roadcuts prone to rockfall.

Field Assessment Component

Following the gathering of any maintenance records, each identified roadcut is visited by a team of two or more raters. At least two persons are always required for field assessment procedures.

Safety. Rater safety is of utmost importance and therefore, safety precautions are the first measures taken when visiting any roadcut. Rater teams must have a minimum of two personnel. One rater is designated safety-coordinator who checks a checklist of the following safety items prior to departure to roadcuts:

- Orange safety vest for each person
- Orange safety cones
- Orange warning sign (and base) alerting motorists to workers ahead
- Vehicle-mounted flashing light
- Orange flags
- Hard hats
- Cell phone

Upon arrival at a roadcut:

Step 1. Identify a safe place to park the vehicle. It is often necessary to drive past the roadcut to identify a safe place to park.

Step 2. Once a safe place to park is identified, turn vehicle flashers on, slow down and move vehicle to shoulder of road outside the white line and park. Leave vehicle flashers on, place flashing light on vehicle roof and turn on. The safety coordinator should make sure all team members are wearing orange safety vests and check to make sure it is safe before exiting the vehicle.

Step 3. Once outside the vehicle, the team should gather and the safety coordinator should discuss safety awareness of oncoming traffic, identify locations to place safety items such as signs and cones that alert traffic of workers, and delegate persons to the placement of safety items. One person should set up the orange warning sign ahead of the roadcut at a distance great enough for motorists to notice and slow down as they approach the roadcut. This placement should normally be done on both sides of the road, but at least on the side of the road where raters will spend the most time. Additionally, another person should set up orange cones along the edge of the road where the majority of work is to be done.

Step 4. When three or more persons are present, one is designated to observe and announce oncoming traffic to other workers so they can take appropriate precautions. When two persons are present, both must and maintain constant awareness of oncoming vehicles and let the other know when a vehicle is coming.

Assigning Preliminary Rating to Roadcut

After all safety precautions are made, raters begin the preliminary rating process.

Step 1. Each person walks the entire length of the roadcut, observing features of the roadcut that influence the potential for rockfall such as the abundance and relative orientations of joints, orientation of rock beds, and weathering characteristics of rocks that indicate potential failure modes; the amount of rock debris at the toe of the roadcut; and block sizes. A rater also considers the potential for rockfall to reach the road by observing: the presence and amount of impact marks on the road made by fallen rocks; the presence and effectiveness of the catchment area, including width and shape of catchment; and the presence of features on the face of the roadcut that could launch a falling rock onto the road. Furthermore, a rater considers the geometric characteristics of the road, such as horizontal and vertical curves in the road that affect decision sight distance and a motorists ability to avoid debris in the road. Based on these observations, each rater decides whether the roadcut should be rated as hazardous (A rating) or not (B or C rating).

Step 2. Once all raters have examined the roadcut and made judgments on the potential for rockfall onto the roadway, they congregate and discuss their observations and ratings, referring to specific locations, and reach an agreement on the potential for rockfall to reach the roadway.

Step 3. The agreed rockfall potential is considered with any historical rockfall activity data to determine the final hazard rating for the roadcut using the following table:

POTENTIAL TO REACH ROAD	ROCKFALL HISTORY	HAZARD	PRELIMINARY RATING
Moderate-to-high	High historical rockfall activity	Moderate-to-High	A
Low-to-moderate	Moderate historical rockfall activity	Low-to-Moderate	B
Negligible-to-low	Low historical rockfall activity	None-to-Low	C

Zero to one rockfall events per year is considered as low historical rockfall activity; two rockfall events per year are considered moderate historical rockfall activity; and three or more rockfall events per year are considered high historical rockfall activity. Information from maintenance records that indicate a greater historical rockfall activity should be considered more heavily than field observations. If records indicate a lower historical rockfall activity, or no records exist, field observations are considered more heavily. All raters must agree on a preliminary rating. If raters are unsure as to which preliminary rating to assign a roadcut, the higher hazard rating is assigned.

Step 4. After assigning and recording a preliminary rating, the GPS waypoint information is collected at roadcuts that receive a preliminary rating of 'A' or 'B'.

Step 5. Digital photographs of the roadcut are made. Take as many photos as necessary to capture key characteristic of roadcut. Document the photograph numbers.

Step 6. The safety coordinator supervises the retrieval and collection of safety equipment, and raters return to vehicle. Depart when it is safe to do so.

Detailed Hazard Ratings

All roadcuts that receive a preliminary rating of 'A' also receive a detailed hazard rating. The detailed hazard rating consists of eight categories, six of which require measurement of roadcut attributes, and two that require observational classification. The six categories requiring measurement are:

- Average vehicle risk (AVR); (requires slope length)
- Roadway width
- Slope height
- Percent of decision sight distance
- Ditch effectiveness
- Geologic characteristics

The two categories requiring observational classification are:

- Presence of water on slope
- Rockfall history

Detailed Ratings Procedure

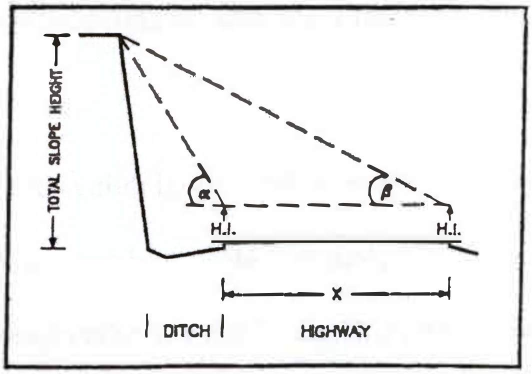
Two or more persons are required for detailed hazard ratings. All safety precautions pertaining to field assessment, as described in the *Preliminary Hazard Ratings* section, are also applied to detailed rating field procedures. These precautions include safety equipment brought to the roadcut, selection of safe parking places, gear set-up, and safety awareness.

All previous information gathered about the roadcut is brought to the roadcut when performing detailed ratings. Additionally, all detailed rating information is recorded with personal digital assistants and data collection software developed for the Tennessee RHRS (Bellamy, 2002).

Step 1. *Slope Length* – The first action of the detailed ratings procedure is for each rater to walk the entire length of the slope and identify, discuss and agree upon the end locations of the hazardous slope length. Then one rater measures the hazardous slope length by walking the length with a measuring wheel and recording the value, which is used in the AVR category. The distance recorded is to the nearest foot.

Step 2. *Roadway width* – Roadway width is measured at the narrowest width. When traffic is absent, one rater begins at the edge of pavement and walks the distance across the roadway using a measuring wheel perpendicular to the longitudinal direction of the road to the opposite edge of pavement. The distance recorded is to the nearest foot.

Step 3. *Slope Height* – The slope height is calculated from: the vertical angles measured from the near (α) and far edges (β) of pavement to the top of the roadcut where it is tallest, the measured width between the edges of pavement where angles are measured (X), and the eye-level height (H.I.) of the rater measuring α and β according to the diagram and equation below (NHI, 1993):



$$\text{Slope Height} = \frac{(X) * \sin\alpha * \sin\beta}{\sin(\alpha - \beta)} + H.I.$$

Where: X = Horizontal distance between α between β
α = Angle measured from near shoulder
β = Angle measured from far shoulder
$H.I.$ = height of clinometer above pavement

A clinometer is used to make three measurements of α and β to the nearest degree, and a second rater records the average values. If α and β are measured at the edges of pavement where roadway width was measured, then the roadway width is used for the calculation. The rater should measure and document his/her eye height. All values are recorded in the PDA, and the software calculates slope height. Verify that the correct information was recorded.

Step 4. *Percent Decision Sight Distance* – Next, the maximum road length distance that a motorist has to identify and avoid a rockfall hazard is measured. With increased experience, raters may wish to estimate this category to save time and if they are comfortable with their estimating abilities. The distance is measured with a wheel along the outer white line of the lane (fogline) that gives motorists the shortest decision sight distance. When lanes in both directions of traffic have similar decision sight distances, distances are measured along both foglines and the shorter distance is used. The starting point is determined by placing a small object, such as aluminum can, along the fogline adjacent to the roadcut. A rater walks away from the roadcut in the direction opposite of which traffic approaches, to where the object is no longer visible. Then the rater turns around and approaches the roadcut in the direction of traffic to the point where the object first becomes visible again. This is the starting point and the distance from this location to the object is measured with the measuring wheel to yield a decision sight distance. Where roadcuts are along horizontal and vertical curves in the road, it may be necessary to measure multiple distances with the object at different locations along the roadcut length to determine the shortest decision sight distance. If such a situation arises, then the object is placed at both ends, and the mid-point of the roadcut, and the distances measured with the shortest distance recorded. The distance recorded is to the nearest foot. Where estimated, the PDA calculates the distance for each category.

Step 5. *Ditch Effectiveness –* A ditch's effectiveness is determined from measuring the catchment width, catchment depth, and observing whether the roadcut has any asperities or launching features that could launch a falling rock onto the road, bypassing the catchment area. First, a rater measures the catchment width with a tape, from the base of the roadcut to the edge of the pavement in at least three locations and the average value is recorded. If the catchment width varies along the length of the roadcut, then measurements are made where catchment widths are visibly distinct and the average width is used. Second, where widths are measured, the rater marks the face of the roadcut, say with chalk, at a level even with the edge of pavement and measures the depth of the catchment and records the average value. Then, it is determined whether the catchment slope has a 6:1 or greater width to depth ratio by recording a "yes" or "no", respectively. Lastly, all raters inspect the roadcut face for the presence of any launching features and the presence/absence of any such features is documented.

