Geology and Viticulture across the Blue Ridge Escarpment, from the Inner Piedmont to the Blue Ridge Plateau: How Rocks and Landforms Play a Critical Role in the Cultivation of Winegrapes in Polk, Henderson and Buncombe Counties, NC

Carolina Geological Society – Guidebook for the 83rd Annual Meeting

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Field Trip Leaders: Joseph Forrest, Rick Wooten, Bart Cattanach

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Cover Photograph

Burntshirt’s high vineyard site at 3400 feet on the
Blue Ridge escarpment.

Carolina Geological Society

2022 Board of Directors

Table of Contents

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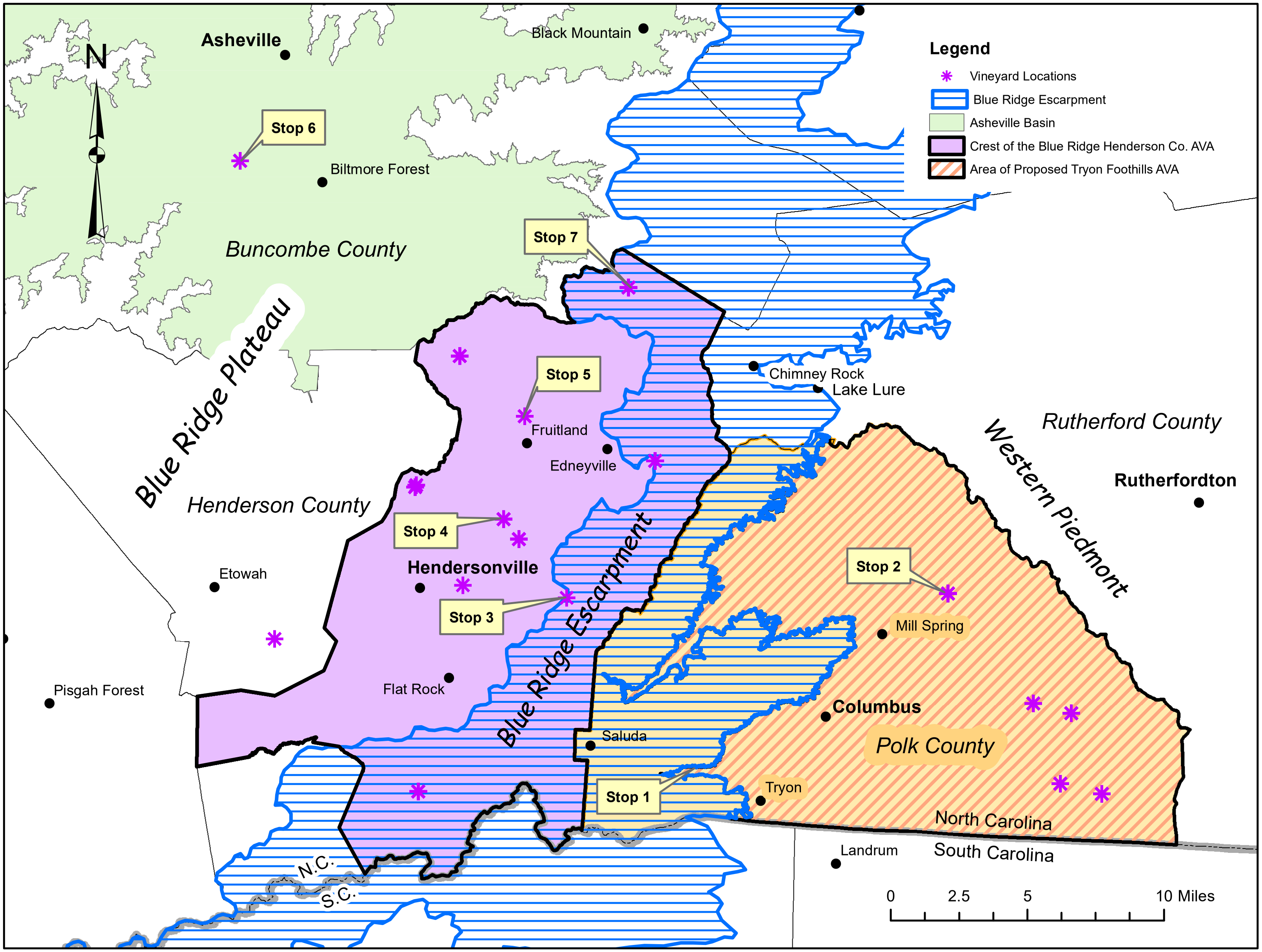

Figure 1. Carolina Geological Society 2022 field excursion area.

Geology and Viticulture across the Blue Ridge Escarpment, from the Inner Piedmont to the Blue Ridge Plateau: How Rocks and Landforms affect the Cultivation of Winegrapes In Polk, Henderson, and Buncombe Counties, North Carolina

Overview and Perspective

Joseph T. Forrest[1]

Introduction

Welcome to the 2022 Carolina Geological Society annual meeting and field excursion. In this year's trip we will explore the relationship of geology to one of the southeast's fastest growing agricultural activities — viticulture, the art and science of cultivating grapes. Though the term viticulture refers to cultivation of all types of grapes, the aspect we will explore is that of the winegrape. Specifically, we will look at how rocks and landforms have influenced the development of grape cultivation and wine-making along the southern Blue Ridge front, making it one of the fastest growing and most important viticultural regions of the eastern United States.

The route of our excursion will begin in the western Piedmont physiographic province (Inner Piedmont geologic province) of Polk County, NC, then cross the Blue Ridge escarpment of Polk and Henderson Counties, and end finally on the Blue Ridge plateau of Henderson and Buncombe Counties. The area lies entirely within the Tugaloo terrane of Hatcher (2002), the rocks of which consist of folded, faulted, and metamorphosed deep-water oceanic crust and rifted fragments of Grenville crust. We will visit vineyards in each of the physiographic provinces and see how geology, mainly reflected in lithologies and geomorphology, has played a role in the development of quite different growing environments. I will leave it to you to decide if these environmental differences equate to differences in the wines produced in each.

Polk, Henderson, and Buncombe Counties, though, are not alone in this story; the precipitous and rugged Blue Ridge escarpment, which trends from southern Virginia to northern Georgia, with maximum exposure in North Carolina, has created a unique juxtaposition of viticulture and geology along the entire southern Blue Ridge front. There are presently seven American Viticultural Areas (AVAs) spread along the mountain front, with the escarpment providing a separation between them. In our discussions at various stops, and in various papers in the guidebook, we relate and contrast the viticultural areas we see in the field stops with other AVAs to the north and south. It is my contention that the escarpment plays a critical role in the viticultural character of the southern Blue Ridge, therefore the geological and geomorphic origins and evolution of this controversial and poorly understood feature, and its relationship to the history of the Inner Piedmont and Blue Ridge plateau, are important themes of this year's field trip.

Geologists and Viticulture

The interest in viticulture on the part of geologists is an old one, related to the concept of "terroir," the idea that winegrape cultivation is a function of the complex interplay of a region's natural environmental

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factors, such as soils, climate, and topography. For Benedictine and Cistercian monks in 13th century Europe, there was no doubt about the relationship of soils to wine quality; they tasted soil mixed in water to determine the best places to establish vineyard sites (Finger and Kündig, 2022 in This guidebook). Since the greater part of soil is composed of inorganic matter derived from the weathering of rocks and minerals, it is logical that geologists should be curious about how the basic materials of their science might have an influence on the quality of grapes and the wines produced from them. Geologists have taken this curiosity to heart and have published numerous books, papers, and popular articles attempting to demonstrate an intimate relationship of geology to fine wine production. Some of the better-known examples from the North American literature include the following:

> Wilson, James E., 1998, *Terroir: The role of geology, climate, and culture in the making of French wines*: University of California Press, Berkeley, 336 p.
>
> Swinchatt, Jonathan and Howell, Davis G., 2004, *The Winemaker's Dance, Exploring Terroir in the Napa Valley*: University of California Press, Berkeley, 229 p.
>
> McQueen, R. W., and Meinert, L. D. (Eds.), 2006, *Fine Wine and Terroir: The Geoscience Perspective*: Geological Society of Canada, Reprint Series 9, 246 p.

In addition, many geological societies have published field guides to areas that have viticultural activity. Here are examples from the Geological Society of America:

> Busacca, Alan J., and Meinert, Lawrence D., *Wine and geology—The terroir of Washington State*: GSA Field Guide 3, 2003.
>
> Pogue, Kevin, 2009, *Folds, floods, and fine wine: Geological Influences on the terroir of the Columbia Basin:* GSA Field Guide 15, 2009.

Finally, three works from the European literature are of personal importance to me, as the authors Alex Maltman, Willi Finger, and Rainer Kündig are personal friends and have been the greatest influences on my thinking about the relationship of geology to viticulture:

> Maltman, A. 2008. *The role of vineyard geology in wine typicity*: Journal of Wine Research, Vol. 19. No. 1, p. 1-17.
>
> Maltman, A., 2018, *Vineyards, Rocks and Soils, the Wine Lover's Guide to Geology*: Oxford University Press.
>
> Kündig, R., Decrouez, D., Finger, W., Haldimann, P., Hofstetter, J-C, Meyer, C., Mumenthaler, T., Sieber, N., Spescha, R., and Testaz, G., eds, 2018, *Stein und Wein, Entdeckungsreisen Durch Die Schweizerischen Rebbaugebiete*:[2] Verein Stein und Wein, Obfelden, Switzerland.

if you go to a wine shop and read the labels on bottles, you will see many references to geology, rocks, and minerals, demonstrating the point that geology has become intimately associated with wines. The naming of vineyards and wines after geological events and phenomena has proliferated, suggesting a

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[2] Translation: *Rock and Wine: Voyages of Discovery through the Vineyard Regions of Switzerland.*

romantic and mystical origin for fine wines, one that can only be totally understood by a geologist who knows the origin of rocks and how they mysteriously impart flavor and texture to wines.

As prolific as the literature is and as beguilingly logical as the relationship of geology to viticulture may seem, it is not as straightforward as you might think; there are many areas of disagreement and controversy. Mark Matthews, professor of viticulture at the Robert Mondavi Institute for Food and Wine Science at the University of California, Davis has wryly questioned why geologists are so obsessed with wine and winegrapes:

> A host of research symposia have been held that include geology reports on the wine regions of the world and the geological basis of wine flavors. There is hardly a geologist to be found at an apple or tomato meeting. Is the grapevine unique, or is it the refreshments? The simple fact is that grapevines have next to no interaction with rocks.[3]

While I disagree with the professor's comment on the interaction of grapevines with rocks, his point about the apple and tomato meetings is well taken. What is it about wine and winegrapes that holds such fascination for geologists? I can attest to the attraction of the refreshment. I can also attest to the simple enjoyment of having a glass of wine with friends while overlooking a beautiful vineyard and thinking about the geological setting and how it might relate to the character of the wine, whether there is any validity to the idea or not. Sitting with a glass of tomato juice overlooking a tomato patch does not have the same appeal. At our last stop on Saturday at St. Paul Mountain Vineyards and Appalachian Ridge Cidery, you will have the opportunity to try both wine and apple cider in a beautiful vineyard setting. The days when geologists start thinking about apples and geology cannot be far behind. I am almost certain, though, that Alex Maltman has already explored this theme, as he has with wines, beer, and whiskies.

My interest in the wine and geology relationship was kindled by Willi Finger and Rainer Kündig, editors and authors of the Swiss book *Stein und Wein*. In 2010, as they were beginning to assemble their data, they proudly showed me their work, and their enthusiasm piqued my interest in a topic I had never thought about. Based on that brief exposure, I decided to test some of their ideas in the United States. I discovered for the first time that an old field area of mine in southwestern, NC had become an area of grape cultivation and wine production. This led to my selection by the winegrowers of Cherokee and Clay Counties, NC and White, Lumpkin, and Fannin Counties in north Georgia to prepare a petition for designation of the Upper Hiwassee Highlands as an American Viticultural Area, which was approved in July 2014. Subsequently, I have prepared petitions for two other North Carolina AVAs - Crest of the Blue Ridge Henderson County, and the proposed Tryon Foothills - as well as for the Dahlonega Plateau region of north Georgia. These projects have afforded me opportunities to meet and befriend a fine group of folks who have courageously undertaken the risks of founding and operating vineyards and wineries. You will meet some of these folks on our excursion.

In the paper that Mark Hoffmann and I have published in this guidebook, we express our opinion that climate, especially temperature regime, is the most important characteristic of a successful vineyard site. Temperature determines the beginning and end of the growing season, and thus its length, and the

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[3] Matthews, Mark A., 2015, *Terroir and other Myths of Winegrowing*: University of California Press, Berkeley, 308 p.

amount of heat accumulation during the growing season, which must be sufficient to ripen grapes. But I do not hold geology guiltless in its relationship to viticulture. In my opinion, there are three areas in which geology plays a significant role: (1) Providing the principal sources – rocks and minerals - of the inorganic component of soils and subsequently creating a substrate that supports the roots and vines and becomes a source of some plant nutrients, (2) sculpting the landscape through the physical characteristics of lithologies (crystalline vs sedimentary, resistance to weathering, permeability, porosity, etc.) and their weathering and erosional characteristics, and (3) creating landscapes that influence and control climate and weather patterns. In a nutshell, lithology and geomorphology – rocks and landforms - are the important elements of geology in viticulture.

Minerality

While it is true that rocks and minerals are the principal source of the inorganic components (clay, silt, sand, gravel, rock fragments) in soils, the idea that rocks and minerals provide flavor compounds that can be detected in wines is one of the most controversial issues concerning geology's role in viticulture. The term "minerality" has become a well-established and overused expression in the viticultural lexicon. Wine professionals—including producers, sommeliers, and reviewers are applying the term increasingly in wine reviews and perpetuating the idea that so-called "mineral flavors" in wines are sourced from the geological minerals in a vineyard's soils.

I have been puzzled for a long time over the meaning of the term minerality and have asked winemakers and other experts to give me an explanation of the term. If a wine is said to display minerality, there must be specific flavors that define and describe the term. I have had little success in finding someone who can describe these flavors. The usual answer is that "Minerality is the characteristic flavor in the wine produced by the terroir of the vineyard." That is not specific. But there are "true believers" who claim to understand the concept and who do offer more specific definitions. Here's a quote from Dr. Vinny (after "Vinifera") of the WineSpectator.com website who attempts to describe the meaning of the term:

> Minerality is one of the hardest wine tasting notes to explain, and it's tricky to communicate because it falls under the category of things that we recognize in wine but that we don't typically put in our mouths (with the exception of salt, obviously). But I consider minerality both a smell and a flavor, and it's mostly considered positive (unless you don't like minerality).
>
> To me, minerality is a savory side of wine that doesn't fall into fruit, herb, spice or vegetal notes. Saline and sea salt flavors are some of my favorite examples. Chalk, crushed rocks, wet stones, slate, talc, limestone, gravel, flint, oyster shell, petrichor (the smell of rain on dry surfaces) or even the aroma of standing next to a hot brick wall are some specific examples of mineral elements in wine. Minerality can also evoke a wine's mouthfeel—pebbles and slate are smooth while gravel or chalk are drying.[4]

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[4] https://www.winespectator.com/articles/what-does-mineral-refer-to-in-wine-tasting-notes. Accessed

The question of whether we can really taste something in wines that comes from the soil has been addressed by Alex Maltman in his 2018 book previously referenced and in his numerous papers and popular articles. See especially his 2008 article reprinted in this guidebook. He argues that rocks and minerals have no inherent taste (with minor exceptions for halite and some zinc minerals), and therefore cannot impart flavors to wines. I have to agree with Alex's logic, but I cannot offhandedly dismiss the observation made by Willi Finger and Rainer Kündig that in numerous wine tastings conducted during the preparation of their book, there was a clear and credible distinction made by tasters between wine made from grapes grown on paragneiss and orthogneiss soils, with the paragneiss wines having a full-bodied, fruity aroma, as compared to the more acidic flavors of orthogneiss wines. Willi and Rainer suggest that these distinctions result from the prevalence of K-feldspars in the paragneisses, which gives them a more basic flavor.

Whatever the truth may be, we still have not arrived at a satisfactory definition of minerality. But the writer Adam Gollner has attacked the problem head-on in an article entitled "Does your wine really taste like rocks," in the May 3rd, 2021 issue of the New Yorker magazine. Here is a quote from that piece:

> In 2013, French researchers found that wine professionals who were asked to define minerality often provided contradictory definitions. When it first appeared in The Oxford Companion to Wine, a cherished encyclopedia of the wine world in 2015, its editor, Jancis Robinson, wrote that the word was "too prevalent to ignore – even if impossible to define."[5]

The term minerality means so many different things to so many people that for me it is useless. Nevertheless, it has played a major role in making a link between geology and viticulture a fact for many wine experts and for the public. For those interested in a scientific examination of the term, I recommend the excellent paper "Minerality in Wine: Towards the Reality behind the Myths" by Parr et al (2018).

American Viticultural Areas

During the excursion and in some of the submitted papers in the guidebook, you will see the term American Viticultural Areas, or the acronym "AVAs," used. Since the term will appear repeatedly during the field trip, we need to explain it before we get started.

Many wine-producing countries have established programs of viticultural zoning in which winegrape growing areas are delineated and designated as areas of significance based on more or less homogeneous occurrences of soil types, climate conditions, topography, geology, or other natural environmental characteristics. Other criteria that are used for defining a viticultural zone include types of grapes being grown and specific wine-production techniques. The areas thus defined comprise terroir regions. The oldest and best known of these zonation programs are in Europe. France, for example, has its *Appellation d'Origine Contrôllée/Protégée* program, while Italy has its *Denominazione di Origine Controllata/Controllata e Garantita*, and Spain has its *Denominación de Origen Protegida* system. The US

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[5] Does Your Wine Really Taste Like Rocks? | The New Yorker

counterpart to these European systems is the American Viticultural Area program (commonly referred to as the "AVA" program), which is administered by the Tax and Trade Bureau (TTB) of the US Department of the Treasury. The AVA program started in 1971 and to date has resulted in the designation of 267 AVAs in the United States (Figure 2), 147 of which are located in California.

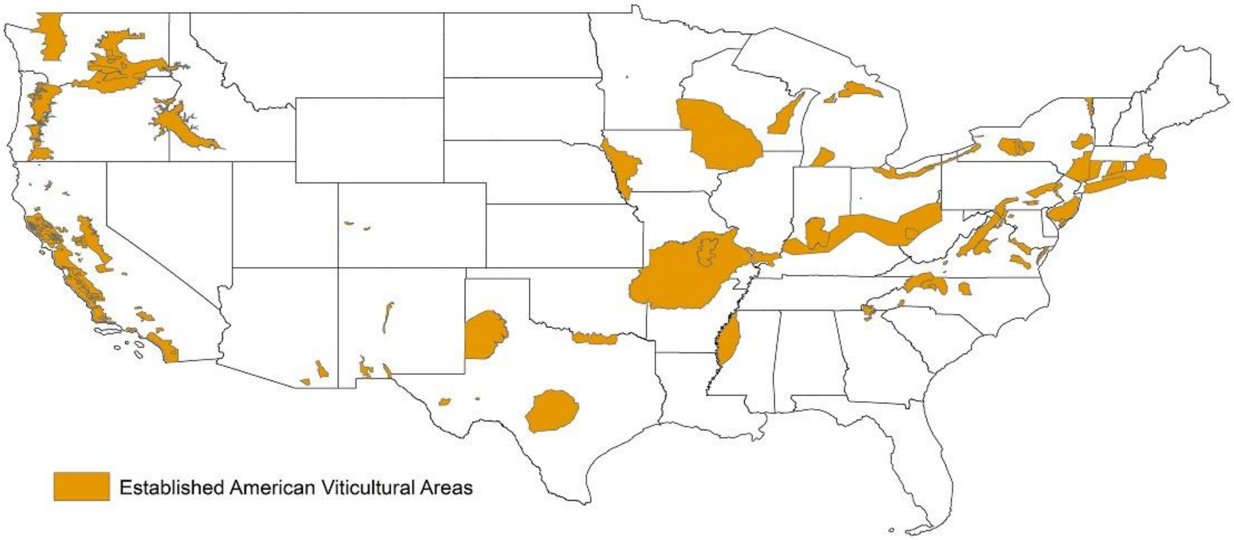

Figure 2. Established American Viticulture Areas.

Applications for an AVA are made by wine-growers of a region and must include 1) a description of the area's natural environmental factors (climate, soils, topography, geology) that directly relate to viticulture, 2) a description of how these environment factors differ from those of surrounding areas, 3) a proposed name that is related to the designated area by usage or tradition, and 4) boundaries that can be shown on USGS topographic maps and that encompass the entirety of the proposed area. In the American system, a vineyard may use the name of the AVA on its wine label if 85% or more of the grapes from which the wine was produced were grown within the bounds of the AVA and the resulting wine produced is finished and bottled within the state or states within which the AVA is located.

The AVAs of North Carolina and the immediately surrounding states are shown in Figure 3. In Table 1, I have summarized climatic characteristics of North Carolina's six approved AVAs, its one proposed AVA, and the Dahlonega Plateau AVA of north Georgia. These characteristics will allow you to compare some of the main environmental differences between the areas. We will visit vineyards in two of these AVAs - Crest of the Blue Ridge Henderson County, and the proposed Tryon Foothills (Figure 1).

For those interested in the details of viticultural zoning worldwide, I recommend the article "A Worldwide Perspective on Viticultural Zoning," by Vaudor and Shaw (2005).[6] The TTB has a number of websites that offer detailed information on the American Viticultural Areas, including sites that allow one to download the actual petition documents submitted by the winegrowers.

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[6] The paper can be downloaded gratis at (15) (PDF) A Worldwide Perspective on Viticultural Zoning (researchgate.net).

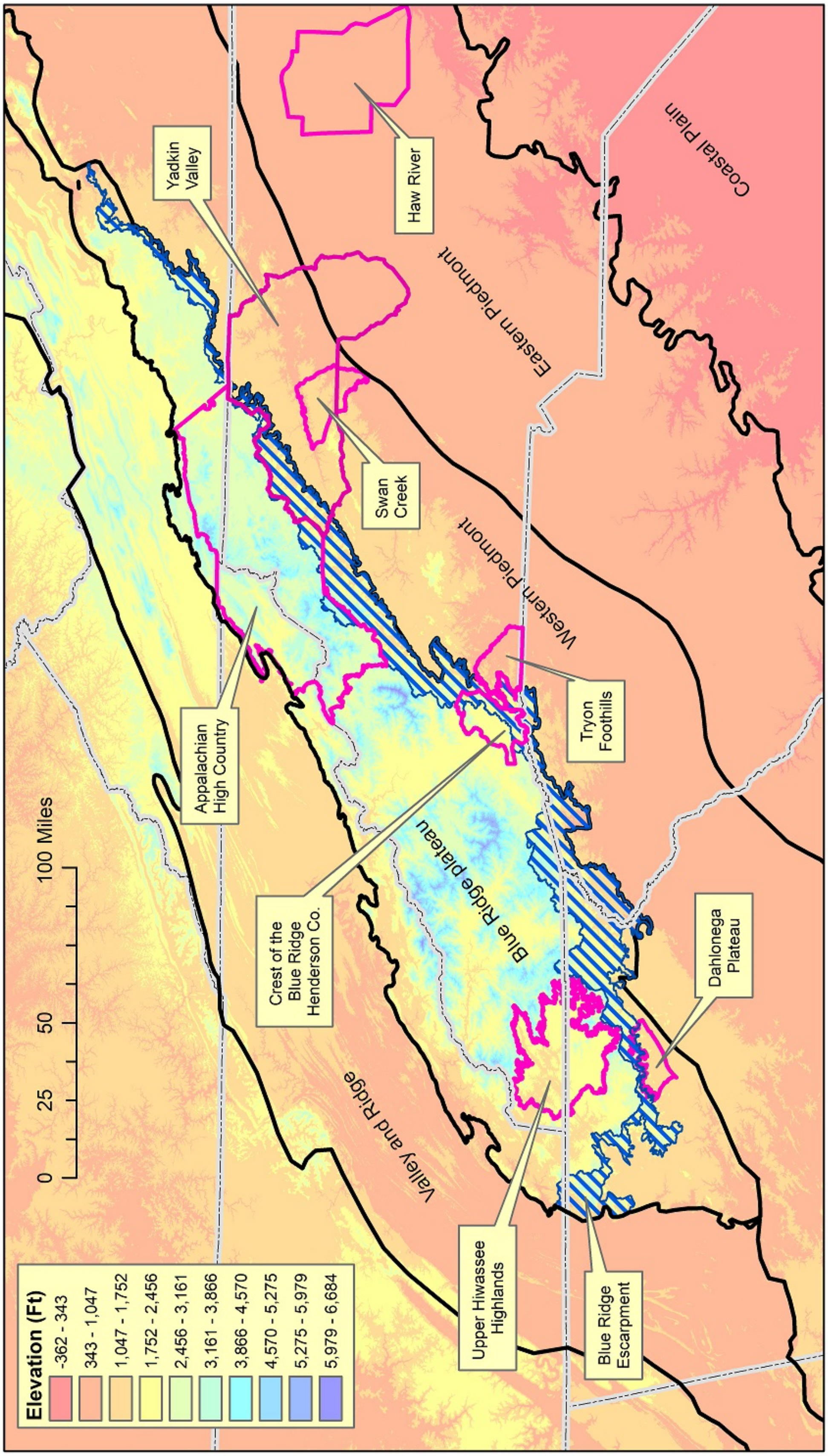

Figure 3. American Viticultural Areas along the southern Blue Ridge front shown on color-coded USGS Digital Elevation Model.

AVA	Area (Sq. Miles)	Elevation (Ft)			Annual Temperature (F°)			Annual Precipitation (In)			Growing Season (Days)		
		High	Low	Mean	High	Low	Mean	High	Low	Mean	High	Low	Mean
AHC	2407	6285	1361	3130	56.5	45.1	51.8	80.0	40.9	53.2	186	139	159
YV	2208	4064	537	1159	59.5	50.2	57.4	62.6	43.7	49.4	220	142	184
SC	230	1897	741	1096	58.4	56.7	57.7	52.5	46.6	49.6	192	181	187
HR	971	975	219	612	59.9	58.8	59.4	48.9	45.6	46.9	216	207	213
CBRHC	215	4414	1400	2366	57.7	51.3	55.4	77.8	49.4	62.7	207	181	192
TF	176	1656	712	988	60.1	58.8	59.5	68.1	50.5	56.3	225	191	202
UHH	691	3659	1504	1979	57.0	54.1	56.1	79.9	46.9	60.9	189	174	181
DP	132	2348	1146	1558	59.7	56.7	58.3	72.8	63.0	65.2	198	189	193

AVA	Growing Degree Days (F°Days)			Est. Last Spring Frost (Date)			Est. First Fall Frost (Date)		
	High	Low	Mean	High	Low	Mean	High	Low	Mean
AHC	3612	1195	2581	12-May	20-Apr	2-May	21-Oct	30-Sep	10-Oct
YV	4285	2287	3854	10-May	2-Apr	20-Apr	5-Nov	2-Oct	20-Oct
SC	4102	3643	3900	22-Apr	16-Apr	19-Apr	24-Oct	18-Oct	20-Oct
HR	4377	4101	4249	5-Apr	1-Apr	3-Apr	4-Nov	28-Oct	1-Nov
CBRHC	3765	2298	3266	22-Apr	9-Apr	15-Apr	30-Oct	18-Oct	23-Oct
TF	4376	4040	4234	18-Apr	30-Mar	11-Apr	7-Nov	24-Oct	28-Oct
UHH	3612	2940	3411	26-Apr	19-Apr	23-Apr	22-Oct	15-Oct	28-Oct
DP	4193	3489	3877	19-Apr	13-Apr	15-Apr	26-Oct	22-Oct	24-Oct

Table 1. Environmental characteristics of American Viticultural Areas along the southern Blue Ridge front. AHC=Appalachian High Country, YV=Yadkin Valley, SC=Swan Creek, HR=Haw River, CBRHC=Crest of the Blue Ridge Henderson County, TF=Tryon Foothills, UHH=Upper Hiwassee Highlands, DP=Dahlonega Plateau.

Field Trip Team

In putting this excursion together over a three-year period, it has been my great pleasure to have the support and assistance of a group of real experts in a number of disciplines: geological, viticultural, horticultural, meteorological, and sociological. I would like now to introduce them and acknowledge the tremendous contributions they have made.

First and foremost, I am grateful to my co-leaders **Bart Cattanach** and **Rick Wooten**. I could not have found two more knowledgeable southern Appalachian geologists than these two. When I realized my deficiencies in modern thinking on the southern Appalachians, Rick and Bart agreed enthusiastically to assist me and have brought me up-to-date on many aspects in a short time. I could not have accomplished this trip without them.

Many people do not realize the long history of viticulture in North Carolina. When I began my first project for the Upper Hiwassee Highlands AVA petition, I was advised to read a book by **Ian Taplin**: *The Modern American Wine Industry: Market Formation and Growth in North Carolina*.[7] Ian is a sociologist at Wake Forest University with dual appointments in the Sociology and the International Studies programs. His specialty in sociology is in the development and evolution of businesses and market trends. His book is a review of the emerging viticulture industry in North Carolina, written at a time when it was beginning a rapid growth spurt that continues today. He is an excellent and humorous speaker and will present a condensed version of North Carolina's fascinating viticultural history.

After my retirement, I had the opportunity to participate in the Geographic Information Science Graduate Certificate program at the UNC Chapel Hill Geography Department. It was there that I met Prof. **Charles 'Chip' Konrad**, who teaches Climatology and is Director of the NOAA Southeast Regional Climate Center. Chip has a background in geophysics, with a good understanding of geology. His comprehensive paper in the guidebook emphasizes the role of geomorphology in western North Carolina climate and weather patterns as they relate to grape cultivation.

In 2012, I happened to be in Murphy, NC during research for the Upper Hiwassee Highlands AVA petition and was informed that a state-sponsored seminar would be presented on viticulture that week at the Tri-County Community College. I signed up and attended the course. Prof. **John Havlin** of North Carolina State University's Dept. of Soil Science was one of the speakers. He presented the best explanation of cation exchange capacity that I had ever heard. When my CGS trip proposal was accepted in 2019, the first person I visited was John, who enthusiastically agreed to participate and write a paper on soils for the guidebook. John's schedule for this year will not permit him to be with us. Nevertheless, his paper does appear in the guidebook. John was responsible for getting permission for us to visit the Biltmore vineyards, for which we are very appreciative.

I felt from day one in my trip planning that an expert on soil geomorphology would be critical to success of the excursion. Prof. Missy Eppes at UNC Charlotte recommended that I contact her former student

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[7] Taplin, I., 2011, *The Modern American Wine Industry: Market Formation and Growth in North Carolina*: London, Routledge, 224 pp. https://doi.org/10.4324/9782325655697.

Brad Johnson who teaches at Davidson College. She could not have suggested a better choice. Brad is a geologist and geomorphologist who specializes in the interpretation of soils and how they relate to geological development. He has written a comprehensive paper for the guidebook that explains soils and soil science from a geological perspective.

Prof. Sara Spayd, North Carolina’s former State Viticulturalist introduced me to Dr. **Mark Hoffmann**, a young German horticulturalist, who teaches and does research in small fruits (strawberries, for example) and grapes at North Carolina State. He is also part of North Carolina Extension and is on call to assist farmers statewide with crop problems. Since we are holding this year’s trip during the grape harvest season, Mark will not be able to join us, but he and I have jointly written a paper for the guidebook that is a preliminary attempt to document the geographic distribution of the state’s grape cultivars.

Anyone who has an interest in North Carolina winegrape cultivation is probably familiar with the viticulture program at Surry Community College in Dobson, NC. I am delighted that **Sarah Bowman**, the lead viticulture instructor in the program, will join us and be available to answer biological and horticultural questions. She will also give us a presentation on the very popular Surry program that has launched many would-be viticulturalists on a challenging new venture.

It is unfortunate that we will not be able to visit the high vineyard on Burntshirt Mountain as we had originally advertised. Due to heavy rains in the spring, the road to the site has been heavily damaged and is almost impassable for the vans we had planned to use. But Mr. **David Fleming**, a recent transplant from the California wine industry, and now General Manager of Burntshirt Vineyards, has agreed to give us a presentation comparing the viticultural industry of the west coast with that of the North Carolina mountains. Dave is an excellent speaker and will give us the perspective of a hands-on winemaker who faces daily decisions on how to handle never-ending problems in the vineyard.

When I recognized that the Blue Ridge escarpment plays such an important role in mountain viticulture, I was told that **Philip Prince** was the individual who should speak to the group on the origin and evolution of the feature. He had recently completed his PhD at Virginia Tech and was working with Appalachian Landslide Consultants on their mapping program for the North Carolina Geological Survey. We are delighted to have him with us this year after having to cancel the trip twice in the past two years.

I have already given you an introduction to my friends **Alex Maltman**, emeritus professor of geology at Aberystwyth University in Wales, **Willi Finger**, geological consultant in Zürich, Switzerland, and **Rainer Kündig**, lecturer in mineralogy at the Swiss Federal Institute of technology in Zürich and former director of the Swiss Geotechnical Commission. These three gentlemen are great geologists and lovers of wine. You will enjoy their papers in the guidebook and listening to them speak to us on Friday evening.

Finally, I want to thank the members of the newly established **CGS Field Trip Committee** for its support in taking over logistical aspects of the trip. They completed what appeared to be an impossible task by quickly organizing and finalizing everything necessary to insure a successful 2022 event. Thank you all from the bottom of my heart for your commitment and hard work.

Concluding Remarks

Geologists can be an argumentative bunch, especially on field excursions, where differences of interpretation at outcrops can be fun for some and maddening for others. Be forewarned, therefore, that many of our geological colleagues hold opposing views on the relationship of geology to viticulture. That is a fact, and you will be exposed to it at our opening night social event when we hear talks by some distinguished European geologists whose views, on both sides of the debate, have been thoroughly researched and convincingly documented in the scientific literature. One of my purposes in this article has been to introduce you to this growing literature. I hope our visits in the vineyards will stimulate you to look critically at some of these works and arrive at some conclusions of your own. At the very least, you will be more aware that the issues are by no means 'cut and dry.'

As a leader of this year's CGS excursion, I felt it is important to express where I stand in the debate. I do feel that geology plays a demonstrable and vital role in viticulture, but it is principally physical, with minor chemical input. None of my opinions, though, are set in stone, and I encourage you to express your own views and argue your case. I have also tried in this article to explain the concept of the American Viticultural Area, which is an important element of the burgeoning southeastern wine industry that is given much importance by winegrowers and wine experts, but is poorly understood by the public.

Finally, an important goal in the vineyard visits and technical papers is to give you enough background information to be able to look critically at different terrains and form a conceptual model of their suitability as vineyard sites. This can be immensely entertaining. Give it a try; it may even lead to your uncovering previously unrecognized roles of geology in viticulture.

I thank you all for your attendance at this year's Carolina Geological Society meeting and offer a toast to your health, well-being, and enjoyment of our beautiful vineyards and Blue Ridge mountains!

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Carolina Geological Society 2022 Field Trip
Bedrock Geological Overview

Bart Cattanach, P.G.[1]

Introduction

The 2022 Carolina Geological Society field trip spans the Blue Ridge and Piedmont physiographic provinces but is geologically located entirely within the Tugaloo terrane of Hatcher (2002) (Figures 1 & 2). The Tugaloo terrane is composed of metamorphosed sedimentary and volcanic rocks deposited primarily on newly created oceanic crust along the rifted margin of Rodinia (ancient North America). It is intensely deformed and metamorphosed and consists of multiple thrust sheets with several mappable components. The largest of these components are the Neoproterozoic to early Ordovician Ashe Metamorphic Suite/Tallulah Falls Formation and Alligator Back Metamorphic Suite. They are primarily thick sequences of complexly deformed meta-sedimentary rocks originally deposited in marine basins. Interspersed with these rocks are lesser amounts of amphibolite and retrogressed to minimally metamorphosed ultramafic bodies. The Ordovician Poor Mountain Formation, a sequence of metasandstones, schists, and amphibolites was deposited unconformably atop the Tallulah Falls Formation (Hatcher, 1993). Tugaloo terrane rocks are locally migmatitic and commonly contain the aluminosilicate minerals sillimanite and kyanite. Numerous Paleozoic granodioritic to tonalitic plutons intrude the Tugaloo terrane (e.g. Henderson Gneiss).

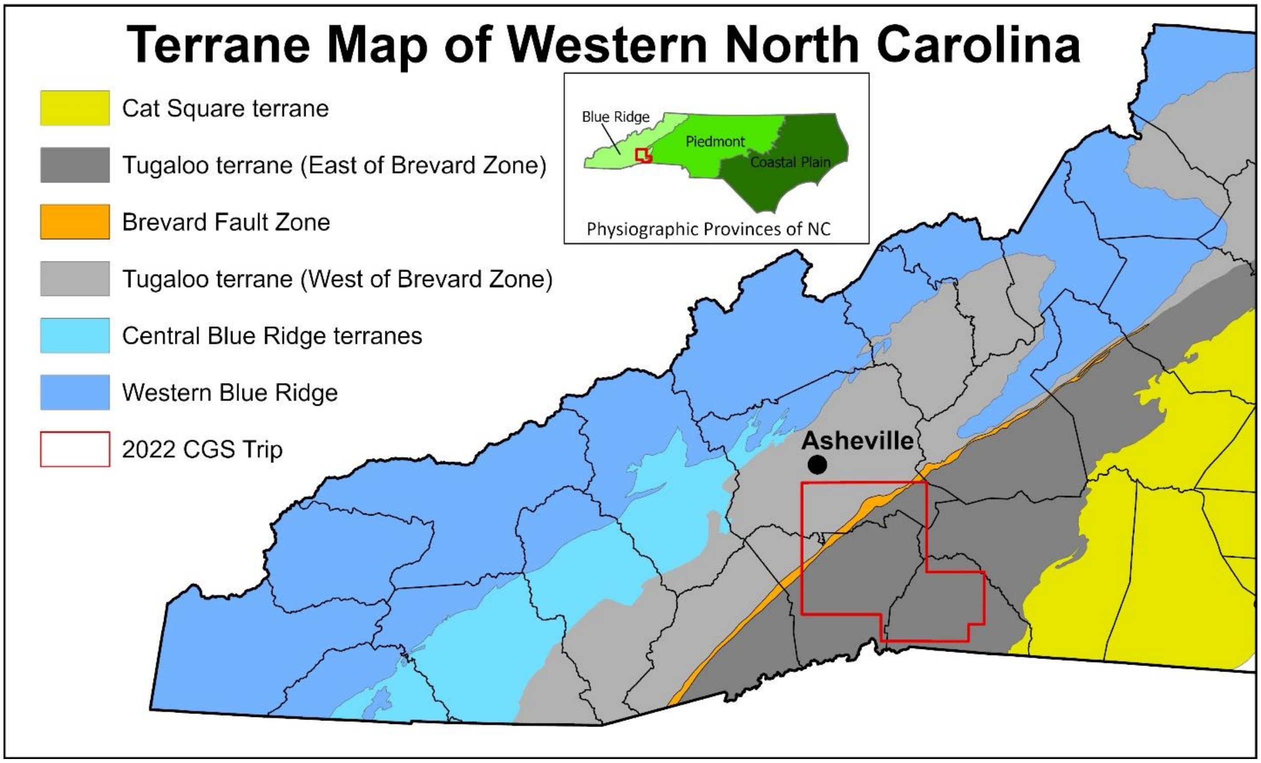

Figure 1. Regional geological setting of the 2022 CGS field trip. Extent of Figure 2 shown by red outline.

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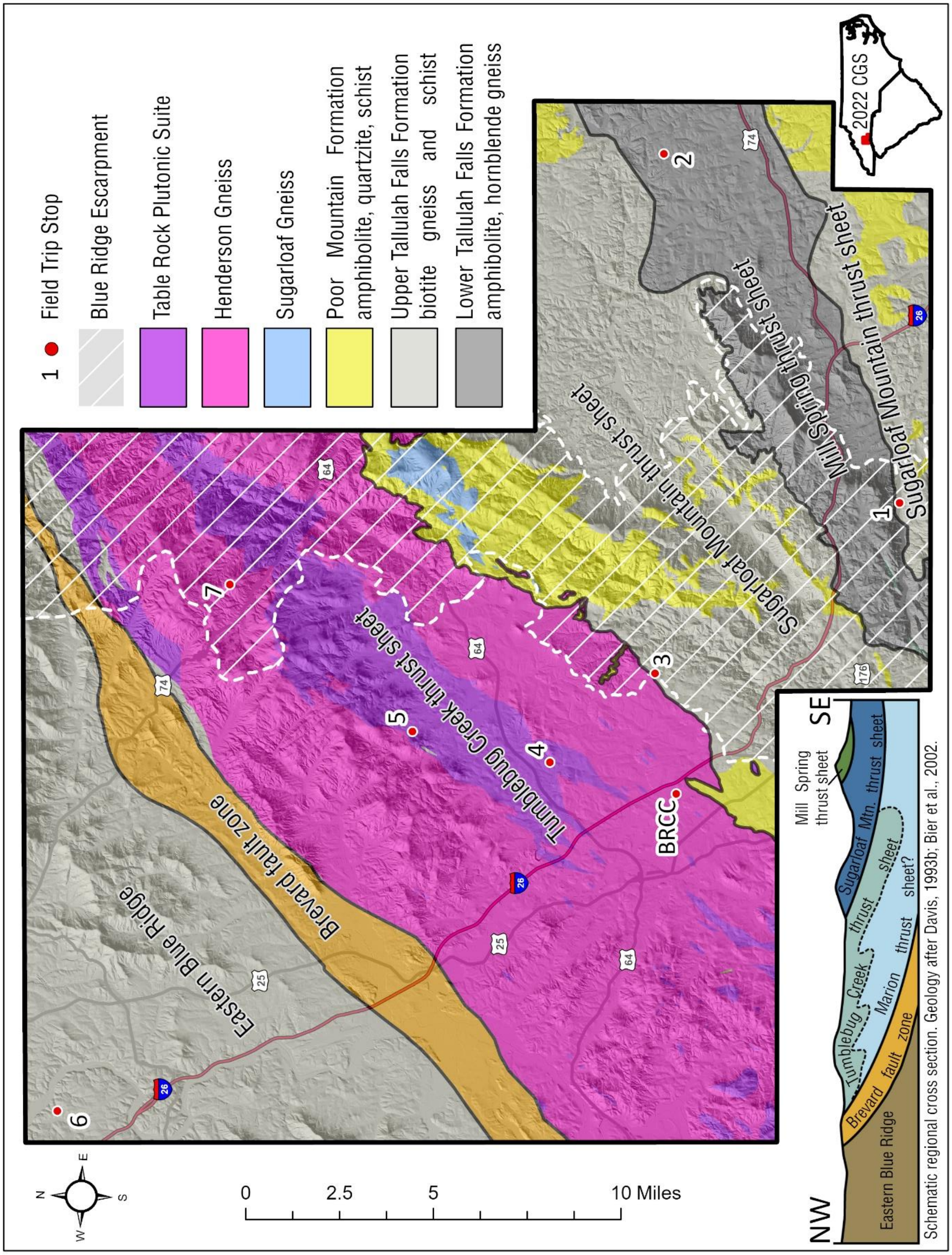

Figure 2. Detailed map of tectonic elements, stratigraphic units, and stop locations in the 2022 CGS field trip (Geology from Davis, 1993; NCGS, 2022). Compiled by Bart Cattanach.

The northeast-trending Brevard fault zone separates the Tugaloo terrane into western and eastern portions (Figures 1 & 2). The Brevard fault zone is a zone of strongly deformed rocks and is one of the major structural features in the southern Appalachian Orogen. Brevard zone assemblages include mylonite, phyllite, graphitic schist, metasandstone, and marble. Peak metamorphic conditions northwest of the Brevard zone in NC were reached during Taconic orogenesis (Moecher and others, 2011) while those southeast of the Brevard zone were reached during Neoacadian orogenesis (Hatcher, 2010). High temperature, ductile oblique and dextral strike-slip motion took place along the Brevard zone during Neoacadian orogenesis. The Brevard zone was reactivated during Alleghanian orogenesis by high temperature strike-slip and brittle reverse motion (Hatcher et al., 2007).

Because this year's CGS trip is focused more on the region's soil and geomorphology, bedrock geology will not be prominent at many of the stops. There will, however, be opportunities to view rock outcrops at several locations. The majority of the field trip takes place in the Columbus Promontory, site of the 1993 CGS field trip led by Bob Hatcher, Timothy Davis and Greg Yanagihara.

Tim Davis' excellent guide to the geology of the Columbus Promontory (Davis, 1993b) is the best overview of these rocks and excerpts of his paper are reprinted below with minor revisions intended to align the text with current terrane-based interpretations of the southern Appalachians. Hopefully these edits do not change the intent of the original manuscript and any errors or misinterpretations are mine alone. We encourage you to read the original document available for viewing and download on the CGS website. The goal is to provide participants an introduction to the rocks to help them think about how the geology may influence the geomorphology and soils critical to the emerging viticultural industry in the region.

Significant changes to Davis's text include: 1) The Mill Spring Group is now tentatively correlated with the Tallulah Falls Formation (Davis, 1993a; Hatcher, 2002). Where "Mill Spring group" occurred in the text it was changed to the appropriate lower or upper "Tallulah Falls Formation". 2) The 438 Ma granitoid of Davis has been changed to the Table Rock Plutonic Suite of approximately the same age to reflect their likely correlation. 3) Davis's original text is in italics. Additions to the text clarifying or adding modern geochronological data are not italicized. 4) Davis's 1993b references and figures are not repeated here but the map shown in Figure 2 of this paper and reproduced on the back cover of the guidebook provides relevant details to use with his text.

From: Davis, T. L., 1993, Geology of the Columbus Promontory, western Inner Piedmont, North Carolina, southern Appalachians, *in* Hatcher, R. D. Jr., and Davis, T. L., eds., Studies of Inner Piedmont geology with a focus on the Columbus Promontory: North Carolina Geological Survey, Carolina Geological Society Guidebook, p. 17–43:

INTRODUCTION

The focus of the 1993 Carolina Geological Society field trip is a crystalline thrust stack exposed in the Inner Piedmont in western North Carolina in the Columbus Promontory (Figure 2 & Back Cover Map). *This crystalline thrust complex comprises three thrust sheets that in ascending order include the Tumblebug Creek thrust sheet, the Sugarloaf Mountain thrust sheet, and the Mill Spring thrust sheet. These thrust sheets contain a distinct lithostratigraphy that helps define their extent. The Tumblebug Creek thrust sheet contains the* **447 Ma (Moecher, 2011)** *Henderson Gneiss and* plutonic bodies of the *~438 Ma* **Table Rock Plutonic Suite** *intruded into the Gneiss; the Sugarloaf Mountain thrust sheet contains rocks of the Poor Mountain Formation, the Sugarloaf gneiss, and upper Tallulah Falls Formation; the Mill Spring thrust sheet contains rocks of the mafic-rich lower Tallulah Falls Formation. The Columbus Promontory is located in a high relief (700-1000 m) area of Blue Ridge topography within the Inner Piedmont that produces continuity* *of outcrop atypical of this terrane, and thus is an outstanding area for study of the complex geologic history of crystalline thrust sheet development.*

Three phases of ductile deformation (D1, D2, D3) are present in the Columbus Promontory which place constraints on the history of emplacement and internal deformation of this crystalline thrust stack. Detailed geologic mapping and mesoscopic analysis suggests that the most significant amount of thrust displacement and internal deformation occurred during D2 which was synchronous with upper amphibolite sillimanite-grade metamorphism **[Neoacadian-Acadian peak metamorphism approximately 360- 350 Ma (Bream, 2002)].** *Detailed mapping and mesoscopic analysis also indicates that the kinematics of flow during D2 was more complex than previously recognized in the Inner Piedmont. This involved a partitioned flow regime involving contemporaneous W-NW directed thrusting and SW-directed stretching caused by the interaction of Inner Piedmont thrust sheets and the listric geometry of the primordial Brevard fault zone; the flow regime in the Columbus Promontory was transpressional. An important consequence of the model presented in this paper is the kinematic linkage between the Brevard fault zone and lnner Piedmont thrust sheets during upper amphibolite facies conditions. The penetrative nature of this D2 deformation in the Columbus Promontory and throughout the lnner Piedmont terrane suggests that the lnner Piedmont may be considered an orogenic or crustal shear zone with the Brevard fault zone as the western boundary.*

Tumblebug Creek Thrust Sheet

Henderson Gneiss. *Keith (1905, 1907) defined and delineated the Henderson Granite, with the type section located in Henderson County, North Carolina. Reed and Bryant (1964) redefined the Henderson Gneiss and restricted the outcrop unit to southeast of the Brevard fault zone. As defined by Reed and Bryant (1964), the Henderson Gneiss extends in the Piedmont from the South Carolina-Georgia border northeastward to the southeastern flank of the Grandfather Mountain window.*

The composition of the Henderson Gneiss varies from that of granite to quartz monzonite and is composed of microcline, oligoclase, quartz, and biotite with accessory muscovite, garnet, allanite, zircon, sphene, and opaque minerals (Lemmon 1973). One of the most distinctive characteristics of the Henderson Gneiss is the presence of distinct K-feldspar augen up to 3 cm long. The augen are white microcline, ovoid to asymmetric in cross section and elongate within the foliation plane. The augen are commonly rimmed by quartz, plagioclase, and embayments of myrmekite. The Henderson Gneiss, in the Columbus Promontory and throughout much of the outcrop length, contains a pronounced NE-SW-trending mineral lineation defined by quartz ribbons, elongate K-feldspar porphyroclasts, flakes of biotite, and occasional muscovite, and in places is an L-tectonite.