Step 6. *Geologic Character* – Rating the geologic character of the roadcut requires multiple raters to minimize error potential and maximize usefulness of the category within the RHRS. First, each rater independently walks the length of the roadcut and examines the geology to identify all potential rockfall modes and visually estimate their abundances. Once each rater has identified potential rockfall modes and their abundances, they congregate and discuss observations to reach an agreement about potential rockfall modes and their respective relative abundances. The agreed rockfall mode and abundance values are then recorded.

- *Rockfall Mode Identification* – Use the Tennessee RHRS photo scoring-aides (Appendix 3) to help identify potential rock fall modes. To identify potential planar rockfall, look for where discontinuities, usually bed surfaces or foliations, are oriented such that the surface dips out of the face toward the road. To identify potential wedge rockfall, look for where two or more sets of discontinuities, which can be a combination of joints, bed surfaces, and foliations, intersect to form wedge-shaped blocks and the lines of intersection plunge out of the roadcut face toward the road. To identify potential topple rockfall, look for where discontinuities are oriented such that the surfaces dip into the slope at a steep angle and have a potential for rotational fall. To identify potential differential weathering rockfall, look for where overhanging rocks occur. To identify raveling rockfall, look for where rocks are separating and coming loose from the face of the roadcut. Rocks with rockfall potential that do not have the criteria required for any of the structural rockfall modes or differential weathering, such as spheroidal weathering, are identified as raveling in the context of the Tennessee RHRS.

- *Rockfall Mode Abundance.* Abundance is the potentially active surface area of the roadcut face susceptible to rockfall by a given mode. The area(s) defining a mode's abundance may be concentrated in one location or dispersed throughout the roadcut face. The abundance of a potential rockfall mode is determined by visual estimation of the proportion of the amount of potentially active material of a rockfall mode to the areal extent of the roadcut. The Tennessee RHRS abundance visual aide (appendix 3) is used to help determine the percentage of potential rockfall material on the roadcut face. Repeat for all identified potential rockfall modes.

To determine the abundance of planar rockfall, consider the area above the lowest discontinuity surface that dips out of the slope toward the road. Also consider release surfaces, which intersect the primary sliding surface that define the lateral extent of potential planar rockfall. To determine the abundance of a potential wedge rockfall, consider the area above the lowest intersection of discontinuities that plunges out of the face and forms wedge-shaped blocks, and the lateral extent of those discontinuities. To determine the abundance of potential topple rockfall, consider the area below the highest discontinuity surface that dips steeply into the slope and the release surfaces that intersect that discontinuity and define the lateral extent for potential topple failure. To determine the abundance of differential weathering rockfall, consider the amount of material above the overhanging surface and any discontinuities that define the lateral extent of the overhang. Is it a single bed that sticks out of the slope face that will fall or is it all of the material above due to a joint subparallel to the slope face behind the overhang? Only the rocks that are most likely to fall are included for the determination of abundance. Lastly, to determine the abundance of raveling, consider the area of the roadcut face where rocks are separating and coming loose and the area of the roadcut face where rocks are spheroidally weathering.

- *Block Size* – For each identified rockfall mode, the longest dimension of affected rock blocks are measured with a tape or estimated. Always measure intact rock blocks where accessible in addition to rocks in the catchment area below the area of potential rockfall. Only select the largest block sizes for measurement or estimation, as they represent the potential of block sizes produced by rockfall of the identified mode. If sizes are uniform, measure the length of at least three rock blocks with a tape and record the average size or estimate the average size. If block sizes are non-uniform, measure the length of at least five rock blocks with a tape and record the average size.

- *Steepness* – Measure the steepness of the dip of primary sliding surfaces of potential planar rockfall and the plunge of the lines of intersection for potential wedge rockfall in at least three locations with a compass clinometer in a direction parallel to maximum inclination. Use the average value.
- *Friction* – Evaluate the friction profile of potential sliding surfaces of planar and wedge rockfall on a macro- and a microscale using the Tennessee RHRS friction profile scoring aides (Appendix 3). Evaluation of surfaces is made parallel to the sliding direction. At least two raters independently identify the macrofriction as planar or undulating (non-planar) on a meter scale by comparison to the Tennessee RHRS friction profile scoring aide, and then they identify the microfriction as rough or smooth on a centimeter scale by comparison to the Tennessee RHRS friction profile scoring aid. Once each rater has made an independent evaluation of the frictional profile, they discuss observations and comparisons to the scoring aid, and reach an agreement for the appropriate profile.
- *Amount of relief* – Where possible, a rater measures the amount of relief for overhangs by placing a tape on the underside of the overhang and measuring the length perpendicular to the roadcut face. Relief is measured where the overhang is greatest. For overhangs that are beyond reach or inaccessible,

visual estimation is made. Measurements are made for the largest overhangs and their average value is used.

- *Block shape* – Block shape is determined visually by inspecting the shape of a rock that will potentially ravel and by inspecting the shapes of rocks in the catchment area below. Tabular-shaped rocks have one dimension significantly shorter than the other two, resulting in a rock with a flat appearance. Blocky-shaped rocks have no dimension significantly longer than another, resulting in a rock with a cubic or shoebox appearance. Round-shaped rocks have spheroidal or rounded appearances with an ability to roll. The block shape recorded should reflect the shape of the majority of rocks susceptible to raveling.

Step 7. *Presence of Water on Slope* – To determine the presence of water, raters inspect the entire roadcut for signs of water and discuss observations with other raters, using the Tennessee RHRS water-scoring aide (Appendix 3) for visual reference. If water is not present and signs of seeping water, such as concentrated areas of vegetation on the cut face are lacking, the presence of water is recorded as '*none*'. If areas of concentrated vegetation are identified on the roadcut face and/or wet rock surfaces without noticeable percolating water are identified, then the presence of water is '*seeping*'. If areas of noticeably dripping or trickling water from the rock face are identified up to an amount similar to that of a running faucet or hose, then record the presence of water as '*flowing*'. If areas are identified where large amounts of water are pouring out from the rocks, then record the presence of water as '*gushing*'. The recent weather conditions should also be noted as recent rainfall or extended drought can influence the rating of the presence of water on a given day.

Step 8. *Rockfall History* – Always give preference to using TDOT maintenance records when available for evaluating the rockfall history of a roadcut. In the absence of maintenance records, determine rockfall history by visually examining road surfaces for impact marks and by noting the amount of rocks in the catchment area. Record the value for the rockfall benchmark using these criteria:

Rockfall Benchmark	Frequency of Occurrence (From maintenance records)	Field Judgment (If no maintenance records exist)
Few	1 or less per year	No impact marks in the road, no rocks in the road, few rocks in ditch
Several	2 per year	No impact marks in the road, no rocks in the road, many rocks in catchment
Many	3-4 per year	Few impact marks or few rocks in road, many rocks in catchment
Constant	5 or more per year	Many impact marks and/or many rocks in the road, many rocks in catchment

Step 9. Any comments regarding the roadcut, such as rock formation, rock type, and geologic structures, and any pertinent roadcut or roadway geometry information are documented.

Step 10. Digital photographs of the roadcut are made. Take as many photos as necessary to capture scoring characteristics of roadcut and include people or man-made objects for scale. Include a photograph taken at an angle to the slope. Document the photograph numbers.

Step 11. After detailed ratings are completed, the safety coordinator supervises the retrieval and removal of safety equipment, and raters return to the vehicle. Prior to departure, double check that all data was gathered and account for all items and persons. When it is safe, depart the site.

Items needed for All Fieldwork

- Orange safety vest for each person
- Orange safety cones
- Orange warning sign (and base) alerting motorists to workers ahead
- Vehicle-mounted flashing light
- Orange flags
- Hard hats
- Personal digital assistant (PDA) with software
- 1:100,000 topographic map of area,
- Geologic map of Tennessee
- Printout of TRIMS information
- Clipboard, pens and pencils
- Tennessee RHRS visual scoring aids
- Appropriate food supplies
- Highway map of Tennessee
- Digital Camera
- GPS hardware
- Two-way radios

Additional Items for Detailed Ratings

- Measuring wheel
- Tape measure
- Sight-clinometer
- Compass with clinometer (Brunton- or Silva-type)
- Rock hammer
- Hand lens
- Small bottle of HCL
- Calculator
- All TRIMS and preliminary rating information
- Paper score sheets
- Permanent marker
- 7.5 minute geologic quadrangle maps of areas visited

Appendix 3

Tennessee RHRS Score Sheet and Scoring Aids

TDOT RHRS FIELD SHEET v1.0

I. TRIMS/ Preliminary Data

Date ________

File No. ________

County No.	________	Rater	________
Route No.	________	Speed Limit	________
Beg. L.M.	________	District	________
RefC/L	________	ADT	________
County	________	Latitude	________
Region	________	Longitude	________

SCORING

1. Slope Height ________
2. AVR ________
3. %DSD ________
4. Road Width ________
5. Ditch Effectiveness ________
6. Rockfall History ________
7. Water ________
8. Geologic Character ________

TOTAL SCORE ________

II. Site and Roadway Geometry

1. Slope Height (ft)

☐ estimated ________

alpha(a) ____ beta(b) ____

width (x) ____ ft instrument height (H.I.) ____ ft

$$\text{Slope Height} = \frac{\sin a \times \sin b \times X}{\sin(a-b)} + \text{H.I.}$$

2. Average Vehicle Risk (AVR)

$$\text{AVR} = \frac{\text{ADT(cars/day)} \times (\text{Rock Slope Length}/5280)}{(24\text{hpd}) \times \text{Speed Limit (mph)}}$$

Slope Length ________ ft Speed Limit ________ mph AVR = ________ %

3. %Decision Site Distance (%DSD)

choose one: adequate, moderate, limited, very limited
3 9 27 81

OR

calculate: ________ / ________ X 100 = ________ %
(observed DSD) / (AASHTO DSD)

4. Road Width (ft.)

____

5. Ditch Effectiveness

Design Catchment Width (feet)

Slope Height (ft)	Recommended width for vertical slope	Recommended width for non-vert slope
0 - 40	18	18
40 - 50	18	24
50 - 60	24	30
60 - 70	28	34
70 - 80	32	38
80 - 100	36	42
100 - 125	36	42
125 - 175	40	48
>175	52	60

Effective catchment width (ft) ________ Launching Features ? (yes or no) ________

6:1 catchment shape? (yes or no) ________

Percent of Design Catchment Width from Table	>90%	70%-90%	50%-70%	<50%
Score with 6:1 or greater catchment slope	3	9	27	81
Score w/ Poor Catchment Slope OR Launch Features	9	27	81	81
Score w/ Poor Catchment Slope AND Launch Features	27	81	81	81

6. Rockfall History

Benchmark	Frequency	Field Judgment	Score
Few	1 or less per year	No impact marks in the road, no rocks in the road, few rocks in ditch	3
Several	2 per year	No impact marks in the road, no rocks in the road, many rocks in the ditch	9
Many	3 - 4 per year	Few impact marks or few rocks in the road	27
Constant	5 or more per year	Many impact marks and/or many rocks in the road	81

III. Geologic Characteristics (circle all that apply; modes are additive)

	Planar				Wedge				Topple			
Abundance	< 10%	10-20%	20-30%	>30%	< 10%	10-20%	20-30%	>30%	< 10%	10-20%	20-30%	>30%
score	3	9	27	81	3	9	27	81	5	14	41	122
Block size	< 1ft	1-3ft	3-6ft	>6ft	< 1ft	1-3ft	3-6ft	>6ft	< 1ft	1-3ft	3-6ft	>6ft
score	3	9	27	81	3	9	27	81	5	14	41	122
Steepness (degrees)	0-20	20-40	40-60	>60	0-20	20-40	40-60	>60				
score	2	5	14	41	2	5	14	41				
Friction (micro/macro)	rough/undulating	smooth/undulating	rough/planar	smooth/planar	rough/undulating	smooth/undulating	rough/planar	smooth/planar				
score	2	5	14	41	2	5	14	41				

Differential Weathering

Abundance	< 10%	10-20%	20-30%	>30%
score	3	9	27	81
Block size	< 1ft	1-3ft	3-6ft	>6ft
score	3	9	27	81
Relief	<1 ft	1-3ft	3-6ft	>6ft
score	3	9	27	81

Raveling

Abundance	< 10%	10-20%	20-30%	>30%
score	3	9	27	81
Block size	< 1ft	1-3ft	3-6ft	>6ft
score	3	9	27	81
Block Shape	tabular	blocky	round	
score	3	9	27	

8. Geology Score =

____

7. Presence of Water on Slope

(choose one) none 3, seeping 9, flowing 27, gushing 81 ________

NOTES:

Figure A-3.1. Tennessee RHRS field scoring sheet.

Tennessee Rockfall Hazard Rating System Scoring Tables

Slope Height / AVR Scoring Table

Height / %AVR	Score	Height / %AVR	Score
9	1	77	29
10 - 20	2	78	31
21-28	3	79	32
29-34	4	80	34
35-38	5	81	35
39-42	6	82	37
43-45	7	83	38
46-48	8	84	40
49-51	9	85	42
52-53	10	86	44
54-55	11	87	46
56-57	12	88	48
58-59	13	89	50
60	14	90	52
61-62	15	91	55
63	16	92	57
64-65	17	93-94	60
66	18	95	62
67	19	96	65
68	20	97	71
69	21	98	74
70	22	99	78
71	23	100	81
72	24	101	85
73	25	102	88
74	26	103	92
75	27	104	97
76	28	105	100

Road Width Scoring Table

Width	Score	Width	Score
18	100	35	10
19	93	36	9
20	81	37	8
21	71	38	7
22	62	39	6
23	54	40	5
24	47	41	5
25	41	42	4
26	36	43	3
27	31	44	3
28	27	45	3
29	24	46	2
30	21	47	2
31	18	48	2
32	16	49	2
33	14	50	1
34	12		

AASHTO Recommended DSD

Decision Site Distance	MPH
300 ft	20
375	25
450	30
525	35
600	40
675	45
750	50
875	55
1000	60
1015	65

% DSD Scoring Table

%DSD	Score	%DSD	Score
36	100	61	26
37	96	62	24
38	90	63	23
39	86	64	22
40	81	65	21
41	77	66	19
42	73	67	18
43	69	68	17
44	65	69-70	16
45	62	71	15
46	58	72	14
47	55	73-74	13
48	52	75	12
49	49	76-77	11
50	47	80-81	9
51	44	82-83	8
52	42	84-85	7
53	40	86-88	6
54	38	89-92	5
55	36	93-97	4
56	34	98-103	3
57	32	104-112	2
58	30	113	1
59	29		
60	27		

Figure A-3.2. Tennessee RHRS field scoring tables.

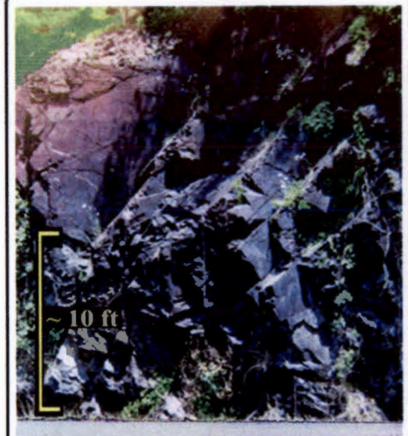
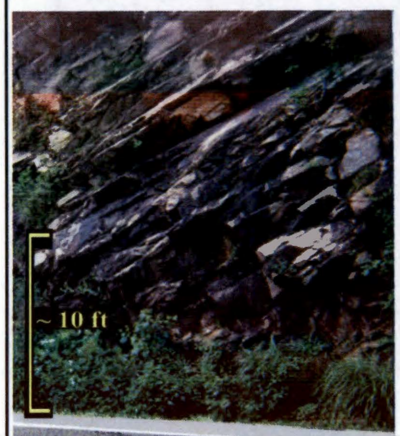
RHRS Field Scoring Aid showing Planar and Wedge Abundance * Note for Scale: Average person height = ~ 6 feet Cone height = 2.5 feet	photo unavailable **Wedge Abundance = 10 - 20%**	photo unavailable **Wedge Abundance = 20 - 30%**	 **Wedge Abundance = > 30%**
 **Planar Abundance = < 10%**	photo unavailable **Planar Abundance = 10 - 20%**	photo unavailable **Planar Abundance = 20 - 30%**	 **Planar Abundance = > 30%**

Figure A-3.3. Planar and wedge rockfall abundance scoring aid.

RHRS Scoring Aid For Topple Abundance

* **Note for Scale:**
Average person height = ~ 6 feet ,
Cone height = 2.5 feet

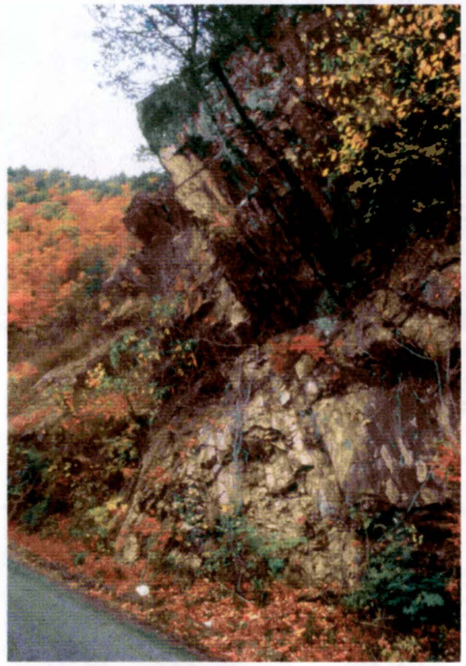
Topple Abundance = 10 - 20%	Topple Abundance = 20 - 30%	Topple Abundance = > 30%
photo unavailable		**photo unavailable**

Figure A-3.4. Topple rockfall abundance scoring aid.