The Henderson Gneiss has been the focus of many geochronological studies, but, unfortunately, many discrepancies exist in the results. **A modern U-PB zircon crystallization age of 447 Ma was reported by Moecher et al. (2011).**

Table Rock Plutonic Suite. *Detailed mapping by Lemmon (1973) and Lemmon and Dunn (1973a and 1973b) in the Bat Cave and Fruitland quadrangles indicate that the Henderson Gneiss was intruded by a younger granite prior to the development of the dominant foliation* (Figure 2 & Back Cover Map). *The contact between the Henderson Gneiss and the granitic gneiss is now concordant and parallel to the regional southeast-dipping foliation. This unit is distinguished from the Henderson Gneiss by the lack of K-feldspar augen, less biotite, and generally lighter color. The composition of this granitoid gneiss varies* *from granite to granodiorite. Odom and Russell (1975) reported a Rb-Sr whole-rock age of 438 Ma, with an initial ^{87}Sr/^{86}Sr of 0.7045 for the granitoid gneiss.*

Sugarloaf Mountain Thrust Sheet

Sugarloaf Gneiss. The Sugarloaf gneiss is confined to the top of Sugarloaf Mountain in the Bat Cave quadrangle (Figure 2 & Back Cover Map). *It represents the structurally highest unit in the Columbus Promontory contained in the Sugarloaf Mountain thrust sheet. This unit was originally included with the Sugarloaf Mountain group by Lemmon (1973). Based on zircon morphology and scatter of Rb-Sr isotopic data, Lemmon suggested that the Sugarloaf gneiss could be a recycled sedimentary rock, but did not rule out the possibility of an igneous protolith for this unit. New isotopic work in progress (Goldberg and Fullagar, this guidebook) should help elucidate the protolith history and age (metamorphic or crystallization?) of this unit. As noted previously, because of the possibility of an igneous origin for this unit, Davis (1993) redefined it as a separate lithologic unit called the Sugarloaf gneiss. A nearly identical group of unnamed gneiss bodies present in the Chauga belt of South Carolina have a Rb-Sr age of 423 Ma (Harper and Fullagar, 1981). Both rock units maintain a similar structural (stratigraphic?) position above the Poor Mountain Formation.*

The modal composition of the Sugarloaf gneiss is granitic to granodioritic in composition and contains predominantly microcline, plagioclase, biotite and muscovite (Lemmon, 1973). Accessory minerals include zircon, sphene, apatite, allanite, chlorite, epidote, and garnet. The rock is light gray to white, massive to well foliated, and contains a pronounced NE-SW mineral lineation defined by oriented micas, and quartz ribbons and elongate feldspar. The contact relationship with the underlying amphibolite is concordant and parallel to the southeast-dipping foliation. locally, the contact is folded.

Poor Mountain Formation. *The Poor Mountain Formation in the Columbus Promontory consists of three mappable units, equivalent to the Poor Mountain amphibolite, Brevard-Poor Mountain transitional member, and the quartzite member recognized in South Carolina by Shufflebarger (1961) and Hatcher (1969, 1970). In descending order, these include: (l) laminated amphibolite and hornblende gneiss; (2) garnet-mica schist and quartzite; and (3) interlayered amphibolite and quartzite. Lemmon (1973) also noted discontinuous lenses of marble interlayered within the mica schist in the Bat Cave quadrangle. The Poor Mountain Formation crops out structurally below and above the Henderson Gneiss in the study area* (Figure 2 & Back Cover Map). *Structurally below the Henderson Gneiss, only Poor Mountain amphibolite has been observed in a window through the Henderson Gneiss along the Tumblebug Creek* (Figure 2 & Back Cover Map). *Structurally above the Henderson Gneiss, all units of the Poor Mountain Formation have been observed in the Sugarloaf Mountain thrust sheet. Stratigraphic and petrologic characteristics of the Poor Mountain Formation of the Columbus Promontory contained within the Sugarloaf Mountain thrust sheet are described below.*

Amphibolite-hornblende gneiss. The amphibolite unit crops out beneath the Sugarloaf Gneiss and is present in the Cliffield Mountain, Saluda, Mill Spring, and Lake Lure quadrangles. The map unit is fine to medium grained, dark gray to black, and is commonly laminated with well-defined quartzofeldspathic layers. Where folded, this laminated amphibolite produces some of the most spectacular mesoscopic folds in the Columbus Promontory. Mineralogically, the unit contains 22-70 percent dark-green pleochroic hornblende, 7-61 percent plagioclase {An 25-37), 0-22 percent quartz, occasional diopside, and small flakes of pleochroic biotite (Davis, 1993). Other accessory minerals include garnet, sphene, tremolite, zircon, *apatite, and opaque minerals. In hand specimen, the amphiboles have a readily discernible nematoblastic shape and define a weak to strong linear fabric in the rock.*

Garnet-mica schist and quartzite. *The garnet-mica schist and quartzite unit generally crops out below the amphibolite-hornblende gneiss unit, although in some areas these units are interlayered by folding. In the northwestern part of the Columbus Promontory, in the Bat Cave, Cliffield Mountain, and Lake Lure quadrangles, it rests directly on the Henderson Gneiss along the Sugarloaf Mountain thrust, forming one of the sharpest fault contacts in the entire study area* (Figure 2 & Back Cover Map). *In many cases, this unit occurs on the topographically highest areas capping the ridge tops. This rock is purplish-red, to brown, to light gray, with the color related to the amount of sillimanite, biotite, or muscovite in the rock and the degree of weathering. The schist consists of folia of strongly aligned grains of biotite {21-40 percent), muscovite (2-38 percent), and fibrolitic sillimanite (0-13 percent) alternating with ribbons or layers of recrystallized quartz (22-50 percent), and minor amounts of K-feldspar (Davis, 1993). Accessory minerals include zircon, apatite, magnetite, ilmenite, and graphite. Garnets have several morphologies: some are elongated parallel to the dominant foliation; others (up to 5mm) are anhedral to subhedral with inclusion-rich cores and clear rims, while others (1-2mm) have sub- to euhedral outlines and lack inclusions. Commonly, a second foliation can be observed that is defined by asymmetric mica grains and sillimanite bundles, and asymmetric quartz-feldspar pods.*

Other minor components of this map unit include quartzite and marble. Mappable quartzite layers also occur folded in with the garnet-mica schist. The stratigraphic position of the quartzite within varies. The quartzite varies from light yellow to brown. Mineralogically it contains predominantly quartz and accessory amount of muscovite, and garnet. Lemmon (1973) also reported pods and discontinuous lenses of marble within the garnet-mica schist unit in the Columbus Promontory. A single chemical analysis of this marble (Lemmon, 1973) reveals the rock is a high-calcium marble.

Quartzite-amphibolite. *The stratigraphically (?) lowest lithology of the Poor Mountain Formation in Sugarloaf Mountain thrust sheet is a discontinuous sequence of interlayered impure quartzite and amphibolite* (Figure 2 & Back Cover Map). *The quartzite varies from light yellow or white to dark brown or black. Mineralogically it contains mostly quartz, although in some cases it does contain muscovite, sillimanite, amphibole, garnet, and other accessory minerals.*

The amphibolite unit is mineralogically and texturally identical to the main body of Poor Mountain amphibolite described above. This quartzite-amphibolite unit is discontinuous and is commonly found at the contact between the Poor Mountain Formation and the underlying rocks of the upper Tallulah Falls Formation. At some localities both rock types are present, while at others only one of the rock units is visible. The contact between the Poor Mountain Formation and the underlying Tallulah Falls Formation is interpreted to be primarily stratigraphic, although this is not entirely clear. The best exposures of this contact occurs on Long Ridge in the Cliffield Mountain quadrangle and at Melrose Mountain in the Saluda quadrangle). At these localities, however, it is difficult to determine if it is a stratigraphic or fault contact. On Long Ridge the contact is sharp and the lowermost quartzite-amphibolite unit of the Poor Mountain Formation has mylonitic characteristics and the amphibolite is occasionally intensely folded. On Melrose Mountain there is a stratigraphic interleaving of the biotite gneiss of the upper Tallulah Falls Formation with the overlying Poor Formation, although the contact could represent either a transposed stratigraphic or early(?) premetamorphic fault contact.

Upper Tallulah Falls Formation. *The upper Tallulah Falls Formation (Davis, 1993) is the stratigraphically lowest unit in the Sugarloaf Mountain thrust sheet* (Figure 2 & Back Cover Map). *The upper Tallulah Falls Formation is dominantly a thick sequence of migmatitic biotite gneiss and metagraywacke, and is distinguished from the lower Tallulah Falls Formation by the lower relative abundance of mafic rocks. It commonly produces massive exposures and forms the cliffs and balds throughout the study area. The mineralogy of the biotite gneiss- metagraywacke is quite variable, but on average contains 12-60 percent plagioclase (An 20.35), 12- 56 percent quartz, 0-25 percent muscovite, 2-19 percent biotite, and minor amounts of sillimanite, garnet, and sphene (Davis, 1993). Accessory amounts of epidote, zircon, and opaque minerals are also present. The biotite gneiss-metagraywacke is light to medium gray, equigranular, fine- to medium-grained, and massive to slightly banded. Locally the grain size of the mica is quite large and the unit resembles mica schist. Foliation is produced by oriented micas and elongated quartz-feldspar layers. In many areas, this unit appears very migmatitic with marked segregations of the felsic, more micaceous, and mafic-rich layers.*

The biotite gneiss-metagraywacke contains pods and lenses of amphibolite parallel to the regional foliation. These lenses commonly have a sill-like geometry and in most cases are parallel to the regional foliation. This unit also contains pods and lenses of pegmatite parallel to the dominant foliation. In the western part of the study area, along the Green River, the biotite gneiss of the upper Tallulah Falls Formation is a porphyroclastic biotite gneiss. These rocks generally have a matrix identical to the biotite gneiss, but contains gray to pink, carlsbad-twinned microcline porphyroblasts.

Mill Spring Thrust Sheet

The Mill Spring thrust sheet (Figure 2 & Back Cover Map) *contains the mafic-rich rocks of the lower Tallulah Falls Formation of Davis (1993). The lower Tallulah Falls Formation consists of a migmatitic sequence of biotite-granitic gneiss-metagraywacke, coarse amphibolite gneiss, and fine- to medium-grained amphibolite. The complex interlayering of these rocks types makes it very difficult to subdivide the individual units.*

Like the biotite gneiss-metagraywacke of the upper Tallulah Falls Formation, the mineral composition of the biotite gneiss-metagraywacke in the lower Tallulah Falls Formation is also quite variable. On average it consists of 10-45 percent plagioclase, 28-35 percent quartz, 0-29 percent K-feldspar, 11-27 percent biotite, and 6-26 percent muscovite. Zircon, apatite, sphene and opaque minerals are generally present in accessory amounts (Davis, 1993). Epidote occurs in veins and as fillings in late brittle fractures. This unit is generally a mesocratic, light-gray, segregation banded, inequigranular, biotite gneiss- metagraywacke. It is permeated by migmatite and concordant pegmatite layers. Amphibolite and amphibole gneiss in the lower Tallulah Falls Formation occur as both large pods and tabular or sill-like stringers. The large pods are commonly permeated with leucogranite or pegmatite layers, as in the biotite gneiss-metagraywacke units. The foliation in the amphibolite and amphibole gneiss is defined by alternating mafic and felsic layers. The mineralogic makeup of the amphibolite in the lower Tallulah Falls Formation is also variable, but on average includes 35-60 percent dark green pleochroic hornblende, 25-50 percent plagioclase (An 20-30), 2-20 percent quartz, 0-30 percent biotite, and minor amounts of epidote, garnet, and opaque minerals (Davis, 1993). Zircon, sphene, and chlorite occur as accessory minerals. Amphibolite of the lower Tallulah Falls Formation is generally more massive and coarser grained than the amphibolite of the Poor Mountain Formation, although this is not always the case. Individual amphibole minerals also have a nematoblastic shape and define a weak to strong linear fabric.

On the top of White Oak Mountain, the migmatitic granitic gneiss and amphibolite of the lower Tallulah Falls Formation grades into a porphyroclastic biotite gneiss similar to that in the upper Tallulah Falls Formation with porphyroclasts composed of white microcline. This unit commonly contains abundant mica and in many cases is very schistose. Thin amphibolite stringers are rare, but do occur within this lithology. Towards the western boundary of the lower Tallulah Falls Formation in the Saluda and Cliffield Mountain quadrangles, migmatitic amphibolite and granitic gneiss grade into a more amphibolite-poor biotite gneiss similar to that in the upper Tallulah Falls Formation. Here the lower Tallulah Falls Formation can be seen overlying the garnet-mica schist of the Poor Mountain Formation and the biotite gneiss-metagraywacke of the upper Tallulah Falls Formation along the Mill Spring thrust.

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The Blue Ridge Escarpment: a unique and dominant Appalachian landform

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Introduction

The rugged Blue Ridge Escarpment (BRE) stretches for over 500 km along the eastern margin of the southern Appalachian highlands from north-central Georgia to Roanoke, Virginia (Figure 1). The BRE represents the boundary between the Atlantic-draining topographic Piedmont surface, characterized by ~350 m MSL elevations at the foot of the BRE, and the higher elevation 600-900 m landscapes (excluding localized topographic highs) of the Gulf of Mexico-draining Blue Ridge Upland, a plateau-like landscape with varying internal topographic relief along its length (Figure 2). The BRE rises 300-600 m above the Piedmont surface, with local relief on the BRE exceeding 1,000 m at Grandfather Mountain, North Carolina. The BRE is characterized by greater long-wavelength slope (25-30 degrees) than the Blue Ridge Upland (15 degrees, with considerable variation) or Piedmont (<15 degrees) landscapes (Spotila et al., 2004). Along the majority of its length, the crest of the BRE coincides with the Eastern Continental Divide, which separates Gulf of Mexico-draining rivers of the Blue Ridge Upland from Atlantic-draining rivers of the BRE face and Piedmont (Figure 2). Within and adjacent to the BRE zone, river channel morphology generally reflects topographic character. The BRE zone hosts steep bedrock stream reaches

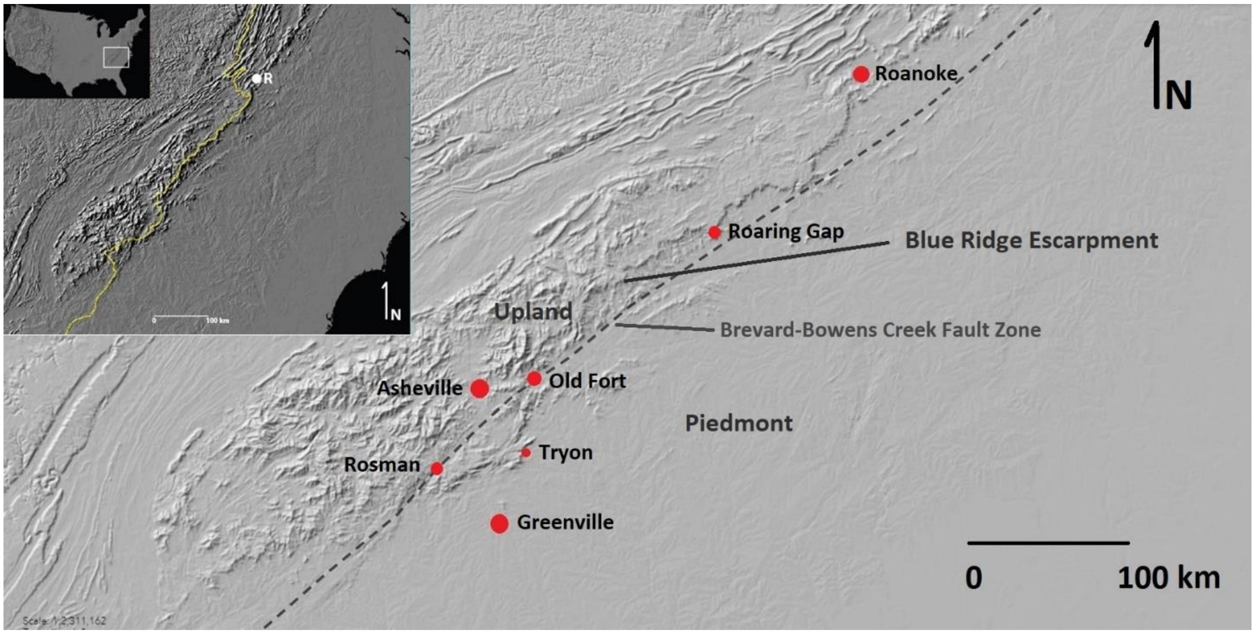

Figure 1. Hillshade map showing the extent of the Blue Ridge Escarpment along the southeastern edge of the Blue Ridge Upland. Hillshade map source: USGS National Map Viewer.

that contrast with more gently sloped channels of the Piedmont and much of the eastern Upland, where alluvial reaches are punctuated by short and localized bedrock reaches.

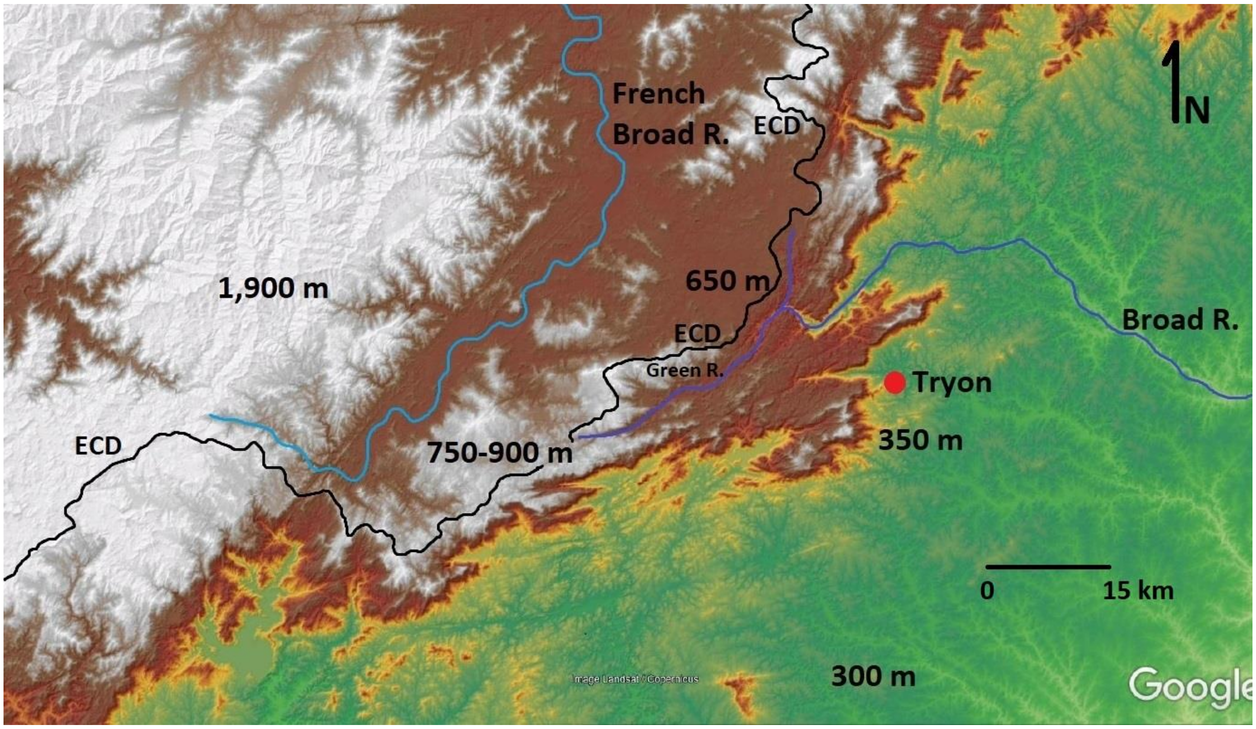

Figure 2. Colored DEM/hillshade combination map superimposed onto Google Earth topography showing generalized elevation distribution across the BRE and Eastern Continental Divide (ECD) on the "Henderson Bulge," where the Upland and BRE project southeast of the of the Brevard-Bowen Creek Fault Zone. Relief on the elevated Blue Ridge Upland surface is quite variable and may be a reflection of bedrock erodibility. The Green River, a Broad River headwater stream, flows several kilometers along the Upland surface before descending through a gorge to the Piedmont. DEM source: USGS National Map Viewer.

Transition from the BRE zone to the adjacent Blue Ridge Upland is abrupt in some locations, with the crest of the BRE passing directly and immediately into broad Upland valleys to create a plateau-like Upland margin. Other locations are characterized by topographic highs at the BRE crest which pass into rugged terrain at the eastern edge of the Upland. Transition from the BRE zone to the Piedmont is equally variable in style, with areas of abrupt transition being distinguishable from other domains in which a foothills zone stretches several kilometers into the Piedmont from the base of the zone of maximum relief and maximum long-wavelength slope (Figure 2). Width of the BRE zone ranges from 5-20 km, with greater width of the rugged zone frequently corresponding to greater relief across the BRE. Regardless of local width and the morphological details of its boundaries, the BRE is a distinct and prominent landform along its entire length and is readily recognizable in any form of topographic mapping. Perhaps the most striking expression of the BRE is its appearance when viewed from the western Piedmont landscape. Surface ruggedness and sinuosity of the BRE face are not visible to the Piedmont observer, making the BRE appear as an unbroken line of high topography relative to the Piedmont. This characteristic appearance has earned the BRE its traditional moniker, "the Blue Wall."

Structure, lithology, and the BRE as we see it

The BRE is arguably the only large-scale Appalachian topographic feature that is not a direct product of lithologic or structural control (Figure 3). The BRE trends sub-parallel to lithologic strike, with bedrock contacts and strike-extensive units cutting across the locus of BRE topography at low angles (Dietrich, 1959; Hack, 1973). No apparent relationship between joint or fracture sets and the trend of the BRE has been observed. In three locations, the BRE steps across the pronounced topographic lineament of the Brevard-Bowens Creek Fault Zone, suggesting displacement on this major Appalachian structure did not initiate the BRE as suggested by White (1950) (Figure 1). While the BRE does cross the Brevard-Bowens Creek Fault Zone, the general trend of the BRE is roughly parallel to the fault zone lineament for 200-300 kilometers, a spatial relationship that is readily observable in digital topography (Figure 1). Less extensive topographic lineaments of uncertain structural significance embay the BRE at varying angles near the North Carolina-South Carolina border. While increased erodibility along the lineaments has almost certainly impacted recent BRE erosion and evolution, no association between structural origin of the lineaments and the BRE itself is known.

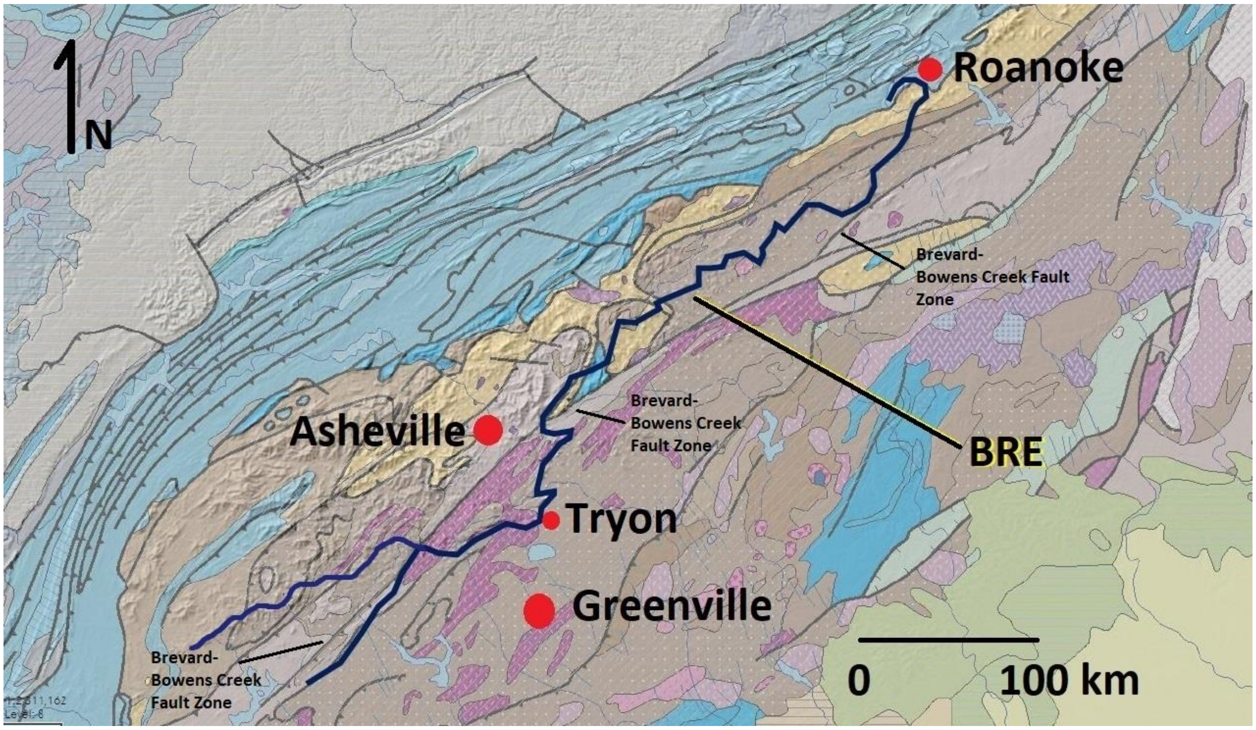

Figure 3. Trend of BRE (heavy, dark blue line) superimposed against geologic map of the United States sourced from the USGS National Map Viewer. The BRE does not correspond to any specific lithologic contact or geologic structure, and many lithologic contacts cut across its trend. Geologic map and transparent hillshade DEM provided by the USGS.

Although the BRE is not localized atop a lithologic boundary or structure, details of lithology strongly influence the local appearance of the BRE zone. Along the North Carolina-South Carolina border, the BRE is locally dominated by near-vertical exfoliation surfaces where granitoid gneisses are exposed within the zone of maximum slope and relief. The exfoliation surfaces produce bold cliffs which are often very light-colored and dominate the “skyline” of the BRE when viewed from the Piedmont, creating popular outdoor destinations such as Table Rock, South Carolina (Figure 4). Comparable cliff-dominated areas occur where the BRE passes through the Grandfather Mountain Window, which exposes basal Cambrian quartzites of the Chilhowee Group. The zone of maximum relief on the BRE occurs at Grandfather Mountain, North Carolina (~1,400 m), with the high elevation of Grandfather Mountain supported by the resistant uppermost pre-Cambrian to basal Cambrian meta-clastic rocks. Notably, the BRE zone also reaches its maximum width of ~25 km in this area, a significant increase from the typical 5-10 km width characteristic of much of its length (Figure 4).

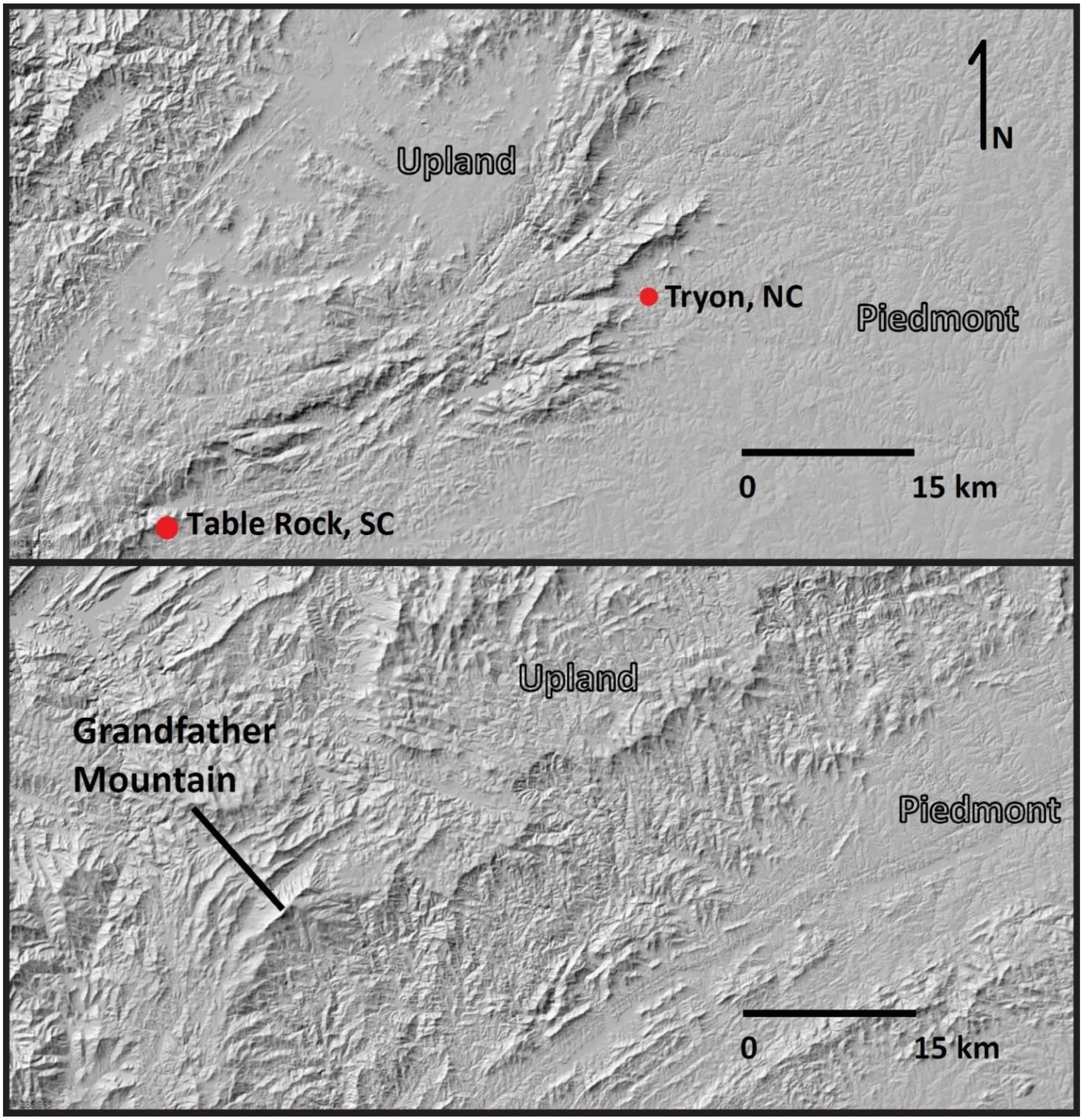

Figure 4. Localized topography along the BRE is variable, ranging from an abrupt, single topographic step to a broad, rugged area. Grandfather Mountain is the highest point along the BRE, rising to 1,812 m above sea level. Below Grandfather Mountain, the BRE is very broad, descending to the Piedmont surface over a distance of 20-25 km.

Portions of the BRE underlain by less resistant (or less exfoliation-prone) lithologies host smaller cliff or outcrop zones and tend to lack the abruptness associated with cliff-dominated areas. Areas underlain by less resistant rock still maintain considerably steeper slopes than are observed atop the same lithologies in the adjacent Upland or Piedmont. While less topographically dramatic, portions of the BRE developed into more erodible rocks that highlight the uniqueness of the BRE zone within the Appalachian topography, as the same units create more muted and thickly soil-mantled landscapes away from the BRE. Rugged topography within weaker rock units that is limited to the BRE zone has been regarded as evidence of the dynamic and disequilibrated nature of the BRE landscape, suggesting its late Cenozoic and Quaternary history has been characterized by more dynamic erosion than the adjacent Upland or Piedmont (Hack, 1973).

Sinuosity of the BRE is highly variable along its length. In Transylvania, Henderson, Polk, and Rutherford Counties, North Carolina, the BRE is deeply embayed by pronounced topographic lineaments of variable trend, often intersecting the BRE at low angle (Figure 2). The North Pacolet River valley west of Tryon, North Carolina, is a prominent example. These lineaments create “trench valleys” stretching kilometers into the edge of the Blue Ridge Upland, producing elongated, narrow Upland domains such as the Columbus Promontory (Hack, 1982). Despite these embayments, the topographic step between Piedmont-elevation landscapes and the Upland is still quite abrupt in these areas, with the BRE zone extending ~5 km from the BRE crest. This strongly embayed, lineament-dominated style fades in the vicinity of Old Fort, North Carolina, with a broader BRE zone (~15 km) being cut orthogonally by large, closely-spaced drainages distinct from the “trench valley” style. In this area, elevation of the BRE crest tends to be higher than in areas to the southwest, and the transition from Piedmont to Upland is accommodated by a more extensive zone of rugged, dissected topography. Northeast of Roaring Gap, North Carolina, the BRE zone narrows significantly and hosts few high-order streams or embayments. Southwest of Rosman, North Carolina, the BRE zone narrows before splitting into two separate bands of rugged topography to the southwest, each displaying its own topographic character (Figures 1, 3, 5).

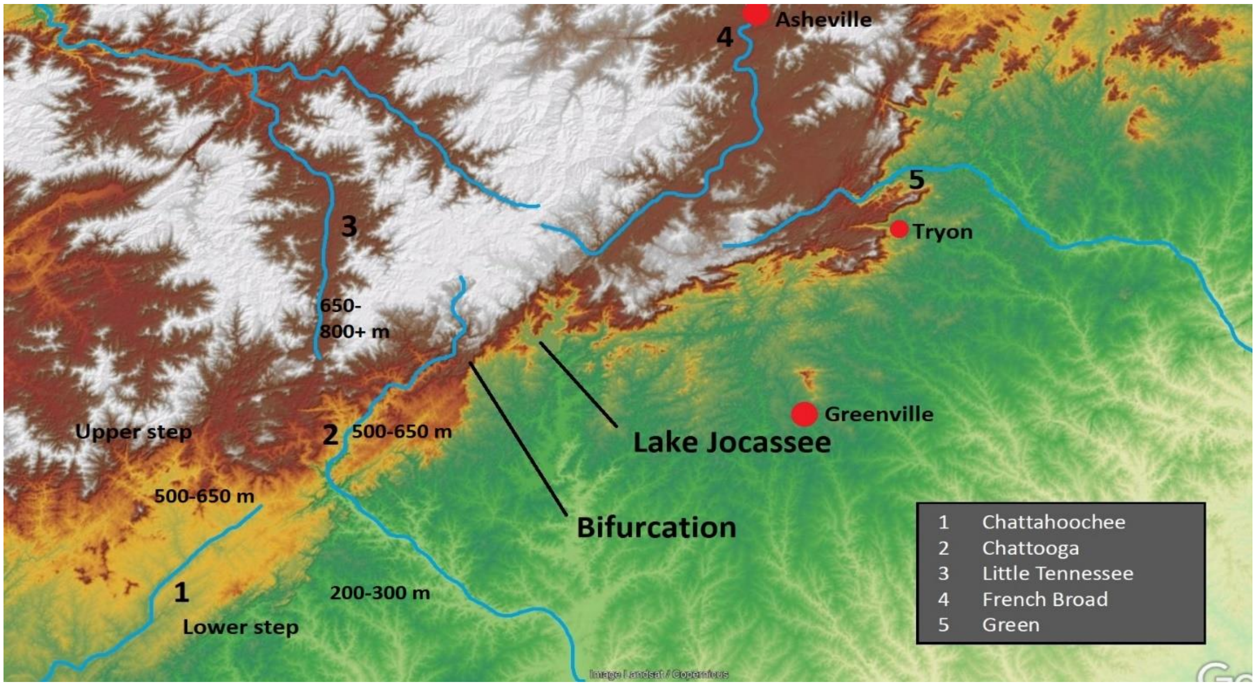

Figure 5. Southwest of Lake Jocassee, South Carolina, the BRE splits into two distinct topographic steps. The lower step separates Atlantic -draining Savannah River headwaters (greens) from Gulf-draining Chattahoochee headwaters (yellows to browns), including the captured Chattahoochee headwaters that form the Chattooga River system (Figures 9 and 10). The upper step separates the Chattahoochee headwaters landscape from the headwaters of the Tennessee River system (brown to white).

The bifurcation of the BRE southwest of Rosman produces a readily apparent “double step” in topography from Piedmont to Blue Ridge Upland (Figure 5). The lower step separates the 200-300 m Piedmont surface from a rolling, low-relief 500-600 m landscape deeply incised by the Chattooga River system. The upper step separates the 500-600 m surface from a much more rugged 650 m-800 m surface continuous with the rest of the Blue Ridge Upland to the northeast and southwest. The Brevard-Bowens Creek Fault Zone passes through the 500 m surface, and neither topographic step coincides with any identifiable lithologic or structural feature. The ~500 m surface does, however, generally define the extent of the upper Chattahoochee River system and its former headwater, the modern-day Chattooga River system (Johnson, 1907). This drainage network is strongly controlled by the Brevard Fault Zone lineament, providing anecdotal evidence of bedrock erodibility allowing inactive geologic structures to passively impact BRE geometry and evolution.

A rift-related feature?

The origin of the BRE, along with its context with respect to the eastern North America passive margin, has been a subject of interest to Appalachian geologists for many years (Wright, 1927; White, 1950; Dietrich, 1959; Hack, 1973, 1982; Pratt et al., 1988; Battiau-Queney, 1989; Hubbard et al., 1991; Pazzaglia and Brandon, 1996; Pazzaglia and Gardner, 2000; Spotila et al., 2004; Prince et al., 2010). Approximately one-third of Earth's passive margins, including western India, southeastern Australia, Madagascar, Sri Lanka, southeast Brazil, western Africa, and southern Africa, host prominent seaward facing escarpments, believed to initially develop as a result of continental rift flank uplift (Ollier, 1984) (Figure 6). Uplift of rift flanks and opening of the new ocean basin in the rift axis creates a new drainage divide on the elevated

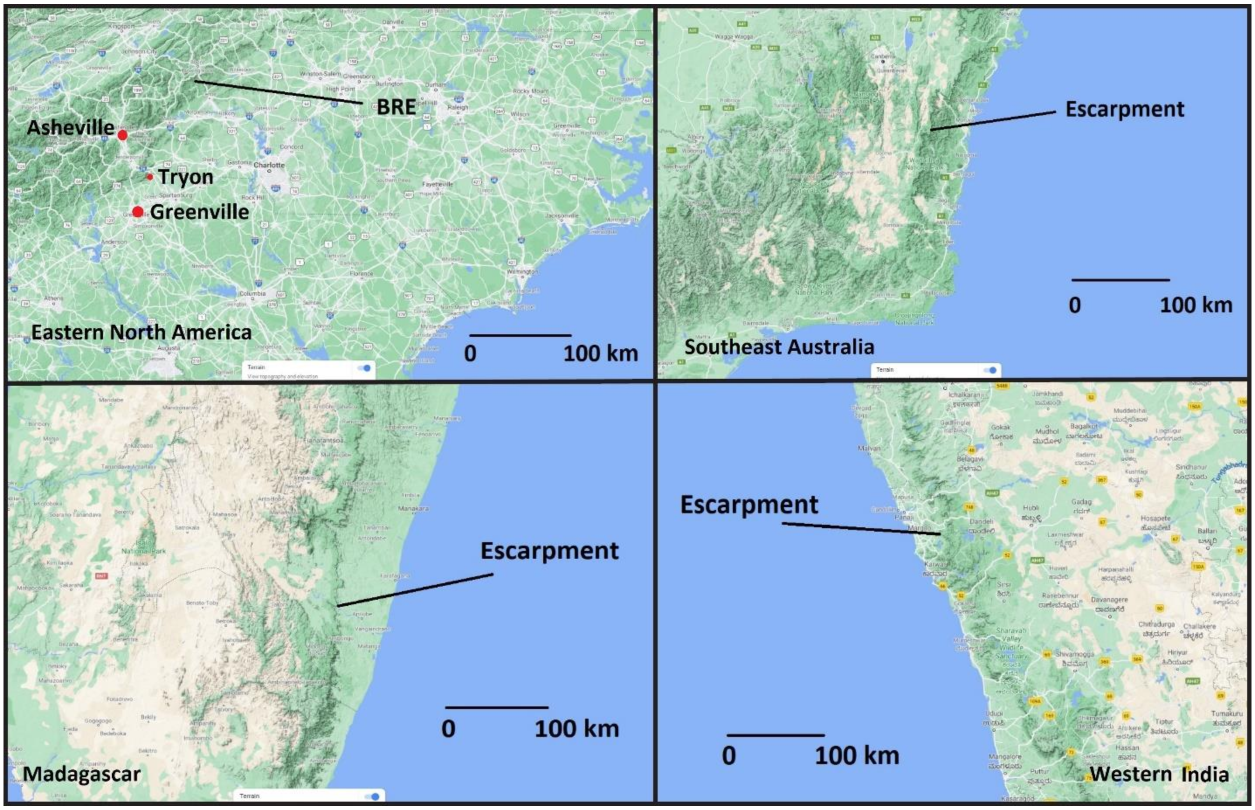

Figure 6. Many of Earth's present-day passive continental margins host seaward facing escarpments. Is the BRE one of these? The BRE is more distant from the continental margin and less topographically prominent than other passive margin escarpments, but these characteristics could be a reflection of its greater age. Imagery retrieved June 30, 2021 from Google.com/maps.

rift flank, with rivers draining to the newly opened ocean basin following shorter, steeper, and thus more erosive paths to base level (Figure 7). As a result, erosion on the seaward side of the new divide is more rapid, driving landward migration of an erosional "wave" from the rift axis which works to sculpt and maintain a seaward facing escarpment (Ollier, 1984, ten Brink and Stern, 1992; Young and McDougall, 1993; Kooi and Beaumont, 1994; Seidl et al., 1996; Gunnell and Harbor, 2008). With its passive margin setting, position landward of Mesozoic rift-related structures, and relationship to a major drainage divide, the BRE shares significant characteristics with Earth's other passive margin escarpments. The other passive margin escarpments are, however, younger, generally more prominent, and rugged, and much closer to the continental margin (Figure 6).

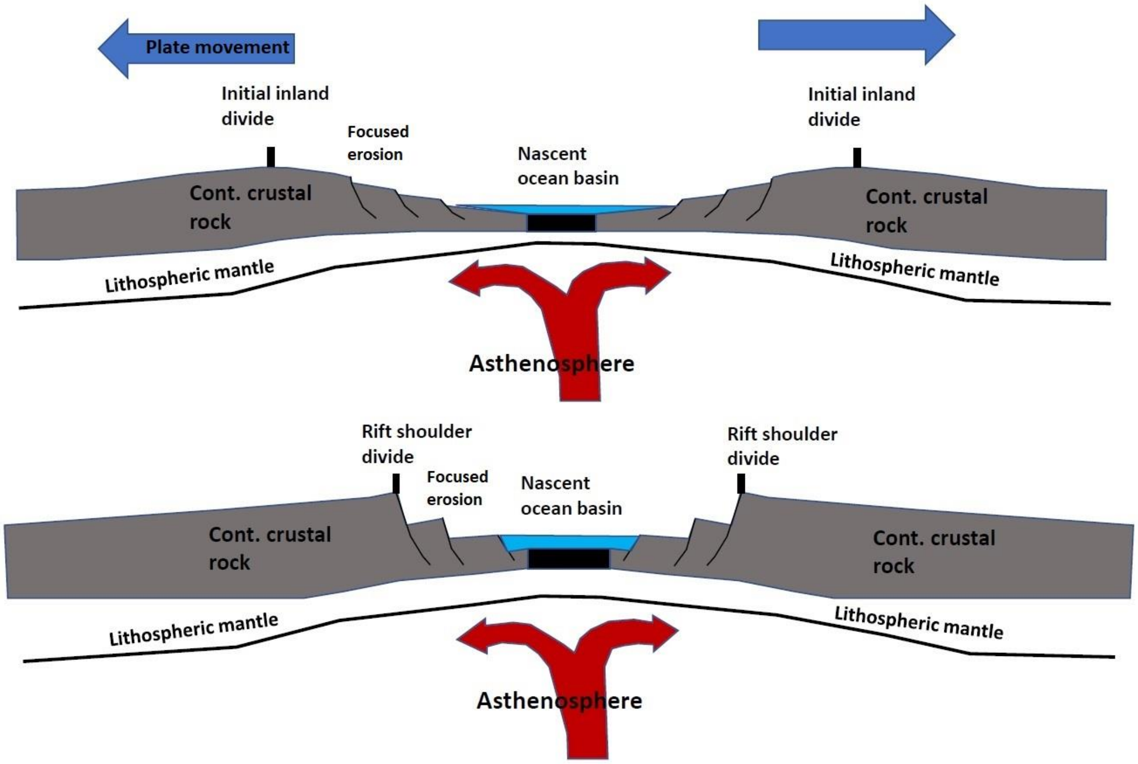

Figure 7. Illustration of two topographic styles resulting from rift flank uplift. The arch-type style (top) produces broad flexure with a drainage divide well landward of the rift axis, while the shoulder-type style develops a drainage divide atop an abrupt scarp at the end of rifting.

Efforts to connect the BRE with patterns of passive margin escarpment evolution have focused on the pattern and mechanism of the landward-migrating erosional "wave." Erosion and landward retreat of passive margin escarpments is described by two distinct models, the shoulder-type escarpment and arch-type escarpment (Matmon et al., 2002) (Figure 8). The position of the drainage divide relative to initial post-rift geometry is the defining aspect of the respective models, as this relationship dictates the development and evolution of subsequent escarpment topography (Moore, 2006). Arch-type escarpments develop a fixed drainage divide well inland from the rift flank at the time of rifting, due to long-wavelength uplift or flexure. Following rifting, rivers draining into the new rift incise to adjust to the base level of the nascent ocean basin. The resulting "downwearing" of the seaward side of the divide progressively excavates an escarpment face on the seaward side of the fixed divide, with escarpment evolution slowing considerably as the seaward rivers complete their adjustment (van der Beek and Braun,

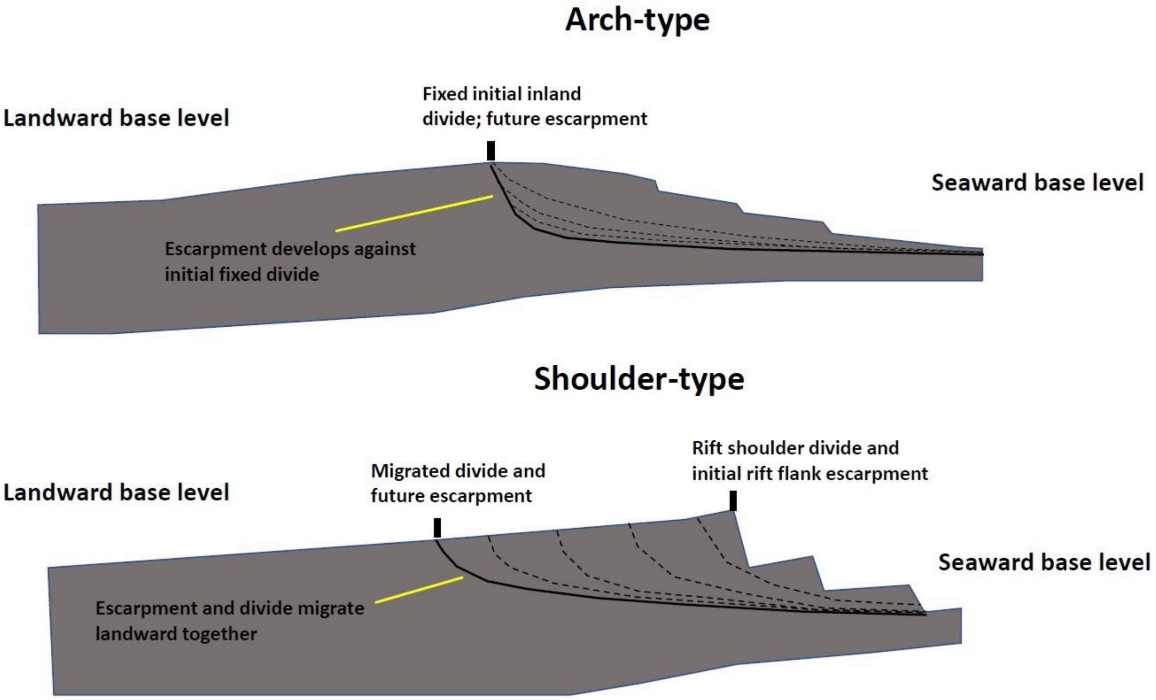

Figure 8. Post-rift escarpment retreat style is thought to vary according to initial post-rift geometry. Black dashed lines represent the evolving topographic surface during erosional evolution. On arch-type margins, an escarpment develops at the initial drainage divide, with the divide being effectively fixed in its position. Shoulder-type margins experience long-term retreat of the escarpment and divide.