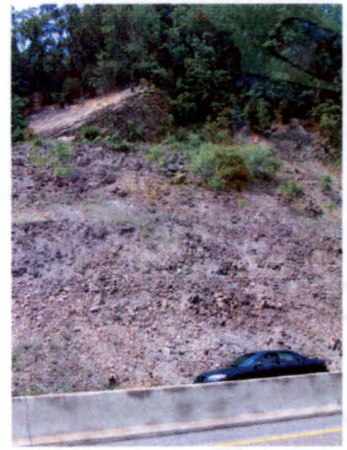
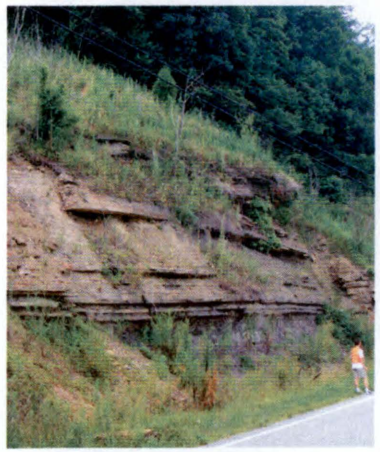
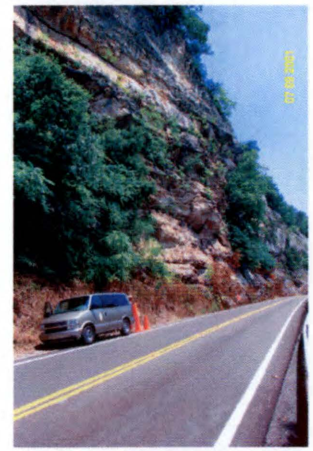
RHRS Scoring Aid showing Raveling and Differential Weathering Abundance * Note for Scale: Average person height = ~ 6 feet Cone height = 2.5 feet	 **Raveling = 10 - 20 %**	photo unavailable **Raveling = 20 - 30 %**	 **Raveling = > 30 %**
 **DW Abundance = < 10%**	 **DW Abundance = 10 - 20%**	 **DW Abundance = 20 - 30%**	 **DW Abundance = > 30%**

Figure A-3.5. Raveling and differential weathering abundance scoring aid.

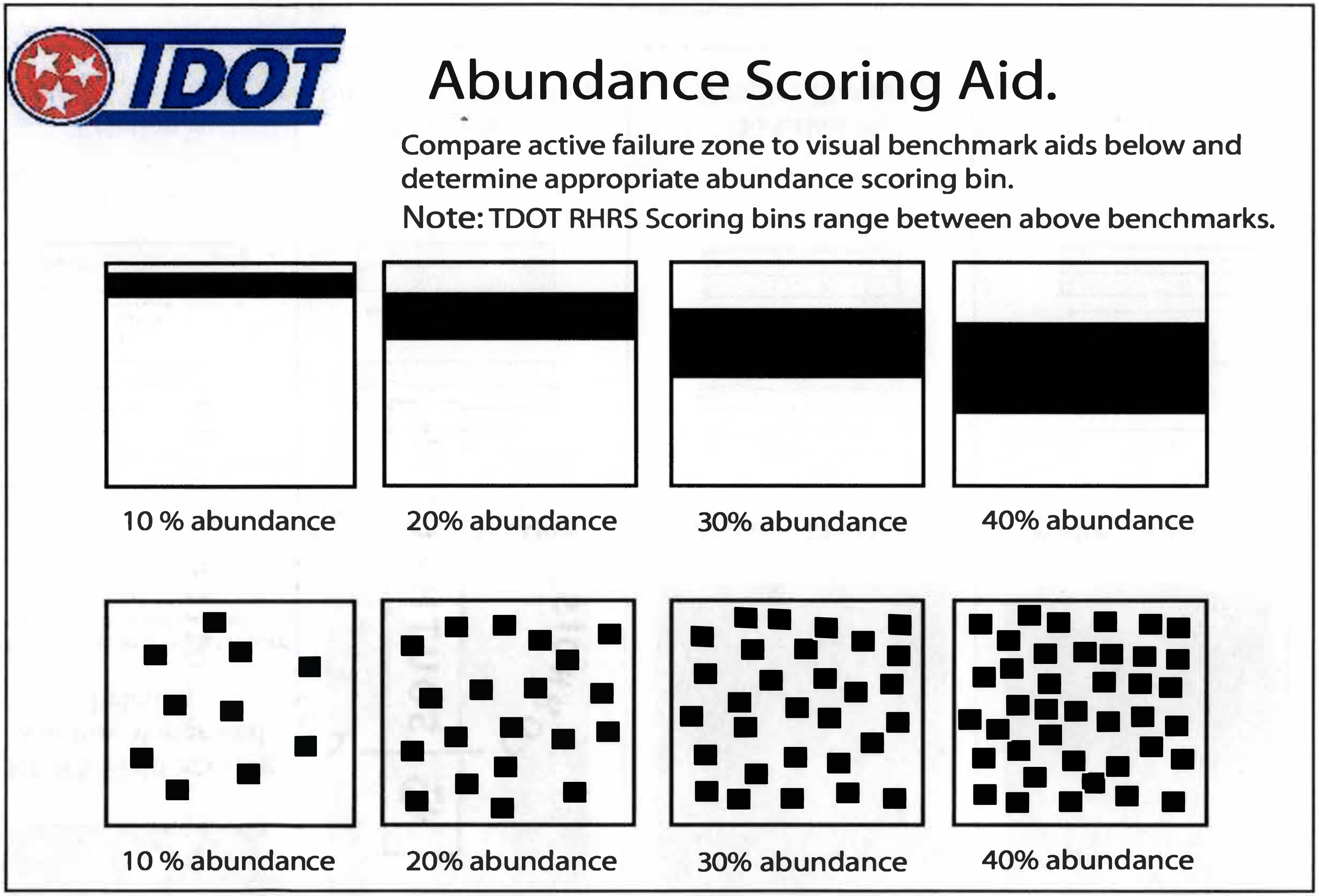


Figure A-3.6. General abundance scoring aid.

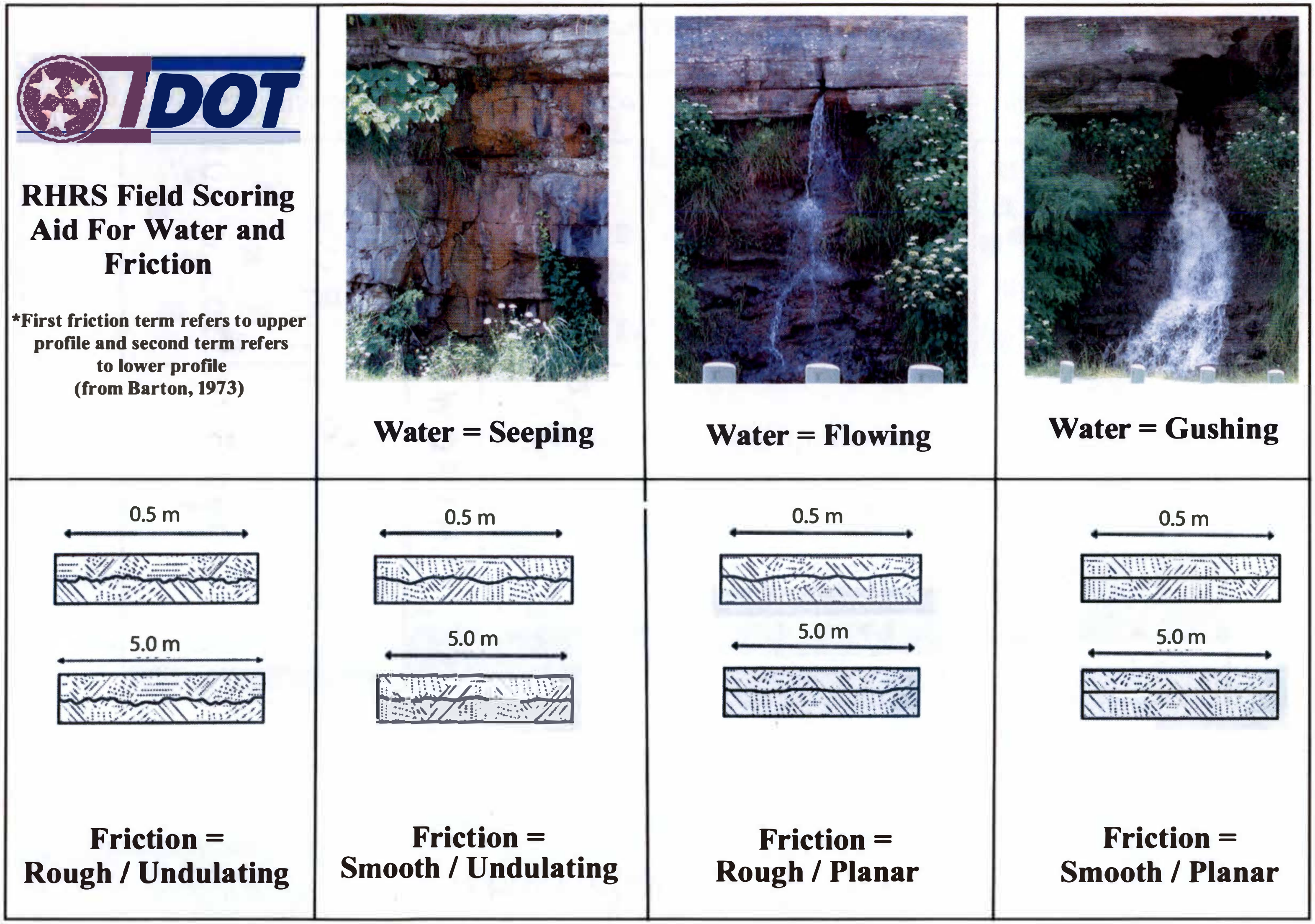


Figure A-3.7. Presence of water and friction scoring aid.