1999; Cockburn et al., 2000; Brown, et al., 2002; van der Beek et al., 2002; Braun and van der Beek, 2004). As seaward rivers adjust to the divide, the resulting escarpment is thought to experience little additional retreat. The southeastern Australian escarpment is an oft-cited example of arch-type escarpment evolution (Nott, 1996; Persano et al., 2002). Shoulder-type escarpments are characterized by a drainage divide positioned at the Escarpment crest at the end of rifting (Matmon et al, 2002). The drainage divide and escarpment experience long-term landward retreat together (parallel retreat) as focused erosion on the steep escarpment face outpaces erosion of the landward-draining upland (Spotila et al., 2004; Gunnell and Harbor, 2008; Prince et al., 2010). Pace and spatial-patterns of post-rift erosion are thus distinct for the two models, with shoulder-type escarpments potentially experiencing longer and steadier landward erosional retreat (Figure 8).

The modern BRE is a shoulder-type escarpment, with the Eastern Continental Divide coinciding with the escarpment crest along the majority of its length. Spotila et al. (2004) used (U-Th)/He apatite thermochronometry to identify the exhumation signature of prolonged erosional retreat of the BRE, conceptually consistent with long-lived, shoulder-type parallel retreat of the escarpment face and drainage divide. Given the indicated timing of exhumation and the ~200 Ma age of Atlantic rifting (Pique and Laville, 1995; McHone, 1996), the BRE could indeed be regarded as a long-lived expression of an initial rift-related escarpment. Such a history could also be viewed as consistent with its moderate topographic relief and position well landward of the continental margin (Figure 6). Significantly, the exhumation ages measured by Spotila et al. (2004) are comparable to those obtained for the much younger (~100 Ma) southeastern Australian escarpment by Persano et al. (2002), suggesting a different style and tempo of erosional evolution by the shoulder-type BRE.

Stream capture and BRE evolution

A critical component of the shoulder-type parallel retreat model is repeated and efficient stream capture, the process through which upland streams are erosionally transgressed by steep, seaward-draining escarpment face headwaters to drive landward retreat of the drainage divide and escarpment (Gunnell and Harbor, 2008; Prince et al., 2010) (Figures 9, 10). Once upland streams are connected to the lower seaward base level, the drainage divide is shifted landward, and the captured drainage network undergoes a pulse of rapid transient incision to topographically adjust to the new base level (Figure 10). When adjustment is complete, the captured basin, formerly topographic upland, is reduced to lower elevation and relief with a new escarpment face on its landward boundary. Repetition of this process along the entirety of the escarpment produces wholesale landward retreat over the long term, as long as elevation contrast between landward and seaward drainage basins persists (Figure 9).

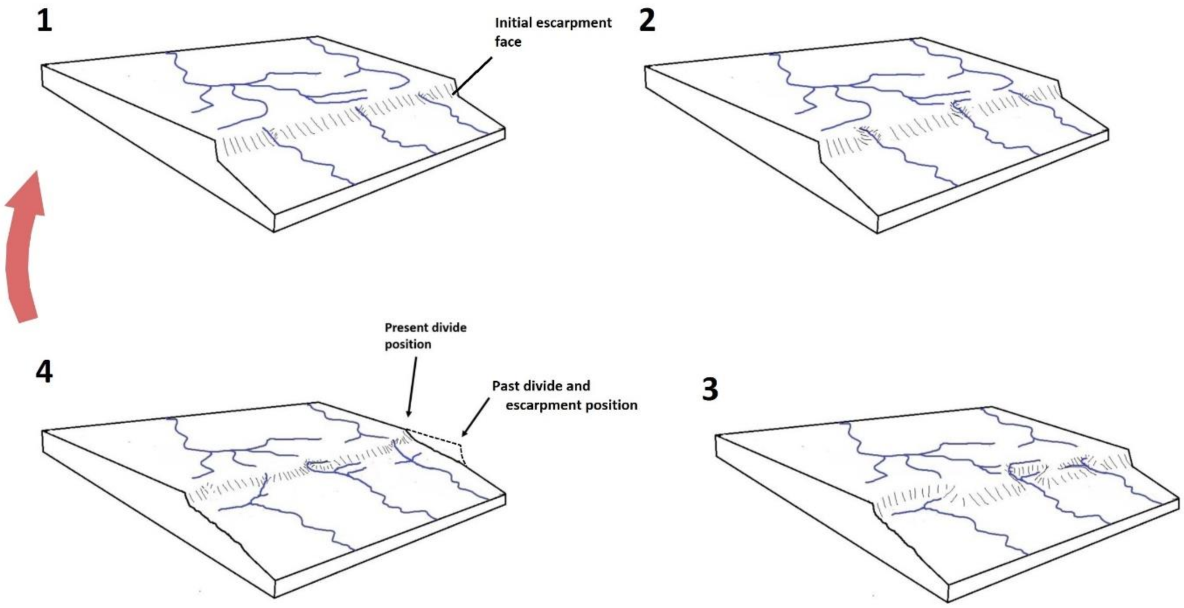

Figure 9. Efficient stream capture to produce drainage divide and escarpment retreat is a key component of the shoulder-type escarpment model. Small, steep headwater streams on the escarpment erode in a headward direction and intersect landward draining upland rivers, capturing their flow and directing it down the steep escarpment. Rapid incision results, eroding the captured basin to Piedmont elevations and driving local escarpment recession. The long-term integrated result of repeated captures is net retreat of the escarpment and divide.

Localized deviations of the Eastern Continental Divide away from the BRE crest have long been considered significant to understanding BRE evolution due to their apparent connection to episodes of stream capture and divide migration (Davis, 1903; Johnson, 1907; Wright, 1927; Dietrich, 1959; Bank, 2001) (see Green River, Figure 2). These deviations are associated with river systems which follow low-gradient courses across the Upland surface for tens of kilometers before abruptly descending across the BRE through deep bedrock gorges to the Piedmont (Figure 10). While these gorges have long been considered anecdotal evidence of stream capture events and parallel BRE/drainage divide retreat, their morphology alone cannot distinguish them from the rivers undergoing the final stages of downwearing and adjustment of a very mature arch-type escarpment (Pazzaglia and Gardner, 2000; Matmon et al., 2002). The deeply incised rivers and their host gorges were noted by Gunnell and Harbor (2008) as an expression of stream capture-driven “butte detachment” as observed in eastern Madagascar and the western Ghats of India, but this interpretation was based on topographic analysis alone.

Intense field reconnaissance by Prince et al. (2010, 2011) identified numerous discrete stranded fluvial gravel deposits along the BRE crest near escarpment-crossing gorge systems (Figures 10, 11). The stranded gravels, many of which were located directly atop the Eastern Continental Divide, provided robust direct evidence of stream capture as driver of drainage divide, and thus BRE, retreat, at least into its present-day position. The deposits were unconsolidated, transported soils of obvious fluvial origin, whose well-rounded vein quartz clasts frequently suggested tens of kilometers of fluvial transport (Prince et al., 2010). Matrix material of the stranded gravels was often distinct from adjacent soils derived from bedrock weathering, and some gravels in Virginia could be associated with source units only in outcrop across the present Eastern Continental Divide position (Prince et al., 2011). The numerous gravel deposits may resemble those described along the Eastern Continental Divide adjacent to the Chattooga River system in northeast Georgia by Johnson (1907) and on the Virginia Blue Ridge Upland by Dietrich (1959), none of which were sampled or photographed.

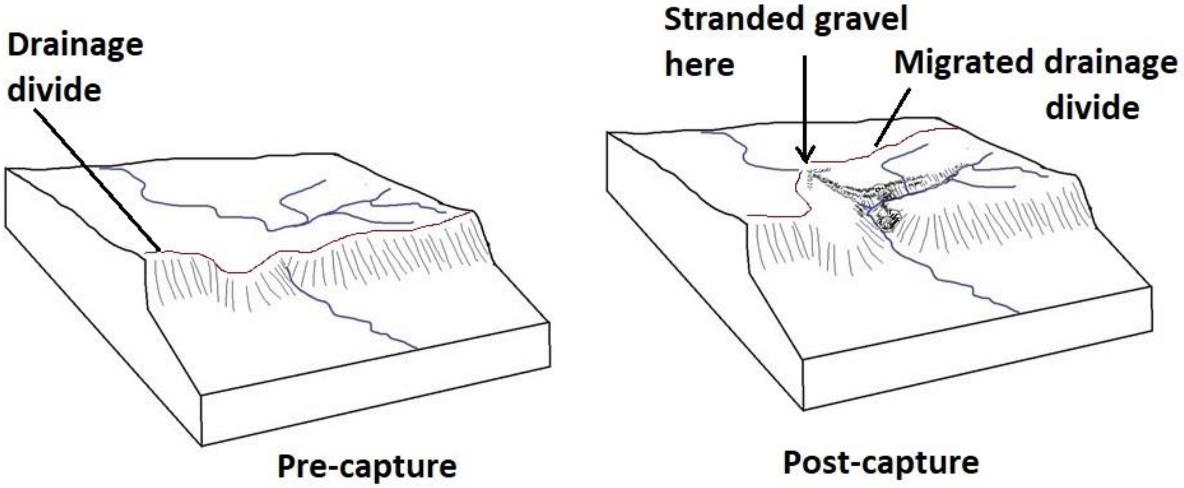

Figure 10. Captured streams along the Upland BRE display several notable features, including stranded gravel deposits atop the drainage divide on their former courses (Prince et al., 2010, 2011), low-gradient upper reaches that descend into deep gorges at high drainage area, and a platform geometry that implies linkage to present-day Upland streams.

The gravels of Prince et al. (2010, 2011) are consistent with faunal evidence (Jenkins et al., 1971) of the role of stream capture events in retreat of the Eastern Continental Divide and the BRE. River systems draining down the BRE face to the Atlantic Ocean often host faunal assemblages of other Atlantic slope streams as well as streams of the Blue Ridge Upland which drain to the Gulf of Mexico. These bimodal faunas have been interpreted as evidence of Atlantic streams capturing Upland streams, allowing the respective faunal assemblages of each to mingle. The widespread presence of brook trout (*Salvelinus Fontinalis*) in Atlantic headwaters on the BRE face is a well-known example of likely capture-related fish species distribution. Brook trout could not survive water conditions of Piedmont streams, preventing migration down the BRE zone, through Piedmont rivers, and back up other BRE streams. Vertical waterfalls within BRE knickzones also present physical obstacles to such a migration, suggesting Atlantic-draining

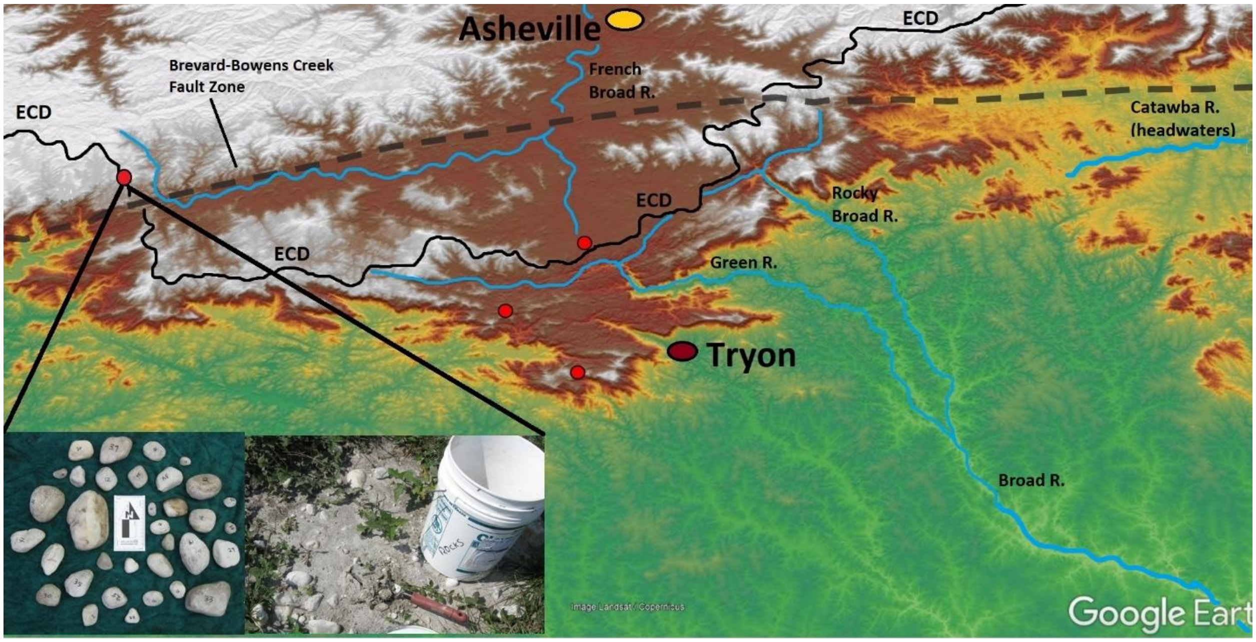

Figure 11. Several gravel deposits (red circles) around the margins of the Hendersonville Bulge reveal past stream capture events that have shaped and continue to shape the BRE and upland margin. Many gravels are associated with gorges and high-order streams that flow along the upland before entering deep gorges. Other gravels likely exist, but land use makes their field identification difficult. Photographs show field expression and clasts of the Flat Creek gravel deposit, which is remarkably preserved and relates to capture of the ancestral French Broad headwaters.

BRE streams gained brook trout populations by capture of Upland streams. Jenkins et al. (1971) provides an extensive review of these bimodal faunas, which have been extensively studied.

Qualitative evidence of differential erosion

In addition to providing robust evidence for stream capture-related retreat, the preservation of unconsolidated fluvial gravels at the BRE crest indicates significantly different erosion rates are active on the BRE and atop the Blue Ridge Upland, a contrast necessary to allow erosional retreat. As the gravels are not stored in closed topographic basins or atop soluble carbonate rock, they are susceptible to physical denudation. The gravels have yet to be removed by surface erosion, and within their preservation lifespan, knickpoints have retreated many kilometers up captured stream networks. Some gravel deposits in southwest Virginia are no longer associated with any captured and incising drainage network, implying that the entire captured basin has been eroded to match Piedmont elevations during the preservation lifespan of the gravels. Conceptually, this model must require order-of-magnitude (or several orders of magnitude) difference in Upland and BRE erosion rates.

Preservation of the gravels within an entirely denudational, crystalline rock landscape that is not prone to solutional surface lowering is particularly interesting. The gravels are entirely unconsolidated and unlithified, suggesting they are truly relict surface deposits which experienced no burial (Prince et al., 2010, 2011). For kilometer-scale captured basins to be completely eroded to Piedmont elevations within the lifespan of the gravels on the land surface, Upland erosion rates must be exceedingly slow (10^0 m/Myr), with erosion rates in the captured stream networks approaching or exceeding 10^3 m/Myr. Slower rates in the captured basins and on the BRE face could be rationalized if the stranded gravel deposits were extremely thick (10’s of meters) or somehow re-worked from low hilltops towards modern-day drainages near the divide, but these mechanisms are difficult to rationalize with accepted understanding of regional geologic and geomorphic history.

Despite the apparent necessity of highly disparate erosion rates for the BRE face and Upland, no quantitative studies have captured significant rate contrasts (Sullivan et al., 2007; Linari et al., 2016). Cosmogenic ^{10}Be studies of BRE and Upland streams typically yield comparable erosion rates between the two topographic zones, with BRE rates being somewhat faster (Linari et al., 2016). The difference in rates never approaches a single order of magnitude and is certainly inadequate to explain the survival of the stranded gravels during erosional removal of the captured source drainage network. Basic relationships between slope, drainage area, and stream power dictate that large streams descending across the BRE should be more erosive than their Upland counterparts. Widespread landslides and debris flows in the BRE zone should also be expected to impact denudation, sediment delivery, and ^{10}Be concentrations. The paradox of ^{10}Be rates and the physical reality of the BRE and Blue Ridge Upland continues to attract research, and numerous sampling campaigns are underway in various locations along the BRE.

While the stranded gravel deposits indicate that stream capture and some amount of retreat have played a role in the evolution of the BRE to its present-day form, they do not constrain the magnitude of BRE retreat or shed light on the origin of the BRE. Vein quartz clasts within the gravel deposits indicate tens of kilometers of transport prior to stranding by capture, pre-capture Upland stream networks likely paralleled the BRE, allowing capture of a large drainage network to produce little net BRE retreat (Prince et al., 2010, 2011). The Dan River of southwest Virginia (Dietrich, 1959; Jenkins et al., 1971; Prince et al., 2010) and the Jocassee headwaters of Jackson and Transylvania Counties, North Carolina (Prince et al., 2010), and the Chattooga River system (Johnson, 1907) typify capture of largely BRE-parallel river networks which add significant drainage area to the Atlantic Slope but result in modest BRE retreat (Figure 5). The Chattooga River, captured from the Chattahoochee River system and its characteristic ~500 m surface by the Savannah River system, is another example of a captured basin whose ultimate erosion to Piedmont levels will produce only modest and basin-scale BRE retreat. For the combined effect of these punctuated events to produce large-scale, wholesale BRE retreat as suggested by Spotila et al. (2004), they must be frequent and result in very rapid topographic evolution within the captured river networks to outpace long-term erosional lowering of the Upland surface.

A non-rift origin?

Despite its passive margin location and apparent history of landward retreat (Spotila et al., 2004), the BRE may not be a reflection of rift flank processes like Earth's other passive margin escarpments. Hack (1973) noted that rivers of the Blue Ridge Upland maintain elevated channels and valleys due to the "base level prop" effect of upper pre-Cambrian/basal Cambrian quartzites along the western margin of the Blue Ridge Upland (Figure 12). Erosional resistance of the quartzites and metagraywackes prevents Blue Ridge Upland rivers from incising to match lower Valley and Ridge base level, allowing the Blue Ridge Upland to remain perched above the Atlantic-draining Piedmont and leaving its rivers susceptible to capture. Episodic captures can continue as long as the elevation contrast persists and lowering of the Upland does not outpace headward advance of BRE-face streams. Due to the apparent role of resistant lithology in preserving Blue Ridge Upland river elevation relative to adjacent domains, more efficient consumption

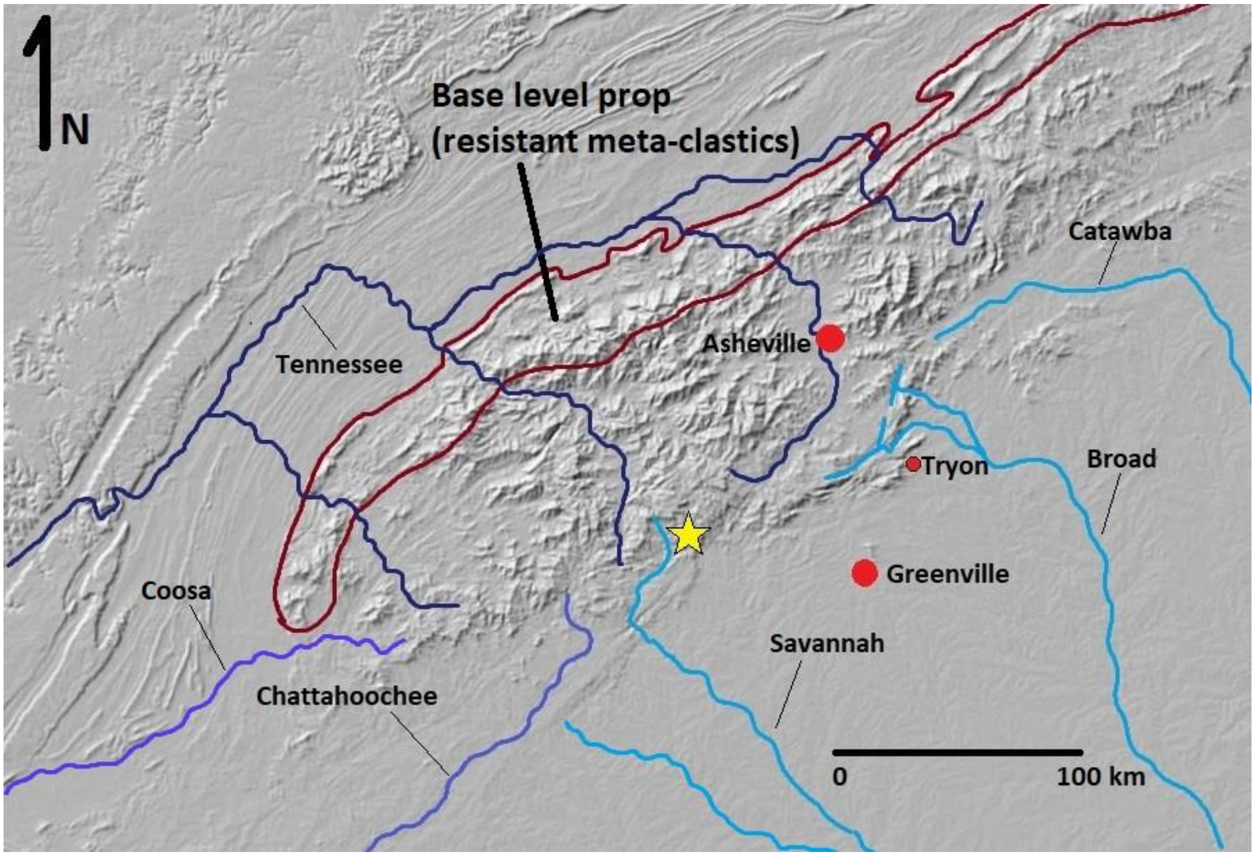

Figure 12. The modern-day BRE is present where landward-draining rivers flow across resistant meta-clastic rocks of the Great Smoky Group (and related units), which slow river incision and keep the Upland at high elevation. Gold star indicates bifurcation point of the BRE. Southwest of this point, Chattahoochee headwaters (including captured Chattooga) follow a more unobstructed path to the Gulf, resulting in systematically lower elevation than Tennessee River headwaters.

and lowering of Atlantic slope topography could have “etched” the present day BRE out of an inland drainage divide that may have been unrelated to rift processes (Figure 13).

Flexural deformation of the Atlantic margin due to sediment loading or other tectonic causes, perhaps as late as the Miocene (Pazzaglia and Brandon, 1996), could have generated a topographic bulge on the Atlantic slope, initiating a progression towards the present-day BRE conceptually similar to the arch-type model (Pratt et al., 1988; Battiau-Queney, 1989; Hubbard et al., 1991; Pazzaglia and Brandon, 1996; Poag and Sevon, 1999; Pazzaglia and Gardner, 2000). This “pseudo arch-type” mode of BRE development has yet to be explored in the context of exhumation data (Spotila et al., (2004) or Atlantic margin sediment loading, which has only been considered north of the present-day BRE zone (Pazzaglia and Brandon, 1996). The Baltimore Canyon Trough contains a significant Miocene sedimentation pulse, which may be a reflection of intensified topographic evolution of the Atlantic slope due to flexure (Pazzaglia and Brandon, 1996). No portion of the modern BRE, however, drains to the Chesapeake/Baltimore Canyon portion of the Atlantic margin. The extent of Chesapeake/Baltimore Canyon drainage coincides with the termination of the Blue Ridge Upland plateau north of Roanoke, Virginia, and could thus be interpreted to represent erosional breaching of the eastern Continental Divide and integration of Valley and Ridge drainage into the Atlantic slope.

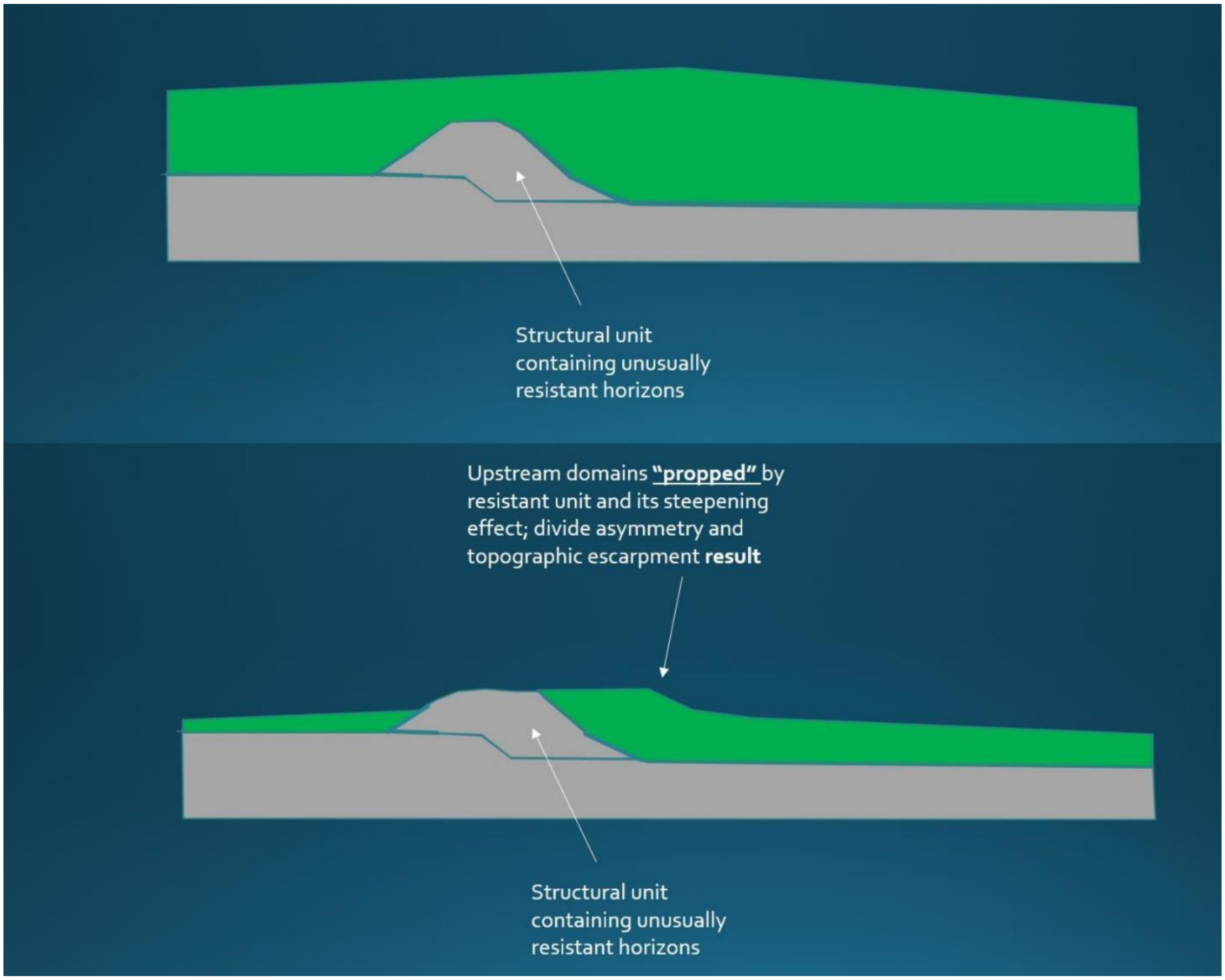

Figure 13. Hack (1973) proposed that resistant meta-clastics have preserved the BRE, but the units could have played a role in development of the BRE. Emergence of resistant units during exhumation can impact and disequilibrate existing river networks, slowing incision in some areas while neighboring catchments incise rapidly. Slowly-incising areas will become perched, creating asymmetric drainage divides that will experience stream capture and migration.

The bifurcation of the BRE near the junction of North Carolina, South Carolina, and Georgia (Figure 5) may hold clues to the role of mechanically-distinct river courses in controlling long-term Atlantic margin evolution. The uppermost topographic level at the bifurcation drains to the Tennessee River system, which experiences strong base level "propping" by meta-clastic rocks of the Great Smokey Group (Figure 12). The 500-600 m surface below it is adjusted to Chattahoochee River system base level, to which the Chattooga system drained prior to its capture (Johnson, 1907). The Chattahoochee system does not cross notable resistant lithologies and follows a shorter course to the Gulf, consistent with its basin hosting systematically lower elevations than the Tennessee headwaters. The Atlantic Piedmont surface below the Chattahoochee landscape, in turn, follows the even shorter and less lithologically obstructed Savannah River system to the Atlantic margin. Each of these drainage networks hosts a systematic and characteristic surface elevation, which is associated with a lithology- and length-specific path to sea level. Both escarpments separating the surfaces decay where respective river courses to sea level become less distinct in terms of length and bedrock erodibility. Significantly, the respective river systems bounded by the escarpments also cross widely separate portions of eastern North America, each of which could have experienced distinct neotectonic or epeirogenic events, precluding a clear association between the escarpments and lithology alone.

Given the age of the eastern North American passive margin, uncertainty about post-Mesozoic tectonic signals, a complex climatic history, and a complex lithologic framework that exerts strong control over landscape evolution, the origin and true tectonic significance of the BRE may never be known. Indeed, initial development of the BRE seems to be a less-pursued research topic, as active studies of the BRE appear to be increasingly focused on the details of late Cenozoic erosion rates within the steep topography relative to adjacent, lower-slope areas. This shift in research focus may lead to interesting results with interdisciplinary relevance, as the regionally atypical BRE topography hosts zones of elevated slope movement hazard as well as great ecological and botanical significance, all of which strongly impact human interface with the landscape.

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PHYSICAL EVIDENCE OF STREAM CAPTURE AS DRIVER OF ACTIVE LANDWARD RETREAT OF THE BLUE RIDGE ESCARPMENT

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INTRODUCTION

The Blue Ridge Escarpment (BRE), a 500-800m (locally 1 km or greater) topographic escarpment separating the Blue Ridge Plateau and Piedmont physiographic provinces, is one of the most striking elements of the southern Appalachian landscape (Fig. 1). Unlike most of the rugged topography of the southern Appalachians, the Escarpment does not coincide with outcrop of resistant lithologies and trends sub-parallel to the prevailing structural and lithologic grain. Along much of its length, the crest of the BRE coincides with the Eastern Continental Divide, which separates streams of the elevated Blue Ridge Plateau, which drain to the Gulf of Mexico, from Atlantic slope streams of the Escarpment face and Piedmont (Hayes and Campbell, 1894; Davis, 1903; Wright, 1927; Dietrich, 1957; Hack, 1973) (Fig. 1). The Blue Ridge Escarpment has been compared to the "great escarpments" of other passive margins, such as southeastern Australia, South Africa, and Madagascar, which also coincide with major drainage divides, but the relationship between the drainage divide and escarpment evolution in all of these settings has remained poorly understood. Understanding of the evolution of these features has been hampered by the tectonic quiescence of their host passive margins, which generally lack sub-aerial depocenters or datable Cenozoic volcanic material, which might provide insight into the mechanism and pace of escarpment evolution.

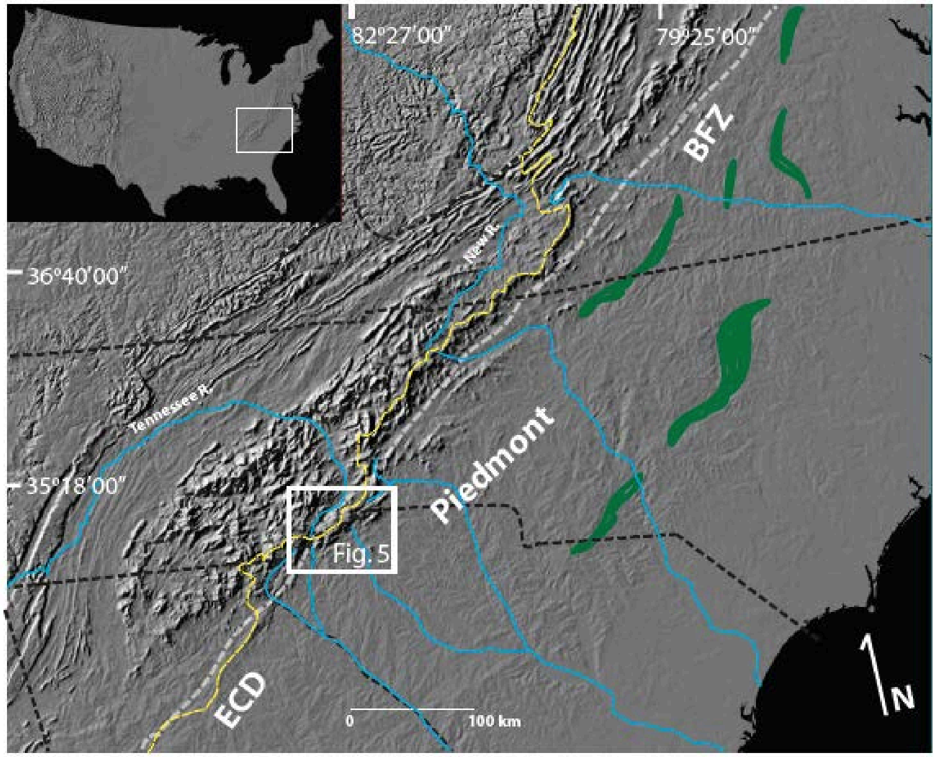


Figure 1. DEM topography of the southern Appalachians. Eastern Continental Divide (ECD) generally coincides with the crest of the Blue Ridge Escarpment. Green areas indicate outcrop of Mesozoic basin fill. DEM source USGS Map I-2206.

Passive margin escarpments are generally regarded as landward-retreating erosional features resulting from rift-flank uplift along nascent ocean basins (Ollier, 1984; Kooi and Beaumont, 1994; Gallagher and Brown, 1997). Opening of a new ocean basin provides a new, proximal base level to the rift flanks, driving accelerated erosion within the new seaward drainage basin (Ollier, 1984; ten Brink and Stern, 1992; Young and McDougall, 1993; Tucker and Slingerland, 1994; Seidl and others, 1996). While this accelerated seaward denudation is accepted to be the major driver of passive margin escarpment evolution, the mechanism through which it proceeds to control escarpment evolution has remained controversial. Some studies have suggested that passive margin escarpments are gradually excavated along a fixed inland drainage divide, which forms at the time of rifting (arch-type escarpments of Matmon and others, 2002; van der Beek and Braun, 1999) (Fig. 2). Others have suggested that a drainage divide forms at the initial rift shoulder, and the divide and escarpment experience landward retreat in parallel following rifting (shoulder-type of Matmon and others, 2002; King, 1962; Gunnell and Harbor, 2008; Gunnell and Harbor, 2010) (Fig. 2). These models have proven difficult to evaluate, as both result in a "wave" of landward exhumation and a pulse of post-rift sedimentation into the new ocean basin as topography adjusts to the presence of the post-rift base level (Spotila and others, 2004). Numerical models have fit present-day passive margin escarpments to both mechanisms as well (van der Beek and Braun, 1999; van der Beek and others, 2002), and the dominance of denudation in the passive margin setting has been assumed to have destroyed any surficial evidence which might shed light on the mechanism of escarpment development.

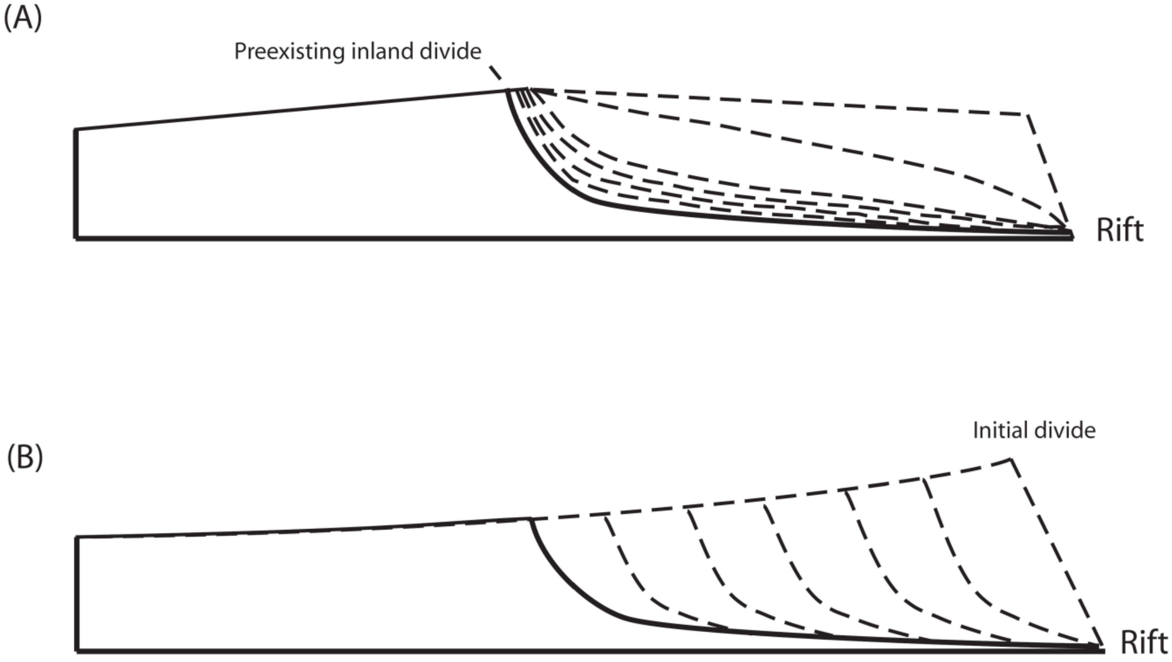


Figure 2. Two popular models of passive margin escarpment evolution. A) Fixed divide model, where an inland drainage divide forms during rifting and the escarpment is excavated seaward of the divide. B) Retreating divide and escarpment model, where a drainage divide forms at the rift shoulder and retreats landward along with the escarpment by focused erosion on the seaward flank of the divide. Both models produce a comparable exhumation signature. After Prince and others (2010).

The predominately shoulder-type BRE has remained a focus of study due to its exceptionally rugged topography and the age of the North American passive margin. The timing of Atlantic opening allows the possibility that the BRE is a very mature feature, and its persistent ruggedness suggests is may still be actively evolving some ~200 Ma after Atlantic Ocean opening (Pique and Laville, 1995; McHone, 1996). While most streams descending the BRE have their headwaters at the escarpment crest, the BRE is locally embayed by steep-walled gorges cut by streams which follow low-gradient courses across the elevated Blue Ridge Plateau before dropping across major knickpoints in the escarpment zone to the Piedmont, and, ultimately, the Atlantic Ocean (selected examples in Fig. 3).

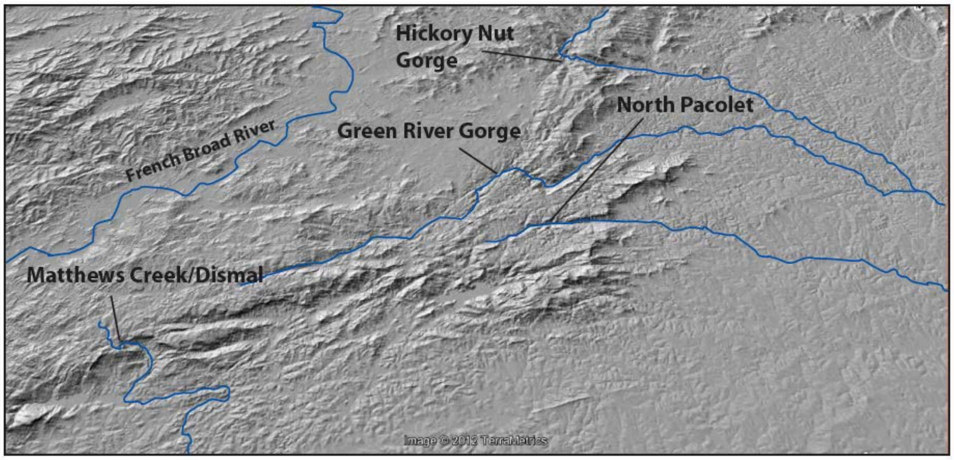


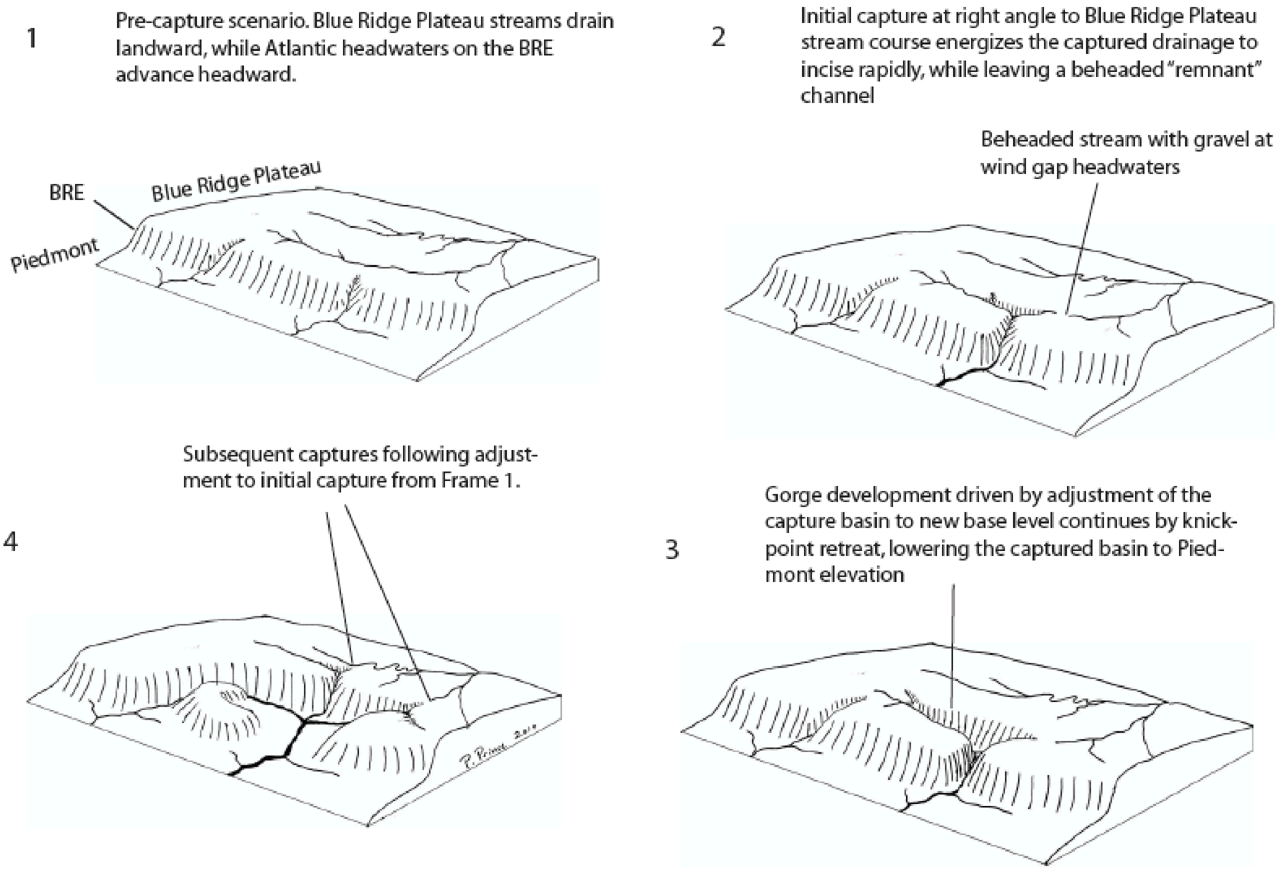
Figure 3. North-oriented inclined "horizon" view of the Blue Ridge Escarpment with selected gorges labeled. These gorges carry streams which flow across the Plateau along low-gradient courses before dropping over major knickpoints to the Piedmont.

In other settings, such streams have been regarded as the last seaward drainages to adjust to the fixed inland divide which formed at the time of rifting, with knickpoint migration proceeding very slowly as the divide is approached (Weissel and Seidl, 1998; Fleming and others, 1999; Heimsath and others, 2000; Matmon and others, 2002; Persano and others, 2002). Numerous workers have cited isostatic rebound related to thickened Appalachian crust or flexural response to offshore sediment loading as drivers of BRE-zone uplift, steepening streams to drive gorge development and BRE evolution (Wright, 1927; Pratt and others, 1988; Battiau-Queney, 1989; Hubbard and others, 1991; Pazzaglia and Brandon, 1996; Pazzaglia and Gardner, 2000). Other models have suggested these streams have been captured from the landward drainage basin into the younger Atlantic basin, with the subsequent rapid incision driving parallel retreat of the BRE and divide (Harbor and Gunnell, 2007; Gunnell and Harbor, 2008, Gunnell and Harbor, 2010). Attempts to prove both of these models have, however, been rooted in models and theoretical topographic interpretation, with little or no supporting physical evidence.

The earliest studies of passive margin escarpment evolution focused heavily on stream capture as the origin of these large streams whose morphologies were consistent with the landward drainage basin before they crossed the escarpment. Field work sought to identify underfed, landward-draining streams with headwaters truncated at the divide, along with stranded alluvium atop the divide, as evidence of drainage rearrangement. Taylor (1911) reported underfed valleys and stranded alluvium at the crest of the southeastern Australia escarpment, and Johnson (1907) described alluvium on the crest of the Chattahoochee-Chattooga divide as indicator of recent Chattooga capture and associated divide retreat and development of the Tallulah and Chattooga gorges. Neither of these studies offered clear descriptions of gravel locations, precluding subsequent study. Wright (1927) and Dietrich (1957) described rounded boulders along the BRE in Virginia, regarding them as evidence that divide and BRE had retreated landward due to stream capture and truncated formerly more extensive landward drainages. Despite this tantalizing physical evidence of capture events, increased acceptance of the dynamic equilibrium model (Hack, 1960) suggested preservation of capture-related gravels was unlikely. Additionally, numerical models and cosmogenic radionuclide studies of the BRE and other passive margin escarpments suggested the features were probably relatively stable, leading to widespread abandonment of the parallel escarpment-divide retreat model by the 1990s and 2000s (Fleming and others, 1999; Bierman and Caffee, 2001, Sullivan and others, 2007).

Spotila and others (2004) re-evaluated the parallel retreat model with apatite thermochronometry and morphologic studies of drainage networks and ruggedness atop the Blue Ridge Plateau and neighboring Piedmont. This study revealed deeper exhumation seaward of the BRE in Virginia, which, combined with differences between drainage patterns on the Blue Ridge Plateau and Piedmont, was viewed as evidence of landward retreat of the BRE and divide by stream capture. Gunnell and Harbor (2010) focused on intersecting, erodible structural elements (faults and joints) as drivers of such stream captures and associated "butte detachment", offering an explanation of the mountain outliers and transitional topography separated from the Blue Ridge Plateau by deep gorges. This study suggested that the BRE experiences "piecemeal," basin-by-basin retreat, fundamentally driven by the erosional adjustment of captured Blue Ridge Plateau streams to their new immediate base level on the Piedmont. The structurally-assisted "piecemeal" capture model was confirmed by the work of Prince and others (2010, 2011), which used stream valley morphology to identify beheaded streams hosting deposits of fluvial gravels atop the Eastern Continental Divide at the crest of the BRE (Fig. 4). Gravel deposits were found to occur near gorges where major streams exit the Blue Ridge Plateau from western North Carolina into Virginia, indicating that gorge development is the transient erosional response following capture of the streams from their landward courses into the Atlantic basin

(Prince and others, 2010). Additional gravels on the BRE crest away from any active gorges suggested complete erosional adjustment of captured basins which formerly extended 10s of kilometers seaward of the present-day BRE (Prince and others, 2010).


1 Pre-capture scenario. Blue Ridge Plateau streams drain landward, while Atlantic headwaters on the BRE advance headward.

2 Initial capture at right angle to Blue Ridge Plateau stream course energizes the captured drainage to incise rapidly, while leaving a beheaded "remnant" channel

Beheaded stream with gravel at wind gap headwaters

4 Subsequent captures following adjustment to initial capture from Frame 1.

3 Gorge development driven by adjustment of the capture basin to new base level continues by knickpoint retreat, lowering the captured basin to Piedmont elevation

Figure 4. Cartoon illustration of the "piecemeal" escarpment retreat model driven by episodic stream capture. Gravel deposits atop the Eastern Continental Divide at the BRE crest in western North Carolina (Prince and others, 2010) confirm the validity of this model.

In western North Carolina, the French Broad River basin has lost considerable drainage area to stream capture and associated erosional retreat of the BRE (Fig. 5). Two recent captures from the French Broad system, which produced the Jocassee Gorges topography and the Green River gorge, were identified through channel morphology and relict gravel deposits by Prince and others (2010). The beheaded streams left by these captures exhibit typical underfed channel morphology, with unusually low headwaters gradients and broad, flat-bottomed alluvial valleys opening into wind gaps at the crest of the BRE. These wind gaps contain mature fluvial gravel, dominated by well-rounded vein quartz clasts, whose shapes suggest many 10s of kilometers of transport (Cailleux, 1947; Sadler and Reeder, 1983) (Fig. 6). The morphological characteristics of these streams, along with their relict gravel deposits, are detailed below.

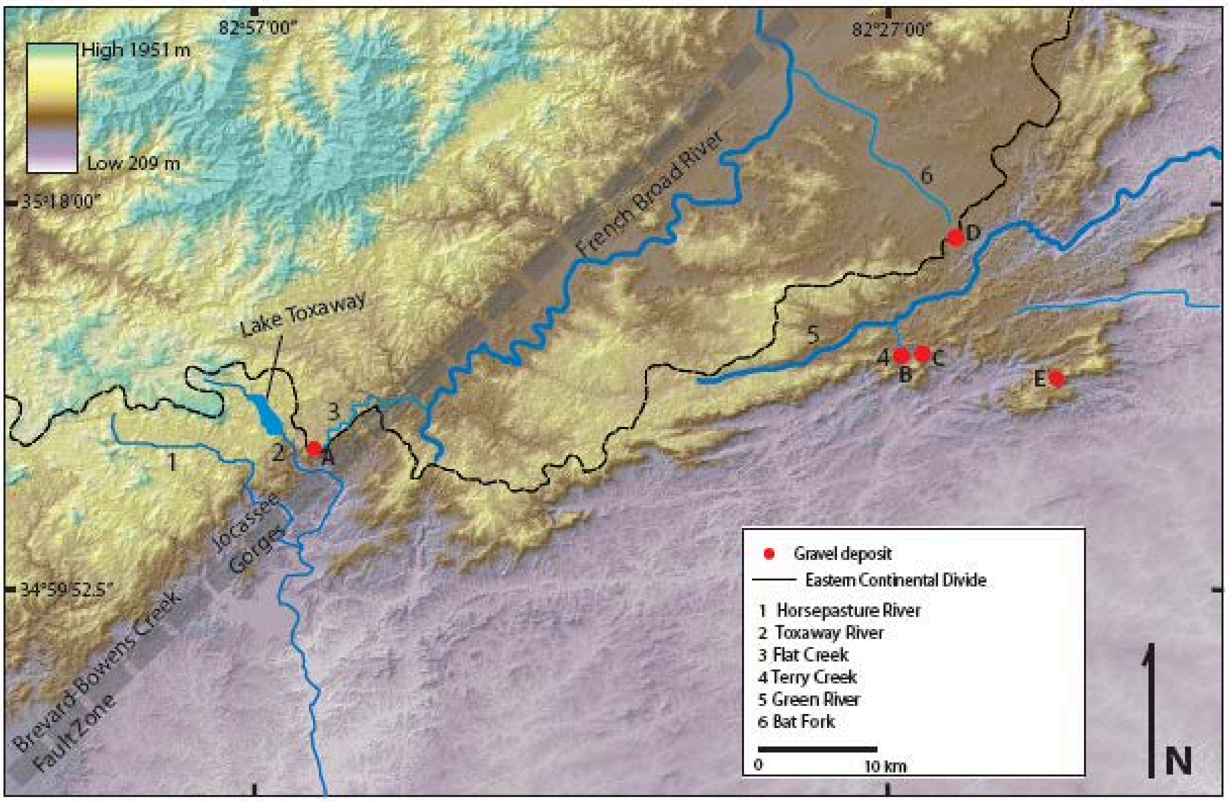


Figure 5. Color-coded DEM with hillshade topography showing gravel deposits related to capture of French Broad River headwaters in western North Carolina. Regional setting of this map is shown in Figure 1. DEM source: www.seamless.usgs.gov.

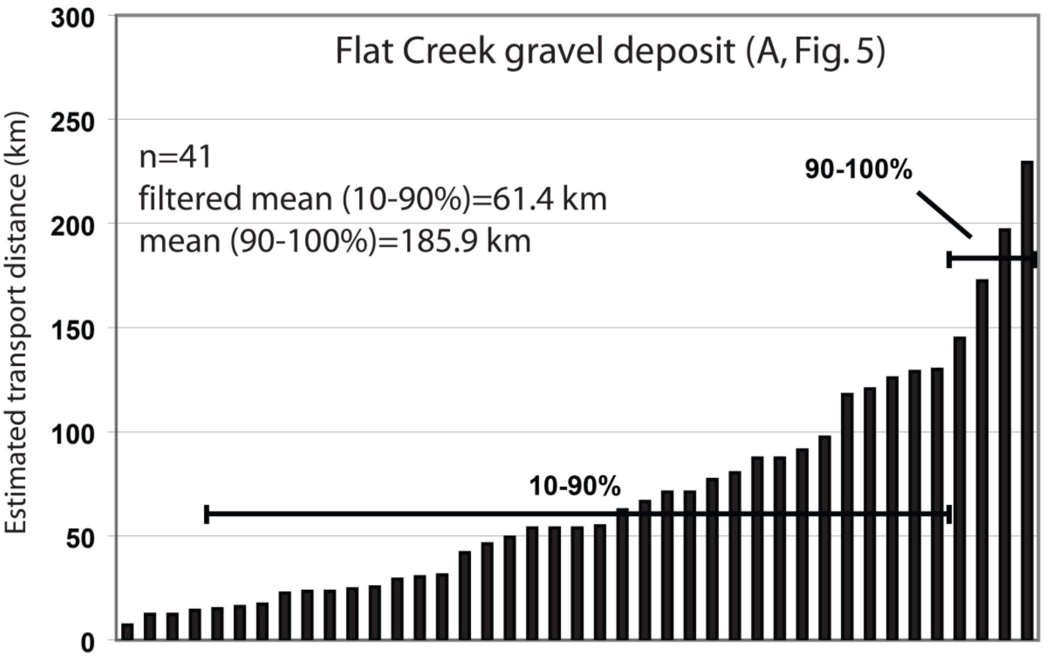


Figure 6. Estimated fluvial transport distances of vein quartz cobbles from the Flat Creek gravel deposit (A, Figure 5). Estimates are based on the methods of Cailleux (1947) and Sadler and Reeder (1983). From Prince and others (2010).

FLAT CREEK VALLEY GRAVEL DEPOSIT

The south fork of Flat Creek (French Broad River tributary) rises in a wind gap 2.7 kilometers southeast of the Lake Toxaway dam (Figs. 5, 7). At its headwaters, the Flat Creek valley is very broad and gives the appearance of a "bottomland" encountered further downstream along the main stem of the French Broad River. The low-gradient topography of Flat Creek valley stands in sharp contrast to the neighboring BRE. Flat Creek exhibits a linear longitudinal profile from its headwaters for ~2.5 km, before it steepens and drops to the present-day West Fork of the French Broad River. Field inspection of Flat Creek valley reveals an unusual white quartz sand soil filled with very well-rounded vein quartz river cobbles. Roundness of these cobbles suggests many 10s of kilometers of transport (Cailleux, 1947; Sadler and Reeder, 1983). Weathering of the cobbles is not advanced, and some contain chalky feldspar crystals that are apparent in hand specimen. Clast density is variable within the deposit, but the soil is locally clast-supported. Clast size is variable, but rounding is very advanced at all sizes, including pea gravel. Local residents are well-aware of the presence of river cobbles inconsistent with the size of Flat Creek, as they are somewhat of an impediment to cultivation of the soil.

Figure 7. Selected photographs of gravel deposits from Figure 5. A) White sand matrix and vein quartz cobbles in gravel deposit A, Figure 5. B) View south across gravel deposit A, Figure 5. Eastern Continental Divides trends across the hill in the distance before crossing the valley floor northwest of the photo. C) Selected well-rounded vein quartz cobbles and pebbles from gravel deposit A, Figure 5. D) Outcrop of fluvially-rounded small boulder, gravel deposit C, Figure 5. E) Outcrop of gravel deposit B, Figure 5, showing reddish clay matrix and quartz cobbles. F) Selected rounded to well-rounded cobbles and small boulders from gravel deposits B and C, Figure 5.

The Flat Creek area is cut by numerous lineaments with northeast-southwest trend (orogenic strike) and northwest-southeast trend (joints of uncertain age and origin). These lineaments intersect at near 90 degree angles, allowing a small amount of headward erosion to lead to capture of a very large drainage area. The size and roundness of cobbles in the Flat Creek Valley suggest that it the remnant of the capture of a stream larger than the modern Toxaway River headwaters. Simultaneous plotting of several Jocassee Gorges rivers reveals that the elevation and gradient of the Horsepasture River is most reasonably projected beyond the entry into its modern gorge and into the Flat Creek headwaters (Fig. 8). The Whitewater and Thompson Rivers were probably tributaries to the Horsepasture, and may have been captured off of the Blue Ridge Plateau before the Horsepasture when the Plateau extended at least as far as the present location of the Jocassee Dam. This profile projection indicates the volume of Blue Ridge Plateau already dissected and lowered by the transient erosional response following capture. Ultimately, the entire Keowee headwaters will be eroded to match Piedmont elevation, removing a substantial area of Blue Ridge Plateau.

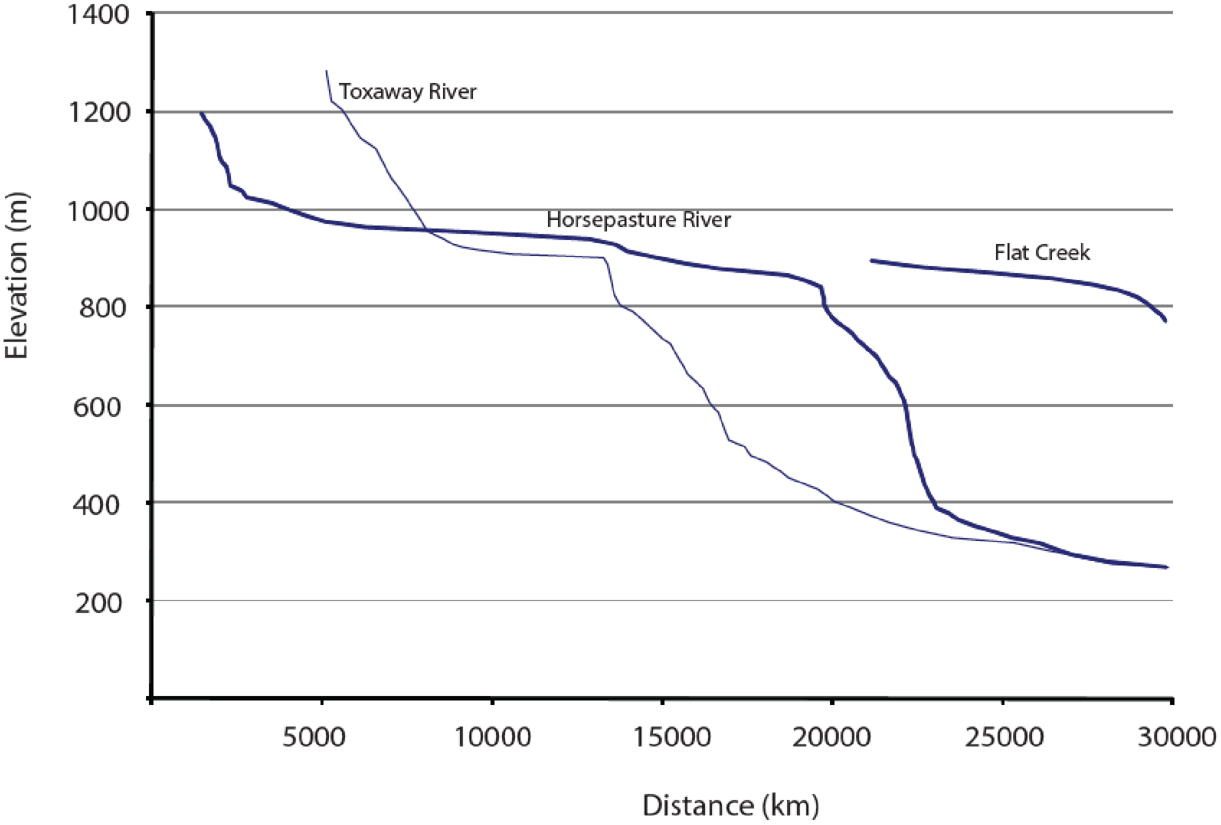


Figure 8. Longitudinal profiles of the Horsepasture and Toxaway Rivers and Flat Creek (Figure 5).

GRAVEL DEPOSITS IN THE VICINITY OF THE GREEN RIVER GORGE

Numerous deposits of rounded fluvial gravel occur at the BRE crest in the vicinity of the Green River gorge south of Hendersonville, North Carolina. South of the gorge, a large “butte” of Blue Ridge Plateau topography now draining entirely to the Green River (Atlantic basin) hosts several gravel deposits in wind gaps at the crest of the BRE (Figs. 5, 7). This “butte” is yet to be reached by knickpoints migrating up Green River tributaries, and maintains the elevation and morphology of the local landward-draining portions of the Blue Ridge Plateau. The gravel deposits along the margins of the butte are unrelated to the most recent capture of the Green River itself, and suggest capture and complete dissection of the basins of former French Broad River tributaries. These gravels are dominated by well-rounded vein quartz cobbles and small boulders set within a red clay matrix. Gravels are associated with broad, aggraded valleys, low gradient stream headwaters, and linear stream profiles, consistent with loss of drainage area to capture. The best exposures can be found along Terry Creek and within the boundaries of a summer camp facility at the headwaters of Terry Creek.

An additional gravel deposit can be found atop the Eastern Continental Divide at the northern margin of the Green River gorge where Upland Road crosses Interstate 26. Interstate 26 enters the French Broad River basin here through a very broad wind gap. The drainage divide itself appears to have no topographic expression, suggesting recent beheading of the remnant French Broad tributary (Bat Fork) and no subsequent adjustment of the stream valley to reduced discharge (Fig. 9). The gravel deposit has been heavily disturbed by construction, but well-rounded vein quartz cobbles can still be found on undeveloped land immediately east of the Interstate. The cobbles are set in a light-colored sandy clay matrix, but whether this matrix is of depositional origin or relates to weathering of the local quartz-rich bedrock is unclear. The elevation of this gravel deposit is consistent with the elevation of the Terry Creek gravels, indicating the likelihood of all the gravels representing the former valley elevation of a stream network following a low-gradient course to the French Broad River. As with the Flat Creek deposit, these gravels represent transient “relict” topography which will ultimately be dissected and lowered to Piedmont elevation by continued headward retreat of knickpoints.

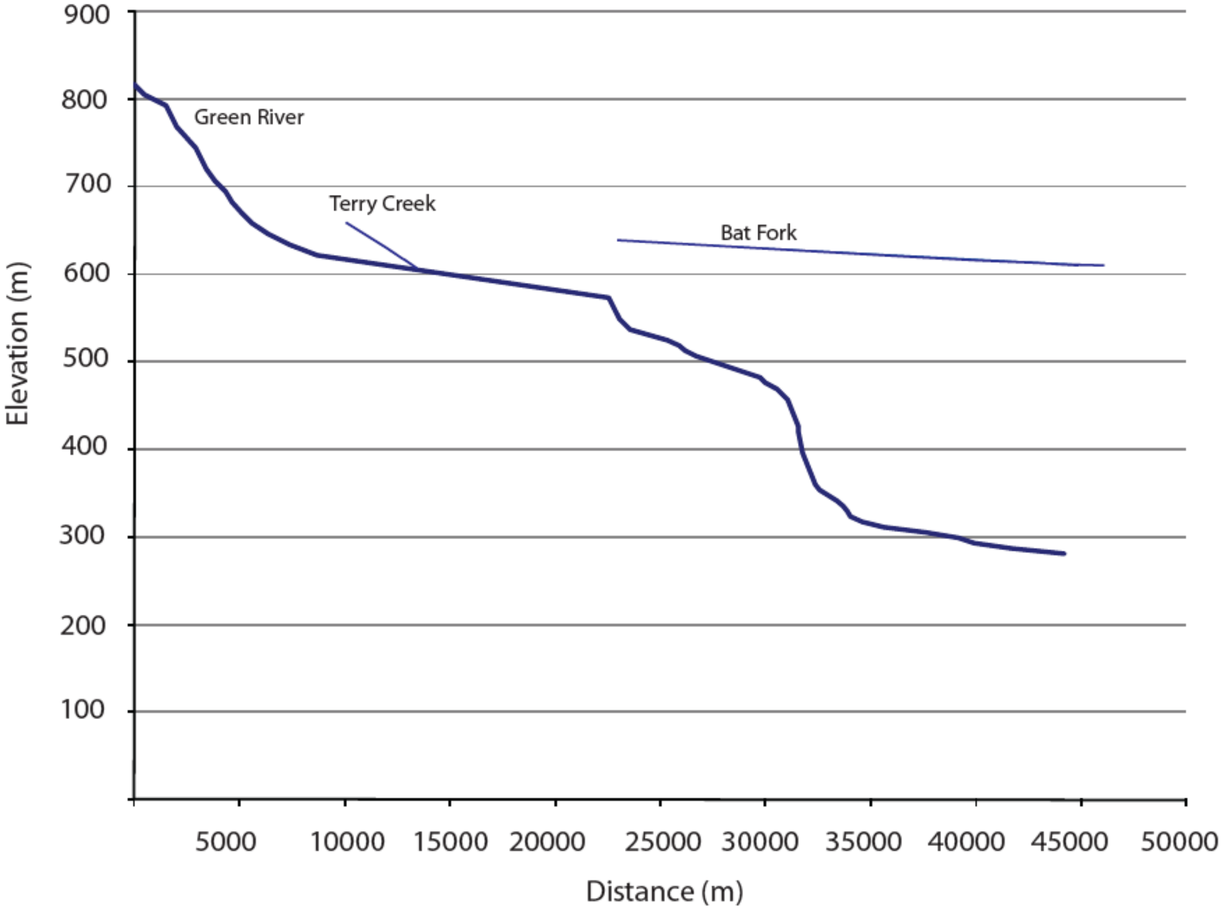


Figure 9. Longitudinal profiles of the Green River, Terry Creek, and Bat Fork (Figure 5).

DISCUSSION

Fluvial gravels preserved along the crest of the BRE in western North Carolina confirm the role of stream capture as the major driver of BRE evolution during the Cenozoic. Complete dissection of the Keowee and Green River headwaters will lead to the local expansion of the Piedmont surface at the expense of the Blue Ridge Plateau, producing local retreat of several kilometers of BRE. While gravels have yet to confirm the capture origin of other gorges such as The Dismal Gorge of Matthews Creek, Hickory Nut Gorge of the Rocky Broad River and the North Pacolet gorge (Figure 3), the characteristics of these streams are consistent with the Jocassee Gorges and Green River gorge and likely reflect a similar capture history. Large detached buttes in western North Carolina, such as the Brushy Mountains and South Mountains, may represent the final stages of adjustment to large captures of the Catawba and Yadkin River systems from the Blue Ridge Plateau into the Atlantic basin. Even if these basins are not the result of capture, continued adjustment in documented captures will drive the Piedmont (Atlantic) base level further into the Blue Ridge Plateau to accomplish further captures. Incision in captured basins is driven by gravitational potential energy of Plateau streams being tapped by Atlantic headwaters, and as long as elevation contrast exists across the BRE, the energetic driver for capture and BRE retreat will be preserved. Prince and others (2011) described the Blue Ridge Plateau as an “energy reservoir,” which stores relict topographic potential energy to drive rapid fluvial incision long after the end of Appalachian orogenesis.

While the fluvial gravels and stream metrics of beheaded streams reveal the capture mechanism, little is known about the timing of capture or the rate of knickpoint retreat and topographic adjustment following capture. Knickpoint retreat and gorge advancement in captured streams certainly outpaces lowering of the surrounding Blue Ridge Plateau, as indicated by preservation of the gravel deposits at the BRE crest. Few constraints on denudation rates of the Plateau surface exist, but rates of <10 m/Myr have been indicated by cosmogenic radionuclide studies (Sullivan and others, 2007) as well as apatite thermochronometry (Spotila and others, 2004). If these rates are accurate and the gravel deposits were not exceedingly (10s of meters) thick, gorge advancement must outpace lowering of the surrounding upland by orders of magnitude. Nott and others (1996) obtained km/Myr knickpoint retreat rates in rivers carving gorges into the southeastern Australia escarpment. These streams are of similar size to the Keowee headwaters and Green River, and flow across a similar substrate in a similar climatic setting. Evolution of the captured streams may have proceeded more rapidly during the Pleistocene, when vegetation and precipitation patterns were different and likely favored more rapid denudation. In any case, captured basins evolve more rapidly than the adjacent Blue Ridge Plateau to accomplish localized retreat of the Eastern Continental Divide and BRE. If this mechanism occurs along the entire BRE over the long term, kilometers of landward parallel retreat of the divide and BRE have likely occurred during the Cenozoic.

The tectonic origin of the BRE also remains uncertain. Gravel deposits and gorge development suggest 10s of kilometers of retreat are certainly possible within the Cenozoic, and this retreat distance can restore the BRE at least as far as the westernmost Mesozoic basins in southern Virginia (Fig. 1). Lack of preservation of such basins in southern North Carolina or South Carolina (landward of the Crowburg basin) makes the limit of major depocenter development during Atlantic opening less clear. The exhumation signature of BRE retreat identified by Spotila and others (2004) in Virginia did not preclude a very large retreat distance, but no exhumation data from the Piedmont further south also limits extrapolation of this data to the western North Carolina BRE. It therefore remains unclear whether the BRE has experienced self-similar retreat since its inception on a rift flank during Mesozoic Atlantic opening, or if BRE formation and retreat was initiated more recently by an unknown flexure and uplift. Improved understanding of post-Mesozoic tectonics in the southern Appalachians may offer insight into these questions in the future.

Whether or not stream capture and divide migration controls the evolution of other passive margin escarpments is also yet to be determined. Inverted dendritic drainage patterns along the southeastern Madagascar escarpment (Gunnell and Harbor, 2008) offer anecdotal evidence of capture events which will ultimately produce escarpment retreat, but no surficial deposits have been located to confirm the process. Gorges cut into the southeastern Australia escarpment, particularly the Shoalhaven gorge, display comparable topography to BRE gorges and also appear to be associated with barbed tributaries and beheaded channels, but no field work has sought to evaluate the capture model due to the acceptance of the arch-type model (Persano and others, 2002). Similar gorges embay the Drakensberg Escarpment of South Africa, but these features have also been attributed to ongoing adjustment towards a fixed inland drainage divide (Moore and Blenkinsop, 2006). Until extensive field work is conducted in these settings, whether or not stream capture is, in fact, a major driver of passive margin escarpment evolution worldwide will remain uncertain.

DIRECTION OF FUTURE RESEARCH

While considerable data regarding BRE evolution has been gathered in recent years, numerous questions remain regarding its tectonic significance and the pace of its evolution. Additional study of a number of aspects of the modern BRE topography, its associated ecosystems, and the detrital signature of its erosional retreat would greatly enhance understanding of the evolution of the BRE and, potentially, passive margin escarpments worldwide.

^{10}Be analysis of bedrock landforms and stream sediments

While ^{10}Be analysis has been applied to sediments in streams draining the BRE, results were fit to a steady-state model which disregarded the transient nature, and thus mixed erosional dynamics, of BRE streams. No study to date has attempted to constrain incision rates or knickpoint retreat rates within the gorge systems of transient BRE streams which are still actively adjusting following capture. Applying the methodology of Norton and others (2008) could potentially reveal incision rates within the rapidly evolving gorge systems, offering quantitative constraint on the pace at which the margin of the Blue Ridge Plateau is consumed following a capture event.

^{10}Be analysis of bedrock exposure age could also shed light on incision rates and rates of hillslope and cliff evolution following capture and incision. Hanging bedforms (flutes and potholes) are known to exist within the gorges of actively adjusting streams, and evaluating there subaerial exposure age in the context of their height above the active channel could be useful in determining incision, and thus adjustment, rates. While cliffs along the gorges are dominated by rockfall due to the intersection of joints and foliation, the rate at which rockfalls occur is unconstrained. Several exposure ages collected along extensive cliff faces could also offer some quantitative constraint on how dynamic these oversteepened slopes may actually be.

Genetic studies of aquatic organisms

Occurrence of fish species and other aquatic organisms endemic to landward drainages in the headwaters of Atlantic basin streams has long been viewed by biologists as the result of stream capture (c.f. Jenkins and others, 1971). The steepness of Atlantic slope headwaters flowing down the BRE would prevent aquatic organisms from travelling down one headwaters to an arterial drainage and then moving back upstream into an adjacent headwaters; species in these headwaters are therefore isolated once detached from the landward basin by capture. Some workers have suggested that comparing genetic mutations in the same species from landward and adjacent Atlantic streams could offer data on the timing of capture. This method would rely on the accuracy of mutation rate applied, but could offer some indication on the timing of captures which have produced a known topographic response.

Offshore sedimentary record

Pulses of erosion following capture events transport several cubic kilometers of rock as sediment to the continental margin. Rapid Miocene sedimentation in the Chesapeake area has been regarded as possible evidence of growth of the Potomac basin by capture, but no similar analyses have been conducted further south along the Atlantic margin. Large capture events might be visible as sediment pulses in the near-shore sedimentary record. Landward erosional retreat of the divide and BRE also connects an ever-changing array of sediment sources to the Atlantic basin over time. Identification of unique tracer minerals or zircons of a given age in offshore strata might indicate the time at which the Atlantic basin breached a particular zone of bedrock through stream capture and associated BRE retreat. The Savannah basin is an excellent candidate for this type of analysis, due to its short length, potentially recent growth from accretionary terranes into Laurentian units, and the lack of anecdotal evidence for alteration of its basin by post-BRE retreat captures within the Piedmont.

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Landslides and the Formidable Blue Ridge Escarpment

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ABSTRACT

The Blue Ridge Escarpment (BRE) extends from northeast Georgia to Virginia, and its crest generally coincides with the Eastern Continental Divide southwest of Roanoke, Virginia. East of the divide the rugged slopes of the Escarpment descend abruptly to the rolling foothills of the Piedmont physiographic province. Ongoing mapping and research reveal a regional pattern of recurring major landslide events along the BRE primarily in North Carolina and Virginia. High relief, steep slopes, and the dissected nature of the BRE, in combination with its orographic influence on rainfall, make it susceptible to mass wasting in general, and to debris flows in particular. From 1901 to 2018, eight storm events have resulted in major impacts from landslides and floods along the North Carolina portion of the BRE. In North Carolina, steep walled, topographic reentrants where streams have incised into the BRE by exploiting ductile and brittle bedrock structures are prone to decadal-scale, recurring landslide activity. The BRE not only influences when and where landslides occur, but its topographic relief influences the impacts from debris flows and flooding produced by these storm events, which can extend up to tens to hundreds of km (>100 mi) downstream into the Piedmont. Mass wasting, erosion, stream capture, bedrock structure, and in some cases, seismicity can be linked to the evolution of the BRE. The many benefits that come from living on and near the BRE, and building, operating, and maintaining the infrastructure that crosses it have been costly in terms of dollars and lives.

INTRODUCTION

Landslides are a recurring form of mass wasting and sediment transport in the landscape evolution throughout the southern Appalachian highlands (SAH) of the USA (Wooten et al., 2016 and references therein). In North Carolina and Virginia landslide activity is concentrated in the Blue Ridge Mountains and adjoining high relief areas of the Piedmont (Figures 1 and 2). Ongoing landslide hazard mapping and research reveals a pattern of frequent mass wasting along the Blue Ridge Escarpment (BRE), in North Carolina and Virginia. Although dominated by debris flows, other types of landslides originating on the BRE include debris slides, rockslides and rockfalls as classified by Cruden and Varnes (1996). The BRE not only influences when and where landslides occur, but its topographic relief influences the downstream extents of impacts from debris flows and flooding. Crossing the BRE continues to be a challenge for critical transportation and energy infrastructure in the region. The many benefits from building, operating, and maintaining infrastructure on the BRE are costly, both in terms of dollars and lives. This paper gives examples of the influence of the BRE on precipitation-driven landslide events in western North Carolina, and the hazards these landslides and rugged terrain continue to pose to public safety and infrastructure.

Recurring extreme rainfall scenarios are linked to landslide events in the mountainous Blue Ridge where debris flows and debris slides, dominant among landslide processes, are triggered when extreme rainfall increases pore-water pressures in steep, soil-mantled slopes. Figure 3 shows a compilation of documented landslide events and associated rainfall amounts for western North Carolina from 1876 to 2021 with the passage of tropical storm Fred, which resulted in fatalities from flooding and a debris flow (Bauer, 2021). Major landslide events affecting I-40 and the Blue Ridge Parkway, critical transportation routes in western North Carolina, are also shown; however, these slope failures do not necessarily coincide with extreme precipitation events. Landfalling tropical cyclones and an extratropical cyclone set off tens to thousands of debris flows in multi-county regions in 1916, 1940, 1977, 2004, 2018, and 2021.

Low-pressure systems, convective storms and atmospheric rivers (Miller et al., 2019), especially when coincident with periods of extended above-normal rainfall, set off tens to hundreds of landslides in 2013, and again in 2018 through 2020. Eight of these storms have resulted in major impacts from landslides and floods along the North Carolina portion of the BRE (Fig. 3).

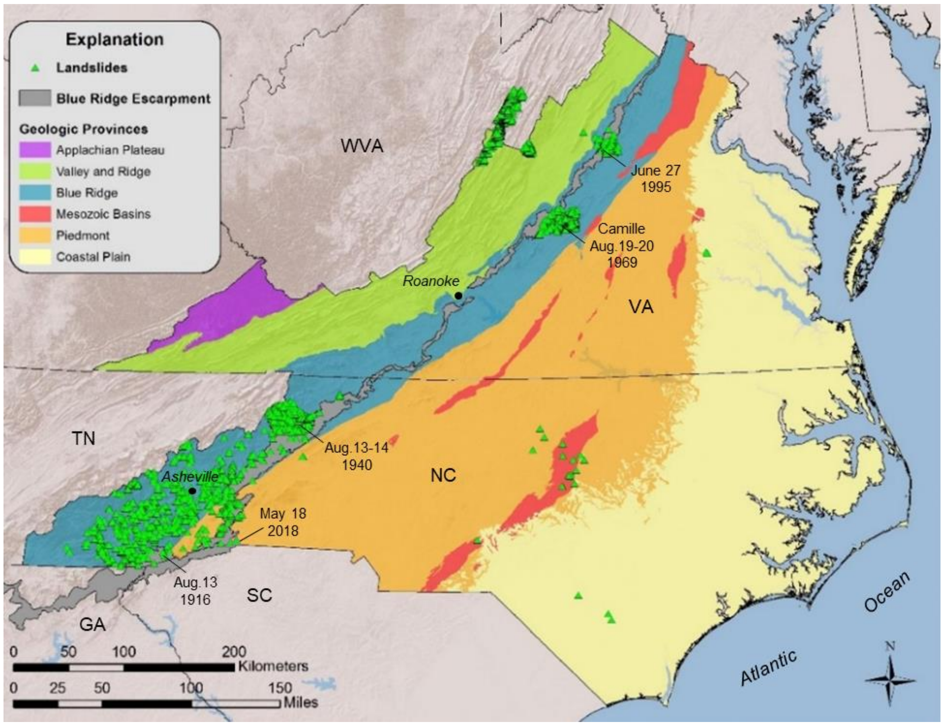


Figure 1. Geologic provinces of North Carolina and Virginia, the Blue Ridge Escarpment, and landslide locations in landslide geodatabases of the North Carolina Geological Survey and Virginia Department of Mines Minerals and Energy (as of 2016). Dates indicate locations of major storm triggered landslide events referenced in the text. Clustered distribution of landslides results from detailed mapping in some areas of major landslide events, and incomplete mapping in other areas. Base map by Anne Witt, adapted from Wooten, et al., 2016). Note how the Blue Ridge Escarpment crosses geologic provinces.

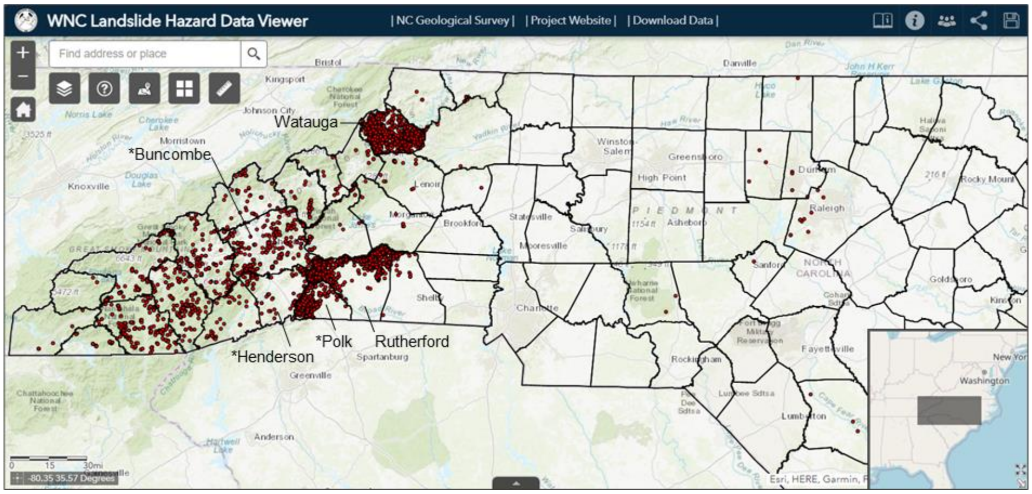


Figure 2. Screen capture of the WNC Landslide Hazard Data viewer developed by the North Carolina Geological Survey in partnership with the National Environmental Modeling and Analysis Center at UNC-Asheville. Red dots = point locations for landslides in the NCGS landslide inventory. Landslide mapping by the NCGS and its contractor Appalachian Landslide Consultants, PLLC. (ALC), accessed July 11, 2022. Labeled counties are ones where landslide mapping has been completed along the Blue Ridge Escarpment; field trip stops are in *counties (Polk, Henderson, Buncombe). Source: http://mapviewer.landslidesncgs.org.

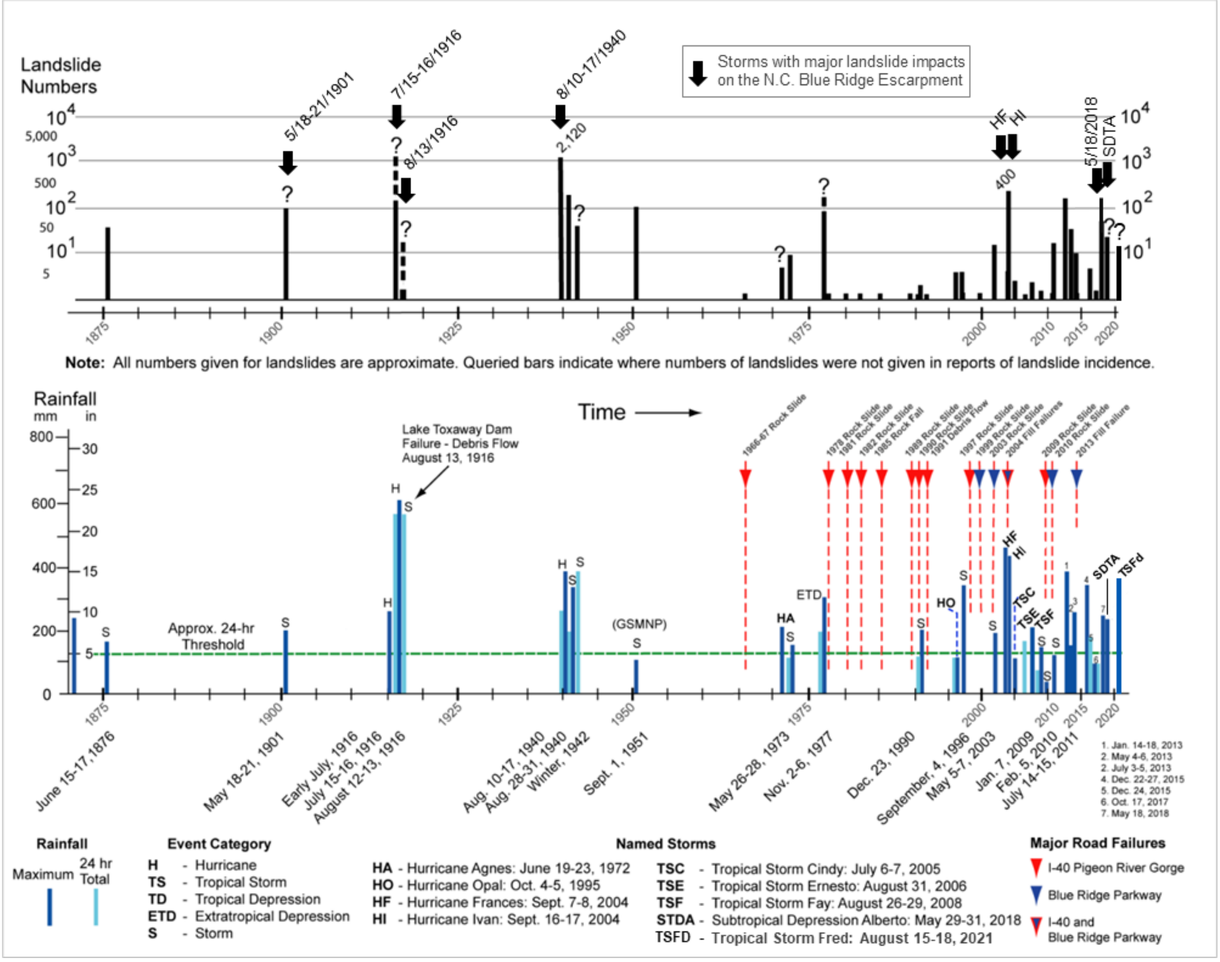


Figure 3. Chart showing documented landslide events and related rainfall for western North Carolina from 1876-2021. Adapted from Wooten et al., 2016. Major landslide events impacting I-40 and the Blue Ridge Parkway, critical transportation routes in western N.C. include those not coincident with major storms. Landslide and storm frequency data are more complete beginning in 1990 when the NCGS formally began landslide hazard studies.

THE BLUE RIDGE ESCARPMENT, LANDSLIDES AND STORM EVENTS

Blue Ride Escarpment

The Blue Ridge Escarpment, which extends from north Georgia to Virginia, is the most prominent regional landform in the Southern Appalachian highlands (Hack, 1982; Clark, 1993; Prince, 2010 and this guidebook). South of Roanoke, Virginia its crest generally coincides with the Eastern Continental Divide, and east of the divide the rugged slopes of the BRE descend abruptly to the rolling foothills of the Piedmont physiographic province. North of Roanoke, the northern Blue Ridge Mountains descend sharply to the foothill zone (Hack, 1982). Although not considered part of the BRE by many workers (e.g., Hack, 1982; Spotila et al., 2004; Prince, this guidebook) this distinct topographic break, also known as the Blue Ridge front, is shown here as an extension of the BRE. High relief, steep slopes, and the dissected nature of the BRE, in combination with its orographic influence on rainfall, make it susceptible to mass wasting in general, and to debris flows in particular. The distributions of areas affected by debris flows from the July 15–16, 1916, the August 13–14, 1940, and May 18-30, 2018 events in North Carolina generally coincide with the BRE, as do the August 19–20, 1969 (Camille) and the June 27, 1995 events in Virginia

(Eaton et al., 2003, Wooten et al., 2016) (Figure 1). In South Carolina Muthukrishnan (2012) documented 1976 and 2006 debris flows where the Middle Saluda River has incised into the BRE along an E-W trend, and Garihan et al.(2010) point out the potential for landslides in the rugged terrain of the BRE on Pax and Glassy Mountains. Orographic forcing of rainfall along the BRE is identified by greater rainfall totals as compared to the surrounding regions for the storms of July 15–16, 1916 (Scott, 1972; Witt, 2005), August 10–17, 1940 (U.S. Geological Survey, 1949), and May 18, 2018 (Wooten, Stop 1, this guidebook) in North Carolina; and, for the storm of June 27, 1995 in Virginia (Wieczorek et al., 2004).

Steep walled, topographic reentrants (i.e., transverse valleys extending into an escarpment) where streams have incised into the BRE by exploiting bedrock structures are also prone to debris flows and other types of mass wasting. Figure 4 shows the locations of reentrants and related cross-structures associated with prehistorical and recurring historical landslide activity along the North Carolina portion of the BRE.

The major storms of July and August 1916 will be discussed first as they serve as benchmark historical events that help illustrate the scope and magnitude of the BRE's influence on meteorological and hydrological events leading to landslides and flooding that extended far downstream. Locations and geomorphic settings where studies have documented decadal-scale, recurring landslide activity along the Escarpment will then be presented, proceeding from Polk County northeast to Watauga County.

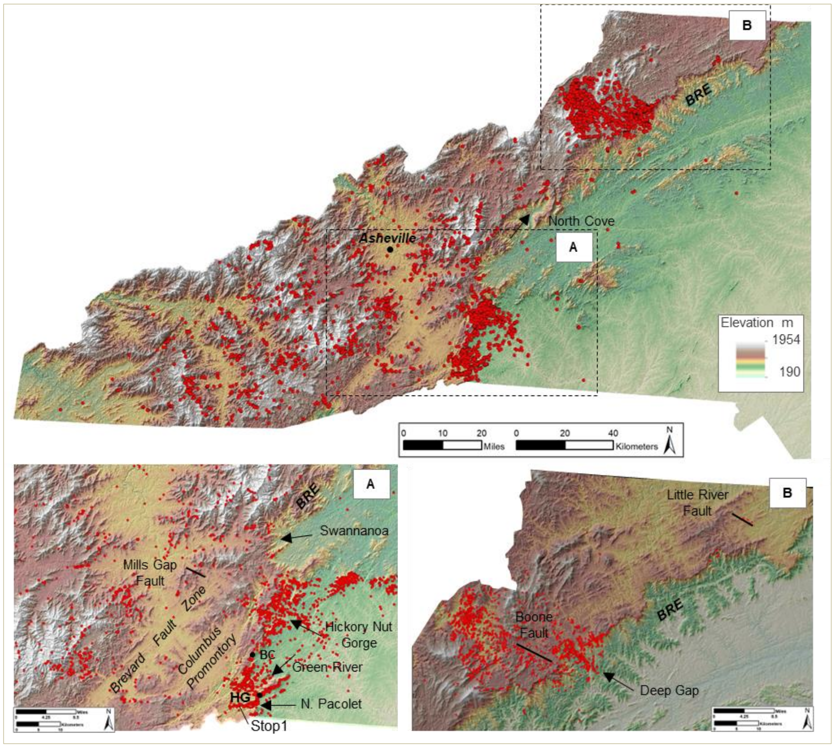


Figure 4. Point locations for landslides (red dots) in western N.C. from the NCGS landslide geodatabase (accessed Nov. 24, 2021). Clustered distribution of landslides results from detailed mapping in some areas of major landslide events, and incomplete mapping in other areas. **A**. Inset map for the southern Blue Ridge Escarpment (BRE) area. Polk County landslide locations: **HG** = Howard Gap, **BC** = Bright's Creek referenced in the text and in Figures 8 and 9 respectively. **B**. Inset map for the northern BRE area. Concentrated landslide occurrence in Watauga County is mainly from the ~2,000 landslides triggered by the August 13-14, 1940 tropical cyclone. Map base: shaded relief color coded by elevation derived from a 6m lidar digital elevation model (DEM).

July 15-16, 1916 Storm

The storm of record for the French Broad watershed at Asheville occurred on July 15–16, 1916 when a hurricane made landfall earlier near Charleston, South Carolina and then moved northwest over western North Carolina causing extensive flooding and triggering numerous landslides (Bell 1916 ; Holmes 1917 ; Scott 1972 ; Witt 2005; Wooten et al., 2016: Bandel, 2016). The storm set the 24-hr rainfall record for western North Carolina of 564 mm (22.2 in) at Altapass on the crest of the BRE in Mitchell County (Figure 4). Earlier, during July 8-9, 1916, a tropical cyclone produced 100–250 mm (~4-10 in) of rain across western North Carolina (Henry 1916 ; Scott 1972). Although no landslides were reported for this early July storm, it created elevated moisture conditions which most likely exacerbated the extent of flooding and landslides that resulted from the July 15-16, 1916 storm.

A compilation of the general areas of reported 1916 landslides shows that they were concentrated along a ~182 km-long (~113 mi) swath of the BRE from the Saluda railroad grade in Polk County (near Stop 1) northeast to the Basin Creek watershed in Allegheny and Wilkes Counties in what is now Doughton Park (Fig. 4). Areas with the highest recorded rainfall are in the upper French Broad watershed in Transylvania County, and along the BRE from McDowell County northeast to Allegheny and Wilkes Counties, coincident with the areas of reported landslides. Although the exact numbers of landslides reported for the July 1916 event are uncertain, given their widespread distribution, coupled with the record rainfall, indicates that they probably numbered in the thousands across western North Carolina.

Official records show that the July 15-16 storm caused 50 fatalities in North Carolina (Bandel, 2016), with an estimated 18 of those, including 11 children, as a direct result of landslides. Devastated by flooding and landslides, the Basin Cove community in Wilkes County (now Doughton Park) never recovered (Fig. 5). Alice Caudill, her son Cornelius, and Wadie Adams, Alice's mother, died when their cabin was swept away by landslides and flooding. The 1916 storm and the Basin Cove community are commemorated by a historical marker for the Martin and Janie Caudill homestead at the Doughton Park overlook on the Blue Ridge Parkway. Landside fatalities also occurred well east of the BRE in the Brushy Mountains near the Wilkes-Alexander county line where three Perry children died.

Flooding from the 1916 storm extended far downstream into the Piedmont along the Yadkin and Catawba river systems whose headwaters originate on the BRE. Severe flood damage impacted the towns of Wilkesboro, North Wilkesboro, and Elkin (Fig. 5) along the upper reaches of Yadkin River in the foothills below the BRE (Bandel, 2016). Significant flooding occurred at the Narrows Dam at Badin in Stanly County, ~240 km (~150 mi) downstream from the Yadkin River's headwaters (Bandel, 2016). In the Catawba River system severe flood damage extended ~185 km (~115) downstream to Belmont in Gaston County near the South Carolina border where 10 fatalities occurred (Bandel, 2016) (Fig. 5).