Appendix 4

Stratigraphy of Study Area

Age	Symbol	Name	Description
Pennsylvanian	Pcm	Cross Mtn Formation	Mostly Shale interbedded with sandstone, siltstone, and thin cola beds, 554 ft max thickness
	Pvm	Vowell Mtn Formation	Shale, sandstone, siltstone and coal, 230-375 ft thick
	Prm	Redoak Mtn Formation	Shale, sandstone, siltstone, and several important coals, 340 - 420 ft thick
	Pgg	Graves Gap Formation	Shale, sandstone, siltstone and coal, 275 - 385 ft thick
	Pib	Indian Bluff Formation	Shale, sandstone, siltstone and thin coal beds, 150 - 415 ft thick
	Psl	Slatestone Formation	Shale, sandstone, siltstone, and several important coals, 500 - 720 ft thick
	Pcf	Crooked Fork Group	Shale, sandstone, conglomerate, siltstone, and coal; 320 - 455 ft thick
	Pcg	Crab Orchard Mtn and Gizzards Group	Sandstone, conglomerate, siltstone, shale and thin coal; 1,200 -1,400 ft thick
Mississippian and Devonian	Mp	Pennington Formation	Reddish and greenish shale and siltstone; fine grained dolomite; dark-gray limestone; and thin bedded sandstone; 150 - 700 ft thick.
	Mfp/Mg Mdc	Fort Payne Fm Grainger Fm Chattanooga Shale	Fort Payne: Bedded chert, calcareous and dolomitic, minor shale; 200 ft. Grainger: Gray to green shale, siltstone and fine-grained glauconitic sandstone; ~1,200 ft. Black carbonaceous shale, fissile; typically 20 - 200 ft thick.
Silurian	Sr	Rockwood Formation	Brown to maroon shale, thin gray siltstone and sandstone, contains thin lenticular layers of red hematite; 200 - 800 ft.
Ordovician	Os	Sequatchie Formation	Maroon and gray shaly limestone, mottled greenish; with interbeds of calcareous, olive to maroon shale and siltstone; ~200 ft.
	Och	Chickamauga Group	Predominantly a limestone sequence, becomes more clastic and thicker to the south east; ~ 2,000 ft.
	Onc On	Newala Formation (Knox Group)	Cherty light gray dolomites of Moscot Dolomite and Kingsport Formation; ~500 - 1,000 ft.
	Olc	Longview Dolomite and Chepultepec Dolomite (Knox Group)	Siliceous gray, fined grained, medium to well bedded dolomite; ~1,100 ft.
Cambrian	Ccr	Copper Ridge Dolomite (Knox Group)	Coarse, dark-gray, knotty dolomite, with gray, well-bedded dolomite, cherty; ~1,000 ft.
	Cmn	Maynardville Limestone	Thick bedded, bluish-gray, ribboned nodular limestone, noncherty dolomite in upper part; ~150 to 400 ft.
	Cn	Nolichucky Shale	Pastel colored, flaky clay shale; commonly oolitic shaly limestone lenses; 100 - 900 ft.
	Cmr	Maryville limestone, Rogersville Shale, Rutledge limestone	Middle members of Conasauga group, gray limestones, and greenish shales; 400 - 1,100 ft.
	Cpv	Pumpkin Valley Shale	Dull-brown to maroon shale with interbeds of thin sandly siltstone; 100 - 600 ft.
	Cr	Rome Formation	Red, green,yellow shale and siltstone, some fine-grained sandstone, limestone and dolomite; up to 2,000 ft.

Modified from Hardeman (1966).

Figure A-4.1. Generalized stratigraphic section of Anderson County.

Age	Symbol		Name	Description
Pennsylvanian	Pcg	Pr	Rock Castle Conglomerate	Conglomeratic sandstone and sandstone, gray to brown, fine- to coarse- grained; 150 to 220 ft thick.
		Pco	Crab Orchard Mountains Group	Conglomerate, sandstone, siltstone, shale, and coal; thickness including Rock Castle Conglomerate is 200 - 950 ft thick.
		Pg	Gizzard Group	Shale, siltstone, sandstone, and conglomerate; 0 - 520 ft thick.
Mississippian and Devonian	Mp		Pennington Formation	Reddish and greenish shale and siltstone; fine grained dolomite; dark-gray limestone; and thin bedded sandstone; 150 - 700 ft thick.
	Mbh		Bangor Limestone and Hartselle Fm.	Bangor Limestone: dark brownish-gray limestone, thick-bedded; 70 - 400 ft thick. Hartselle Fm.: thin-bedded, fine-grained sandstone, with gray shale interbeds; 0 -80 ft thick.
	Mm		Monteagle Limestone	Mainly fragmental and oolitic, light gray limestone; 180 - 300 ft thick.
	Msw		St. Louis and Warsaw Limestones	St. Louis: fine-grained, brownish-gray limestone, dolomitic and cherty; 80 - 160 ft. thick. Warsaw: medium- to coarse-grained gray limestone with minor sandstone and shale; 100 - 130 ft thick
	Mfp		Fort Payne Fm and Devonian age Chattanooga Shale	Fort Payne: Bedded chert, calcareous and dolomitic, minor shale; 100 -275 ft thick. Chattanooga Shale: black carbonaceous shale, fissile; typically 20 - 30 ft thick.
Silurian	S		Brassfield Formation	Olive-gray, fine-grained, cherty limestone and calcareous shale; 60 - 130 ft thick. Only present in Sequatchie Valley
Ordovician	Ou		Upper Ordovician Formations	Contains Sequatchie, Leipers, Inman, and Catheys Formations, Calcareous shales, shaly limestones, and limestone; 125 - 765 ft thick.
	Obh		Bigby-Cannon Limestone and Hermitage Fm.	Bigby Cannon Limestone: dark to light gray limestone; 80 - 150 ft thick. Hermitage Fm.: gray, fin-grained, thinly bedded argillaceous limestone and shale; 50 - 100 ft thick.
	Oca		Carters Limestone	Fine- grained, yellowish brown limestone. Contains thin bentonite beds. Thickness 60 -250 ft.
	Olb		Lebanon Limestone	Thin-bedded, gray to yellowish-brown limestone, slightly dolomitic with thin calcareous shale partings; ~100 ft thick.
	Ord		Ridley Limestone	Medium to very thick bedded, fine- to medium grained, gray dolomitic limestone with prominent greenish-gray shale bed in the middle of unit. Thickness 200 to 275 ft.
	Opm		Pierce and Murfreesboro Limestones	Medium- to very thick-bedded, fine-grained, gray limestone, thin-bedded, nodular and shaly, greenish gray limestone in places. Thickness 200 to 500 ft.
	Onc		Knox Group	Knox Group (above Copper Ridge Dolomite): gray, cherty dolomite and limestone; 600 - 650 ft thick.

Modified from Hardeman (1966).

Figure A-4.2. Generalized stratigraphic section of Bledsoe County.

Age	Symbol	Name	Description
Ordo-vician	Osv	Sevier Shale	Calcareous, bluish-gray shale, weathers yellowish-brown; with thin gray limestone layers; sandstone, siltstone, and local conglomerate; Thickness 2,000 to 7,000 ft.
Cambrian	OCk	Knox Group	Siliceous, well-bedded dolomite and magnesian limestone; Thickness about 3,000 ft
	Ccu	Maynardville Limestone and Nolichucky Shale	Thick bedded, bluish-gray, ribboned nodular limestone, noncherty dolomite in upper part; ~150 to 400 ft.
			Pastel colored, flaky clay shale; commonly oolitic shaly limestone lenses; 100 - 900 ft.
	Chk	Honaker Dolomite	Dark-gray, medium-bedded dolomite with minor dark limesone beds; locally cherty; cryptozoans abundant in places; Thickness about 1,500 ft.
	Cr	Rome Formation	Red, green, yellow shale and siltstone, some fine-grained sandstone, limestone and dolomite; Thickness up to 2,000 ft.
	Cs	Shady Dolomite	light-gray, well bedded dolomite with interbedded limestone, yellowish brown residual clays; Thickness about 1,000 ft.
	Ce	Erwin Formation	White, vitreous quartzite, massive, with interbeds of dark-green silty shale, minor siltstone and sandstone; Thickness 1,000 -1,500 ft.
	Ch	Hampton Formation	Dark greenish-gray, silty and sandy, micaceous shale with medium-grained feldspathic sandstone interdbeds; 500 -2,000 ft.
	Cu	Unicoi Formation	Sequence of gray feldspathic sandstone, arkose, conglomerate, graywacke siltstone and shale, greenish basalt flows near middle and base; Thickness 2,000-5,000 ft.
Precambrian	pCba	Bakersville Gabbro	Metagabbro, dark, porphyritic; contains diorite, basalt, anorthosite, and diabase; occurs as thin to massive dikes and lenticular masses.
	pCb	Beech Granite	Granite, porphyritic, light gray to reddish granite; coarse potash feldspar crystals with clustered interstitial mafics give spotted appearance.
	pCr	Ashe Formation *	Layered hornblend and garnet gneiss and granitic migmatite with zones of mica schist and amphibolite; contains numerous granitic and gabbroic dikes.
	pCc	Cranberry Gneiss *	Complex of intertonguing rock types including migmatite, granitic gneisses, monzonite, quartz diorite, shists and granitic pegmatites.

Modified from Hardeman (1966).

* Current names from Rankin (1970). Ashe Formation and Cranberry Gneiss are respectivley equivalent to Roan Gneiss and Cranberry Granite used by Hardeman (1966).

Figure A-4.3. Generalized stratigraphic section of Carter County.

Age	Symbol	Name	Description
Mississippian and Devonian	Mn	Newman Limestone	Shaly limestone, shale, siltstone, and sandstone; ~ 700 ft thick.
	Mfp/Mg	Fort Payne Fm and Grainger Fm	Fort Payne: Bedded chert, calcareous and dolomitic, minor shale; 200 ft Grainger: Gray to green shale, siltstone and fine-grained glauconitic sandstone; ~1,200 ft.
	Mdc	Chattanooga Shale	Black carbonaceous shale, fissile; typically 20 - 200 ft thick.
Silurian	Sc	Clinch Sandstone	Clean, white, well sorted sandstone, locally gray siltstone and shale; thickness ~ 600 ft.
Ordovician	Oj	Juniata Formation	Maroon claystone, siltstone, and shale, less calcareous than Sequatchie Formation; ~300 ft.
	Och	Chickamauga Group	Predominantly a limestone sequence, becomes more clastic and thicker to the southeast; ~ 2,000 ft.
	Onc: On	Newala Formation (Knox Group)	Cherty light gray dolomites of Moscot Dolomite and Kingsport Formation; ~500 - 1,000 ft.
	Onc: Olc	Longview Dolomite and Chepultepec Dolomite	Siliceous gray, fined grained, medium to well bedded dolomite; ~1,100 ft.
Cambrian	Ccr	Copper Ridge Dolomite (Knox Group)	Coarse, dark-gray, knotty dolomite, with gray, well-bedded dolomite, cherty; ~1,000 ft.
	Cmn	Maynardville Limestone	Thick bedded, bluish-gray, ribboned nodular limestone, noncherty dolomite in upper part; ~150 to 400 ft.
	Cn	Nolichucky Shale	Pastel colored, flaky clay shale; commonly oolitic shaly limestone lenses; 100 - 900 ft.
	Cmr	Maryville limestone, Rogersville Shale, Rutledge limestone	Middle members of Conasauga Group, gray limestones, and greenish shales; 400 - 1,100 ft.
	Cpv	Pumpkin Valley Shale	Dull-brown to maroon shale with interbeds of thin sandly siltstone; 100 - 600 ft.
	Cr	Rome Formation	Red, green,yellow shale and siltstone, some fine-grainedsandstone, limestone and dolomite; up to 2,000 ft.

Modified from Hardeman (1966).

Figure A-4.4. Generalized stratigraphic section of Grainger County.

Age	Symbol	Name	Description
Miss. and Dev.	Mfp	Fort Payne Fm and Devonian age Chattanooga Shale	Fort Payne: Bedded chert, calcareous and dolomitic, minor shale; 100 -275 ft thick. Chattanooga Shale: black carbonaceous shale, fissile; typically 20 - 30 ft thick.
Silurian	S	Brassfield Formation	Olive-gray, fine-grained, cherty limestone and calcareous shale; 60 - 130 ft thick. Only present in Sequatchie Valley
Ordovician	Ou	Upper Ordovician Formations	Contains Sequatchie, Leipers, Inman, and Catheys Formations, Calcareous shales, shaly limestones, and limestone; 125 - 765 ft thick.
	Obh	Bigby-Cannon Limestone and Hermitage Fm.	Bigby Cannon Limestone: dark to light gray limestone; 80 - 150 ft thick. Hermitage Fm.: gray, fin-grained, thinly bedded argillaceous limestone and shale; 50 - 100 ft thick.
	Oca	Carters Limestone	Fine- grained, yellowish brown limestone. Contains thin bentonite beds. Thickness 60 -250 ft.
	Olb	Lebanon Limestone	Thin-bedded, gray to yellowish-brown limestone, slightly dolomitic with thin calcareous shale partings; ~100 ft thick.

Modified from Hardeman (1966).

FIGURE A-4.5. Generalized stratigraphic section of Smith County.

Appendix 5

SAS Code and Results for Statistical Analysis

```
  *** Logistic Regression Analysis: FAILTYPE WEATHERING***;
  options pageno=1;
proc logistic data=_PROJ_.Sastable3_26 DESCEND;
     class SLOPEDIR (ref='South') ROCK_ (ref='Carbonate
     Sedimentary') DISCSETS1 LITHVAR (ref='no') /
     param=ref;
     model ROCKFALL_ = SLOPEDIR ROCK_ LITHVAR DISCSETS1
     LITHVAR*ROCK_ /
          selection=stepwise sle=0.05 sls=0.05 scale=none
          lackfit;
run;

          *** Logistic Regression Analysis: BLOCKSIZE > 0.3
m ***;
options pageno=1;
proc logistic data=_PROJ_.Sastable3_26  DESCEND;
     class ROCKFALL_ (ref='Weathering')
     ROCK_(ref='Carbonate Sedimentary') DISCSETS1 THICKNESS
     FIS (ref='N')LITHVAR (ref='no')/ param=ref;
     model BLOCKSIZE_1 = ROCKFALL_ THICKNESS LITHVAR FIS
     ROCK_ DISCSETS1 THICKNESS*FRACSETS1  ROCKFALL_*ROCK_/
          selection=stepwise sle=0.05 sls=0.05 scale=none
lackfit;
run;

           *** Logistic Regression Analysis: ABUNDANCE >
20% ***;
options pageno=1;
proc logistic data=_PROJ_.Sastable3_26  DESCEND;
     class SLOPEDIR (ref='South') ROCK_(ref='Carbonate
     Sedimentary') PRESENCE_OF_WATER_ON_SLOPE (ref='none')
          DISCSETS1 LITHVAR (ref='no') THICKNESS FIS
          (ref='N') BLAST (ref='N') NSYSFRAC(ref='N')/
          param=ref;
     model _ABUNDANCE_20 = SLOPEDIR ROCK_
     PRESENCE_OF_WATER_ON_SLOPE DISCSETS1 LITHVAR THICKNESS
     FIS BLAST NSYSFRAC SLOPEDIR*PRESENCE_OF_WATER_ON_SLOPE
     LITHVAR*FIS/
          selection=stepwise sle=0.05 sls=0.05 scale=none
lackfit;
run;
```

The LOGISTIC Procedure

Model Information

Data Set	_PROJ_.SASTABLE3_26	
Response Variable	Rockfall_	Rockfall_
Number of Response Levels	2	
Number of Observations	134	
Model	binary logit	
Optimization Technique	Fisher's scoring	

Response Profile

Ordered Value	Rockfall_	Total Frequency
1	Weathering	107
2	Structural	27

Probability modeled is Rockfall_='Weathering'.

Stepwise Selection Procedure

Class Level Information

		Design Variables		
Class	Value	1	2	3
SlopeDir	East	1	0	0
	North	0	1	0
	South	0	0	0
	West	0	0	1
Rock_	Carbonate Sedime	0	0	
	Clastic Sediment	1	0	
	Crystalline	0	1	
DiscSets1	0	1	0	0
	1	0	1	0
	2	0	0	1
	3	0	0	0
LithVar	no	0		
	yes	1		

Step 0. Intercept entered:

Model Convergence Status

Convergence criterion (GCONV=1E-8) satisfied.

Residual Chi-Square Test

Chi-Square	DF	Pr > ChiSq
30.6529	11	0.0013

Step 1. Effect DiscSets1 entered:

Model Convergence Status

Convergence criterion (GCONV=1E-8) satisfied.

Model Fit Statistics

Criterion	Intercept Only	Intercept and Covariates
AIC	136.661	125.510
SC	139.558	137.101
-2 Log L	134.661	117.510

Testing Global Null Hypothesis: BETA=0

Test	Chi-Square	DF	Pr > ChiSq
Likelihood Ratio	17.1507	3	0.0007
Score	19.0574	3	0.0003
Wald	16.2251	3	0.0010

Residual Chi-Square Test

Chi-Square	DF	Pr > ChiSq
13.4143	8	0.0984

Step 2. Effect LithVar entered:

Model Convergence Status

Convergence criterion (GCONV=1E-8) satisfied.