August 13, 1916 Lake Toxaway Dam Failure

The largest known historical debris flow in western North Carolina is related to human activity and occurred on August 13, 1916 when the original earthen dam at Lake Toxaway failed. Perhaps weakened by the earlier July storms, the dam failed catastrophically when a low-pressure system dropped 584 mm (~23 in) of rain in 24 hours over Transylvania County beginning on August 12th (Wooten et al. 2003a, b). The dam failure triggered a debris flow covering a minimum area of 1.22 km^2 (~0.46 m^2) along an 11.4 km (~ 7 mi) reach of the Toxaway River in North Carolina as it flowed down the BRE before entering South Carolina (Fig. 6). Damage extended another ~19 km (~12 mi) into South Carolina where floodwaters destroyed the Chapman Bridge across the Keowee River (Pickens Sentinel, 1916). In the August 18, 1916 issue of the Savannah Union Times, S.W. McCallie, State Geologist of Georgia, summed up the event this way, "approximately 5,376,548,571 gallons of water changed hands."

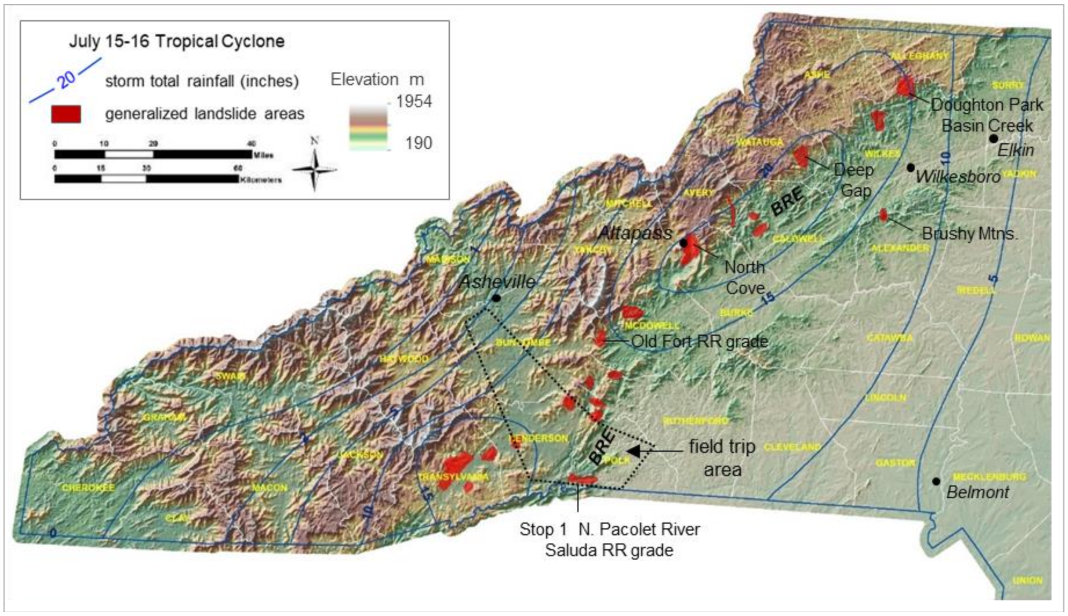


Figure 5. Map of storm total isohyets from the July 15-16, 1916 tropical cyclone (from Scott, 1972) and generalized locations for landslides reported for the storm. Rainfall and landslides are generally concentrated along the Blue Ridge Escarpment (BRE). Severe flooding occurred along the Catawba River system as far downstream as Belmont. Landslide data sources: (Bell, 1916; Holmes, 1917; Southern Railway Co., 1917; Witt, 2005; Wooten et. al., 2011; Bandel, 2016; Wooten et al., 2017). Map base: shaded relief derived from a 6m lidar DEM color coded by elevation. Note: Locations of 1916 landslides in Transylvania County are under revision with mapping by ALC and the NCGS.

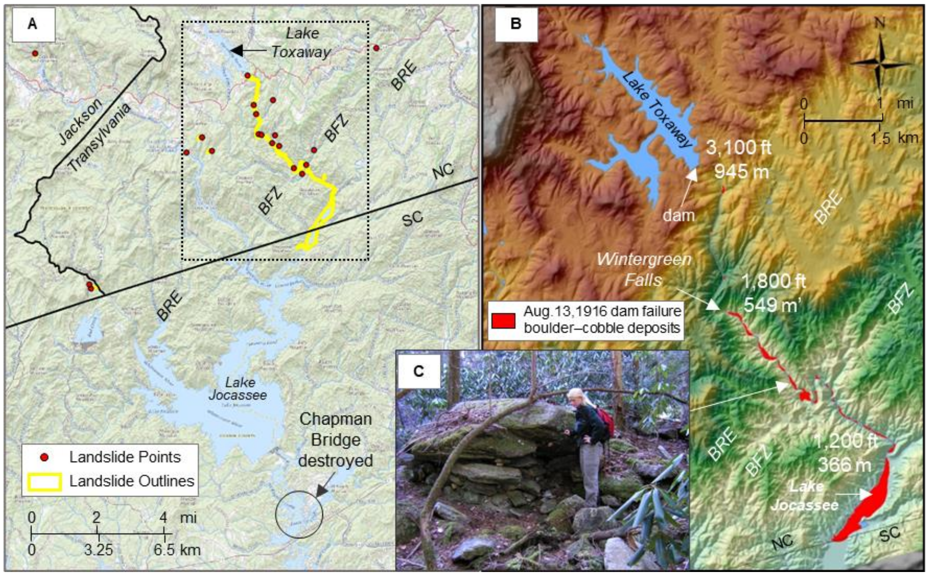


Figure 6A. Map showing the extent of the flood-debris flow (yellow outline) from the August 13, 1916 Lake Toxaway dam failure in Transylvania County, N.C. Extensive damage occurred along a ~11.4 km (~7 mi) reach of the Toxaway River on the Blue Ridge Escarpment (BRE). Flood damage extended over another ~19.5 km (~12 mi) into S.C. where floodwaters destroyed the Chapman Bridge across the Keowee River. BFZ = Brevard Fault zone. Map source: WNC Landslide Hazard Data viewer http://mapviewer.landslidesncgs.org; accessed 07/27/2022. **B.** Map of the boulder-cobble deposits from the dam failure along the Toxaway River in Gorges State Park (inset area map left). As flood waters descended the BRE, scour dominated along the river gorge from the Lake Toxaway dam to Wintergreen Falls. Most deposits are preserved from Wintergreen falls downstream to Lake Jocassee. Map base: shaded relief color-coded by elevation derived from a 6m lidar DEM. Reference elevations in feet and meters. Adapted from Wooten et al., 2003a. **C.** Imbricated clasts in a boulder levee from the dam failure debris flow. Top of the levee here is ~5.5 m (~18 ft) above the present river level. 2003 NCGS photo.

Field investigations bear out the eyewitness accounts of “a wall of water 30 feet high,” and “rocks as large as train cars thundered down the valley.” The enormous outflow from the breached dam, calculated to be on the order of 8,665 m^3/sec (~300,000 ft^3/sec) scoured the steep valley walls and transported boulders as large as 18 m (~60 ft) long (Wooten et al. 2003a,b; 2010b). Scour lines still present along the gorge walls indicate floodwaters reached levels ~10.7 m (~35 ft) high. The anthropogenic deposits from this event are preserved in Gorges State Park and beneath the upper portion of Lake Jocassee. The debris flow scoured the upper reach of the river channel to bedrock along 3.7 km (2.3 mi) from Lake Toxaway downstream to Wintergreen Falls (Fig. 6B), a condition that persists today. Boulder levees and other deposits from the debris flow below Wintergreen Falls (Fig. C) now support some vegetation, and initial revegetation probably began soon after the debris flow. Tree ring studies in Gorges State Park (Wooten et al. 2003a, b) show 1917 to be the beginning growth year for a pitch pine (*Pinus rigida*) now established on the 1916 boulder deposits near the confluence of Bearwallow Creek and the Toxaway River. Among the lingering impacts from the dam failure are several active landslides along the Toxaway River in Gorges State Park that likely initiated after the debris torrent over-steepened footslopes along the valley walls (Wooten et al., 2003b).

Polk County

The earliest accounts of landslides in Polk County are from the July 15-16, 1916 storm that triggered numerous slope failures along the Saluda railroad grade where it crosses the BRE (Southern Railroad Company, 1917). Scott (1972) recounts a July 18, 1916 Atlanta Journal Constitution newspaper article that reported "...landslides from the mountains buried the road for long distances." where the Saluda to Tryon road crosses the Escarpment in the Howard Gap area. Numerous slope stability problems were encountered during the construction of I-26 through Howard Gap, and elsewhere along the Saluda road grade, beginning in 1968 and continuing into the 1970s, which delayed the opening of I-26 through the region (Glass, 1977; Sams and Gardner, 1974). More recently, a series of thunderstorms on the evening of May 18, 2018 triggered at least 240 debris flows and debris slides concentrated in the North Pacolet River and Green River reentrants and adjacent areas of the BRE (Wooten et al., 2022b) (Fig. 4). These landslides resulted in a fatality, destroyed homes and severely damaged infrastructure. Refer to Stop 1 for further discussion of this event in the North Pacolet River Valley (Wooten et al., this guidebook).

Pacolet and Green River Reentrants

The highest concentrations of landslide features in Polk County, including those from the May 18, 2018 storm, are along the slopes of the BRE, especially on the steep valley walls where the North Pacolet and Green Rivers have incised into the BRE (Fig. 4) (Wooten et al., 2022a). These rivers exploit post-orogenic brittle fractures to form linear reentrants into the BRE (N. Pacolet E-W, Green SW-NE) on the Columbus Promontory where the May 2018 and other landslides are concentrated. One of the highest rainfall accumulations for the May 17-18, 2018 storm sequence (6.00-7.99 in; 152-203 mm) coincides with the area of concentrated debris flow activity in the North Pacolet River Valley in western Polk County (see Stop 1, Fig. 1-5), indicative of the orographic influence of the BRE on rainfall.

The May 18, 2018 storm is one of the largest landslide events in North Carolina in the last 80 years with respect to landslide density (spatial frequency). Comparable events occurred in September 2004 and in August 1940. Rainfall from tropical cyclones Frances and Ivan during September 6-17, 2004 triggered approximately 400 landslides distributed over a 12-county region of western North Carolina (Wooten et al., 2008a; 2016). The August 13-17, 1940 tropical cyclone triggered more than 2,000 debris flows and debris slides over a 1,197 km^2 (462 mi^2) area of Watauga County (Wooten et al., 2008b). Although the 1940 storm produced an order of magnitude greater number of landslides in Watauga County than the 2018 Polk County storm, the maximum landslide density from the 1940 event (20.7 landslides/km^2; 0.37

mi^2) was approximately half of the observed maximum density from the 2018 event (38.9 landslides/km^2). Fortunately, because of the localized nature of the intense rainfall of the May 18, 2018 storm (see Stop 1 Figs. 1-4, 1-5) the 241 landslides were limited to a 67 km^2 (~25.9 mi) area of western Polk County along the BRE.

Saluda Railroad Grade

The Saluda railroad grade is the steepest standard gauge mainline railway in the United States where it crosses the BRE along the valley walls of the North Pacolet River and its tributary Joel's Creek from Tryon to Saluda (Fig. 4). Because of the steep grade (avg. 4.24%) this section of railway became known for downgrade runaway train wrecks and associated fatalities from the 1880s to 1971 (Phillips, 1986; Hill, 2006). The July 15-16, 1916 storm triggered numerous landslides along the Saluda railroad grade (Fig. 7A), disrupting a vital transportation link to the region already devastated by the storm (Southern Railway Co., 1917). Designated as an inactive railway section in 2001, the Saluda grade has experienced other slope failures since 1916. The NCGS identified 18 landslides along the Saluda railway grade (Wooten et al. 2022a) including an embankment failure-debris flow attributed to rainfall from tropical cyclone Frances or Ivan in September 2004 (Fig. 7B and Stop 1, Fig. 1-7) Wooten et al., 2012).

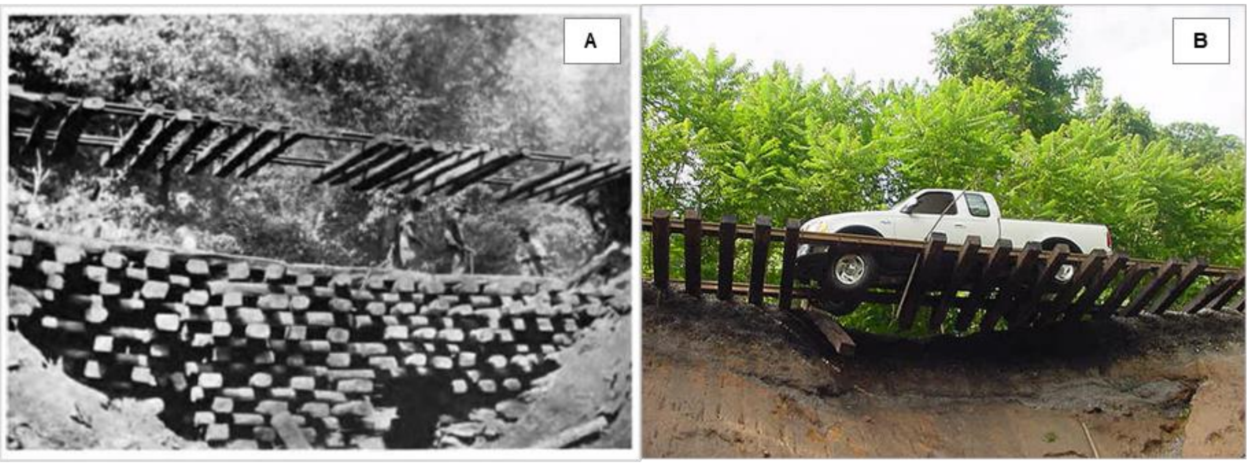


Figure 7A. View of tracks suspended above a July 15-16, 1916 embankment failure on the Saluda railroad grade where cribbing is being added as a temporary repair. The 1916 storm triggered numerous slope failures on the Saluda railroad grade where it traverses the Blue Ridge Escarpment along the Joels Creek and N. Pacolet River valleys in Polk County. Source: Southern Railway (1917). **B.** Citizen photo of a vehicle on tracks suspended above a September 2004 embankment failure on the Saluda railroad grade reported in Wooten et al., 2012. The Saluda grade became an inactive segment of the Norfolk Southern Railroad in 2001.

I-26 Saluda Grade - Howard Gap Landslide

Landslides have had adverse impacts on transportation infrastructure in The Howard Gap area of the BRE (Fig. 4) in 1916, the 1960s-70's, and more recently in 2018 when landslides also damaged power and water transmission utilities. Figure 8 shows some of 2018 slope movements relative to I-26, Howard Gap Road, and the Duke Energy 440kv transmission line. Some of the 2018 landslides upslope of I-26 recurred in unstable areas identified by Sams and Gardner (1974) during construction of I-26. Ground surface changes shown in Figure 8 were derived by comparing 2017 (pre-2018 storm) and 2020 0.5 m resolution airborne lidar DEMs (Scheip, 2021), which augmented field mapping by the NCGS and Appalachian Landslide Consultants, PLLC (ALC) in cooperation with NCDOT.

The active Howard Gap debris slide is located on the south-facing slopes of the BRE, approximately 160 m below I-26 (Fig 8.), (Wooten et al., 2019a, 2022b). Localized slope failures triggered by the May 18, 2018 storm damaged Howard Gap Road and adjoining private property, and in January 2019 after heavy rainfall on December 28, 2018, the NCDOT closed a 160 m-long section of Howard Gap Road when downward vertical displacement made it impassable. Mapping by the NCGS and ALC delineated an active ~45,000 m^2 (~484,376 ft^2) debris slide with most activity occurring within a 29,000 m^2 (~312,153 ft^2) region of the slide. Based on preliminary lidar-derived topographic profiles of the landslide from November 2020, the maximum slide thickness may be on the order of 20-30m (~65-98 ft). Movement at these depths and locations of nearby bedrock outcrops suggest that weathered bedrock may be involved in the rupture surface at depth. As of July 2022, Howard Gap Road remains closed, and the slide has damaged electrical utility lines, and severed emergency water supply lines that once connected the towns of Saluda and Tryon. Continued slow advancement of the slide presents a potential threat to a home and private property downslope. Additional potential threats to downslope areas are rapidly moving debris slides and debris flows originating from the over-steepened face of the slide mass undergoing extension and internal break-up (Fig. 10A, B).

The NCGS partnered with the U.S. Geological Survey and established two monitoring stations on the Howard Gap slide in June 2019 (Fig. 8A, B). As of early 2022, cable extension transducer data indicated slide displacement at HG-1 remained inconclusive, whereas meter-scale movement at HG-2 has been observed from field observations and total station measurements of survey stakes. Field observations identified increasing displacement of ground ruptures (scarps) on the over-steepened face of the slide mass above a residence and other private property. Additionally, repeat UAS flights have detected continued detachment and internal break-up of the slide mass there (Fig. 8B). Differential movement within the 29,000 m^2 portion of the slide mass has persisted at least into 2020.

Bright’s Creek Debris – Weathered-Rock Slide

The Bright’s Creek debris–weathered-rock slide complex is located on the southeast-facing slopes of the BRE, north of the area of concentrated landslide activity from the May 18, 2018 storm (Wooten et al., 2022a) (Figure 9). Shortly after the passage of Alberto in May 28-31, 2018 the Bright’s Creek community became concerned about large cracks that appeared in their roadways. Initial investigations by the NCGS, and later detailed mapping by ALC delineated a 0.4 km^2 (0.15 mi^2) area of active slide movement within a 0.98 km^2 (0.38 mi^2) composite debris deposit, comprised in part of other dormant debris slides and rockslides, and deposits from past debris flows (Bauer et al., 2020). Deep-seated slide movement resulted in scarps and tension cracks across a segment of a natural gas pipeline corridor. This regional pipeline supplies natural gas to private and commercial customers and is the primary source of natural gas for the electrical power plant serving Asheville and other areas of western North Carolina. The gas utility company has undertaken ongoing monitoring and mitigation, including installation of inclinometers, strain gauges on the pipeline, and re-bedding a segment of the pipeline to accommodate slide movement at an estimated cost of ~$ 4.5 million as of 2020. Extensive composite debris deposits like those at Bright’s Creek are common along portions of the BRE in Polk and Rutherford Counties (Korte, et. al., 2022; Wooten et al., 2022a,b,c), and portions of these deposits can reactivate or become active slides during periods of extended above-normal rainfall (Wooten et al., 2017, 2022b; Bauer et al., 2020, 2021).

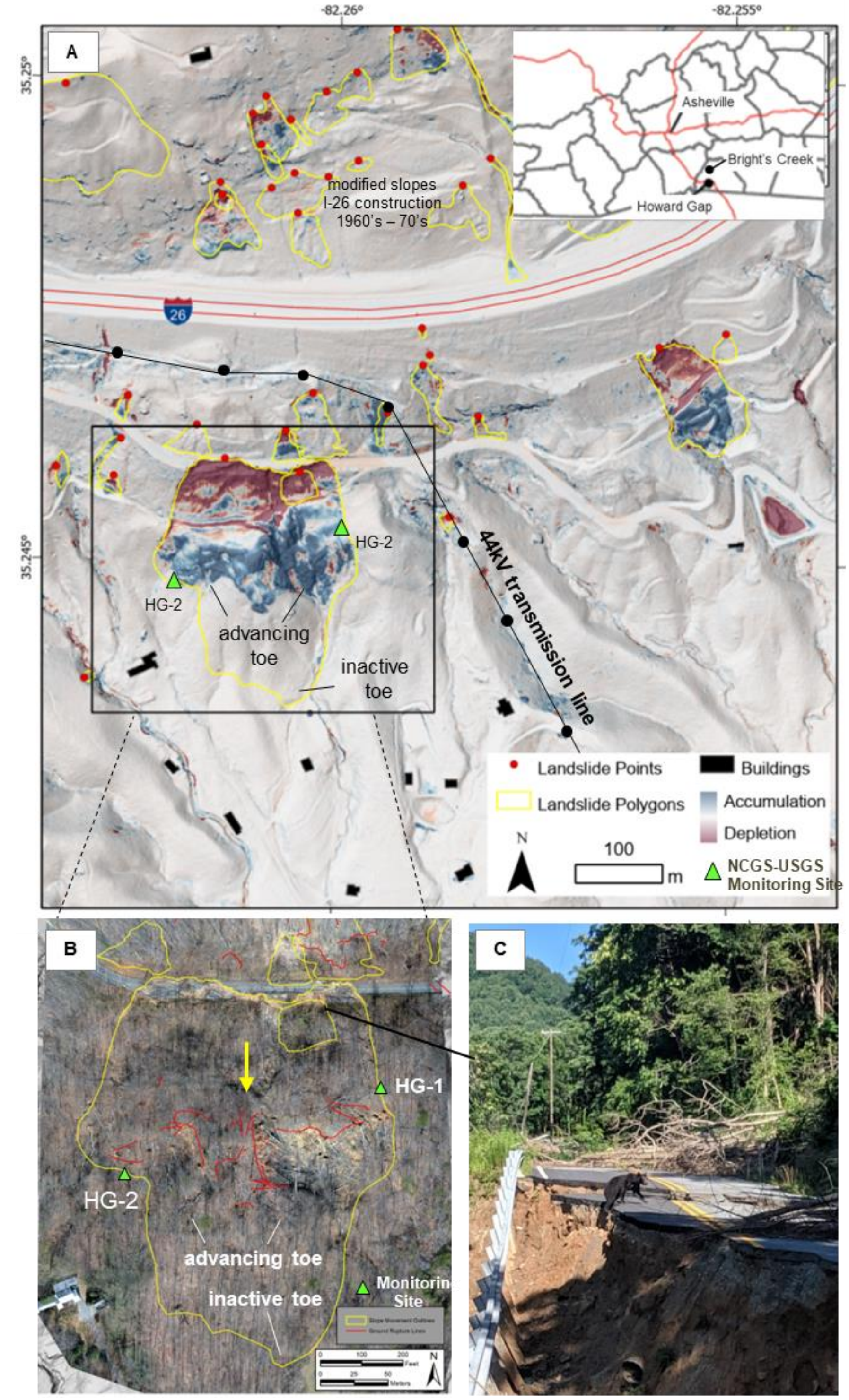


Figure 8A. Landslide features in the Howard Gap area along the I-26 Saluda grade on south-facing slopes of the BRE in Polk County. Ground surface changes (accumulation and depletion zones) derived from comparison of 2017 and 2020 0.5m resolution airborne lidar DEMs. Lidar base map by Scheip (2021); 2020 lidar funded by a data grant collaboration with NCSU and the National Center for Airborne Laser Mapping (U. Houston); landslide mapping by the NCGS and ALC in cooperation with NCDOT. **B.** January 2020 NCGS UAS image of the Howard Gap landslide (inset top map). Scarps and tension cracks (red lines) highlight the advancing face of the slide. **C.** June 14, 2019 NCGS photo of Howard Gap Road impacted by the landslide. Black bear for scale (view looking west).

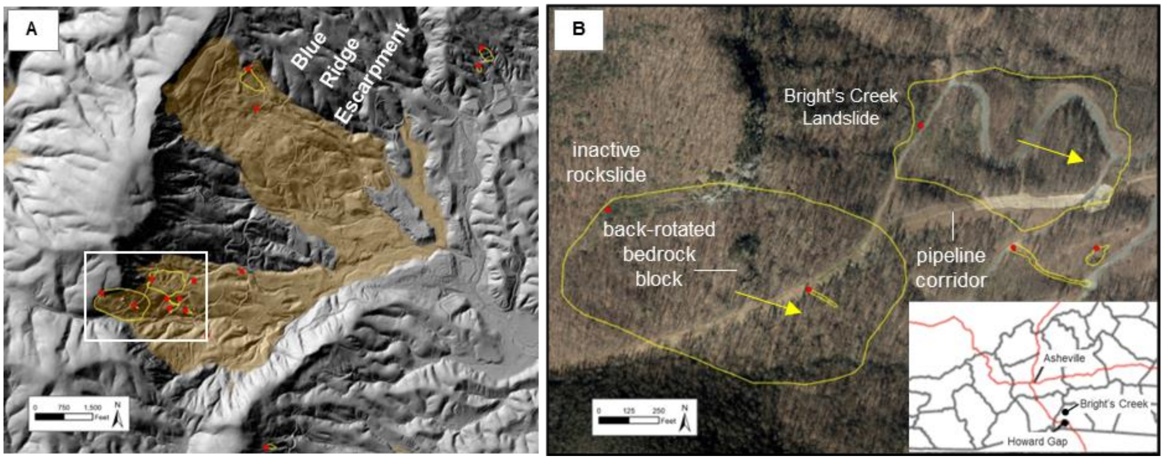


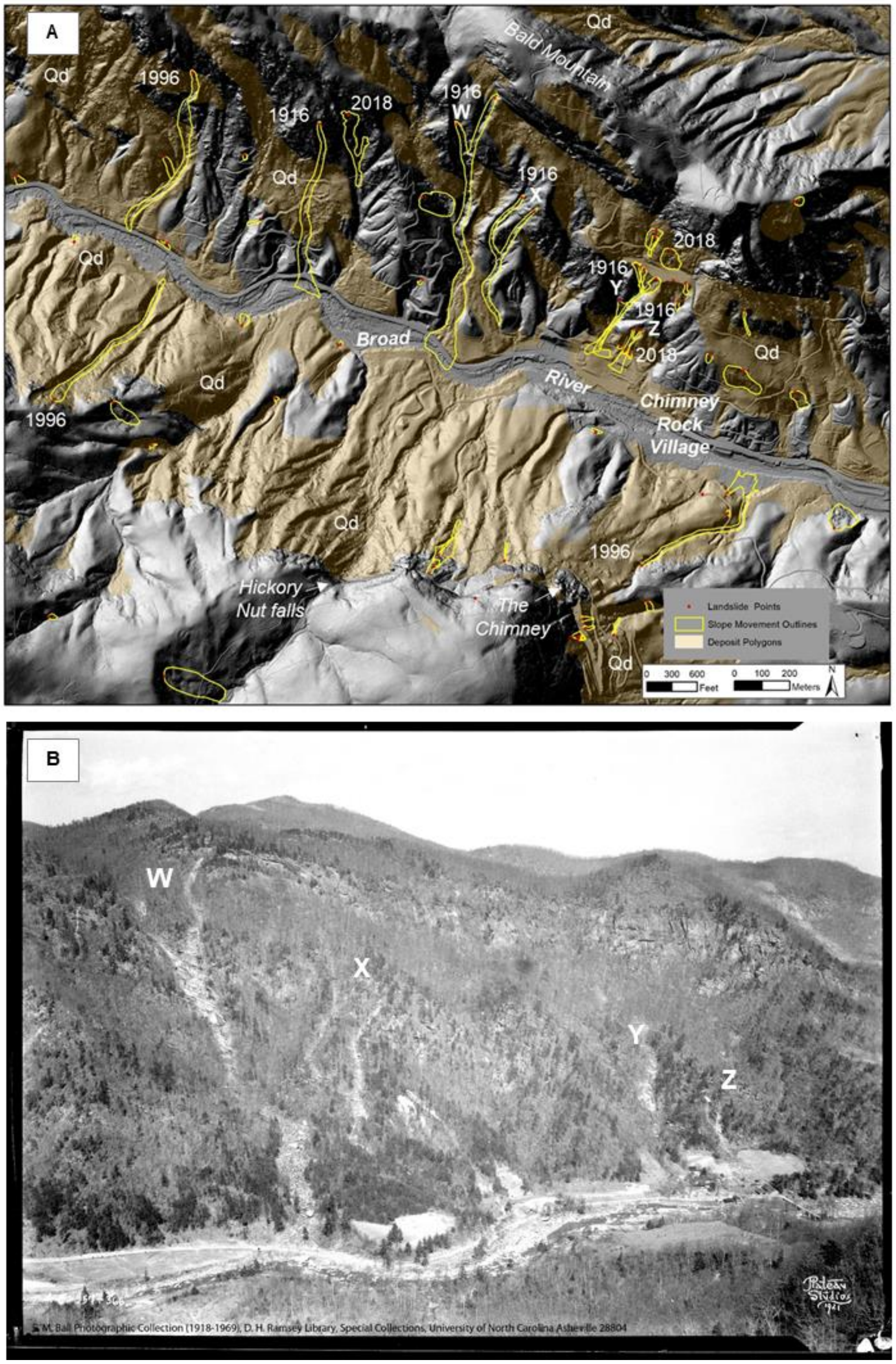
Figure 9A. Landslides within composite debris deposits (brown) mantling the slopes of the Blue Ridge Escarpment in the Bright's Creek area, northern Polk County. Map base: shaded relief map derived from a 2017 0.5m resolution lidar DEM. **B**. Inset area left. The Bright's Creek landslide (upper right) is a large debris slide – weathered-rock slide complex consisting of a 44,000 m² active portion within a 980,000 m² composite debris deposit (map left). Large back-rotated bedrock blocks comprise portions of an inactive rockslide (lower left). Yellow arrows show general movement direction. Map base: 2019 orthophotography. Landslide feature mapping by ALC and the NCGS.

Hickory Nut Gorge Reentrant

The Hickory Nut Gorge (HNG) lineament swarm transects the BRE with a WNW trend controlled at least in part by fracture orientations (Wooten et al., 2022b) (Fig. 4). Ongoing research in Hickory Nut Gorge has identified fracture networks with WNW, NW, and NE sets (Waters-Tormey, et al., 2022). Their studies found that taller, vertical fracture sets may have influenced the formation of lateral stress relief fracturing in cliffs in the massive intervals of the Henderson gneiss that delineate linear topographic features. Where the HNG lineament swarm extends WNW into the Mills Gap area of Buncombe County (Fig. 4) detailed mapping and structural analysis identified the brittle Mills Gap fault and associated fracture sets that are subparallel to the HNG trend (Wooten et al., 2010a).

Within the Rutherford County portion of HNG, extensive foot- and mid-slope deposits of debris, with areas dominated by rock blocks and boulders, reveal that the gorge walls have been prone to numerous Quaternary debris flows, debris slides and rock slope failures (Fig. 10). Documented historical landslide events include those in 1916, 1994, 1996, 2008, 2012, 2013, and 2018 (Soplata, 2016; Wooten et al., 2017, 2019b 2022b). Numerous debris flows and debris slides triggered by rainfall from subtropical storm Alberto during May 29-31, 2018 affected Chimney Rock State Park and the Town of Chimney Rock. Rock slope failure types include rockfalls, rockslides, and topples, emplaced in various transport rates such as rapid-catastrophic failures; slow-moving incremental failures; and complex failures with multiple failure mechanisms (Korte et al, 2022; Wooten et al., 2022b, c, d).

The HNG reentrant and others like it may influence local weather patterns. Lee and Goodge (1984) suggest that the HNG may have provided an opening in the BRE barrier that focused low-level upslope flow into a flash flood-producing thunderstorm complex in 1978. Johnstone and Burrus (1997) point to the unique terrain of the HNG as a geomorphic factor in the September 4, 1996 flash flood that produced more than 300 mm (~12.8 in) of rain in 3 hours triggering debris flows and causing extensive damage in the Gorge and the Town of Chimney Rock (Fig. 10A) They concluded that the predominant mechanism responsible for the heavy rainfall was the orographic rise of moist unstable air up the east slope of the BRE, but one that could be indirectly linked to the concurrent passage of Hurricane Fran 320 km (~200 mi) to the east in the North Carolina Piedmont and Coastal Plain.



E. M. Ball Photographic Collection (1918-1969), D. H. Ramsey Library, Special Collections, University of North Carolina Asheville 28804

Figure 10A. Landslide features in Hickory Nut Gorge in the area of Chimney Rock State Park and Chimney Rock Village. Year of occurrence is given for selected debris flows. Qd = Quaternary debris deposits. Lettered locations W, X, Y, Z for the July 15-16, 1916 debris flow tracks correspond to those in B below. Data sources for landslide features: NCGS landslide geodatabase (https://landslidesncgs.org); Soplata, 2016; L. Haydock, personal communication). Map base: shaded relief map derived from 0.5m lidar DEM. **B.** Circa 1921 photograph of the south facing slopes of Hickory Nut Gorge. Lettered locations W, X, Y, Z for July 15-16, 1916 debris flow tracks correspond to those in Figure 10A above. Photo source: E. M. Ball Collection, UNC-Asheville courtesy of Katherine Scheip, Chimney Rock State Park.

Swannanoa Reentrant

The Swannanoa reentrant coincides with WSW-ENE trending Swannanoa lineament (Dennison and Stewart, 2001; Hill, 2013) where it crosses the BRE near Old Fort and Ridgecrest, North Carolina near the McDowell-Buncombe county line (Fig. 4). This area of the BRE has a history of recurring landslide events, reported in 1916 (Southern Railway Company, 1917), and in 2004, 2013, 2015 and 2018 as documented in the NCGS landslide geodatabase. In 1879 the cost to North Carolina to build the railroad between Old Fort and Ridgecrest had been $2 million and the lives of 125 men, who were disproportionally black convict laborers, to complete the nine miles (~14.5) km of railroad grade between two points which were only ~3.4 air miles (~5.5 km) apart (Abrams, 1976). The deadliest single slope failure recorded in the NCGS landslide geodatabase is the Swannanoa Tunnel cave-in that killed 21 men shortly after its completion on May 11, 1879 (Abrams, 1976). The Old Fort railroad grade suffered scores of landslides during the 1916 storm including many cut slope and embankment failures (Southern Railway Company, 1917) (Fig. 11A). A landslide that killed a railroad worker near the Licklog Tunnel on May 6, 2013 was in the same through-cut for the tunnel portal as July 15-16, 1916 landslides documented by the Southern Railway Company (1917) (Fig. 11B). Impacts on highway infrastructure include recurring slope failures and associated mitigation costs from 1991-2018 on I-40 at the crest of the Blue Ridge Escarpment near the Buncombe-McDowell County line (Landon, et al., 2022)

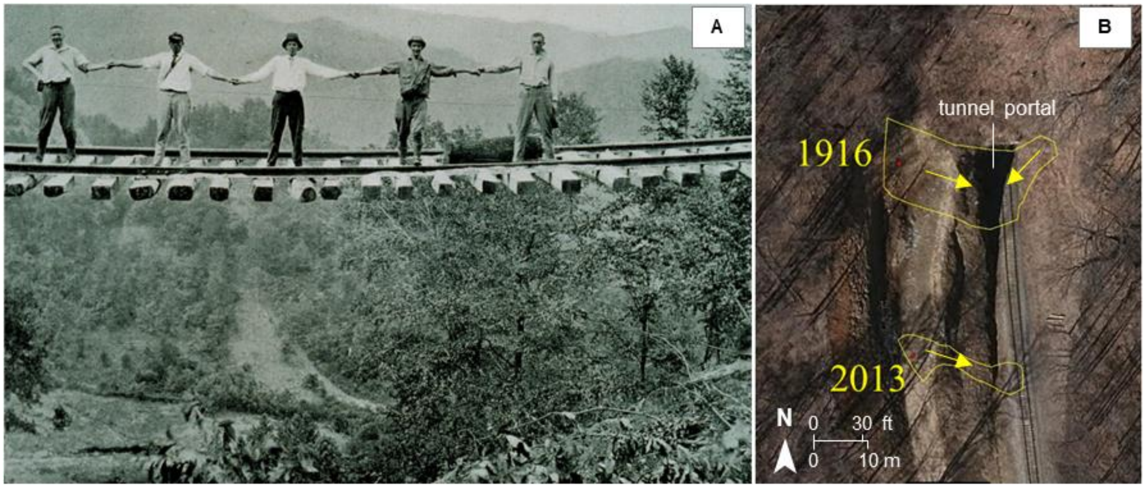


Figure 11A. Railroad workers stand on tracks suspended above one of the many July 15-16, 1916 embankment failures on the Old Fort railroad grade that traverses the Blue Ridge Escarpment from Ridgecrest at the Buncombe-McDowell County line to Old Fort, McDowell County. Source: Bandel, 2016. **B**. Approximate outlines of slope failures from July 15-16, 1916 and May 5-6, 2013 at the north portal of the Licklog tunnel on the Old Fort railroad grade. Arrows indicate slide movement direction. The 2013 slide killed a railroad worker inspecting the tracks after reports of an earlier slide. As seen in the orthophoto the east-facing slope above the tracks was benched for stability after the 2013 slope failure. Map base: 2019 orthophoto. Data sources: Southern Railway (1917), NCGS landslide geodatabase (https://landslidesncgs.org).

North Cove Reentrant

The North Fork of the Catawba River has incised into the BRE to form a large steep-walled valley, here called the North Cove reentrant (Fig. 4). The overall NE-SW alignment of North Cove (Fig. 12A) generally parallels the trend of the Linville Falls fault there as mapped by Brant and Reed (1970), and more recently in the Marion West 7.5-minute quadrangle by Cattanach et al., 2020. In the Marion West quadrangle, a large portion of which is along the BRE, structural data collected by Cattanach et al. (2020) show that foliation and mylonitic foliation generally strike NE-SW and dip moderately to the SE. They also identified a NE-SW striking, steeply dipping fracture set, although the main set strikes NW-SE.

Although detailed landslide mapping is not yet complete for North Cove, existing information shows the area to be susceptible to mass wasting. North Cove experienced debris flows in the 1916 and 1940 storms, and extensive debris deposits and coalescing debris fans from past mass wasting mantle the foot slopes (Bryant and Reed, 1970; Cattanach and Wooten, 2019). Collins (2008) and Latham et al. (2009) describe three major, long-runout debris flows that significantly damaged the Blue Ridge Parkway and slopes below in the Pisgah National Forest during tropical cyclone Frances in September 2004 that originated as fill slope failures on the Parkway (Figure 12). Owing to the rugged high relief of the BRE here, the Licklog and Bear Drive debris flows each traveled over 3 km from the Blue Ridge Parkway onto the Pisgah National Forest and into Curtis Creek. Further up North Cove where topographic relief is less, the Chestoa debris flow traveled 2.4 km where it deposited material onto a pre-existing debris fan on the English Farm (Cattanach and Wooten, 2019). Repairs for the Chestoa slope failure alone cost ~$700,000, including construction of a new retaining wall. Eight major landslides, primarily cut slope and embankment slope failures, forced closure of major segments of the Blue Ridge Parkway after Frances and Ivan. The Parkway is the most visited unit of the National Park System, and, in addition to the millions of dollars in repair costs, its closure for months after September 2004 adversely affected the communities along the Parkway dependent on tourism dollars generated by Parkway visitors.

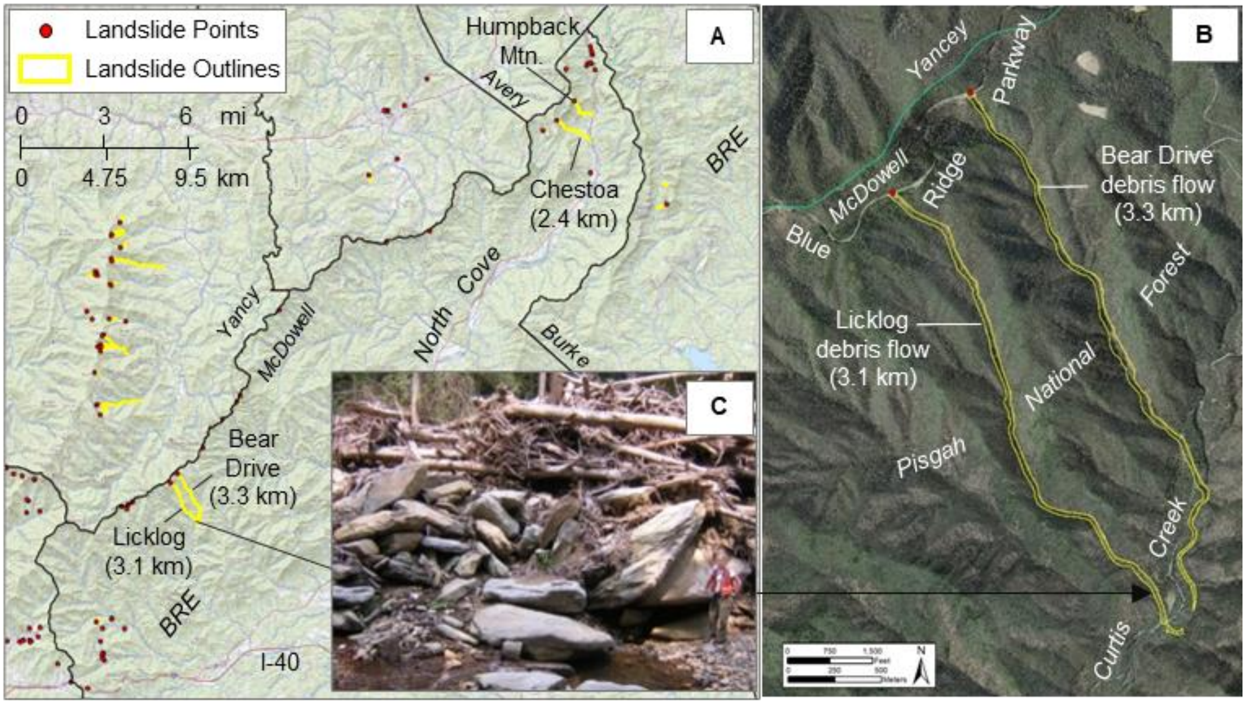


Figure 12A. Map showing locations of the Licklog, Bear Drive and Chestoa debris flows in North Cove where the North Fork of the Catawba River has eroded into the Blue Ridge Escarpment (BRE). These long-runout debris flows originated in embankment slopes on the Blue Ridge Parkway during heavy rainfall from tropical cyclone Frances during September 6-8, 2004. Map distance track lengths in kilometers. The July 15-16, 1916 storm triggered the Humpback Mtn. debris flow and likely others in North Cove. An August 13-14, 1940 debris flow in North Cove caused a fatality. Map source: WNC Landslide Hazard Data viewer http://mapviewer.landslidesncgs.org; accessed 07/27/2022. **B.** Mapped tracks of the Licklog and Bear Drive debris flows that each traveled over 3 km from the Blue Ridge Parkway onto the Pisgah National Forest and into Curtis Creek. Map base: 2019 orthophotography. **C.** Boulder and large woody debris deposits in the lower runout zone of the Licklog debris flow near Curtis Creek, Pisgah National Forest. November 17, 2004 NCGS photo.

Deep Gap Reentrant

Bedrock structure can be related to recurring debris flow activity in the Deep Gap area of Watauga County (Fig. 4) where over 600 debris flows occurred during the August 13–14, 1940 storm (Greene, 1941; Wieczorek et al., 2004; Wooten et al., 2008b). Green (1941) also recounts debris flows in the Deep Gap reentrant triggered by heavy rainfall from the July 15-16, 1916 tropical cyclone. Here, Elk Creek and its tributaries form a highly dissected erosional reentrant within the BRE that coincides with WNW-trending ductile faults (Bryant and Reed 1970) and other WNW-trending topographic lineaments, and associated fractures and brittle faults that intersect the BRE (Gillon et al., 2009; Hill 2018). Unstable rock slopes occur west of the Deep Gap reentrant where these WNW-trending brittle structures associated with the Boone Fault (Hill, 2018; Hill and Stewart, 2018) overprint the Linville Falls Fault (Wooten et al., 2008b and Gillon et al., 2009). Hill (2018) and Hill and Stewart (2018) present strong evidence for Cenozoic movement on the Boone fault linked to post-orogenic uplift and mantle dynamics in the Appalachians.

Devastating impacts from flooding and landslides from August 13-14, 1940 storm were felt throughout Watauga County, as well as portions of Ashe, Caldwell, Wilkes and McDowell counties along the BRE. Landslide hazard mapping identified over 2,000 1940 landslides (mainly debris flows and debris slides) in Watauga County alone (Wooten et al., 2008b, 2018) where the storm caused 17 fatalities, with 14 as a direct result of landslides (Witt and Wooten, 2018). Nine of the deaths were related to debris flows in the Deep Gap-Stony Fork areas (Witt and Wooten, 2018). The storm also had severe impacts on transportation infrastructure. Landslides severed U.S. 421 in many places, including several locations in Deep Gap (Fig. 13) closing the road between Boone and North Wilkesboro until September 18, 1940 (Witt and Wooten, 2018). In addition, the 1940 storm severely damaged the Linville River Railway, putting an end to railroad service into Boone.

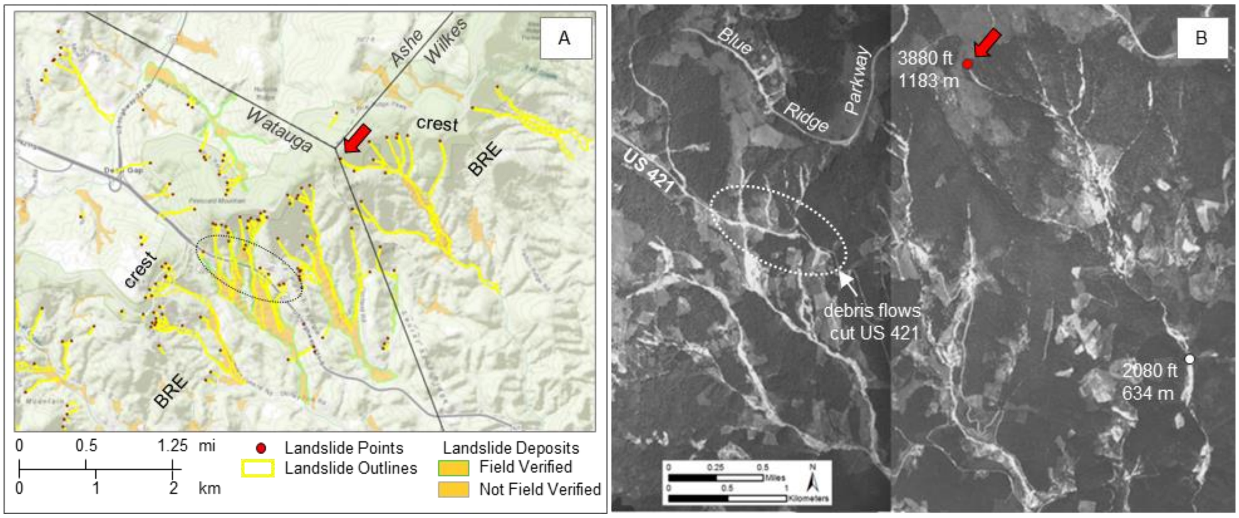


Figure 13. Debris flows from the August 13-14, 1940 tropical cyclone in the Deep Gap area of Watauga, Wilkes and Ashe Counties, N.C. Dashed oval areas outline an area of US 421 cut by debris flows. Note the long tracks of debris flows that descended the Blue Ridge Escarpment relative to the tracks northwest of its crest. **A.** Map of the area from the WNC Landslide Hazard Data viewer http://mapviewer.landslidesncgs.org; accessed 07/27/2022. **B**. September 1940 aerial photograph mosaic of the Deep Gap area showing debris flow tracks from the August 13-14, 1940 storm. Reference elevations are given in feet and meters for the western debris flow track that dropped ~550 m (~1,800 ft) in elevation over a map distance of ~3 km (1.86 mi). Red arrow points to a debris flow source area shown in A and B. Flooding and sedimentation extended well downstream from the mapped debris flow tracks.

Here, in Deep Gap, as in other locations on the BRE, debris flows originating southeast of the BRE crest traveled great distances down the BRE, with flooding and sedimentation extending significantly further downstream (Fig. 13). Topographic relief, locally in excess of 500m (~1,800 ft), and coalescing debris flows along first- and second-order stream channels at or near peak discharge produced debris flows with km-scale runout distances. These long runout debris flows contrast with the much shorter debris flows that originated northwest of the crest of the BRE where there is a marked decrease in topographic relief (Figure 13). The Sherwood area in northwest Watauga County was also a location of concentrated debris flow activity from the 1940 storm. The Deep Gap debris flows were longer, inundated a greater planimetric area, and were far more destructive than those in the Sherwood area where topographic relief is generally less (Witt et al, 2008).