Model Fit Statistics

Criterion	Intercept Only	Intercept and Covariates
AIC	136.661	118.948
SC	139.558	133.437
-2 Log L	134.661	108.948

Testing Global Null Hypothesis: BETA=0

Test	Chi-Square	DF	Pr > ChiSq
Likelihood Ratio	25.7123	4	<.0001
Score	25.4111	4	<.0001
Wald	19.9287	4	0.0005

Residual Chi-Square Test

Chi-Square	DF	Pr > ChiSq
7.6153	7	0.3677

NOTE: No (additional) effects met the 0.05 significance level for entry into the model.

Summary of Stepwise Selection

Step	Effect Entered	Effect Removed	DF	Number In
1	DiscSets1		3	1
2	LithVar		1	2

Summary of Stepwise Selection

Step	Score Chi-Square	Wald Chi-Square	Pr > ChiSq	Variable Label
1	19.0574	.	0.0003	DiscSets1
2	7.8209	.	0.0052	LithVar

Type III Analysis of Effects

Effect	DF	Wald Chi-Square	Pr > ChiSq
LithVar	1	6.6935	0.0097
DiscSets1	3	14.1584	0.0027

Analysis of Maximum Likelihood Estimates

Parameter		DF	Estimate	Standard Error
Intercept		1	-0.3064	0.4098
LithVar	yes	1	1.7582	0.6796
DiscSets1	0	1	2.2684	0.6618
DiscSets1	1	1	1.7882	0.7576
DiscSets1	2	1	1.3934	0.6077

Analysis of Maximum Likelihood Estimates

Parameter		Wald Chi-Square	Pr > ChiSq
Intercept		0.5590	0.4547
LithVar	yes	6.6935	0.0097
DiscSets1	0	11.7495	0.0006
DiscSets1	1	5.5722	0.0182
DiscSets1	2	5.2574	0.0219

Odds Ratio Estimates

Effect	Point Estimate
LithVar yes vs no	5.802
DiscSets1 0 vs 3	9.664
DiscSets1 1 vs 3	5.979
DiscSets1 2 vs 3	4.028

Odds Ratio Estimates

95% Wald Confidence Limits	
1.531	21.979
2.641	35.355
1.355	26.391
1.224	13.255

Association of Predicted Probabilities and Observed Responses

Percent Concordant	72.8	Somers' D	0.576
Percent Discordant	15.2	Gamma	0.654
Percent Tied	12.0	Tau-a	0.187
Pairs	2889	c	0.788

Partition for the Hosmer and Lemeshow Test

		Rockfall_ = Weathering		Rockfall_ = Structural	
Group	Total	Observed	Expected	Observed	Expected
1	22	9	9.33	13	12.67
2	19	14	14.21	5	4.79
3	7	6	5.67	1	1.33
4	16	13	13.04	3	2.96
5	29	26	25.43	3	3.57
6	22	21	20.79	1	1.21
7	19	18	18.54	1	0.46

Hosmer and Lemeshow Goodness-of-Fit Test

Chi-Square	DF	Pr > ChiSq
0.9126	5	0.9693

The LOGISTIC Procedure

Model Information

Data Set	_PROJ_.SASTABLE3_26	
Response Variable	**Block_Size_1**	**Block Size>1**
Number of Response Levels	2	
Number of Observations	134	
Model	binary logit	
Optimization Technique	Fisher's scoring	

Response Profile

Ordered Value	Block_ Size_1	Total Frequency
1	yes	65
2	no	69

Probability modeled is Block_Size_1='yes'.

Stepwise Selection Procedure

Class Level Information

Class	Value	Design Variables 1	2	3
Rockfall_	Structural	1		
	Weathering	0		
Rock_	Carbonate Sedime	0	0	
	Clastic Sediment	1	0	
	Crystalline	0	1	
DiscSets1	0	1	0	0
	1	0	1	0
	2	0	0	1
	3	0	0	0

Class Level Information

Class	Value	Design Variables 1	2	3
Thickness	0.2m - 0.5m	1	0	0
	0.5m - 1.0m	0	1	0
	< 0.2m	0	0	1
	>1.0m	0	0	0
Fis	N	0		
	Y	1		
LithVar	no	0		
	yes	1		

Step 0. Intercept entered:

Model Convergence Status

Convergence criterion (GCONV=1E-8) satisfied.

Residual Chi-Square Test

Chi-Square	DF	Pr > ChiSq
52.1202	22	0.0003

Step 1. Effect Rockfall_ entered:

Model Convergence Status

Convergence criterion (GCONV=1E-8) satisfied.

Model Fit Statistics

Criterion	Intercept Only	Intercept and Covariates
AIC	187.644	165.275
SC	190.542	171.071
-2 Log L	185.644	161.275

Testing Global Null Hypothesis: BETA=0

Test	Chi-Square	DF	Pr > ChiSq
Likelihood Ratio	24.3691	1	<.0001
Score	22.0747	1	<.0001
Wald	15.7540	1	<.0001

Residual Chi-Square Test

Chi-Square	DF	Pr > ChiSq
36.5372	21	0.0190

Step 2. Effect LithVar entered:

Model Convergence Status

Convergence criterion (GCONV=1E-8) satisfied.

Model Fit Statistics

Criterion	Intercept Only	Intercept and Covariates
AIC	187.644	163.225
SC	190.542	171.918
-2 Log L	185.644	157.225

Testing Global Null Hypothesis: BETA=0

Test	Chi-Square	DF	Pr > ChiSq
Likelihood Ratio	28.4192	2	<.0001
Score	25.6841	2	<.0001
Wald	19.1948	2	<.0001

Residual Chi-Square Test

Chi-Square	DF	Pr > ChiSq
34.4589	20	0.0232

Step 3. Effect Thickness entered:

Model Convergence Status

Convergence criterion (GCONV=1E-8) satisfied.

Model Fit Statistics

Criterion	Intercept Only	Intercept and Covariates
AIC	187.644	157.257
SC	190.542	174.644
-2 Log L	185.644	145.257

Testing Global Null Hypothesis: BETA=0

Test	Chi-Square	DF	Pr > ChiSq
Likelihood Ratio	40.3871	5	<.0001
Score	34.7217	5	<.0001
Wald	25.1234	5	0.0001

Residual Chi-Square Test

Chi-Square	DF	Pr > ChiSq
25.5400	17	0.0833

Step 4. Effect DiscSets1 entered:

Model Convergence Status

Convergence criterion (GCONV=1E-8) satisfied.

Model Fit Statistics

Criterion	Intercept Only	Intercept and Covariates
AIC	187.644	154.814
SC	190.542	180.894
-2 Log L	185.644	136.814

Testing Global Null Hypothesis: BETA=0

Test	Chi-Square	DF	Pr > ChiSq
Likelihood Ratio	48.8304	8	<.0001
Score	40.9461	8	<.0001
Wald	28.4905	8	0.0004

Residual Chi-Square Test

Chi-Square	DF	Pr > ChiSq
17.1471	14	0.2484

NOTE: No (additional) effects met the 0.05 significance level for entry into the model.

Summary of Stepwise Selection

Step	Effect Entered	Effect Removed	DF
1	Rockfall_		1
2	LithVar		1
3	Thickness		3
4	DiscSets1		3

Summary of Stepwise Selection

Step	Number In	Score Chi-Square	Wald Chi-Square	Pr > ChiSq	Variable Label
1	1	22.0747	.	<.0001	Rockfall_
2	2	4.0322	.	0.0446	LithVar
3	3	11.6282	.	0.0088	Thickness
4	4	8.3522	.	0.0393	DiscSets1

Type III Analysis of Effects

Effect	DF	Wald Chi-Square	Pr > ChiSq
Rockfall_	1	15.4568	<.0001
Thickness	3	8.8206	0.0318
LithVar	1	10.9679	0.0009
DiscSets1	3	7.8810	0.0485

Analysis of Maximum Likelihood Estimates

Parameter		**DF**	**Estimate**
Intercept		1	0.7241
Rockfall_	Structural	1	2.9613
Thickness	0.2m - 0.5m	1	-1.2244
Thickness	0.5m - 1.0m	1	-0.7725
Thickness	< 0.2m	1	-2.0471
LithVar	yes	1	1.7160
DiscSets1	0	1	-0.7509
DiscSets1	1	1	0.2553
DiscSets1	2	1	-1.5100

Analysis of Maximum Likelihood Estimates

Parameter		**Standard Error**
Intercept		0.7844
Rockfall_	Structural	0.7532
Thickness	0.2m - 0.5m	0.7037
Thickness	0.5m - 1.0m	0.7206
Thickness	< 0.2m	0.7262
LithVar	yes	0.5181
DiscSets1	0	0.6418
DiscSets1	1	0.8203
DiscSets1	2	0.6598

Analysis of Maximum Likelihood Estimates

Parameter		**Wald Chi-Square**
Intercept		0.8523
Rockfall_	Structural	15.4568
Thickness	0.2m - 0.5m	3.0276
Thickness	0.5m - 1.0m	1.1491
Thickness	< 0.2m	7.9456
LithVar	yes	10.9679
DiscSets1	0	1.3689
DiscSets1	1	0.0968
DiscSets1	2	5.2385