Reentrants, Cross Structures, and Seismicity

Some WNW-ESE brittle cross-structures that coincide with landslide prone reentrants in the BRE discussed here are also linked to seismicity in the region. Reinbold and Johnson (1987) describe shaking events from an 1848-1874 earthquake swarm near Rumbling Bald Mountain in Hickory Nut Gorge that suggest seismically induced rockfall. Soplata (2016) postulates a coseismic origin for massive rockfall deposits mapped in detail in that area of Hickory Nut Gorge. Along the WNW-oriented lineament swarm trend from Hickory Nut Gorge (Fig. 4), the Mills Gap fault zone is in the general epicentral area of the 1916 magnitude 5.2 Skyland earthquake (Stover and Coffman, 1993; Bechtel, et al., 2006) and shows evidence of Cenozoic movement (Wooten et al., 2010). The seismically active, ESE-trending lineament that contains the Boone fault that traces directly in line with the Deep Gap reentrant in Watauga County (Hill, 2018) also houses the estimated epicenter of the magnitude 5.0 earthquake in Wilkes County (Stover and Coffman, 1993; Bechtel, et al., 2006). The recently identified and mapped ESE-striking Little River Fault in Allegheny County, North Carolina produced ground rupture from the magnitude 5.1 Sparta earthquake, and the first evidence for motion along a post-orogenic lineament that crosses rocks of the Blue Ridge (Hill, et al., 2020, Figueiredo, et al., 2022).

Mass Wasting, Bedrock Structure and Landscape Evolution

Detailed studies have shown mass wasting to be a significant process in the evolution of the Blue Ridge Mountains and BRE in North Carolina (Wooten et al. 2016, 2022b), and in Virginia (Eaton et al, 2003; Sas and Eaton, 2008). In North Carolina, brittle and ductile bedrock structures influence the location and development of topographic reentrants incised into the BRE, which are areas of concentrated, recurring mass wasting. At the landform and hillslope scales, bedrock fracture systems play a prominent role in slope instability in the North Pacolet, Green River, Hickory Nut Gorge and Deep Gap reentrants (Fig. 4). In addition to controlling the locations of some stream channels and thereby debris flow pathways, fracture systems also facilitate channel development through plucking by debris flows (Wooten et al., 2022a). Fractures and other bedrock discontinuities are also important factors in debris flow initiation and landscape evolution in Virginia (Sas and Eaton, 2008). Research in South Carolina and adjacent North Carolina shows that rivers erode into the BRE by plucking along joint systems that also influence the development of prominent knickpoints (Lasley and Ranson, 2018; Wheeler and Ranson, 2019; Egan and Ranson, 2020; Skipper and Ranson, 2020).

A growing body of evidence shows that post-orogenic uplift (Hill, 2018; Hill and Stewart, 2018) and topographic rejuvenation (Gallen et al., 2013) drive aspects of the landscape evolution of the North Carolina Blue Ridge. Stream capture and subsequent rapid incision by the capturing stream is also a significant driver in landscape evolution in the southern Blue Ridge and along the BRE (Prince et al., 2010, Johnson, 2020; Prince this guidebook). Rapid incision following stream capture can produce steep valley walls prone to mass wasting like Linville Gorge (Johnson, 2020), and drainages along structurally controlled topographic lineaments such as Hickory Nut Gorge and the Green River gorge (Prince et al., 2010; Wooten et al., 2022a). Capture of the French Broad headwaters produced the Jocassee Gorges area (Prince et al., 2010) which includes the Toxaway River gorge. Aligned with NW-SE trending lineaments and fractures (Merschat et al., 2003; Wooten et al. 2003a; Prince et al., 2010), the Toxaway River gorge also exhibits a variety of mass wasting features (Wooten et al., 2003a, b).

CONCLUSIONS

The high relief, steep slopes, and the dissected nature of the BRE, coupled with its orographic influence on rainfall, make it susceptible to debris flows in particular, but also to debris slides, rockslides and rockfalls. Eight storm events produced major impacts from landslides and floods from 1901 to 2018 along the North Carolina portion of the BRE. Steep walled, topographic reentrants where streams have incised into the BRE by exploiting ductile and brittle bedrock structures are prone to decadal-scale, recurring landslide activity. Owing to the topographic relief in headwater areas of major rivers along the Escarpment, impacts from storm-triggered debris flows and flooding can extend from tens to hundreds of km (>100 mi) downstream into the Piedmont. Mass wasting, erosion, stream capture, bedrock structure, and in some cases seismicity, can be linked to the evolution of the BRE. The rugged terrain and associated landslide hazards along the BRE continue to pose threats to public safety, and to critical transportation and energy infrastructure corridors. The many benefits that come from living on and near the BRE, and building, operating, and maintaining the infrastructure that crosses it have been costly in terms of dollars and lives.

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LANDSLIDE RESOURCES ONLINE

NCGS WNC Landslide Hazard Data viewer: http://mapviewer.landslidesncgs.org

- interactive web map viewer
- data download
- landslide hazard mapping status

NCGS WNC Landslide Hazards website: http://landslidesncgs.org

- landslide data tour guide
- information on landslide hazards
- story maps on landslide hazards and events.

N.C. Department of Environmental Quality website:
https://deq.nc.gov/about/divisions/energy-mineral-land-resources/north-carolina-geological-survey/geologic-hazards/landslides

- information on landslides and other geologic hazards
- historical landslide events – hurricanes and landslides

Appalachian Landslide Consultants, PLLC :https://appalachianlandslide.com.

- information on landslide hazards
- interactive web map viewer
- landslide mapping using lidar
- landslide presentations

HazMapper https://hazmapper.org/

- Google Earth Engine application, open-source and open-access mapping of global natural hazards including landslides (Scheip and Wegmann, 2021).

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The Climate of the Southern Blue Ridge Mountains and Its Influence on Viticulture

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INTRODUCTION

The southern Blue Ridge mountains, which extend from southern Virginia to northeastern Georgia, display an intricate climate, with much local to regional variation in temperature, precipitation, and moisture. These variations are largely related to the topographic complexity of the mountain range, and they are observed across multiple scales (e.g., regional to local, with unique processes contributing at each scale). Day-to-day and seasonal variations in wind direction and air mass character add to this complexity. There is much temporal variability as well, including year-to-year fluctuations in atmospheric circulation that result in significant interannual temperature and precipitation swings, for example, periods of extreme wetness and droughts.

Over broad scales, the climate (i.e., macro-climate) of the mountain range is dictated by elevation. The lowest elevations (i.e., valley floors) display a humid subtropical climate (Cfa) with warm, moist summers and relatively mild winters that are punctuated by occasional winter storms and outbreaks of frigid Canadian air. The higher elevations, in stark contrast, are wetter and much windier and cooler, especially during the cooler months of the year. The highest elevations (5000-6684') of the mountain range, for example, exhibit a sub-arctic Boreal (Dfc) climate with temperatures that are often well below freezing in the winter.

In this paper, the complexities of Blue Ridge climate are described with some attention given to climate attributes that favor or hinder viticultural operations. In the first section, temperature variations across the mountain range are outlined and related to atmospheric processes from the regional to local scale, where topographic features control air movements. Special consideration is given to the region immediately southeast of the highly incised Blue Ridge escarpment, including the thermal belt, where relatively milder temperatures favor viticulture. In addition, secular temperature trends are identified over the last 120 years and related to climate change. In the second section, precipitation and moisture patterns are described and linked to the topography of the mountain range, especially the southwest portion of the Blue Ridge escarpment, which often experiences the heaviest rainfall. These topographic linkages are related to the prevailing wind directions as well as local patterns of convection that set up on during the summer. Lastly, secular trends in precipitation and drought are summarized.

TEMPERATURE PATTERNS

Temperatures, on average, decrease with elevation in the Blue Ridge Mountains, and the spatial pattern of temperature therefore mimics elevation contours on a topographic map (Figure 1). There are some important variations in this pattern, however, that are pertinent to viticulture and described in this section. The elevational drop in temperature is illustrated by comparing temperatures near the top of Mt Mitchell, NC, the highest peak in eastern North America, and Marion, NC, which sits 5000 feet below in a valley fifteen miles to the southeast. (Table 1).

Temperatures are much cooler atop Mount Mitchell, with significant seasonal and diurnal variations in the rate of temperature drop. Several factors are responsible for this temperature decrease and each can vary in its influence depending on the general weather conditions: On fair weather days, the earth's surface absorbs a good portion of the solar radiation, largely visible light, and warms up. The atmosphere is quite transparent to the incoming shortwave radiation, provided that there are relatively few clouds; in effect, the atmosphere acts like glass, which allows light to pass through it. Mountain ranges, being well above the mean surface level of the earth, are removed from this radiatively warmed surface. While they are warmed radiatively at a local scale, cooler air from the atmosphere readily mixes in via convective circulations.

The elevational decrease in temperature is also tied subtly to the decreased influence of greenhouse gases (e.g., carbon dioxide, methane and water vapor) higher in the atmosphere. These gases selectively absorb outgoing infrared radiation (IR) and re-radiate a portion of this radiation back to the surface. The concentration of these gases decreases with elevation, thus the amount of IR absorbed and re-radiated downward from the atmosphere is lessened at higher elevations. This reduced greenhouse effect induces a slight cooling effect.

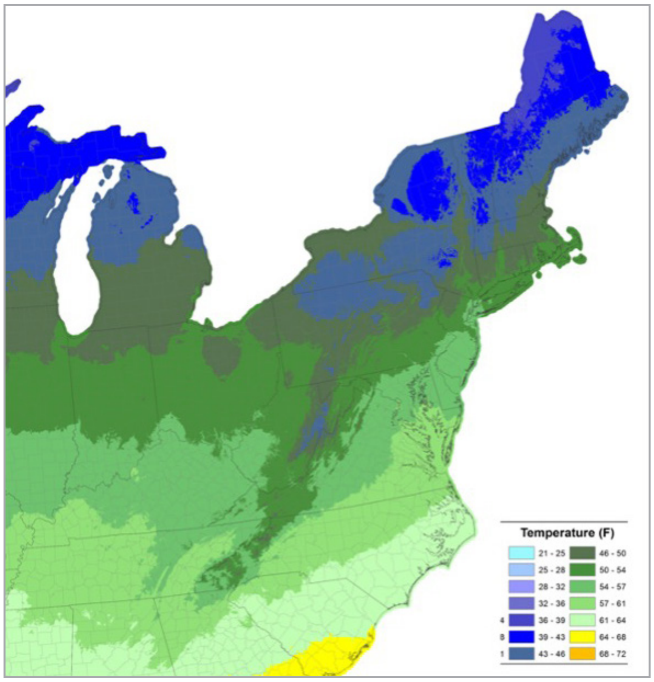


Figure 1. *Mean annual temperature. Map constructed from PRISM data https://prism.oregonstate.edu/normals.*

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Marion Tmax	50	55	63	72	78	85	87	86	80	71	61	53
Mt. Mitchell Tmax	34	36	42	50	58	64	66	65	61	54	46	38
Difference	16	19	21	22	20	19	21	21	19	17	15	15
Marion Tmin	26	29	36	44	52	61	64	63	57	45	35	29
Mt Mitchell Tmin	18	20	25	33	41	49	52	52	47	37	29	22
Difference	8	9	11	11	11	11	12	11	10	8	6	7

Table 1. *Comparison of mean monthly maximum (Tmax) and minimum (Tmin) temperatures (F) at Marion, NC (1204') and Mt. Mitchell, NC (6240').*

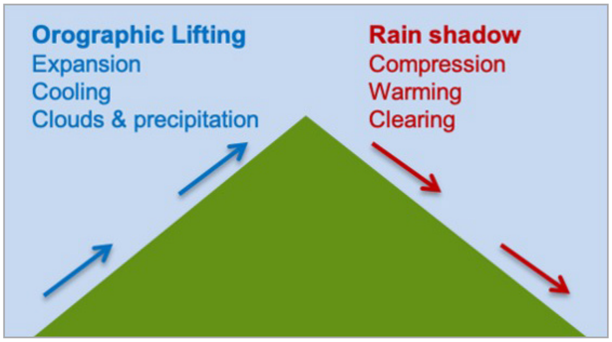


Figure 2*. Changes in air properties as large scale synoptic winds are forced over a mountain ridge.*

On many days, the temperature decrease with elevation is further accentuated by vertical air motions. When air rises, it expands because it encounters a progressively thinner atmosphere. This expansion induces cooling that occurs at a constant rate of approximately 5.4 F per 1000 feet, the dry adiabatic lapse rate. Rising air always cools at this rate unless it becomes saturated, whereupon heat, liberated by the processes of condensation or deposition, cuts the cooling rate nearly in half. Sinking air warms at the dry adiabatic lapse rate, leading to markedly warmer temperatures in the valley bottoms (Figure 2). This effect is especially pronounced on windy days.

Vertical air motions are observed on most days across the Blue Ridge and are forced by wind circulations on two distinctly different spatial scales. On a synoptic or weather map scale, winds circulating around high or low pressure systems are forced over mountain ridges (Figure 3). Orographic lifting occurs on the windward side of ridges, and when the air is sufficiently moist, temperatures cool to the point that rising air cannot hold all of their moisture (Figure 2). This results in condensation, cloud production, and an increased probability of precipitation, especially towards the ridge tops. This scenario is quite common along the Blue Ridge escarpment when southerly or southeasterly winds advect moisture from the Atlantic Ocean or Gulf of Mexico. It will be discussed in more detail in the second part of the paper. The downsloping flow on the leeward side of the mountain results in warming and drying of the atmosphere, especially towards the valley bottom. While its warming influence is felt in the valleys of the inner Blue Ridge, it is especially marked in the inner Piedmont and foothills region due to the big elevational drop across the escarpment.

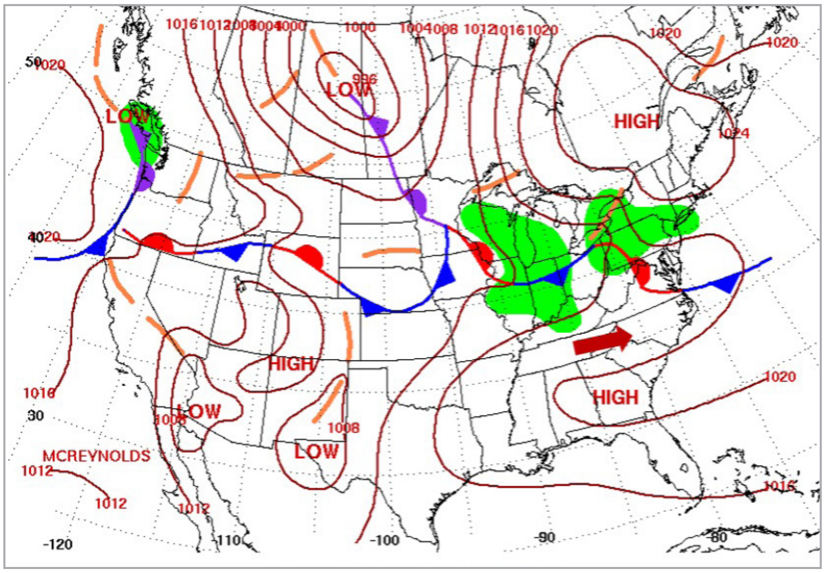


Figure 3. *Surface weather map for August, 21 2007 (NCEP 2021). The westerly circulation north of the high pressure system (red arrow) produces orographic lifting and cooling on the northwest slopes while downslope flow causes warming on the southeast slopes of the Blue Ridge Mountains.*

On a local scale, the warming of air in the valley and mountain sides during the day expands and lightens air parcels as they rise convectively towards the mountain top. This process produces convective cells in which valley air rises/cools and air aloft warms/sinks into the valley (Figure 4). Owing to a higher solar elevation and longer periods of daylight, these convective circulations are strongest and deepest during the late spring andearly summer.

The daily range in temperature at Marion is roughly double that of Mount Mitchell (Table 1), as valley temperatures warm up more during the day and cool off more at night. The daytime warming on fair weather days is driven both by the increased sensible heat flux over the radiatively warmed surface and wind circulations that draw adiabatically warmed air down to the valley surface. This average daytime elevational difference is especially great during the spring and summer months as it is the high sun season (i.e., long days and high sun angle). Also, the higher solar radiative inputs drive deeper and more persistent convective cells that draw down more adiabatically warmed air from higher levels in the atmosphere.

The reduction in the elevational temperature gradient at night is largely tied to valley cooling, which is caused by outgoing infrared radiation (IR) emanating from the surface and the resultant cold air draining down the slopes into the valley. As the air cools, its density increases (mass per unit volume), and earth’s gravitational force

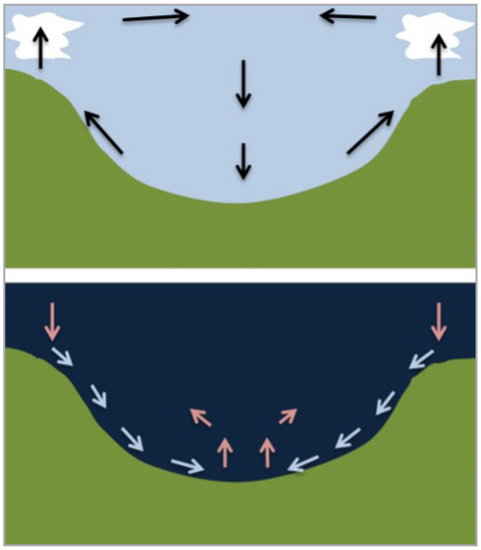


Figure 4. *Typical valley and ridge circulations on sunny day (top panel) and a clear, calm night (bottom panel). Black arrows indicate convective cells driven by daytime heating. Blue arrows show cold air drainage, and the red arrows reveal the movements of relative warmer air in response to the cold air drainage.*

(mass* gravity) increases the downslope pulling (Figure 4). The cumulative effect of the cold air drainage process over the course of the night is an extremely inverted temperature profile, opposite of the daytime pattern, in which the very coldest air lies at the very bottom of the atmospheric column (Figure 5). The resultant nocturnal inversion layer can be anywhere from 500 to more than 1500 feet thick. Above this layer, temperatures typically drop with elevation at the rate observed on a typical day, unless there is subsidence and attendant adiabatic warming higher in the atmosphere. Interestingly, winds often speed up at night immediately above the nocturnal inversion layer, providing a stark contrast with the still conditions within the inversion layer. This phenomenon is referred to meteorologically as a nocturnal low-level jet, and it periodically affects the higher mountains in the Blue Ridge, especially where the winds are funneled through wind gaps.

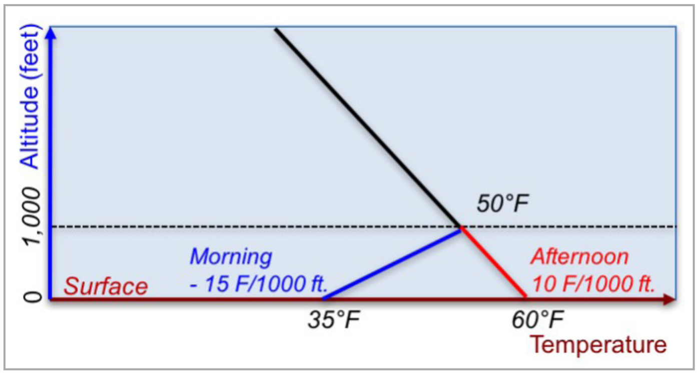


Figure 5. *Vertical temperature profile in the morning, featuring a strong radiation inversion (blue), and the afternoon (red), showing atemperature drop with elevation.*

Nocturnal radiation inversions and cold air drainage commonly develop when skies are clear to partly cloudy, and winds are relatively light (Figures 4 and 5). As air drains downslope, its molecules make contact with the ground and gradually conduct away their heat. Consequently, the air gets colder and colder before pooling up in a basin or frost hollow. The effects of radiative cooling and cold air drainage are most pronounced in the fall and winter, as the hours of darkness exceed the hours of light. This explains why the difference in daily minimum temperature between Maron and Mt. Mitchell (Table 1) is the lowest during this time of the year. The radiative cooling effect is further enhanced because the humidity is especially low. Since water vapor is a greenhouse gas, its absence allows more of the radiated IR to escape into space instead of being re-radiated back to the surface. Nocturnal radiation inversions and cold air drainage typically occur within sprawled out high pressure systems (e.g., Figure 6) where there is an absence of pressure isobars and hence wind (i.e., note that wind speed correlates with the pressure gradient). Radiative cooling is also greater in broad valleys and basins, as they have a greater sky view and hence a larger atmospheric window to emit IR out to space (Henry, 1923).

Windy conditions at night mute the effects of radiative cooling by keeping the air well mixed. Chaotic air flow, induced by obstacles on the ground (e.g., hills, trees, building etc.), mix the radiatively cooled air upwards into the atmosphere thus drawing down relatively warm air aloft. This chaotic flow is exemplified by exceeding gustiness in the wind and is especially prominent in the valleys. In contrast, winds are stronger and steadier on the ridge tops, as they are exposed to a freer-flowing atmosphere. Windy conditions are largely restricted to the winter and shoulder seasons, spring and fall, when strong low and high pressure systems and attendant cold fronts periodically sweep through the area.

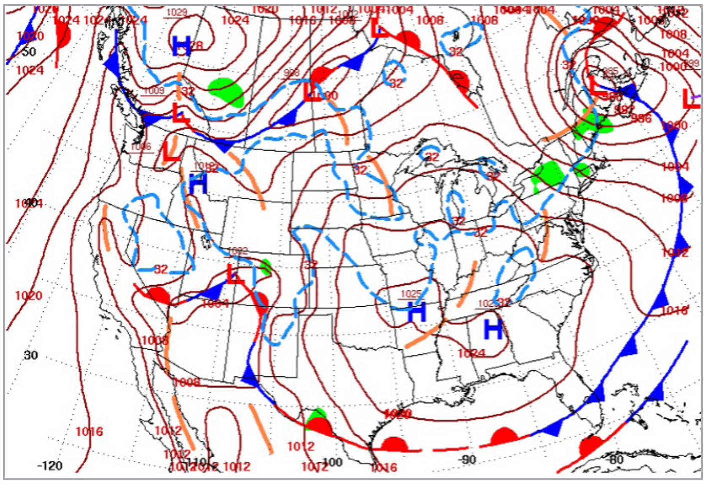


Figure 6. *Surface weather map for April 22, 2021 (NCEP 2021).. The relative absence of isobars (i.e., pressure differences) within the large surface high pressure system provides calm conditions across the southern Blue Ridge Mountains. These conditions, coupled with a very dry atmosphere, provides an ideal environment for nocturnal radiational cooling.*

Spatial and temporal variations of temperature across the Blue Ridge are especially important in dictating where crops can and cannot be cultivated. Extreme cold can injure vines, while freezing or subfreezing temperatures in the spring can kill vine shoots, especially if a warm air outbreak early in the spring encourages early budbreak and shoot growth (Patterson and Buechsenstein 2018). On the other hand, extremely hot conditions can decrease wine quality when fruits are ripening during the late summer. A relatively mild temperature regime, as exemplified by a Mediterranean climate, is especially favorable for grape cultivation (Patterson and Buechsenstein 2018). In the Blue Ridge Mountains, vineyard sites are largely confined to lower elevations, especially areas of sloped terrain above valley bottoms (e.g., frost hollows). The climate in the higher mountains is too cold during the winter and spring to support viticulture. On the other hand, valley bottoms (i.e., frost hollows) are unfavorable, as they are subject to the nocturnal pooling of cold air and therefore an increased probability of damaging spring frosts.

Grape cultivation is hindered by two types of cold events during the spring (Poling et al. 2019). Most common is a radiative frost in which radiative cooling on clear nights creates a nocturnal inversion layer with the coldest air pooling in frost hollows, as discussed earlier. During the spring, these events typically occur on the tail end of an unseasonably strong cold outbreak. Cold air deposited in the area within a large high pressure system (Figure 6) is especially dry, hence it possesses a lower greenhouse gas concentration and cloudless skies. These conditions promote more radiative cooling, and the absence of wind allows the air to effectively drain into low-lying valleys and basins. Much less common during the spring is an advective freezing event in which Arctic air is rapidly drawn southward by strong winds between a cyclone and strong anticyclone. Figure 7 provides a vivid example of exceptional advective event in April 2007 that decimated various agricultural crops (e.g., peaches in the Carolinas). The advection of cold air results in a long period of subfreezing nocturnal temperatures and windy conditions that injure or kill grape shoots and buds. All areas of the landscape - ridge tops, slopes and valley bottoms - are affected by advective cold events. However, their frequency increases markedly with elevation, occurring virtually every spring in the higher elevations (e.g., 3500' and higher). These events are partly responsible for the upper elevational limit on grape cultivation across the region.

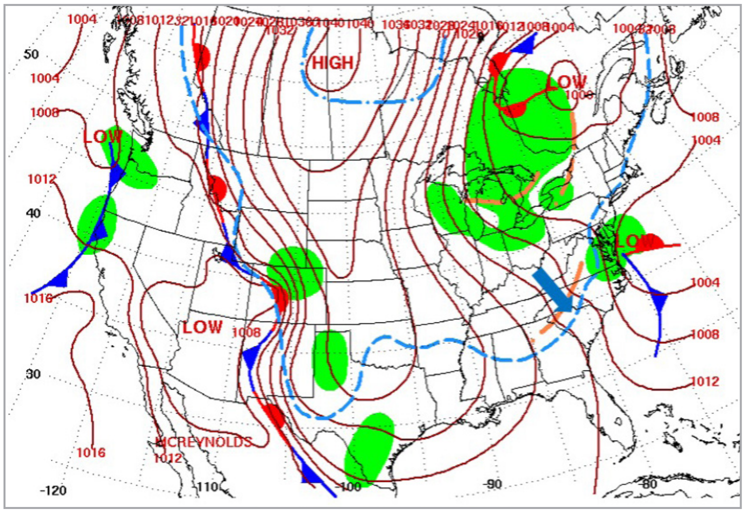


__Figure 7.__ Surface weather map for April 7, 2007 (NCEP 2021). The pressure gradient between the low pressure situated off the Virginia coast and the high pressure centered in central Canada generates strong northwesterly winds (blue arrow) across the Blue Ridge Mountains. These winds advect unseasonably cold air across the region. Temperatures are below freezing, even in the deep valleys and inner Piedmont, as the blue dashed line identifying the 32F isotherm, is situated southeast of the mountain range.

The Blue Ridge Mountains and adjacent inner Piedmont exhibits much topographic complexity with numerous small mountain chains and valleys and ridges on a regional scale, plus many hills on a local scale (Figure 8). Consequently, slopes dominate much of the region, providing many potentially suitable sites for viticulture. While there are numerous frost hollows, they are generally small in size and cover only a small portion of the landscape.

This complicated topographic pattern is especially evident on the edges of the highly dissected Blue Ridge escarpment and adjacent inner Piedmont from southern Virginia to northern Georgia. This region is known as a "thermal belt", as it displays a relatively milder temperature regime more suitable for fruit cultivation. In southern Virginia, the thermal belt is known to extend as high as 2200 feet in elevation (Poling et al. 2019). The relatively mild temperatures in the thermal belt relate to several factors: First, there is an abundance of sloping terrain, as discussed above, which is accentuated by the general decrease in elevation from the escarpment southeastward across the inner Piedmont. Second, the slopes are relatively steep in places, which reduces the sky view, thus decreasing the net outgoing radiation and radiative cooling (Henry, 1923). Third, the area is situated on the leeward side of the escarpment and is therefore more protected from advective cold events, which are described above. This protection is provided by downslope flow associated with northwesterly winds that induce adiabatic warming and warmer temperatures. The Polk-Rutherford County region in North Carolina appears to be especially protected from the cold air because of the concave orientation of the escarpment (i.e., the SW to NE oriented escarpment trends north and then curves to the east-northeast). This orientation permits cold air advected by winds from multiple directions (e.g., west, northwest, and north) to descend and warm adiabatically (Figure 8). Also, the South Mountains, which are situated northeast of the region, induce warming when cold air is advected from the northeast. Fourth, the downsloping winds are sufficiently strong on occasion to keep the lower atmosphere well mixed so that any radiatively cooled air at the surface is readily mixed upward and replaced with warmer air above. This prevents cool air drainage and radiation inversions from developing. Indeed, Henry (1923) found that Tryon, NC, which is situated in Polk County, experienced fewer inversions on average than four other study sites.

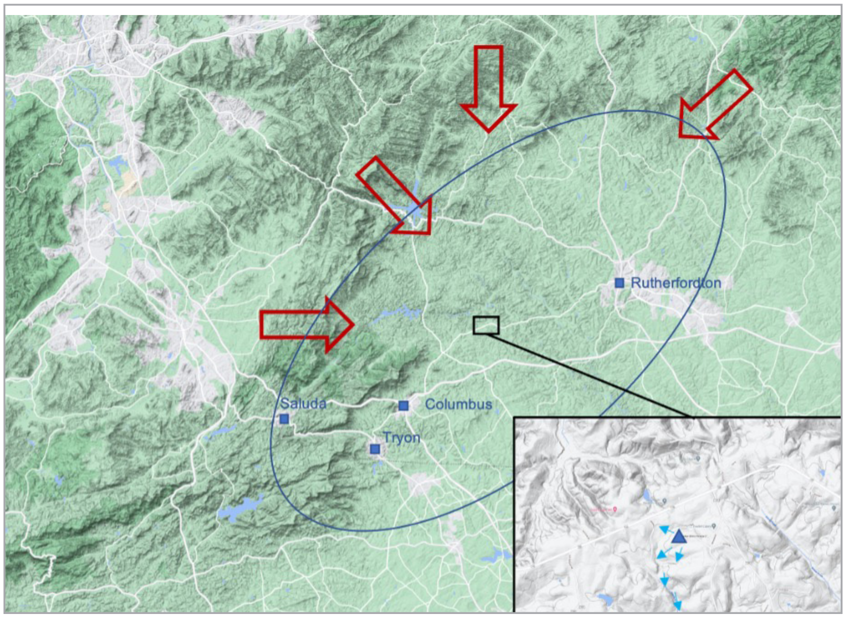


Figure 8. *Topographic map of the Blue Ridge escarpment centered on the thermal belt region (blue oval). The expanded inset map highlights the local scale terrain in the vicinity of the Parker-Binns vineyard. Radiatively cooling air (light blue arrows) drains downslope from the vineyard (blue triangle) then southeastward through a frost hollow. The red arrows identify, for an advective cooling event, downslope warming accompanying winds coming from different directions.*

Temperatures across the southern Blue Ridge Mountains are projected to increase in response to human-induced climate change (Konrad and Fuhrmann, 2013). Average temperatures, however, have increased only slightly over the last 120 years (Figure 9), and there has not been any increase in average summer season temperatures. While the planet as a whole has warmed dramatically over the last century, there are areas, including the Southeast U.S., that have experienced little or no increase in temperature (Konrad and Fuhrmann, 2013). This is due in part to the vagaries of climate variability that are forced by various mechanisms, including changes in solar intensity, large scale circulation, land cover and concentrations of atmospheric aerosols. It should be noted that the warmest temperatures over the last 120 years occurred in the early part of the 20th century, culminating in the Dust Bowl era of the 1930's. The exceptional dryness in the Great Plains and associated anomalous circulation pattern resulted in very hot weather, and this heat was periodically advected eastward to the Blue Ridge during the warm season.

Temperatures have increased markedly over the past 40 years (1980-2020), and climate scientists believe that some portion of this warming is the result of the reduction in particulate matter from coal burning power plants. The cleaner air is slightly more transparent, thereby allowing more solar radiation to reach the surface and warm it. The warming observed over the last 40 years can be tied to modest increase in the growing season length, roughly 0-4 days across the Blue Ridge Mountains. Much of this increase is tied to a slightly earlier average date of the last spring freeze (32F or less) (Figure 10).

Most evident in the temperature time series is the high degree of interannual temperature variability. This variability greatly exceeds the modest positive trend in temperature over the last 120 years, and, when coupled with intra-seasonal variability, presents a challenge to viticulturalists, who must contend with the attendant temperature fluctuations, for example, an exceptionally warm late winter followed by a killing frost in the spring.

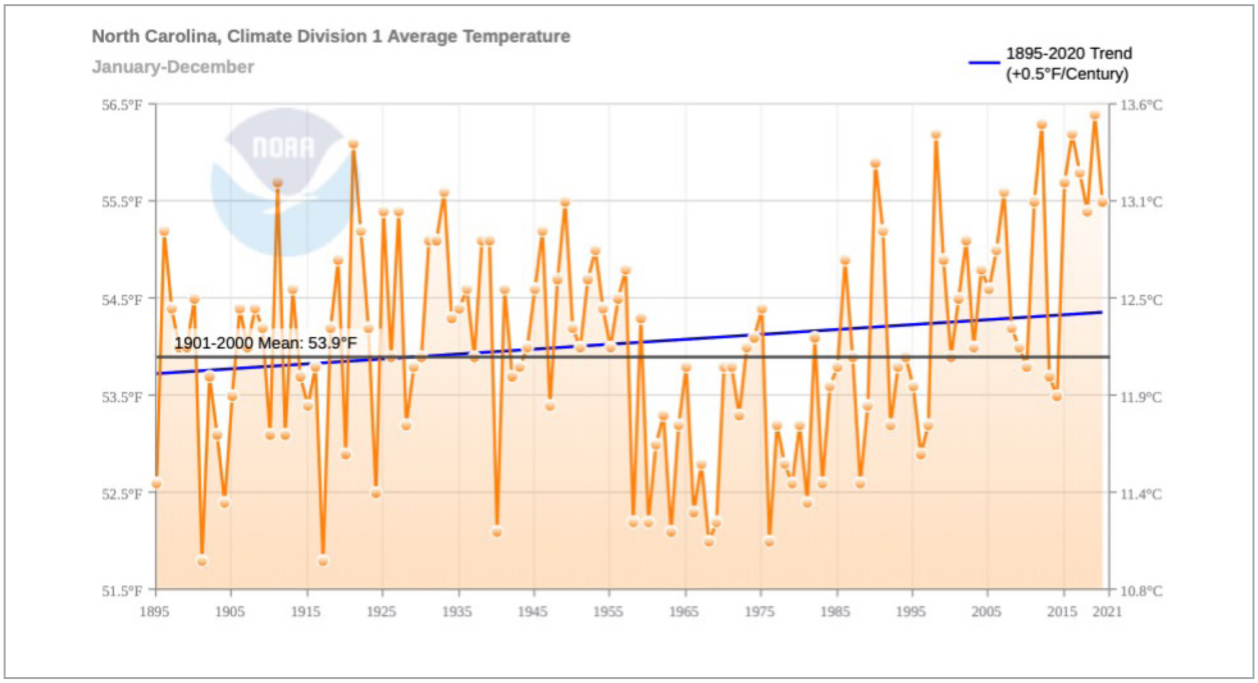


Figure 9. *Time series of mean annual temperature for the NC Southern Mountains climate district, which covers much of the southern Blue Ridge Mountains (NCEI 2021).*

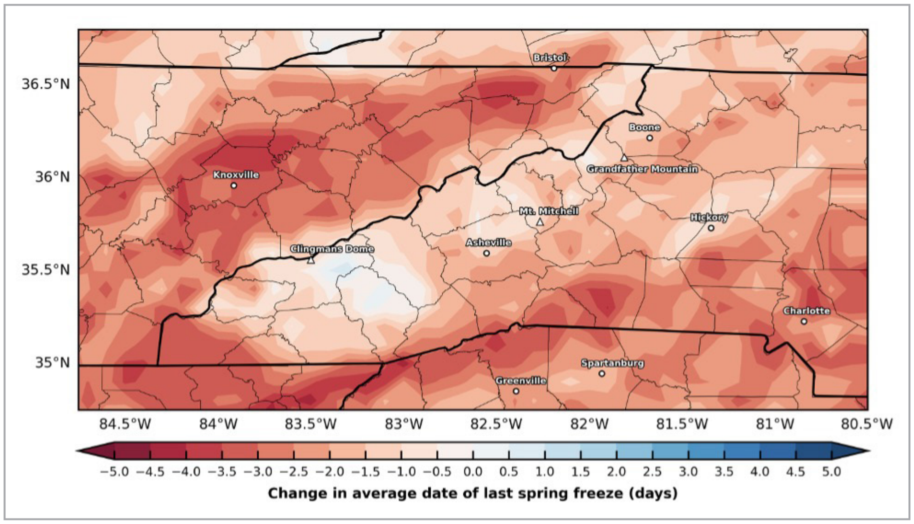


Figure 10. *The change in the average date of the last spring freeze from 1981 to 2020. The temperature data were obtained from the ERA-Interim model initialized analysis that combines surface weather observations and modeled data.*

PRECIPITATION AND MOISTURE PATTERNS

There is much variability in mean annual precipitation across the southern Blue Ridge Mountains (Figure 11). The heaviest precipitation occurs in the vicinity of the escarpment south of Cashiers and Sapphire, NC, where over 80” of precipitation is observed on average. The driest region is situated only 50 miles away in the region around Weaverville and Marshall, north of Asheville, NC, where less than 38 inches of precipitation falls in an average year. This precipitation variability is largely related to elevation and slope orientation relative to different moisture sources.

Precipitation requires two basic ingredients: 1) water vapor, which is often imported from the Gulf of Mexico or Atlantic Ocean and 2) rising air that is generated by convection or forced lifting. In the Blue Ridge Mountains, forced lifting is typically provided by passing weather disturbances (e.g., approaching front and low pressure systems) and enhanced greatly on the windward side of mountain ridges via orographic lifting. As discussed in the prior section, rising air always expands and cools. Because it has a finite capacity to hold moisture (i.e., water vapor) the rising air ultimately reaches saturation at the lifting condensation level (Figure 12). Further lifting condenses out a portion of this moisture, forming cloud water droplets and ultimately precipitation. The precipitation rate depends on how much moisture is in present in the atmosphere and how fast the air rises through the atmospheric column. Warm air has a much greater capacity to hold water vapor and, being lighter, has an increased propensity to lift convectively. Convective lift is roughly 500 times faster (~40 ms-1) than forced lifting (Figure 13). Consequently, precipitation rates are often much greater in the summer. The resultant convective cells, however, occur over much smaller areas and shorter time intervals (e.g., brief afternoon thundershowers that frequently bubble up over the highest terrain). This is polar opposite of the typical winter precipitation event in which a front or low pressure system passes through the region, producing widespread light to moderate precipitation via slow, forced lifting.

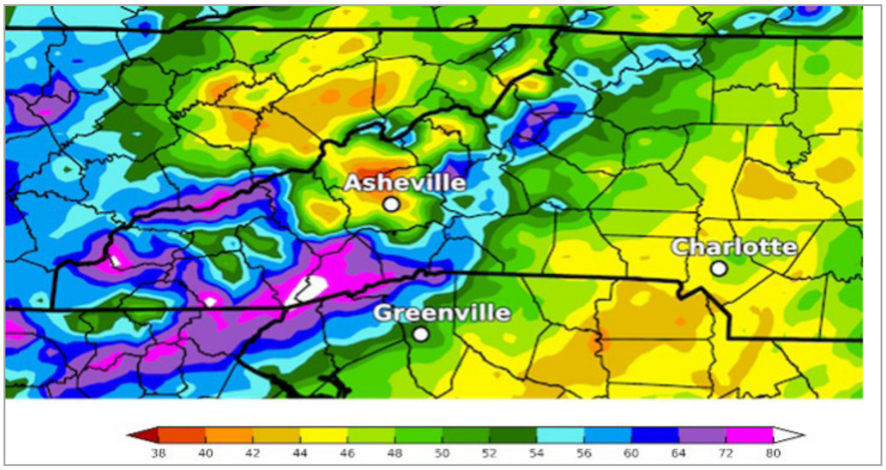


Figure 11. *Mean annual precipitation for the period: 1895-2016. The map was constructed from monthly PRISM data, which is found in the Hydroclimate Extremes Atlas (CISA 2021).*

The spatial pattern of precipitation across the southern Blue Ridge Mountains does not show much seasonal variation (Figure 14); however, there is marked seasonality in the atmospheric circulations and processes that produce these variations (Konrad, 1996). During the cool season (October-April), winds blow most frequently from the west and northwest. Consequently, orographic lifting occurs most commonly on the western and northwest slopes of the Blue Ridge, along the Tennessee – North Carolina border (e.g., the Smoky Mountains). On many days, this air mass is of a continental origin, relatively cold and dry. As a result, clouds may develop but the rising air parcels lack the water vapor to produce precipitation. When precipitation does occur, it is typically light. When cold Canadian air passes over one or more of the Great Lakes, however, it can absorb enough moisture to produce orographic precipitation on the western slopes. And this precipitation often falls in the form of snow over the higher elevations (Perry and Konrad,

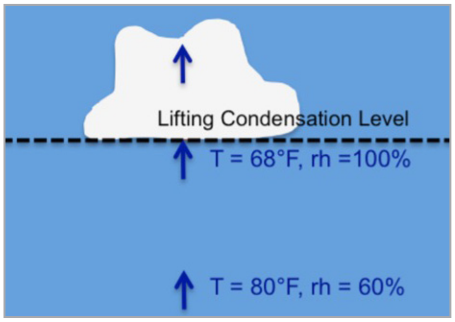


Figure 12. *Rising air expands and cools, causing the relative humidity (rh) to increase. Note that the relative humidity expresses how close the air is to saturation. Since cooler air cannot hold as much water vapor, the relative humidity increases to the point that the air becomes saturated at the lifting condensation level (rh = 100%). Condensation, which is required to remove the excess water vapor, results in microscopic-sized water droplets that form the convective cloud.*

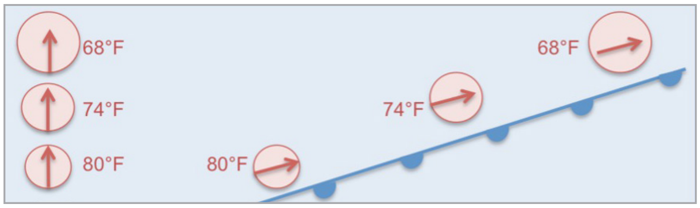


Figure 13. *Convective lifting (left) is associated with a radiatively warm surface. Forced lifting can occur in several ways, including the lifting of warmer air over cooler air along a front (right).*

2006; Perry et al 2010). On the northwest slopes, the greatest proportion of orographically enhanced precipitation occur when Gulf air swings around in a clockwise fashion (i.e., southerly to southwesterly flow that becomes more westerly) as it approaches the mountain ridges. This commonly occurs as a high pressure system departs to the east and a weak low pressure system approaches from the west.

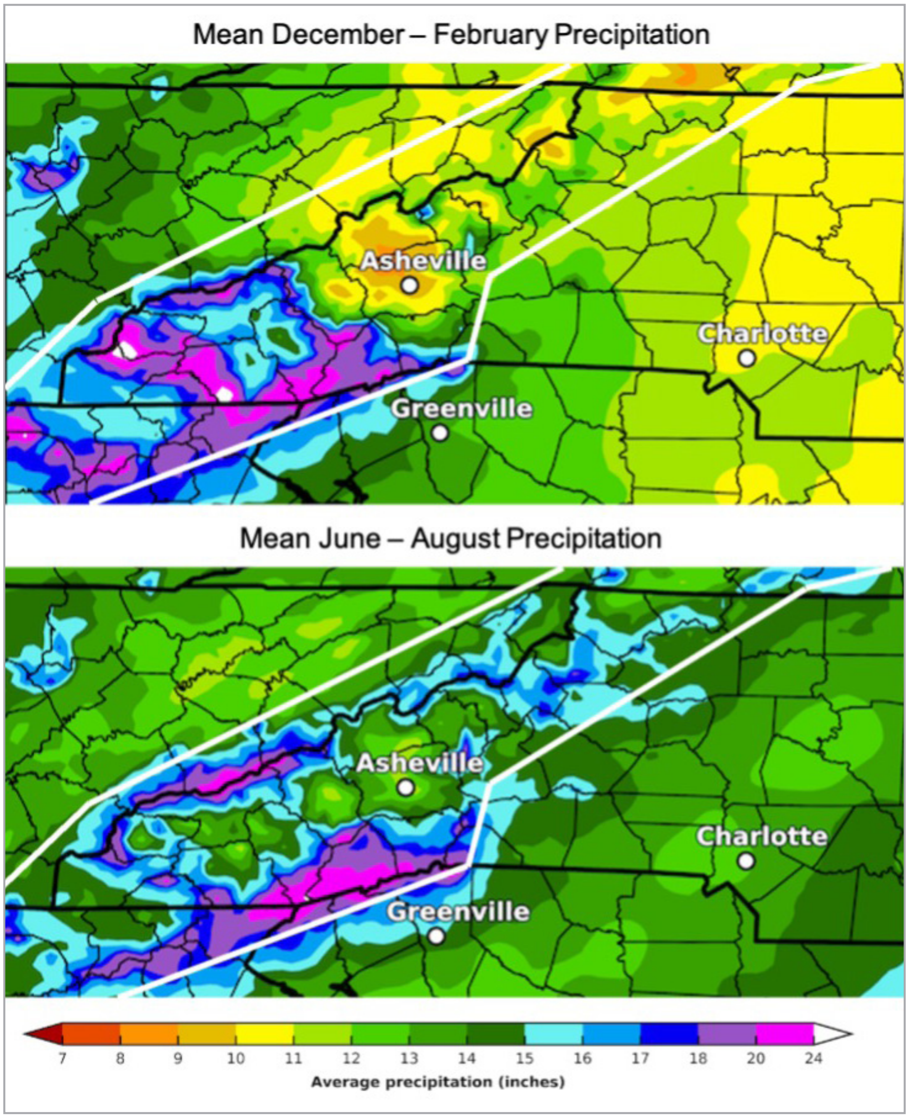


Figure 14. *Same as figure 11, except for winter (December-January) and summer (June-August). The white polygon roughly circumscribes the southern Blue Ridge mountains.*

During the cool season, the prevailing west to northwesterly circulation is punctuated by short periods in which an approaching strong low pressure system draws warm and moist Gulf air farther to the north. This air is forced orographically over the Blue Ridge escarpment, especially its south and west-most section, which receives the highest precipitation totals on average. When the approaching low pressure passes to the south, easterly or southeasterly winds ahead of the system can advect copious amounts of Atlantic moisture against the entire escarpment region, resulting in heavy precipitation. And if temperatures are sufficiently cool, exceptionally heavy snowfall can occur. The March Superstorm of 1993, which dropped 50" of snow near the top of Mount Mitchell, provides an excellent example (Figure 15). While orographically enhanced heavy precipitation events along the escarpment occur much less frequently, the collective contribution of these events to the cool season total often exceeds the amount contributed by more frequently occurring precipitation events moving in from the west.

The inner Blue Ridge Mountains and plateau region receives much less precipitation than the escarpment and ridges to the southeast and northwest, respectively. This occurs because the area is rain-shadowed no matter what direction the winds are blowing. The rain shadow effect is especially pronounced in the French River Valley north of Asheville and the New River Valley around Galax and Independence, VA. The effect is greatest in the winter season, as these valleys receive only about a third of the precipitation that typically falls along the southwest portions of the Blue Ridge escarpment (Figure 14).

During the warm season (May – September), winds show less day-to-day variation, as the clockwise circulation of the Bermuda High, situated to the east, provides a persistent warm and moist southwesterly to southerly flow. This is especially the case in the months of July and August. In this maritime tropical regime, cold fronts approaching from the northwest or north, often slow down or stall out, bringing with them widespread showers and thundershowers. The warmth and moisture, coupled with longer days and a higher solar azimuth, provides an ideal environment for deep convection and the production of afternoon to early evening thundershowers. A portion of this precipitation is recycled, as water vapor evapotranspired from the moist soils and lush vegetation provide additional moisture to feed the convection.

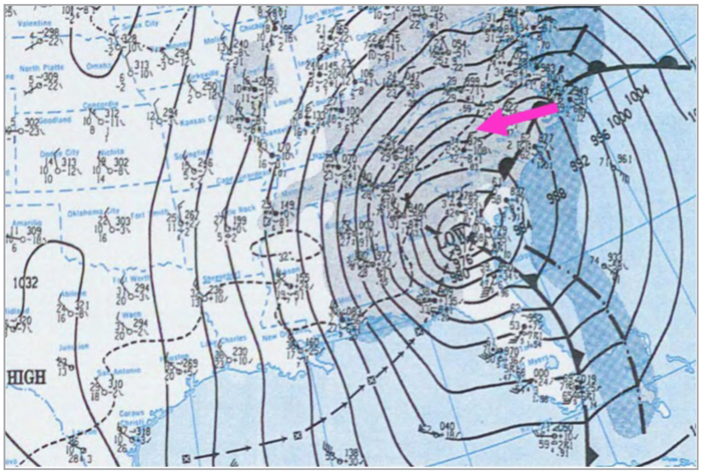
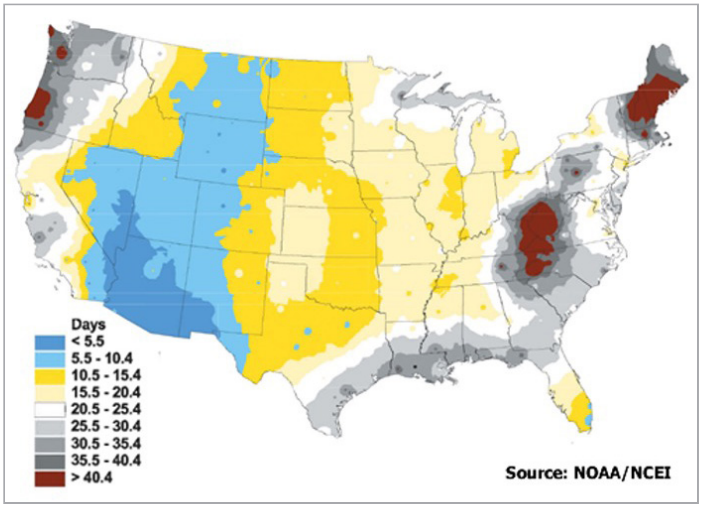


Figure 15. *Surface weather map for March 13, 1993 depicting the March Superstorm. Strong easterly winds are denoted by the pink arrow (NCEP 2021).*

On a typical day, convective uplift is focused over the higher ridges and peaks, as discussed earlier (Figure 4). These areas, being relatively warmer than the air above the adjacent valleys, act as an elevated heat source. During periods of fair weather, the convection remains anchored there and produce, at most, towering cumulus clouds and a few light showers during the afternoon. When the atmosphere is more moist and convectively unstable, thundershowers develop there and drift downstream over the adjacent valleys, carried by the regional scale winds (Sugg and Konrad, 2017; Sugg and Konrad, 2019). If there is a weather disturbance approaching the area (e.g., cold front), the thunderstorm cells can organize into a squall line while advancing eastward or southeastward over the inner Piedmont and foothills.



Source: NOAA/NCEI

Figure 16. *Mean annual number of days with dense fog (visibility <.25 miles).*

Dense fog occurs more frequently in the interior Blue Ridge Mountains and the adjacent Tennessee Valley relative to other areas of the country (Figure 16). The moist air mass combined with the common occurrence of afternoon convective precipitation primes the atmosphere for radiation fog in the valleys, where the cooler air drains and pools. This is especially the case around streams, which being relatively warm in the summer, provide additional water vapor via the process of evaporation (Figure 17). Radiational fog is most prevalent in the late summer and early fall because of the extended period of radiational cooling associated with the lengthening period of darkness. Occasionally, the fog can linger through the morning hours, especially in deep valleys that remain shaded by the mountain ridges for an additional hour or two. During the late summer and early fall, high pressure systems are frequently present in the region, and the associated absence of winds further promotes fog development and persistence. With little or no wind, there is no mechanism for mixing out the moisture until convection commences later in the morning.

While the high humidities in the region reduce moisture loss on grape vines during hot periods, it encourages fungal disease development (Patterson and Buechsenstein 2018). Average relative humidities during the late summer are higher both in the bottom of valleys where fog occurrence is maximized and in the higher mountains, where temperatures are cooler. Given the marked interannual variability in warm season precipitation and temperature, there can be much year-to-year variability in the occurrence of fungal disease and heat stress in the vineyards. This variability is expected to increase as the climate continues to warm.

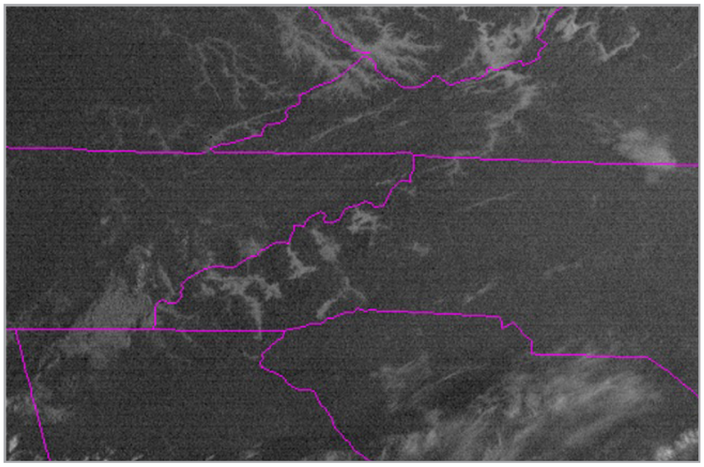


Figure 17. *Visible satellite image depicting early morning fog (areas of white) over stream valleys in the southern Appalachian Mountains.*

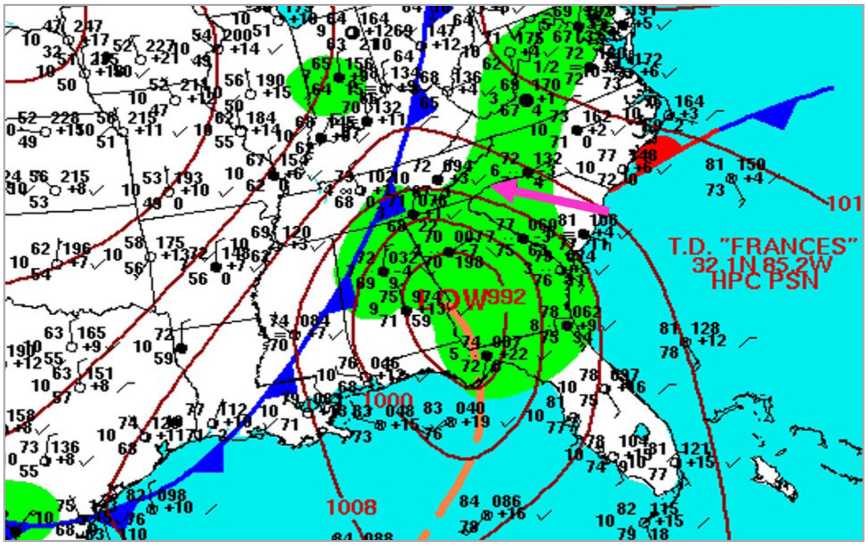


Figure 18. *Surface weather map for September 14, 2004 depicting Tropical Depression Frances (NCEP 2021). Easterly winds are denoted by the pink arrow.*

The heaviest rainfall events in the southern Blue Ridge Mountains are usually associated with weakening tropical systems (e.g., tropical storms or depressions) moving northward out of the Gulf of Mexico (Konrad 1994; Konrad and Perry 2010). These systems typically strike in late August and September during the peak of the hurricane season. The southerly to easterly circulation on the north side of these systems (e.g., TD Frances as shown in Figure 18) generates strong orographic lifting along the escarpment, where prodigious quantities of tropical moisture are wrung out of the atmosphere. The heavy rainfall (Figure 19) often produces localized flash flooding and broader scale river flooding downstream in valleys situated on either side of the escarpment. In addition, debris flows can be activated on steep slopes, especially if the soils are saturated (Fuhrmann et al., 2008). A vivid example is provided by Tropical Depression Frances and Tropical Storm Ivan, which struck the region just nine days apart in September 2004. Besides much river flooding, the deluge produced about 400 debris flows (Wooten et al, 2007). While tropical systems strike the southern Blue Ridge mountains about once every three years, on average (Konrad and Perry, 2010), they often cluster together in time during especially active tropical seasons, like 2004. Consequently, there can be streaks of 5 to 10 years without any tropical systems.

In the southern Blue Ridge Mountains, average annual precipitation has increased about 3% (1.68” per century) over the last 125 years (Figure 20). This increase has occurred solely during the cool season (October-April), as warm season (May-September) precipitation has not shown any long-term trend. Similar to the temperature trend, there is much interannual variability in the annual precipitation totals, and this variability has increased dramatically over the

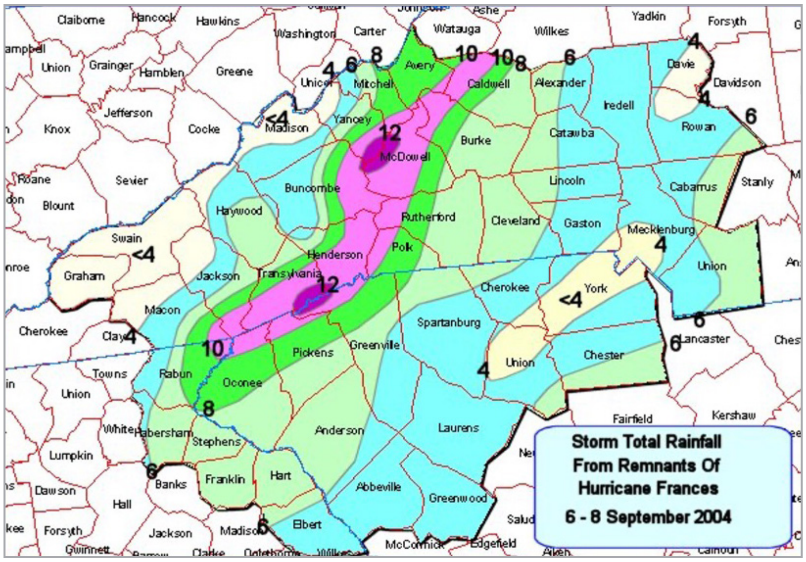


Figure 19. *Map of precipitation totals from Tropical Depression Frances. Note the area of heaviest precipitation is coincident with the Blue Ridge escarpment. Map courtesy of the Greer NWS office.*

last 60 years. In fact, three of the wettest years have occurred in the last 8 years. And two out of three of the driest years have happened over the last 15 years. Accompanying the trend in increased precipitation variability is an increased occurrence of both drought and extreme wetness, as revealed by the time series of drought (Figure 21).

Some of these droughts have contributed to wildfires, especially the brief and intense drought in late 2016 that culminated in the deadly Gatlinburg wildfire (Konrad and Knox, 2018). This increased hydroclimate variability is consistent with climate change projections. Greenhouse warming increases rates of evaporation in the soil thereby

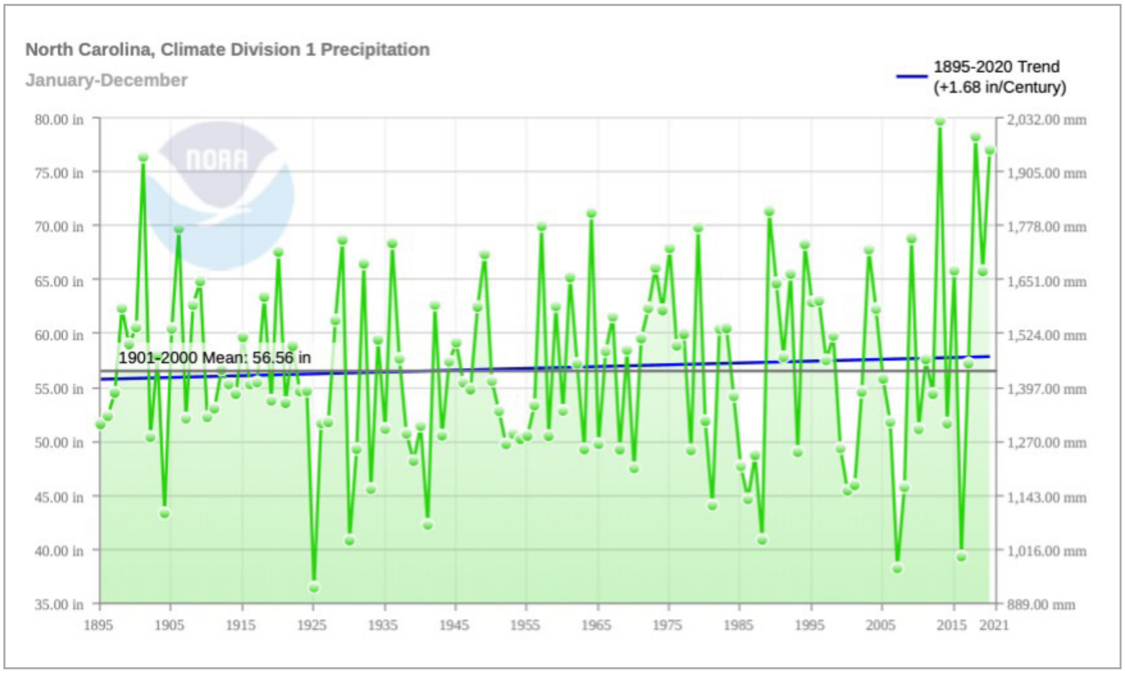


Figure 20. *Time series of mean annual precipitation (1895-2020) for the NC Southern Mountains climate district, which covers much of the southern Blue Ridge Mountains. (NCEI 2021)*

encouraging drought. The associated warming of water bodies, which cover more than two-thirds of the planet, also induces more evaporation. The atmosphere, being warmer, can hold more of this water vapor and consequently produce higher rates of precipitation when lifted.

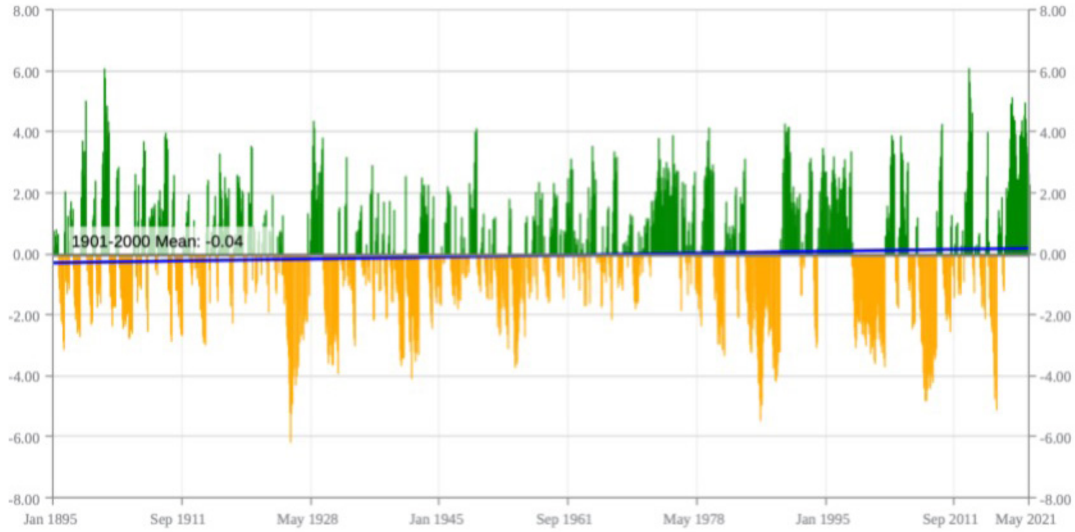


Figure 21. *Time series of drought (orange lines for each month from 1895-2020) for the NC Southern Mountains climate district. Green lines depict months that were wetter than normal. The magnitude of drought and wetness corresponds with the length each line. (NCEI 2021)*

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An Overview of Soil Geomorphology in North Carolina

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Introduction

Soils serve as an interface between the geosphere, the biosphere, the atmosphere, and the hydrosphere. As such, soils can be valuable tools in understanding the broader environment in which they form. Agricultural productivity is often limited by soil fertility and composition as most crops are fairly picky about their preferred soil ecosystem. As a result, any farmer thinking about a new crop should be highly aware of their local soils' properties. Geology is a primary driver of soil variability and as a result soil suitability is often the result of broader geologic processes.

Soils provide a useful window into the geology and geomorphology of a region. 'Old' landscapes, where soils are weathered directly into bedrock, are likely to be lower in nutrients than 'young' landscapes where fresh sediment is delivered, or recently exposed bedrock is weathered providing replenished nutrients. Even in areas across very small spatial scales (hundreds of meters), some landscape positions are more likely to be geomorphically active than others resulting in a diversity of soil compositions.

Within North Carolina, each of the three physiographic provinces (Coastal Plain, Piedmont, Blue Ridge) has unique soils that are related to their geologic history. Broadly, the Coastal Plain typically features sandier soils formed in Mesozoic and Tertiary marine sediments. Piedmont soils are typically formed directly into Proterozoic and Paleozoic metamorphic and igneous rocks resulting in well-developed, clay-rich soils with a distinctive 'red' hue. Blue Ridge soils typically develop in Precambrian metamorphic and metasedimentary rocks although high relief topography throughout the region leads to more geomorphically active areas and therefore a greater diversity of soils.

The three provinces have one similarity in that soils in North Carolina are typically quite old due to a lack of recent geomorphic activity. Much of North America was subject to intense geomorphic reworking during the Pleistocene because of glaciation and broad climate fluctuations. While climate was likely much different in North Carolina during the Pleistocene, much of the soil was left undisturbed by geomorphic activity. As such, soils throughout the region tend to be older than many other soils in North America. That said, recent research has highlighted that landscape positions where geomorphic activity is likely (e.g., hillslopes and near rivers) have soils dating to the Holocene or Anthropocene – an indication that the landscape is more active than it is often given credit for.

My goal in this paper is to summarize the work that has been done to characterize the geomorphology of North Carolina and the impact that geomorphology has on soil formation. Specifically, I hope to help the reader understand the relationship between long-term geologic processes, short-term geomorphic processes, and the soils that we observe today. In the end, I hope that you can recognize the variety of soils in North Carolina, the processes behind their creation, and the impacts that geomorphology may have on agriculture. Or perhaps you will simply appreciate the work that many authors have done to help us understand the soils of the region. The work presented here was mainly done by soil geomorphologists – shovel in hand.

Lastly, a couple of authors notes. First, I plan to leave the agronomy to others and instead to focus on the geology and its impact on soil formation. Also, I have decided not to use any figures in this paper because there are plenty of great pictures of soils on the internet – typically better than what I would provide from my own collection. I encourage you to pull the original papers cited here if you have questions because this summary tends to paint with broad strokes and eliminate the underlying data.

Some Soil Basics

In order to understand the diversity of soils and the role that geology plays in their formation, it is important to first understand the basics of soil formation. For those who want additional depth, this material is well covered in various textbooks including Birkeland (1999) and Schaetzl and Thompson (2015). For questions about application, Eppes and Johnson (2022) provide a more detailed discussion about how to use soils to answer geomorphic questions and how soils can be reproducibly described in the field.

Soils form as a function of climate, organisms, relief, parent material, and time (Jenny, 1941). Within this construct, any single soil forming factor can be examined while the other factors are held constant. This allows for one to isolate a single soil forming factor and see how it impacts soil development within a region. For instance, if the climate, organisms, relief, and parent material are roughly the same for a given field area, then soils of different ages should present evidence of different levels of soil development. Obviously, this is a useful tool for geomorphologists who are interested in the ages of various landforms in a mapped area.

Soils are formed *in situ* from the top down as a result of physical and chemical weathering. Thus, soils are fundamentally different from sediment, which is, by definition, transported. That said, soils can form in sediment (i.e., a soil forming on a stabilized dune), but they can also be formed directly into bedrock as the bedrock chemically and physically weathers. Top-down weathering processes are the result of interactions between the atmosphere, water, and the soil surface. As such, many of these processes are stronger at the surface and decrease with depth. The result is a series of horizons. A horizons – laterally continuous, roughly surface-parallel zones with similar weathering characteristics - should not be confused with sedimentary layers that have accumulated from the bottom up. Top-down weathering leads to translocation within soil profiles with silts, clays, and dissolved ions moving from the top of the soil profile towards the bottom as water moves through the system. Elluvial horizons are those from which material is translocated, and illuvial horizons are those that receive material from above.

The top horizon in most soil profiles is an A horizon that comprises a mix of organic material and mineral content. We would most commonly recognize this as topsoil in humid-temperate environments like North Carolina. Below the A horizon, some well-developed soils have an E horizon. Within the E horizon, top-down leaching exceeds inputs leading to a fully leached horizon. Together, the A and the E horizons make up the zone of leaching (the elluvial zone). Below, the zone of accumulation consists of the B horizon and sometimes the C horizon. The B horizon is the peak horizon for materials accumulated (the illuvial zone) from the zone of leaching. Below the B, the C horizon is a transition from the B into the unweathered parent material. As such, the C horizon is typically altered from the parent material through limited weathering and translocation. It is important to note that not all horizons are likely to be present in any given soil.

For a geologist's purposes, the parent material is perhaps the most relevant soil forming factor. The parent material determines what the starting point is for the soil and therefore impacts what the ending point is, even millions of years later. For instance, a soil that forms on a dune will always be impacted by the fact that the parent material is fundamentally sandy. In this case, the fact that sand is highly permeable will be relevant for as long as the soil is stable.

The impact of relief on soil formation is also important in geomorphic research. Specifically, soils at the tops of slopes are more likely to erode due to higher potential energy. Meanwhile, the eroded soil may be added continuously to the base of the slope. The result is a somewhat thin soil at the top of a slope and a somewhat overthickened soil (i.e., cumulic soils) at the base of the slope. In this sense, soils at the top and bottom of the same slope may evolve differently but are nonetheless intrinsically related to one another. These related soils, including those in the middle of the slope, are called a catena (i.e., a chain).

Additionally, since soils form *in situ* they are an excellent indicator of landscape stability and thus serve as a valuable tool for geomorphologists. This tool can work in two directions. First, a well-developed soil on a surface can indicate long term stability of that landform. Desert pavements, for example, are pedogenic features and have long been used in deserts to indicate long-term stability since they are slow to develop. On the other hand, buried soils can be used to indicate intermittent stability. A fluvial terrace with a buried soil and a surface soil would be interpreted as intermittently stable with a period of instability (deposition) in-between. Cumulic soils can be interpreted to be the result of consistent sedimentological inputs concurrent with soil formation. For instance, dust can be added consistently to a profile during soil formation.

Geomorphologists looking to better understand landform age can use soils to build a chronosequence that will provide relative ages (e.g., Birkeland and Burke, 1988; Markewich and Pavich, 1991; Fulop et al., 2019). In this framework, climate, organisms, relief, and parent material are held constant while soils are examined across features of different ages. As such, older landforms should have more developed soils than younger ones since the other soil forming factors are roughly the same. For example, a series of terraces are all in the same area (climate is the same), are flat (similar relief), have consistent vegetation (similar organisms) and formed on fluvial deposits (similar parent material). Therefore, the soils should have formed under the same conditions with the exception of age. Older soils should be significantly more developed compared with younger soils because they have had more time to evolve. Soils develop differently depending on their region, and so the degree of soil development must be approached holistically. Common soil properties that change with development include increased oxidation, increased thickness, increased horizonation, increased clay (and clay films) in B horizons, changes in elemental composition, the formation of an E horizon, and many other possible soil properties.

Coastal Plain

Wineries in the Coastal Plain either grow and use muscadines or scuppernongs or else source their grapes from other regions. This makes the Coastal Plain the least relevant physiographic province for our field trip. Nonetheless, it seems useful to discuss the soil geomorphology for the region – even if only to set the stage for the Piedmont and Blue Ridge.

Soils of the coastal plain are generally sandy as a result of marine sedimentation during periods of high sea level. In the southern portions of the North Carolina Coastal Plain, Cretaceous marine sediments are preserved (North Carolina Geological Survey Section. et al., 1985) while the northern portion is dominated by Pliocene and younger sediments (Dowsett and Cronin, 1990). A series of marine terraces formed as sea level dropped resulting in generally high (although variable) sand quantities throughout the Coastal Plain (Daniels et al., 1978). Sand content is especially high in the Sandhills and the upper Coastal Plain and, as a result, soils are normally well-drained (Gamble et al., 1970a). Coastal Plain soils generally form in one of two pathways, towards Spodosols (strong E horizons with illuvial organic material below) or towards Ultisols (thick, clay-rich B horizons; Markewich and Pavich, 1991).

In Spodosols, the dissolution and subsequent translocation of oxyhydroxides and organic matter lead to strong E horizons and organic material in the B horizon. Specifically, this is possible because organic material is moving through the profile fast enough that it does not have a chance to oxidize and break down first (Markewich and Pavich, 1991). Spodosols do not appear to form consistently through time and thus they are not particularly useful in chronosequence studies (Markewich and Pavich, 1991).

Alternatively, Ultisols form because oxyhydroxides accumulate while organic material oxidizes and breaks down. The oxyhydroxides, most commonly Fe-oxyhydroxides, accumulate along with clay minerals in the B horizon. B horizons can grow to more than 1.5m thick in some areas (Markewich et al., 1986). While it is commonly assumed that the majority of clays are translocated from upper portions of the profile, argillic (i.e., clay-rich) horizons in the Coastal Plain generally form through *in situ* clay mineral formation (Markewich and Pavich, 1991). Because clay mineral formation and oxyhydroxide accumulation happen consistently through time, Ultisols in the region are much more useful in chronosequence studies. For instance, Gamble et al. (1970b) found significant differences in soil development between Pliocene and Pleistocene Ultisols.

A number of studies also highlight ‘hybrid’ soils which have argillic B horizons located below spodic (Bh) horizons (Daniels et al., 1975; Holzhey et al., 1975; Markewich and Pavich, 1991). Markewich and Pavich (1991) indicate that these may be the result two different periods of soil formation, a change in climate, and/or a result of soil formation mechanisms that are not particularly well understood.

Of particular note are very thick Bh horizons that appear in some Spodosols within the region. Specifically, Daniels et al. (1975) and Holzhey et al. (1975) detail Bh horizons that are up to 9 m thick in the Coastal Plain. The authors confirm that these are pedogenic (i.e., post-depositional) features and not simply organic-rich sediment. High mobilization rates in the upper portions of the profile are likely the result of acidic soils but immobilization in the Bh horizon remains more curious.

A number of studies highlight random or chaotic soil formation in a number of parts of the Coastal Plain (Phillips, 1993b, 1993a; Phillips et al., 1996). Phillips (1996) suggests that soil moisture and vegetation differences may play a role in this chaos. Some of this interpretation may be related to scale as soils are indeed highly heterogeneous, especially over relatively small spatial scales.

In the section on the Piedmont, we will examine extensively the evidence for soil erosion driven by Euro-American settlers. It has commonly been thought that low relief and well-drained soils minimized soil erosion on the Coastal Plain (Bennett, 1939; Kennedy, 1964). However, more recent evidence suggests that Euro-American settlers likely caused soil erosion in the Coastal Plain and that humans likely have had more impact on this landscape than previously thought (Phillips 1993c).

Piedmont

The fall line divides the marine sediments of the Coastal Plain from the crystalline bedrock of the Piedmont. However, little of this crystalline bedrock is actually exposed because of regional stability during the Cenozoic. This stability has led to thick weathering profiles including Ultisols at the surface underlain by up to 20 m of saprolite (Pavich, 1989; Holbrook et al., 2019). Many of the highest interfluves in the Piedmont are flat indicating that there may have been a peneplain that is currently being incised into by larger rivers and their tributaries (White, 1953; Pavich, 1989). Pavich (1989) further hypothesized that the incision was caused by tilting of the Piedmont as a result of continued uplift in the southern Appalachians – a conclusion that is roughly consistent with White's (1953) hypothesis.

As the surface of the Piedmont lowered due to slow, steady erosion, monadnocks were exhumed from the surface and many small mountains now dot the region. These mountains are generally thought to be the result of small differences in mineralogy that are magnified by chemical weathering over long timescales (e.g., Potter, 1953, 1954; Bradley, 2014).

Non-monadnock surfaces instead develop thick saprolite sequences through chemical weathering. Saprolite is more heavily weathered near the surface and eventually transitions to crystalline bedrock at a depth of 10 – 20 m (Pavich, 1989; Pippin et al., 2008). ^{10}Be concentrations suggest that a minimum age for Piedmont saprolite would be on the order of 800,000 years with an erosion rate between 4.5 and 8 m Ma^{-1}. The authors (Pavich et al., 1985) also note that if ^{10}Be is consistently transported from the system, the dating mechanism breaks down. Pavich (1989) later refined these numbers and concluded that the maximum rate of saprolite production and erosion (assuming a steady state) was 20 m Ma^{-1}. As a result, the saprolite likely has a residence time of 1 – 5 Ma as a result of uplift and/or tilting through the Cenozoic (Pavich, 1989). More recently, Bacon et al. (2012) further refined residence time to between ~1.3 and 3.1 Ma. In the end, soils in the Piedmont can be thought of as forming from the Pliocene through the Pleistocene, but any landscape with signs of erosion is likely Pleistocene or younger (Markewich et al., 1990).

Primary porosity is poor in the crystalline bedrock and so most flow is through regional fracture sets (Pippin et al., 2008). This trend continues up into the saprolite where slow water throughflow likely limits saprolite formation and chemical weathering more broadly (Buol and Weed, 1991; Holbrook et al., 2019). The authors found that saprolite thickness is lesser over felsic rocks compared with mafic ones although more recent work has found the opposite (Bazilevskaya et al., 2013). Specifically, Bazilevskaya et al. (2013) found that faster weathering may lead to thin regolith while slow weathering may allow for deeper saprolitization. Secondary mineralogy in saprolite is, not surprisingly, controlled by depth from surface and bedrock type. The results are well-presented in Buol and Weed (1991) although the details are best left for those with a proclivity for clay mineralogy.

Typical soil profiles in the Piedmont comprise A/Bt/C horizonation. They are categorized as Ultisols which would be expected to have an E horizon as well but most soils in the region are missing the E for reasons that are discussed below. The Bt horizon is rich in the red clays the region is famous for, although they are typically sandier than my students expect them to be. Red and orange colors in the Bt horizons are derived from iron oxidation including hematite, goethite, limonite, and ferrihydrite (Melear, 1998; Johnson et al., 2015). Mica is common throughout the bedrock and regolith. Some of this mica breaks down and provides higher potassium levels compared with Ultisols in other regions. However, sand sized mica is resistant to weathering (Buol and Weed, 1991) and is commonly found in streams and reservoirs. In soils near the water table, redoximorphic features containing manganese are especially common as a result of alternating oxidizing and reducing conditions as the water table fluctuates.

Soils in the Piedmont are most commonly in the Cecil soil series which extends throughout the Piedmont of the southeast. The extent of Cecil soils depends somewhat on who mapped the area and how much they subdivided their mapping area (soil surveys are done at the county level which can lead to significant differences in adjacent areas), but the interfluves are almost always mapped as Cecil soils. Valley bottoms and tributaries tend to be mapped as a great variety of soils. A yellow to white clay locally known as 'bull tallow' is common in the subsoil although that term does not appear anywhere in the literature.

Piedmont soils have been described as predisposed to soil erosion during land use change because the original Ultisols comprised loose A and E horizons on top of dense, impermeable Bt horizons (Spell and Johnson, 2019). Soil erosion likely started as soon as Euro-American settlers initiated deforestation (Spell and Johnson, 2019), and by the 1800s gullies were a known problem in the region (Lyell, 1849; Ireland, 1939; Kennedy, 2001; Sutter, 2015). In the 1930s, Ireland et al. (1939) began extensive investigations into gully formation processes and concluded that the saprolite (termed 'rotten rock' in the paper) was easily eroded once the B horizon was breeched. By 1939, many of these features were recognized to be quite old and more recent work confirmed that gully formation likely started in the late 1700s and early 1800s – almost immediately after Euro-American settlers arrived (Spell and Johnson, 2019). This timing is consistent with initial deforestation and not with peak agriculture as has often been assumed (James et al., 2007; Jefferson and McGee, 2013). While the gullies of the Piedmont are generally stabilized today, they continue to impact the hydrology of small watersheds (Chen et al., 2020a). Recent unpublished work from my students indicates that this change in hydrology significantly reduces biodiversity by converting wetlands into riverbanks (Mullinax et al., in prep).

Changes in land use not only led to gully formation, but the entire surface soil was eroding in most places as well (Trimble, 1972; Costa, 1975; Trimble, 2008b). Specifically, the A and E horizons were eroded completely as the impermeable Bt horizon acted as an erosion surface and water carried away the topsoil. In fact, exposed Bt horizons can act as impervious surfaces thereby increasing runoff even in forested areas (Johnson et al., 2022). Thus, the famous red clays of the Piedmont were not initially at the surface but instead formed in the subsurface and were exposed as a result of anthropogenic impacts on the landscape. Settlers in the Piedmont were not necessarily harder on the landscape than settlers in other regions and were likely unaware that the most common regional soils were predisposed to erosion. A horizons in the Piedmont today are young and have formed superimposed on the Bt horizons of much older soils. These A horizons tend to be quite thin and poorly developed.

Sediment eroded from the uplands in historic times tended to have collected in the valley bottoms (Happ, 1945). Much of this sediment is impounded in valleys and would take thousands of years to erode via modern erosion rates (Jackson et al., 2005). These legacy sediments are often meters thick and have been incised through by modern streams (Dearman and James, 2019). Organic material appears to have broken down during transportation because legacy sediments are quite low in organic carbon (Wade et al., 2020). While mill dams were present throughout the Piedmont, on-going research suggests that they were not a major cause of valley bottom sedimentation (Johnson, in prep.), a finding that is consistent with some other regions (Trimble, 2008a). Native Americans likely also impacted the landscape although their impact appears to be more limited. This may be, in part, due to the fact that Euro-American settlers often homesteaded on abandoned Native American settlements (Coughlan and Nelson, 2018).

Broadly, landscape position impacts soils in the Piedmont quite strongly as a result of this regional erosion history. Davidson College students have dug 30+ soil pits in the past 10 years as part of Soil Science coursework. From these pits, a local catena has developed. Pits at the tops of hillslopes generally lack any developed A horizon with most soils having either no A or a very thin (<5 cm) A. Toe slope positions tend to be cumulic or have buried A horizons within them. Ryland et al. (2020) found a similar trend along hillslopes albeit with thicker A horizons in all positions. Toe slope pits commonly contain charcoal which dates to the late 1700s or early 1800s (Spell and Johnson, 2019). Mid-slope positions often contain more complicated soils which have mixed erosional and depositional histories. For instance, it is not unusual to find an A/B horizonation formed in young sediment overlying a Btb horizon that originally formed as part of the much older residual soil. Dr. Martha Cary (Missy) Eppes at UNC Charlotte has also opened and described 5-10 pits per year across the Piedmont of the Charlotte region for coursework since ~2004, and our findings are consistent with hers over the past 15 years.

Most studies focusing on legacy sediments in valley bottoms also noted (overshadowed) Holocene sediments (e.g., Johnson et al., in prep). In locations where legacy sediments are absent (due to either lack of Euro-American impact or local geology), it is possible to study these Holocene sediments more purely. Recent work in one of those areas found that valley bottoms contain Holocene aged alluvial fans (Opalka et al., 2022). Rock type had a significant impact on alluvial fan size with more erodible argillites producing larger fans than harder rhyolites. Soil profiles in the study were deemed to be cumulic indicating that the fans formed slowly through time although debris flows do occur occasionally.

Terry Ferguson has revived old research on sedimentary deposits in the upper portions of colluvial hollows (mentioned in Eargle, 1940). These deposits, which can resemble saprolite in places (Nelson et al., 2022), are the remnants of a much older Pleistocene upper surface (Eargle, 1977). Colluvial hollows have provided preservation for these sediments while much of the paleosurface was eroded (Richter et al., 2020). A better understanding of these Pleistocene and earlier sediments may help us to understand why the tops of larger interfluves in the Piedmont are often suspiciously flat (Ferguson, in prep). Similarly, the Catawba River has a series of terraces that reach up to 42 m above modern surface. Layzell et al. (2012) developed a chronosequence on these deposits and determined that oxidation color and oxidized iron both increased through time.

Blue Ridge

As the southern Appalachians extend into North Carolina, the Valley and Ridge physiographic province pinches to the west into Tennessee such that only the Blue Ridge is present in North Carolina (which conveniently limits the number of sections in this paper). The Blue Ridge comprises Mesoproterozoic to Cambrian crystalline rocks thrust up and over Cambrian sedimentary and metasedimentary rocks. In a number of places, ‘windows’ are open to the younger, underlying rocks that have been thrust upon (e.g., Adams and Su, 1996). Within the region lie many of the tallest mountains in the Appalachians including the tallest, Mount Mitchell (see Cattanach et al., 2018 for details). High relief within the Blue Ridge provides a greater diversity of geomorphic landforms, and therefore soils, compared with the other two regions. As such, this section provides more focus on various geomorphic processes and the role they play in creating parent material.

Despite its elevation and colder temperatures during the Pleistocene (Delcourt and Delcourt, 1984), the Blue Ridge was not glaciated during the Last Glacial Maximum although the topic was widely debated in the 1970s (Haselton, 1973; Berkland and Raymond, 1974; McKeon et al., 1974). There is evidence of periglacial activity in the region in the form of block fields, patterned ground, block streams, and other similar features (e.g., Clark and Ciolkosz, 1988). Mills and colleagues found weaker soil development at the highest elevations of Roan Mountain and Grandfather Mountain – perhaps as a result of periglacial processes during the Last Glacial Maximum (Raymond, 1977; Mills, 1981b; Mills and Allison, 1995b). This is consistent with evidence from Flat Laurel Gap of periglacial processes in the Late Pleistocene and the Early Holocene (Shafer, 1988).

Bedrock conversion to saprolite is thought to follow similar mineralogical pathways in the Blue Ridge as it does in the Piedmont (Buol and Weed, 1991) although the time scales may vary due to colder temperatures and higher rainfall. Saprolite is present in outcrops throughout the region especially on ridgetops – although there are no known studies that focus on the evolution of relict soils on ridgetops in the region. The lack of work on saprolitization on ridgetops is partly due to the fact that the very highest ridgetops likely form through alternative, cold climate geomorphic pathways. For instance, heath balds are fairly common in the region and at least some appear to have formed in the Late Holocene according to pollen records (Shafer, 1986). In the Late Pleistocene, it is likely that periglacial processes are dominant above 1500m or so (Mills, 1981b; Shafer, 1988; Clark and Ciolkosz, 1988). The elevation for periglacial processes likely decreases to the north in the Blue Ridge (Whittecar and Ryter, 1992) and the Valley and Ridge province (Mills, 1988; Merritts and Rahnis, 2022). Recent modeling indicates that during the Last Glacial Maximum, frost weathering would have been possible throughout the entire state and permafrost was likely present in the Blue Ridge (Marshall et al., 2021).

High relief in the Blue Ridge means that a high percentage of the landscape is mantled by colluvium and thus soils are more commonly formed in sediment compared with the Piedmont. Soils forming in colluvium in the Blue Ridge do so inconsistently due to mixing near the surface (Stiefel et al., 2021). Specifically, trees grow quickly in the region and thus go through life cycles more quickly. Dead trees, and trees killed during storm events, are likely to topple and stir the topsoil. Tree 'throws' are ever-present during field examinations and quite obvious on modern LiDAR data. Data from well logs indicates that colluvium is underlain by saprolite (Mills, 1981b) although some landslides are the result of colluvium that lies directly on top of bedrock (Wooten et al., 2008; Wieczorek et al., 2009).

Fires may play an oversized role in the evolution of colluvial slopes and hollows. Stiefel et al. (2021) found that crest stage gauges in colluvial hollows never registered flow except in recently burned areas. This is likely the result of temporary increases in hydrophobicity in the 1-2 years after a fire (Chen et al., 2020b, 2020c). Alternatively, Mills (1981a) proposes an alternate model in the adjacent Valley and Ridge physiographic province that involves hollow shifting through time as a result of armoring from boulders and evolution during millennial scale rain events. For those interested in the interplay of periglacial and colluvial processes further to the north, Mills (1987, 1988) provides a nice literature review and sedimentology from the Valley and Ridge Province.

Compared with geomorphic literature from the rest of the state, Blue Ridge alluvial fans have been fairly widely studied. Mills initially described fans on Roan Mountain as pediments. His interpretation was that the different surfaces formed as a result of changes in the fluvial system (i.e., stream captures and lateral erosion) through time (Mills, 1983) as opposed to fans in the western US which form as a result of glaciation (e.g., Ritter et al., 1993). Mills expanded this focus on alluvial fans across multiple sites within the Blue Ridge. Three separate fan surfaces have been mapped at a number of those sites (Mills, 1983;

Mills and Allison, 1995a, 1995b). In places, the oldest fans have evidence of reversed magnetism indicating that they are at least 780 ka old (Mills and Allison, 1995c).

The majority of fans in Mills' studies formed as debris flow deposits and are generally rich in clay (Mills and Speece, 1997; Mills, 2000b). Alluvial fans can be as thick as 19 m in places and are generally underlain by saprolite (Mills, 1983). While fans in Mills' studies are attributed to debris flows, Whittecar and Duffy (2000) found that surface water did deliver quartzite cobbles to fan surfaces indicating that there may be regional variability. Fan shape is constrained by the topography available for deposition, and there is a negative correlation between fan slope and drainage area (Mills, 2000b).

Along Richland Creek, larger basins appear to have created fans that are more likely to be preserved. Specifically, one side of the valley is dominated by younger fans, and the authors interpret this to be the result of smaller basins on that side of the valley (Mills and Allison, 1995a). The three surfaces on most mapped fans provide an ideal substrate for the creation of chronosequences. Soils on these surfaces show strong age relationships with increases in thickness of Bt horizons, clay content, and oxidized color (Mills and Allison, 1995b). Weathering rinds in amphibolite clasts can also be useful in determining approximate ages (Mills and Allison, 1995c) as they show clear weathering trends through time.

Many studies use a height index to infer ages of fluvial terraces and alluvial fans where absolute ages are not available (Mills and Wagner, 1985; Mills and Allison, 1995b; Whittecar and Duffy, 2000; Mills, 2000a, 2005). That approach highlights the presence of a significant number of old surfaces that are preserved in the Blue Ridge despite high relief in the region.

In valley bottoms, most of the work has focused on relatively recent deposits. Leigh (1996) developed a chronosequence on five terrace levels along the 5th order Brasstown Creek. In that study, the floodplain was shown to have very little soil development while Pleistocene terraces had Bt horizons and were increasingly clay-rich and oxidized with age. During the Holocene, some streams show signs of significant aggradation with increasing depositional rates after Euro-American settlement (Leigh and Webb, 2006). Sedimentation during the Holocene and burial of Native American artifacts indicate that many streams were 'naturally' entrenched before Euro-American settlement. While humans clearly impact these systems, the impacts are not always clear in the mountains, and poorly understood thresholds may play a significant role (Price and Leigh, 2006).

These published studies on valley bottom sedimentation are similar to unpublished work that is on-going in my lab. We have mapped and examined terraces within Linville Gorge that are Holocene in age and contain few cobbles – especially compared with the modern river. From this, we have interpreted those terraces to be the result of overbank deposition during very large storms (Stanley, in prep.). Along Upper Creek, we expected to find significant legacy deposits as a result of an extensive history of deforestation. Instead, we have found Holocene and Late Pleistocene sediments preserved in terraces that lie 1-3 meters above the modern river. Morphological and sedimentological data suggest a highly dynamic river environment whereby the river uses the entire width of the valley (Ornes, in prep.). These works indicate that soil erosion during the last two hundred years was minimal despite intense deforestation in the Blue Ridge. As a result, we find much older soils and higher levels of soil development. This may mean that soil chronosequences may continue to be useful tools in the region since all geomorphic surfaces are not covered in legacy sediments. That said, steep climatic gradients within the Blue Ridge may make chronosequences difficult to develop.

Questions remain about how the escarpment and the Blue Ridge have remained steep despite tectonic inactivity (Gallen et al., 2011, 2013). Nonetheless, we can be certain that stream capture plays a role in preserving relief throughout the region (Prince et al., 2010, 2011; Johnson, 2020). Any process that preserves relief is important to the broader geomorphic picture because the majority of geomorphic processes in the region are driven by high relief and the resulting steep slopes. These active geomorphic processes drive soil diversity in the region by providing new sediments and reworking deeply weathered saprolite. More broadly, in an old geologic region, it would be possible for all soils to be very old and deeply weathered. Instead, we find a mix of older and younger soils due to ongoing geomorphic processes.

Topographic rejuvenation also drives landslides, are perhaps the most aggressive drivers of landscape evolution in the region (Eaton et al., 2003). In fact, individual storms can produces dozens to hundreds of landslides in a single day (Wooten et al., 2008). Valley walls and bottoms throughout the region are filled with evidence of thousands of landslides from historical events (Wooten et al., 2016). Older landslides could be dated through superposition and occasionally by charcoal ages. Landslides transport developed soils and saprolite from upper hillslopes to valley bottoms – thereby driving continued landscape change and soil renewal. It is tempting to develop chronosequences on the surfaces of these deposits but it is important to remember that the inherent heterogeneity of landslide deposits can complicate soil development (Johnson et al., 2017).

Summary

Geomorphic and soil data does not come easily in North Carolina. Nearly every surface in the state is covered to some degree by vegetation, and the hot and humid climate makes it difficult to do field work for much of the year. Bedrock, saprolite, and sediment are commonly heavily weathered and difficult to distinguish. Nonetheless, a number of people have worked hard to understand the landscape, and I hope that I have represented their work appropriately.

Soils can be a tool for understanding geomorphology, and geomorphic research and mapping can be a tool for better understanding soil development. In this sense, the two are inherently related and cannot be differentiated from each other. This is true everywhere but seems especially true in North Carolina where much of the landscape is old – but ever-growing research on young surfaces requires a detailed understanding of weathering processes and an ability to distinguish things that look old from those that are old.

As for this field trip, I have told you very little about soil nutrients or how soils support crops. Instead, I have focused on something more fundamental: the impact of geology, geomorphology, and landscape position on how soils form. It is these factors that are fundamental to understanding what the soil is and how it might impact agriculture.

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Western North Carolina Soils, Geology and Wine

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Introduction

The North Carolina (NC) wine and grape industry contributes over $2 billion to the state's annual economy and employs approximately 10,000 people associated with 200 vineyard/wineries, 525 commercial grape growers, nearly 2500 acres, and 2.5 million gallons of annual wine production (7th in USA). Wine grape production occurs in three general NC regions. The Coastal Plain is the largest region (~45% of NC) where native Muscadine grapes *(Vitis labrusca* and *Vitis rotundifolia*) grapes are dominantly produced (~ 1000 ac), although muscadine vineyards and wineries can be found throughout the state. Muscadine production information can be found in Hoffmann et al. (2020). Both the Piedmont region (~40% of NC) and the Appalachian mountain regions, or Blue Ridge plateau, are home to three American Viticultural Areas (AVAs) each (Fig. 1).[2] The dominant wine grapes produced in the western or Inner Piedmont and mountains of North Carolina are *Vitis vinifera*, which includes the "old world" or European varieties, and both French and American hybrids. *Vinifera* production information can be found in Poling (2007).

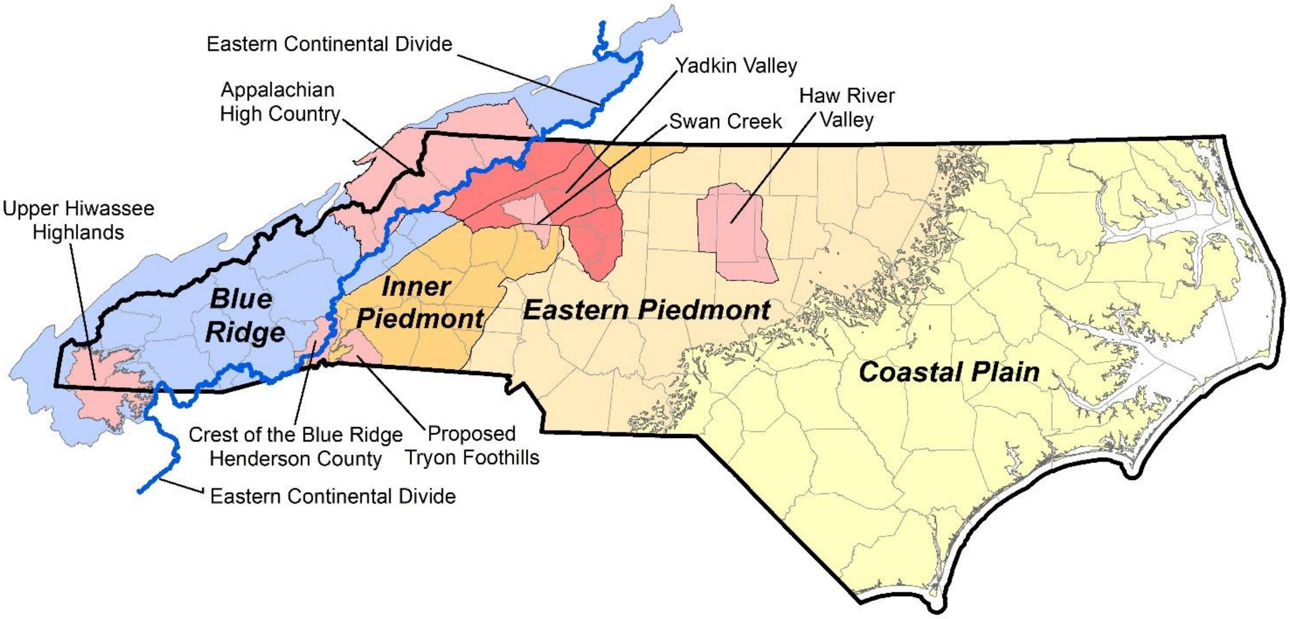

Figure 1. Wine production areas of North Carolina and associated American Viticultural Areas (AVAs)

Piedmont and Mountain Region Geology and Soils

The Blue Ridge and western Piedmont geologic areas comprise complex thrust sheets of folded and faulted rocks transported miles to the northwest during various mountain building events. The many guidebooks published over the years by the Carolina Geological Society[3] attest to years of field mapping and interpretation of these complex areas and to the strides that new technologies have made in deciphering the geologic history

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[2] The Upper Hiwassee Highlands AVA lies entirely within the Blue Ridge plateau. The Appalachian High Country and the Crest of the Blue Ridge Henderson County AVAs are partially in the Blue Ridge plateau and partially within the Innner Piedmont. The Tryon Foothills AVA, if approved, will be entirely within the Inner Piedmont.