Analysis of Maximum Likelihood Estimates

Parameter		**Pr > ChiSq**
Intercept		0.3559
Rockfall_	Structural	<.0001
Thickness	0.2m - 0.5m	0.0819
Thickness	0.5m - 1.0m	0.2837
Thickness	< 0.2m	0.0048
LithVar	yes	0.0009
DiscSets1	0	0.2420
DiscSets1	1	0.7557

Analysis of Maximum Likelihood Estimates

Parameter		Pr > ChiSq
DiscSets1	2	0.0221

Odds Ratio Estimates

Effect	Point Estimate	95% Wald Confidence Limits	
Rockfall_ Structural vs Weathering	19.322	4.415	84.565
Thickness 0.2m - 0.5m vs >1.0m	0.294	0.074	1.167
Thickness 0.5m - 1.0m vs >1.0m	0.462	0.112	1.896
Thickness < 0.2m vs >1.0m	0.129	0.031	0.536
LithVar yes vs no	5.562	2.015	15.356
DiscSets1 0 vs 3	0.472	0.134	1.660
DiscSets1 1 vs 3	1.291	0.259	6.443
DiscSets1 2 vs 3	0.221	0.061	0.805

Association of Predicted Probabilities and Observed Responses

Percent Concordant	81.3	Somers' D	0.647
Percent Discordant	16.5	Gamma	0.662
Percent Tied	2.2	Tau-a	0.326
Pairs	4485	c	0.824

Partition for the Hosmer and Lemeshow Test

Group	Total	Block_Size_1 = yes Observed	Block_Size_1 = yes Expected	Block_Size_1 = no Observed	Block_Size_1 = no Expected
1	14	0	1.23	14	12.77
2	16	3	2.89	13	13.11
3	12	3	2.97	9	9.03
4	13	4	4.31	9	8.69
5	13	7	5.43	6	7.57
6	12	7	6.03	5	5.97
7	13	7	7.56	6	5.44
8	15	12	10.91	3	4.09
9	13	9	11.21	4	1.79
10	13	13	12.47	0	0.53

Hosmer and Lemeshow Goodness-of-Fit Test

Chi-Square	DF	Pr > ChiSq
6.7141	8	0.5678

The LOGISTIC Procedure

Model Information

Data Set	_PROJ_.SASTABLE3_26	
Response Variable	**Abundance_20**	**Abundance >20**
Number of Response Levels	2	
Number of Observations	134	
Model	binary logit	
Optimization Technique	Fisher's scoring	

Response Profile

Ordered Value	Abundance_ 20	Total Frequency
1	yes	46
2	no	88

Probability modeled is Abundance_20='yes'.

Stepwise Selection Procedure

Class Level Information

Class	Value	Design Variables 1	2	3
SlopeDir	East	1	0	0
	North	0	1	0
	South	0	0	0
	West	0	0	1
Rock_	Carbonate Sedime	0	0	
	Clastic Sediment	1	0	
	Crystalline	0	1	
Presence_of_Water_on_Slope	flowing	1	0	
	none	0	0	
	seeping	0	1	
DiscSets1	0	1	0	0
	1	0	1	0
	2	0	0	1
	3	0	0	0
LithVar	no	0		
	yes	1		
Thickness	0.2m - 0.5m	1	0	0
	0.5m - 1.0m	0	1	0
	< 0.2m	0	0	1
	>1.0m	0	0	0
Fis	N	0		
	Y	1		
Blast	N	0		
	Y	1		
NSysFrac	N	0		
	Y	1		

Step 0. Intercept entered:

Model Convergence Status

Convergence criterion (GCONV=1E-8) satisfied.

Residual Chi-Square Test

Chi-Square	DF	Pr > ChiSq
25.9693	23	0.3023

Step 1. Effect Fis entered:

Model Convergence Status

Convergence criterion (GCONV=1E-8) satisfied.

Model Fit Statistics

Criterion	Intercept Only	Intercept and Covariates
AIC	174.375	167.359
SC	177.273	173.155
-2 Log L	172.375	163.359

Testing Global Null Hypothesis: BETA=0

Test	Chi-Square	DF	Pr > ChiSq
Likelihood Ratio	9.0158	1	0.0027
Score	9.5449	1	0.0020
Wald	7.9815	1	0.0047

Residual Chi-Square Test

Chi-Square	DF	Pr > ChiSq
17.8285	22	0.7161

NOTE: No (additional) effects met the 0.05 significance level for entry into the model.

Summary of Stepwise Selection

Step	Effect Entered	Effect Removed	DF
1	Fis		1

Summary of Stepwise Selection

Step	Number In	Score Chi-Square	Wald Chi-Square	Pr > ChiSq
1	1	9.5449	.	0.0020

Summary of Stepwise Selection

Step	Variable Label
1	Fis

Type III Analysis of Effects

Effect	DF	Wald Chi-Square	Pr > ChiSq
Fis	1	7.9815	0.0047

Analysis of Maximum Likelihood Estimates

Parameter		DF	Estimate
Intercept		1	-0.8473
Fis	Y	1	1.7636

Analysis of Maximum Likelihood Estimates

Parameter		Standard Error	Wald Chi-Square
Intercept		0.1992	18.0914
Fis	Y	0.6242	7.9815

Analysis of Maximum Likelihood Estimates

Parameter		Pr > ChiSq
Intercept		<.0001
Fis	Y	0.0047

Odds Ratio Estimates

Effect	
Fis	Y vs N

Odds Ratio Estimates

Point Estimate	95% Wald Confidence Limits	
5.833	1.716	19.828

Association of Predicted Probabilities and Observed Responses

Percent Concordant	20.8	Somers' D	0.172
Percent Discordant	3.6	Gamma	0.707
Percent Tied	75.7	Tau-a	0.078
Pairs	4048	c	0.586

Partition for the Hosmer and Lemeshow Test

		Abundance_20 = yes		Abundance_20 = no	
Group	Total	Observed	Expected	Observed	Expected
1	120	36	36.00	84	84.00
2	14	10	10.00	4	4.00

Hosmer and Lemeshow Goodness-of-Fit Test

Chi-Square	DF	Pr > ChiSq
0.0000	0	.

Appendix 6

RHRS Field Activity Time Log

*Activity time is recorded in "team hours" and includes travel time to destination from Knoxville, Tennessee

TRIMS Data gathering

Summary of time using TRIMS to gather county road data prior to preliminary ratings. Broken down by county.

Anderson:	4.0	team hours			
Bledsoe:	4.0	team hours			
Carter:	8.0	team hours			
Grainger:	4.0	team hours			
Smith:	6.0	team hours			
Total:	26.0	team hours	Average:	5.20	team hours per county

RHRS Preliminary Ratings

Summary of time applying RHRS Preliminary Rating to road cuts.

Anderson:	16.0	team hours			
Bledsoe:	10.0	team hours			
Carter:	30.0	team hours			
Grainger:	9.0	team hours			
Smith:	24.0	team hours			
Total:	89.0	team hours	Average:	17.80	team hours per county

RHRS Detailed Ratings

Summary of time performing RHRS Detailed ratings to "A" cuts.

Anderson:	16.0	team hours			
Bledsoe:	10.0	team hours			
Carter:	34.0	team hours			
Grainger:	4.0	team hours			
Smith:	20.0	team hours			
Total:	84.0	m hours	Average:	16.80	team hours per county

Total Team Hours = 199.0 **Average Team Hours Per County = 39.8**

Appendix 7

Digital Data Tables

Plate 1 (in pocket) contains Appendix 7 material, which includes three digital data tables that have the following names:

- Appendix_7_A_RHRS_Data.xls,
- Appendix_7_B_Geologic_Attribute_Data.xls, and
- Appendix_7_C_SAStable.xls, and

The files are in Microsoft Excel® format. Simply insert the CD into the computer's CD ROM drive, navigate to the correct drive, open the folder entitled "Appendix7_Data_Tables", and select the file to open by double-clicking on its icon.

Appendix 8

Digital Photos of Evaluated Roadcuts

Plate 1 (in pocket) contains Appendix 8 material, which includes digital photos of evaluated roadcuts and text files with brief descriptions of the photos. The photos are categorized by first by county, then by road number, then by roadcut ID-number. To view photos, insert the CD into the computer's CD ROM drive, navigate to the correct drive, open the folder entitled "Appendix8_Digital_photos". Select a county by double-clicking on its folder icon to open the folder, then select a state road number by double-clicking on its folder icon. Next, select a roadcut number and open its folder to view JPG photo files and Microsoft Word® files about the roadcut.

VITA

Christopher J. Vandewater was born in Rochester, New York on January 21, 1975. He was raised in Rochester and graduated from Gates-Chili High School in 1993. From there, he went to Monroe Community College in Rochester where he received an A.S. in liberal arts and science in 1996 and then transferred to the State University of New York College at Geneseo, where he received a B.A. in geology in 1998. After graduating, Christopher spent his time traveling the country and gaining professional experience as a geologist for an environmental consulting firm in Golden, Colorado. In August 2000, he began pursuing a M.S. degree in geological sciences at the University of Tennessee, Knoxville. In December 2002, Christopher accepted employment as a geologist with ExxonMobil, to follow the successful completion of his M.S. degree in May 2003.