[3] https://www.carolinageologicalsociety.org/guidebooks/

of plate tectonics, uplift, erosion and depositional cycles. Sorry to have to inform the geologists about this, but plants are totally ignorant of the complexity of events that generated the rocks and soils in which they grow. Soil scientists, on the other hand, must be fully aware of the composition of the various lithologies that form the subsurface. After all, rocks and their component minerals are the ultimate source of the inorganic component of soils, which form by *in situ* weathering and decomposition, by mass wasting, or by erosion, transport and deposition.

Figure 2 is a geological map of the western part of North Carolina. Though the map is small and detail is difficult to see, the reader needs only a quick glance to have a good idea of the major rock types of the western part of the state. The dominant areas of gray represent biotite gneiss, schist, metagreywacke, with minor amphibolite; the pink colors are granite and granitic gneiss; the tan colors are metasandstone, metagreywacke, metasiltsone, metaconglomerate, schist and phyllite; and finally the blues represent biotite-hornblende gneiss and amphibolites. It is a great variety of rocks, but actually the chemical compositions of these lithologies are very similar. It is just the degree of metamorphism, strain, and recrystallization they have undergone that distinguishes them. The type of soils they form, though, can be quite different, and depend on the climatic and geomorphic situations in which they occur after exhumation by erosion and exposure to surface weathering. Geological processes have produced soils in western North Carolina with chemical and physical properties that are very amenable to the viticulture industry. Commonly, these soils are fine-textured, acidic to slightly acidic, low in plant available phosphorus (P), potassium (K), and less often magnesium (Mg). Most micronutrients are relatively plant available.

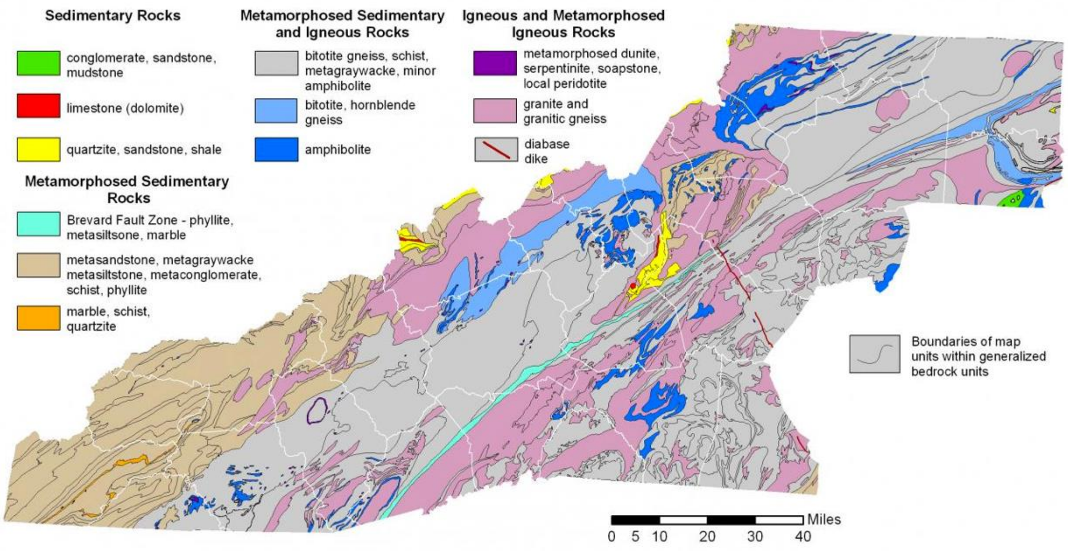

Figure 2. Generalized geology of the Inner Piedmont and Blue Ridge regions of NC (NCGS, 2016).

One remarkable thing about western North Carolina is the general scarcity of carbonates (limestones, dolostones, and calcitic and dolomitic marbles) which form important soils in some of the world's premier wine-producing regions; in the western Piedmont and Blue Ridge carbonates are a rarity, and are thin, complexly folded and faulted, and do not form widespread areas of significant soils.

As a brief aside to the geomorphologists, the disciplines of geology and soil science share an interest in age-dating. Soil scientists use the same relative and absolute dating techniques used by geologists, though the soil techniques are normally for much younger dates than for geological events. For absolute dating, soil scientists utilize ^{14}C, ^{10}Be, and ^{26}Al radiometric techniques, as well as archeological methods. One technique that is of great interest, and is not commonly applied by soil scientists, is paleontology, which could be useful in dating floodplain and lacustrine deposits. Geologists looking for relevant age-dating for geomorphic analysis may find helpful data in the pedological literature.

Piedmont AVAs

Figure 3. Shelton Vineyard in the Yadkin Valley AVA.

The *Yadkin Valley* AVA (est. 2003) includes around 35-40 active vineyards (~800 acres) in eight counties of approximately 1.4 million acres in the Piedmont and foothills of the Blue Ridge Mountains (800-1200 ft. elevation) (Fig. 3). About 60% of the *Swan Creek* AVA (est. 2008) comprises nearly 10 vineyards (~130 acres) and overlaps the *Yadkin Valley* AVA. *Swan Creek* AVA was established to reflect the area's slightly higher elevation, lower temperate regime, and more homogenous soil types compared to the surrounding *Yadkin Valley* AVA. The *Haw River Valley* AVA (est. 2009) encompasses 2-4 active vineyards in six counties of ~0.5 million acres. The significantly lower elevation (350-800 ft.) compared to *Yadkin Valley* (800-1200 ft.) increases the temperature and humidity regime, enhancing potential plant disease pressure and limiting anthocyanin and phenol content due to enhanced nighttime respiration.

Soils of the Yadkin Valley and Swan Creek AVAs

The soils are formed mainly from residuum (saprolite) weathered from felsic metamorphic rocks (gneisses, schists, and phyllites) and from metamorphosed granitic rocks of the inner Piedmont. A minor portion in the southeast corner of the *Yadkin Valley* AVA is formed from saprolite weathered from intrusive igneous rocks (granites, gabbros and diorites) and some gneisses and schists, all from the Charlotte Belt. The dominant soil series are highly variable, but all have clayey or fine-loamy surface soils and subsoils with good internal structure and moderate permeability. They are mostly very deep (> 5 ft.) and well drained. These soils are acidic and have low natural fertility, requiring regular liming. Many vineyards are located on either previous animal (dairy, beef, etc.) and/or tobacco farms. Long-term application of animal waste or P and K fertilizers results in adequate or high soil test P and K levels compared to soil with no previous history of agricultural production.

Figure 4: Typical vineyard on the valley floor and lower mountain slopes of the Upper Hiwassee Highlands AVA.

Mountain Region AVAs

Upper Hiwassee Highlands AVA (est. 2014) is nearly 0.5 million acres and encompasses the Hiwassee River basin in Cherokee and Clay Cos. in NC, and Towns, Union, and Fannin Cos. in Georgia. Most of the 8-10 active vineyards (~80 acres) are located between 2000-2400 ft. elevation, which lowers the temperature regime and humidity compared to the Piedmont AVAs. *Upper Hiwassee Highlands* AVA designation was granted due to relatively gentle landscapes compared to the more mountainous surrounding land (Fig. 4).

Soils of the Upper Hiwassee Highlands

These soils are derived from metasedimentary rocks such as phyllites, slates, schists, sandstones, and marble. They are generally deep, moderately to well drained, and moderately fertile. Once vines are established (2 yrs), supplemental irrigation is not needed, although most growers install permanent drip lines. Although soils are relatively deep, vine rooting depth is only 2-3 ft. Good drainage reduces root disease potential related to saturated soil. Moderately fertile soil provides adequate nutrition to the vines without promoting excessively thick leaf growth that shades grape clusters and increases foliar and cluster disease pressure. The relatively high temperature and moisture regime is ideal for numerous leaf and cluster diseases, requiring growers to apply fungicides weekly throughout the growing season (late April-early September). Organic grape production is difficult or nearly impossible under these conditions.

*Appalachian High Country AVA (*est. 2016*)* comprises 1.5 million acres spanning five counties in NC, two in Tennessee, and one in Virginia. The 8-10 active vineyards and wineries are located between 2200 and 4000 ft. elevation on relatively steep slopes (Fig. 5). More than half of the vineyards are located at or above 3,000 ft. in elevation. Growers commonly plant American hybrids more suited to the cooler temperature regime.

Figure 5: Grandfather Vineyards in the Appalachian High Country AVA.

Soils of the Appalachian High Country AVA
The soils are derived from igneous and metamorphic rocks (e.g. gneiss, granite, etc.) and are well-drained, fine, loamy texture, slightly acidic, and higher soil organic matter than lower elevation AVAs. Soils in the *Appalachian High Country* AVA distinguish it from the surrounding regions. For example, two of the eight most prevalent soil series are not found in the surrounding regions.

Figure 6: Burntshirt Vineyards in the Crest of the Blue Ridge Henderson County AVA.

Crest of the Blue Ridge Henderson Co. AVA (est. 2019) represents approximately 0.14 million acres with 8 – 10 active vineyards (~70 acres). The AVA covers part of the Blue Ridge escarpment and Blue Ridge plateau, separated by the Eastern Continental Divide (Fig. 6). Justification for this AVA is based on generally lower elevation compared to regions to the west, but higher than in the north, south, and east; slightly cooler temperature regime than regions to the south and east but warmer than regions to the north and west. In addition, annual precipitation amounts in the AVA are generally lower than regions to the south, west, and east and higher than regions to the north. Warm days and cool nights during the growing season provide favorable conditions for enhanced production of anthocyanins and other flavor compounds in the grape skins. Soils are formed in colluvium and alluvium derived from materials weathered from felsic to mafic, high-grade metamorphic and igneous rocks. Slopes are commonly 2-10% but range up to 25%.

Example Vineyard Soil at Burntshirt Vineyards

Burntshirt Vineyards is located in the *Crest of the Blue Ridge Henderson County* AVA and includes 30 acres at two different sites located on both sides of the Eastern Continental Divide. The winery overlooks 19 acres east of downtown Hendersonville. Although several soil series are represented in the 19 acres, the Bradson gravelly loam (BaB) is the most common (Fig. 7). The Bradson soil is a very deep, well drained, moderately permeable soil on high stream terraces, colluvial fans, and foot slopes.

Taxonomic Class: clayey, parasesquic, mesic Typic Hapludults

Soil horizons

Ap (0-6 in.)	reddish brown gravelly loam; weak coarse and fine granular structure; friable; many fine roots; few fine flakes of mica; about 20% quartz gravel; moderately acid.
Bt1 (6-24 in.)	red clay; medium subangular blocky structure; firm, sticky, slightly plastic; few fine roots; clay films on faces of peds; fine mica flakes; 10% quartz gravel; strongly acid.
Bt2 (24-40 in.)	red clay loam; medium subangular blocky structure; friable, slightly sticky, slightly plastic; few fine roots; clay films on faces of peds; fine mica flakes; strongly acid.
BC (40-65 in.)	red clay loam; weak medium subangular blocky structure; friable, slightly sticky, slightly plastic; few faint clay films on faces of peds; fine flakes of mica; soft fragments of parent minerals; very strongly acid.
C (65-75 in.)	reddish yellow loam; massive; friable; slightly sticky and slightly plastic; very strongly acid.

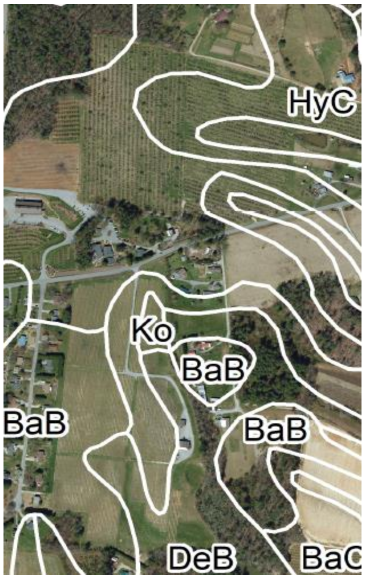

Figure 7: Soil map of Burntshirt Vineyards, Henderson, NC site.

Typical characteristics**:** Solum thickness ranges from 60-80 inches. Depth to hard bedrock is more than 72 inches. Content of rock fragments ranges from 5-35% in the A or Ap horizons and 0-15% in the B horizon; and 3-35% in the C horizon. Rock fragments consist mostly of gravel in some pedons. Flakes of mica range from none to common throughout. The soil is very strongly acid to moderately acid unless limed.

Related soil series: Braddock, Brevard, Evard, and Hayesville soils are closely related and occur in this AVA and throughout the Mountain region. Braddock soils are mixed mineralogy, while Brevard and Evard soils are fine-loamy family. Hayesville soils are kaolinitic. In addition, Evard and Hayesville soils are formed in residuum and have C horizons of saprolite. Evard-Cowee soils are moderately deep with variable depth to bedrock (20-60 in.) due to slope steepness and extent of previous soil erosion (Fig. 11). These soils are well drained, exhibit moderate to low water holding capacity, and are strongly to moderately acidic. Native soil fertility is relatively low.

Biltmore Vineyards is located in Buncombe Co. about 2 mi south of Asheville, NC and 1 mi south of Biltmore Estate (Fig. 8). While the vineyard is not within a formal AVA, the geology, soils, climate, and topography are similar to AVAs in the Mountain region discussed previously. The majority of soils in the County (e.g. Wayah, Burton, Chestnut, Edneyville, Cleveland, and Ashe soils) weather from felsic high-grade metamorphic rocks (granite, gneiss, and schist). These soils vary in depth and color due to the degree of resistance to weathering

Figure 8. Biltmore vineyard in Buncombe Co., NC

exhibited by the parent material and the variation in mineral composition. Other soils, including the common Clifton and Evard-Cowee map units, originate from parent materials rich in clay-forming minerals found in mafic high-grade metamorphic rocks (e.g. amphibolite and metagabbro) (Fig. 9). These are red and very deep and have relatively higher natural fertility. Figure 10 shows the soil survey map for Biltmore Vineyard, where the common Evard soil series (EwD) is shown (see right side of the lake also shown in Fig. 8). Evard soil represents 55% and Cowee soil 35% of the region. These residiuum soils are weathered from felsic or mafic high-grade metamorphic or igneous rocks (e.g. hornblende gneiss, biotite gneiss, or amphibolite). They occur at 2,300-3,600 ft. elevation on 10-30% slopes.

Figure 9. Typical relationship of soils, landform position, and parent materials in the Clifton, Evard-Cowee, and Tate soil map units common to Biltmore Vineyard.

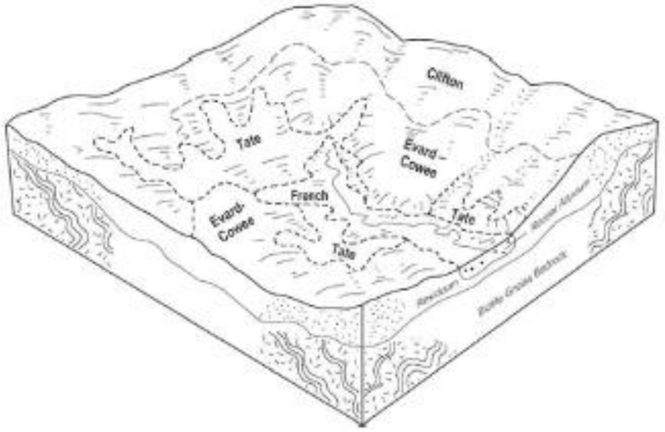

Figure 10: Aerial view (left) and soil survey map (right) of Biltmore Vineyards, showing Evard (EvD) soil series common to the vineyard (e.g., see right side of lake).

O (0 -2 in.)	slightly decomposed leaves, twigs, roots, and other organic matter.
A (2-7 in.)	reddish brown gravelly sandy loam; weak fine granular structure; very friable; fine and medium roots; common fine and medium flakes of mica; 20% gneiss gravel; strongly acid
Bt1 (7-15 in.)	red gravelly sandy loam; weak medium subangular blocky structure; friable, slightly sticky, slightly plastic; fine roots; faint clay films on peds; fine and medium flakes of mica; 20 % gneiss gravel; strongly acid.
Bt2 (15-29 in.)	red gravelly sandy clay loam; weak medium subangular blocky structure; friable, slightly sticky, slightly plastic; few fine roots; fine and medium flakes of mica; faint clay films on peds; 30% gneiss gravel; strongly acid.
C (29-62 in.)	weathered, multicolored hornblende gneiss; rock structure; few fine roots in cracks.

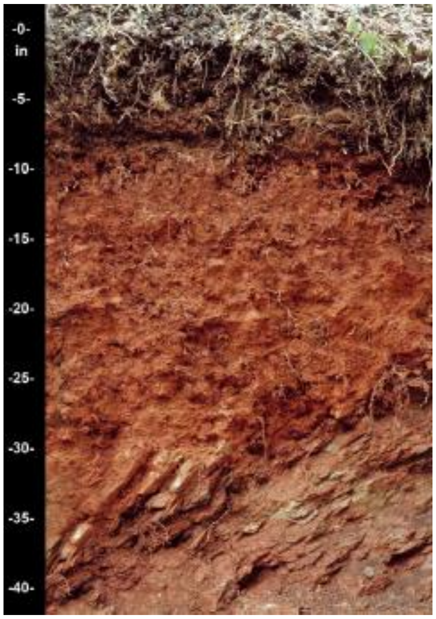

Figure 11. Soil profile description for Evard-Cowee map unit commonly found on Biltmore Vineyard.

Samples were collected from four soils at Biltmore Vineyard in 2009 (Table 1). These data show moderately low pH and very low plant available phosphorus (P), which are typical of many soils in the Mountain region. For example, of nearly 200 samples collected on NC vineyards approximately 60-70% exhibited plant available P and potassium (K) below optimum levels, while 40% of samples were below optimum soil pH.

Soil Properties	**Soil Depth (in)**			**Optimum soil test levels**
	0-4	***4-8***	***8-24***	
Humic Matter (%)	0.7	0.4	0.1	NA
CEC (meq/100g)	7.4	5.7	5.5	NA
Base Saturation (%)	73	69	76	75-90
Soil pH	5.9	5.8	5.9	6-6.5
P (ppm)	73	6	0	25-30
K (ppm)	176	110	78	60-80
Ca (ppm)	829	583	571	600-1200
Mg (ppm)	155	123	157	120-140
S (ppm)	22	49	109	10-30
Mn (ppm)	107	109	73	1-2
Zn (ppm)	6	2	1	0.5-1.0
Cu (ppm)	14	5	2	0.5-1.0
Na (ppm)	27	25	26	NA

Table 1. Soil test levels at Biltmore Vineyard. Data are average of four varieties (Havlin et al., 2012).

Soil, Vine Health, and Wine Quality

Wine quality is determined by many interacting viticultural and enological factors. Production of healthy vines depends on many site-specific soil and plant management factors, e.g. water, nutrition, disease, and pests control. Vine health influences sugar content (brix), titratable acidity (TA), pH, yeast assimilable N (YAN) and many other parameters affecting the microbial oxidation of sugars to alcohol and ultimately flavors of the finished wine. Ultimately, *terroir* is influenced by many interacting factors related to meso- and micro-climate, soil and soil management, vine canopy management, and numerous factors within the wine-making process. Plants absorb water and dissolved ions, while plants manufacture the complex suite of organic compounds (anthocyanins, phenols, etc.) that comprise the distinct flavors of a wine variety produced on a specific site (topography, soil, etc.) in a given year.

Without question, the variability in soil depth, clay content and composition, and soil chemical (nutrient) composition can have marked effects on wine flavor. Obviously on a specific site, annual variations in climate strongly affect soil water availability, evapotranspiration, and drainage, which affects nutrient and other elements available for plant uptake. All these interacting factors are difficult to separate in traditional field experimental designs, therefore, the literature contains many conflicting assessments of soil effects on wine flavor or terroir. Examples include Mackenzie and Christy (2005), Huggett (2006), Maltman (2008), Teil (2012), Anesi et al. (2015), and Urvieta et al. (2021). Meinert (2018) provided the most complete assessment including articles by van Leeuwen and de Resseguier (2018), Jones (2018), Koundouras (2018), Swinchatt et al. (2018), and Hall (2018).

While variation in geology and soil properties may affect wine quality, climate dominantly influences the ultimate flavor profiles in NC *vinifera* wines. Except at higher elevations (> 2500 ft.), nighttime temperatures remain high enough (> 70-75 °F) for vines to continue respiration with subsequent reduction in concentration of amino acid-based flavor compounds. In the southern U.S. where excessive plant available water encourages vine growth and soils are low in organic matter (Table 1; Havlin et al., 2012), little or no N is applied early in the growing season to avoid the potential negative consequences of excess vegetative growth (Jackson and Lombard, 1993; Keller, 2005).

Adequate N availability is required to support optimum grape yield and fruit quality. Application of N fertilizers to vineyard soils can be an effective management tool, particularly in the southeast where soil N status is low (Poling, 2007). In N deficient soils, soil-applied N may optimize yield and minimize 'stuck' fermentations[4] at the winery; however, in humid regions, growers are generally hesitant to apply N because of the increased risk of excessive vine vigor, reduced fruit set,[5] delayed ripening, and enhanced disease pressure. Under elevated N supply, canopy density (leaf area) increases, reducing airflow through the canopy and extending the duration of leaf and cluster wetness. This change in microclimate increases the potential for *Botrytis*[6] and other leaf and cluster diseases. In addition, extensive shoot growth from full bloom to post-veraison[7] often requires additional thinning to create an acceptable canopy microclimate for fruit and wood maturation (Christensen, 2005). Yields can also be reduced by inadequate fruit set in the current year, where vigorous shoot tips provide a stronger "sink"[8] than flower clusters for carbohydrates and other photosynthates necessary for good fruit set.

Consequently, YAN in grape must[9] is frequently below the minimum threshold (140 mg N/L) for completion of fermentation (Spayd et al., 1995; Monteiro and Bisson, 1991) and often fall below the level required to avoid stuck fermentation (Hannam et al., 2014). Grape must YAN composition represents NH_4^+ and amino acids (except proline) and influences the extent of fermentation and formation of flavor compounds in the wine (Bell

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[4] A fermentation that has ceased prematurely, leaving a higher residual sugar content than desired in the final wine.

[5] The process of a flower forming a berry, roughly defined by peppercorn-sized berries immediately after bloom.

[6] A necrotrophic fungus that affects many plants, notably wine grapes.

[7] Veraison is the start of the ripening process in which grapes change color and sweeten.

[8] The points of sugar delivery, such as roots, young shoots, and developing seeds, are called sinks.

[9] Freshly crushed fruit juice that contains skins, seeds and stems. Making must is the initial step in winemaking.

and Henschke, 2005). Wines produced from low-YAN musts are prone to develop a disorder called “atypical aging”[10] that occurs after bottling.

The problem of low YAN is not exclusive to NC. For example, 13% of the grape musts in CA, OR, and WA vineyards were <140 mg N/L YAN (Butzke, 1998); 50% of musts selected from WA, OR, and ID vineyards had YAN values <150 mg N/L (Hagen et al., 2008). Although food grade mono- or diammonium phosphate are commonly added to supplement grape must N levels prior to fermentation, wine flavors are generally inferior to wines with sufficient grape must YAN levels prior to fermentation (Henschke and Jiranek, 1991; Pardo-García et al., 2014). Therefore, it is more desirable to enhance YAN levels through vineyard N management practices than during fermentation (Conradie, 2001).

Based on nutrient survey data in NC, approximately 70% of vines were below established critical levels (CL) of petiole[11] N, likely resulting in low YAN at harvest (Havlin et al., 2012).

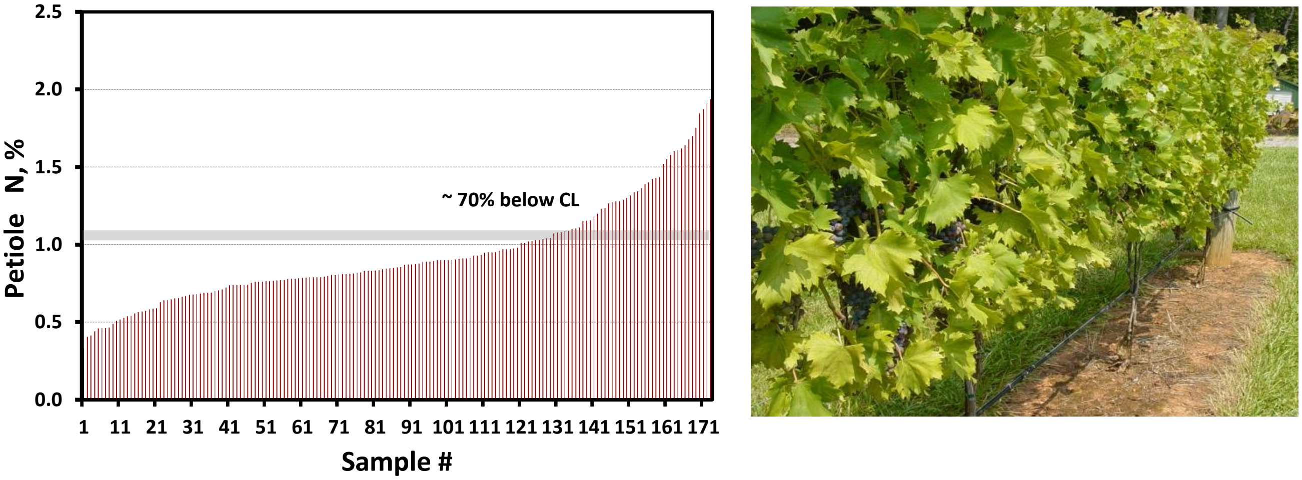

Figure 12. Petiole N content at full bloom in nearly 200 sites in NC vinifera wine grapes sampled between 2006-08 (left). Typical N deficiency at veraison in wine grapes, where petiole N was below critical level (<1-1.2% CL) at full bloom.

To address grower concerns for excessive vine vigor[12] associated with N applications to *vinifera* grapes grown in NC and the resulting low grape must YAN, a potential solution is to foliar[13] apply N in late-season to increase YAN while causing minimal changes to vine growth, fruit yield, or disease potential. At veraison, a large part of the N uptake is translocated to the grape clusters (Conradie, 1986). Late-season soil applied N may not be effective in enhancing cluster N due to low surface soil moisture content (Howard, 2014), reducing N absorption by roots. If N uptake were increased with soil applied N at veraison, enhanced vine vigor is not desirable because of increased disease potential. In contrast, grape leaves are able to absorb N as urea[14] and is usually taken up rapidly by the leaf cuticle (Dong et al., 2002).

In one of the first studies of late-season foliar N on wine quality, Lacroux et al. (2008) demonstrated soil applied N increased vigor and *Botrytis* incidence, whereas, foliar N improved vine N status and enhanced aroma

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[10] Atypical aging is a flavor defect in white wines, particularly but not limited to aromatic whites, where wine loses its varietal flavors very rapidly and atypical, waxy, furniture varnish, and dish rag like aromas appear when the wine is only 6 months to just over a year old.

[11] The stalk that joins a leaf to a stem.

[12] Vigor refers to the growth rate of a grapevine. Both high and low rates can be detrimental to the winemaking process.

[13] Related to leaves.

[14] A nitrogen-rich grapevine fertilizer.

characteristics of sauvignon blanc[15] without increasing vigor or *Botrytis* susceptibility. Other recent studies confirm the positive effects of foliar N on increased YAN and wine aromatics (Ancín-Azpilicueta et al., 2013; Lasa et al., 2012; Dufourcq et al., 2009). In particular, foliar N was more effective in increasing juice YAN compared with early season soil applied N (Garde-Cerdan et al., 2014). These results confirm significant improvements in the aromatic profile and greater aromatic intensity of wines made from Tempranillo grapes treated with foliar N. Lower aromatic intensity and pronounced herbaceous flavors were observed in wines not treated with foliar N. In addition, foliar N increased grape amino acid concentrations, which improved must N composition and enhanced fermentation kinetics. The above studies demonstrate that the use of 1-2% (w/v) urea foliar applied at veraison shows considerable promise compared to traditional soil applied N.

Field studies were conducted between 2016-18 to assess foliar N effects on grape N content, YAN, and other grape quality parameters. Treatments included foliar urea (1% w/v) applied during veraison (2 weeks prior through four weeks after) at 0, 10, 20 and 40 lb N a^{-1} with three replications (Table 2).

N rate[1]	**total N**[1]	***YAN***[2]
---------- *lb N* ac^{-1}	-----------	---- *mg* L^{-1} ----
0	0	152
10	10	177
20	20	198*
10x2	20	227*
10x3	30	237*
40	40	188
20x2	40	221*
10x4	40	241*
Soil N	120	173
p > F		***<0.001***

*represent on application at designated N rate or split N application where total N applied is shown; soil N applied prior to budbreak

**yeast assimilable N, should be > 140 mg L^{-1}; *significantly different from check treatment (0 lb N ac^{-1})

Table 2. Effects of foliar urea N on vinifera grape YAN at harvest. Data are average of two sites at Shelton Vineyard over three years (2016-18).

These results suggest that foliar N applied pre- and post-veraison significantly improves grape N content, YAN, and other parameters critical to enhancing flavor compound concentrations, without increasing vine vigor. Split N applications generally increased winegrape quality parameters to a greater extent than single foliar applied N or pre-bud break soil applied N. *Therefore, identifying N deficient grape plants at full bloom by either plant sampling/analysis or through remote sensing can direct the vineyard manager to initiate late-season foliar N management to improve wine grape quality*.

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[15] A green-skinned vinifera grape used in making white wine.

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The Role of Vineyard Geology in Wine Typicity

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ABSTRACT *Vineyard geology—bedrock and overlying soils—is widely supposed to help explain the typicity of wine from a particular area, though there has been little analysis of how this might come about. Such an evaluation is attempted here. Geology does underpin some of the physical parameters that affect vine performance, but in an indirect way and the factors are commonly manipulated artificially. A direct geochemical influence on wine flavour is widely inferred but remains undemonstrated. The popular model of nutrients being taken up by the vine and persisting to be tasted in the finished wine is untenable. The amounts that reach the fermenting must are minuscule, bear little relation to the substrate composition, and can be further complicated by contamination and fining. In the final wine these inorganic nutrients normally exist in concentrations far below human recognition thresholds and are 'swamped' by the organic secondary metabolites that do dominate wine flavour. Hence, any geochemical influence, like that of the physical factors, has to be highly complex and indirect. The notion of being able to taste the vineyard geology in the wine—a* goût de terroir*—is a romantic notion which makes good journalistic copy and is manifestly a powerful marketing tactic, but it is wholly anecdotal and in any literal way is scientifically impossible. Thus critical evaluation leads to the conclusion that the role of geology tends to be exaggerated.*

Introduction

Vineyard geology—the bedrock and soils derived from it—is commonly mentioned in the technical literature as an important influence on vine growth and wine character (e.g. White, 2003; DPIW, 2007). Some winemaking consultants believe it is responsible for the character of the wine from a particular area, for example, "the soil gives a wine its typicity" (M. Rolland, in Joy, 2007), as do some producers: "How else can you explain the iodized notes in Chablis if not by the composition of its soil?" (B. Billaud-Simon, in Joy, 2007). Popular wine writers enthuse about the importance of vineyard geology in endowing wine typicity, as in "what really makes Alsace wines unique is the preponderance of fossilized seashells in the soil" (Wille, 2001) and "the

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red soil is generally agreed to be of critical importance in making Coonawarra Australia's greatest red wine region" (Halliday and Johnson, 2006). Similarly, Champagne is commonly associated with chalk slopes, Chablis with Kimmeridgian limestone, Moselle wines with slate, Beaujolais with granite, etc. (e.g. Jefford, 2002).

Consequently, it has become *de rigueur* when describing a vineyard to specify its geology, even to detail the geological history and age of the materials involved. At the same time, tasting notes frequently employ geological words such as earthy, stony, and minerality, and this tends to promote further an inferred direct link between the vineyard substrate and the resulting wine. Some writers make explicit a connection with wine taste: "drinking wine helps us taste geology" (Jefford, 2000); "infused in the wine is a goût de terroir, a taste of the soil" (Kramer, 2008). Such perceptions bolster a valuable tactic for the wine trade, as, being one of the few aspects of wine production that cannot be translocated or easily replicated elsewhere, a vineyard's geology is something that can be invoked to promote a wine's typicity, to give it a marketable uniqueness.

However, there has been remarkably little attempt to analyse how any connection between vineyard geology and wine might come about, and especially to evaluate critically the geological factors that might influence the finished wine. This is the purpose of the present article. The discussion begins by considering the physical factors that might influence vine performance and hence wine character, and then examines the possibility that vineyard geochemistry can affect wine taste. Finally, the idea that vineyard geology can be directly sensed in the finished wine—that the wine possesses a *goût de terroir*—is considered.

Role of Physical Geology

Geology and Landform

Within the world's temperate climate belts, the interplay between crustal uplift, the spatial arrangement of surface rocks, their relative durabilities and geological processes of erosion fundamentally controls the distribution of sites suitable for grape growing. A summary of the resistance to weathering and erosion of common rock types, and how their 3-D arrangements affect landforms is given in Maltman (1998). In other words, bedrock geology determines the topographic relief of an area, at both regional and local scales, and this interacts with its hydrogeology and with a host of influential climatic factors. These include altitude (Mateus *et al.*, 2001) and exposure (Mazza *et al.*, 1999), together with slope aspect, convexity and inclination (Dumas *et al.*, 1997). Solar warmth generally increases with greater slope inclinations (e.g. see Robinson, 2006), which is helpful during fruit ripening (Huggett, 2006) though possibly damaging in high-altitude vineyards that rely on persistent snow cover to protect the vines during winter dormancy (Hamman *et al.*, 1998). Slope character influences the exposure of the fruit to ultra-violet radiation (Smart, 2002).

Landform governs airflow patterns and velocities, which can be important factors in vine performance. A modest flow helps reduce fungal problems but can hinder fruit set. Vortices can help combat ground frosts and hence lengthen the growing season, as, for example, at Niagara, Canada (Haynes, 2000). However, excessive wind can not only damage vines (Kliewer and Gates, 1987) but through its cooling effect can reduce photosynthetic activity, though Mayberry (1987) reported that the mistral of the Rhone Valley helped concentrate solids in the grapes of Chateauneuf-du-Pape, France. Wind funnelled along valleys eroded in weak rocks can have important local effects. In Franconia, Germany (Wahl, 1988), the Main river has eroded weaker layers in a series of sandstones and clayey limestones, and here Freeman and Kliewer (1983) have argued that the channelled wind is more influential in grape ripening than either air temperature or sunshine hours. High wind speeds have been offered as an explanation for the high-acid grapes in parts of the Salinas Valley, California, eroded in a wide zone of complex faulting (Wahl, 1988).

Airflow can also affect cloud cover, which influences photosynthesis (Kliewer, 1970). Spayd *et al.* (2002) showed that in the Yakima Valley of Washington, USA, exposure to sunlight has a greater influence on grape flavonoid concentrations than temperature. The Willamette Valley, Oregon, achieves sufficient sunlight and avoids Pacific dampness through being in the rain shadow of the Coast Range to its west (Swinchatt, 2006). The orientation of the mountain ranges in the high rainfall area of the Paarl region, South Africa, controls localised rain shadows; the Franschoek Valley benefits from its sheltered location in a zone preferentially eroded along faulted and hence fractured and weakened granite and conglomerates (Bargmann, 2003).

Vineyard Soil and Bedrock Properties

Apart from vineyards sited on alluvial deposits, such as on valley floors or alluvial fans, virtually all vineyard soils are derived from the underlying or immediately upslope bedrock. The nature of this bedrock and its degree of weathering greatly influences the physical properties of the soil, an important influence on vine-root growth (e.g. Morlat and Jacquet, 1993). In fact, Smart *et al.* (2006) have shown the substrate properties to be more influential on root growth than the genotype of the rootstock itself. The properties can also be important in vineyard management. For example, in sloping sites the mechanical strength of the soil determines its resistance to downslope creep and erosion (Meyer and MartõÂnez-Casasnovas, 1999) and hence the need for terracing (e.g. Pla *et al.*, 2006). Soil strength also affects the extent to which machines can work the vineyard soil (Ferrero *et al.*, 2005).

The surface of the topsoil influences its heat transfer and storage properties (e.g. Maschmedt *et al.*, 2002). For example, stony soils reflect heat if they are pale-coloured. The white cobbles or *galets* of Chateauneuf-du-Pape, the pebbly *caillottes* at Sancerre, France, and the *codols* (pebbles) at Monsant, Spain, are often mentioned in this respect, as are the pale *albariza* soils of Jerez, Spain. In contrast, the metamorphic rocks and grey limestones of the Franconia district of Bavaria, Germany, provide dark-coloured soils that warm relatively quickly and store heat, thus promoting ripening in this northerly region (Michel *et al.*, 2002).

The thermal behaviour of surface stones also involves their ability to absorb impingent heat radiation as opposed to reflecting it, depending on the surface albedo (Evett, 2002). For example, smoothly surfaced white stones provide a far greater albedo than rough, dark basalts, which will therefore warm more quickly but re-radiate the heat more quickly at night (Dvoracek and Hannabas, 1990). The vineyards of the Ahr Valley in southwestern Germany, among the most northerly in Europe, are able to ripen red grapes probably because of the wealth of dark-coloured, low albedo, rocks that form the vineyard surfaces and in places comprise the embankments of the steep terraces as well as natural outcrops. The lower, western, part of the steep-sided valley is dominated by dark-grey slates and greywackes and the upper part by very dark basalt. Similarly, low-albedo basalt-derived surfaces in the north Willamette Valley, Oregon, USA, enhance cytokinin synthesis through spreading the diurnal heat load (Nikolaou *et al.*, 2000); similar effects arise further north in parts of the Walla Walla Valley, Washington, USA (Meinert and Busacca, 2000).

Water Availability in the Vineyard Substrate

The importance of water in vineyards has been much discussed (e.g. van Leeuwen *et al.*, 2004; Van Leeuwen and Seguin, 2006; Merouge *et al.*, 1998), following the now classical work of Seguin (1986). Although the vineyard soil is commonly the predominant hydrogeological medium (White, 2003), the ability of vines to exploit bedrock for water can be significant (Hancock, in Robinson, 2006), especially in arid areas and where the overlying soils are thin. Ashenfelder and Storchman (2001) observed how the depth to the bedrock in the Mosel vineyards, Germany, becomes an important parameter where the overlying soils give poor storage. Hancock and Huggett (2004) argued that vines in the Coonawarra district of Australia excel not because of the much-vaunted surficial *terra rossa* but because of the hydrogeological properties of an unusual breccia in the underlying limestone. In the belief that bedrock-penetrating roots are beneficial, some new vineyards in Bandol, France, have been excavated deeply and substantial quantities of soil removed, in order to prompt the vine roots to grow into bedrock (White, 2003).

In addition to the hydrogeological properties of the rock, a relevant parameter is the degree of its resistance to root penetration. Myburgh *et al.* (1996) correlated diminished grape yields with restricted root development and documented how this depends on the root-resistance of the growing medium. This latter property is a function not only of rock type but whether or not the bedrock contains planes of weakness, and their spacing and orientation. The Upper Douro area of Portugal provides an illustration. That the best grapes are produced from areas with schistose bedrock rather than the associated granite is enshrined in the official system of ranking the vineyards of the region. The explanation may lie in the greater degree of root and rain penetration offered by the schist. Soils are exceedingly thin in this arid area and offer little water storage. The granite bedrock is massive (meaning, in geological terminology, that it lacks planar features) and root penetration is therefore low. In contrast, the foliation (schistosity) intrinsic to schists not only provides weak surfaces but also generally in the Upper Douro it is steeply dipping or vertical, ideally oriented for roots to exploit.

The presence of clay in soil is well known to provide potentially vital water storage. The clay may have been sedimented *in situ*—as in the famous 'mounds' of Bordeaux soils (Seguin, 1986), derived from a clay-rich bedrock—as in the *galestro* soils overlying the argille scagliose of the Chianti region, Italy (Cita *et al.*, 2004), or produced by weathering of a parent rock type that is not obviously clayey. For example, the feldspar minerals that are the dominant constituent of granite weather readily, especially in the presence of water, to the clay mineral kaolinite and thus increase the storage capacity of the weathered material. This applies, for example, to vineyard soils in northeastern Spain (Ubalde *et al.*, 2005) and in South African vineyards based on granite, such as in the Stellenbosch region (Bargmann, 2003).

Assessing the Importance of Vineyard Physical Geology

In ways such as those mentioned above, physical factors—underpinned by geology—help explain local variations in vine behaviour. Moreover, a range of microsensor technologies are now available (e.g. Hubbard and Rubin, 2004) which are revealing unprecedented fine-scale physical differences between sites. Thus *in principle*, geology is playing a significant role in the vineyard and therefore potentially in helping define wine typicity.

However, there are a number of arguments that tend to lessen this apparent importance in practice (Maltman, 2003). First, the connection as outlined above can be seen as rather academic. Most grape-growers are not interested in why their vineyard is sloping, the soil pale-coloured, etc. but how to deal with the result. And, of course, although such principles are enthusiastically dissected and debated in the literature on wine they apply to a greater or lesser extent to all plants and crops. In any case, from a physical viewpoint, it is not the lithology (*type* of rock) itself that matters—and certainly not its geological age and history—but specific physical properties that result. For example, limestone is often mentioned as being an ideal vineyard substrate (presumably because it happens to underlie several classic areas in France). In warmer parts of France, however, limestone soils are less esteemed and may even be of marginal suitability for viticulture (Hancock, in Robinson, 2006). The only unusual property that limestone confers is soil alkalinity, and there is no evidence that this is particularly beneficial to vines (Bavaresco and Poni, 2003). In fact, high pH reduces the availability of essential cations such as zinc and iron (Hellman, 2004) and leaf chlorosis can result (Gruber and Kosegarten, 2002). Limestone does, however, commonly provide good drainage (e.g. Huggett, 2006)—as do a number of other rock types. In other words, although the ancient geological histories of vineyards are commonly elaborated by wine writers, together with discussions and maps of the actual lithologies, important in practice are the drainage, physiographic, thermal, and other physical parameters that the geology dictates.

A second argument does much to demote the role of geology in practice: most of the physical factors mentioned above are routinely manipulated artificially. Landform is the exception, but even here earth moving, land levelling, and terracing (e.g. Pla *et al.*, 2006), together with wind screening/wind machines, etc. (e.g. Fraser *et al.*, 2006), are widely employed, diminishing the importance of the natural geology. Soil colour becomes less relevant as cover-cropping and mulching grow in popularity (e.g. Pinamonti, 1998). Even the classic wine districts have a long history of intervention. According to White (2003), the famous chalk slopes of Champagne "have been augmented for centuries with lignite from local clays and silts" while the archives at Chateau Latour record three centuries of soil building and replacement. Of course, the all-important factor of water availability is no longer dependent on the natural drainage and water retention properties of the vineyard but is dealt with artificially: the science of vine irrigation has lead to highly sophisticated vineyard technologies. (Even in France, recent legal changes now allow some irrigation.)

Third, the celebrated correspondence between the typicity of some classic wine districts and their geology is based on a fragile logic. A number of French *appellation controlée* sites were defined partly according to geological boundaries, but this was merely following historical dogma (e.g. Hanson, 1982). Thus inferring now an importance for geology because of its correlation with vineyards of high status is based on cyclical reasoning. And because certain wine styles have become so firmly established in particular classic regions, it is unknown to what extent their vineyards could succeed with modern alternatives. As Johnson (1998) remarked, such questions "will never be answered because the pattern is set".

Examples of the neat coincidence of bedrock strata with vineyard rank are usually presented on geological cross-sections, classically of the Côte-d'Or escarpments (e.g. Vigneaux and Leneuf, 1980), but rarely with accompanying maps, where the coincidence starts to fail. Horizontal or very gently dipping strata—as in the Côte-d'Or—in map view must approximately follow topographic contours round a hill, but maps of the district show the vineyard classifications to be related to slope aspect, that is, exposure to the sun. That is, the neat correspondence between bedrock geology and wine classification apparent in cross-section fails in map view. The official Chablis area was originally defined strictly according to geological boundaries, following historical practice, but Huggett (2006) discusses how after much controversy this restriction was recently abandoned, tacitly recognizing the greater importance of slope properties and reducing bedrock geology to an indirect role.

Furthermore, in relating vineyard geology to a certain wine type there is a common tendency to overlook the numerous geological complications that arise in nature. Many rock formations are distinctly heterogeneous at a given site, and in addition can change laterally. For example, the celebrated Kimmeridgian limestone of Burgundy has very variable amounts of marl and clay intercalated with it and smeared along joint planes (Hancock, in Robinson, 2006). The much-vaunted chalk of the Champagne region in fact occupies only about a third of the surface area, with beds of clay and sand being more preponderant elsewhere (Lorson, in Jefford, 2002). Even where the Chalk is outcropping—and hence depicted on a geological map—the vine roots may be tapping underlying formations of different lithology (e.g. Hancock, in Robinson, 2006). Conversely, the outcropping bedrock may be overlain by such a substantial depth of broken and weathered regolith and soil that it is these horizons that are influencing vine growth, despite what is shown on the geological map. For example, the Beaujolais area is normally depicted as being dominated by granite, but in places there are several metres of material so decomposed that the vine roots are largely in a medium effectively behaving as sand (Hancock, in Robinson, 2006).

Finally, the foregoing discussion largely concerns the influence of physical geological factors on vine growth and berry ripening: the extent to which this affects the resulting wine and its typicity is another matter. There are difficulties with seeing it as an important influence. For example, vineyards in different regions but sited on similar bedrock and soils produce widely differing wine styles. Kimmeridgian limestone is often claimed to account for the character of wines from Chablis and Sancerre but this same formation is widespread across France and well beyond, where it yields undistinguished wines and, in parts of the Champagne district, wines of quite different character. The granite at Dambach in Alsace, France is said to give wines that have "a beautiful elegance and very fine fruitiness" (http://vins-beck-hartweg.chez-alice.fr/granit_angl.htm), yet those produced on granite at Cornas attract words such as "impenetrable", "meaty", "powerful" and "brutal" (http://winetasters.ca/SemNotes/cornas.html). Conversely, the Côte Rotie, France, is classified and usually regarded as an entity, producing wines that are consistently different from nearby districts yet the hill has a diverse geology, including alluvial gravels, quartz-mica-schists, gneisses and granites—materials of highly differing physical properties. Examples abound of contrasting wine styles produced from bedrock and soils that are similar, and similar wines from areas with differing geology.

Even so, it is conceivable that physical geological factors do have some role in giving typicity, but in such an indirect and complex way that science is still some way from unravelling it. It is possible that interplay between soil temperature, slope, drainage, etc. influences development of the flavour precursors in the ripening grapes that will ultimately have some effect on the taste of the eventual wine (e.g. see Goode, 2005). The results of some recent studies are in line with this notion (e.g. Jackson and Lombard, 1993; Gómez-Míguez *et al.*, 2006; Andrés de Prado *et al.*, 2007; Bauer, quoted in Werner, 2008). Schlosser *et al.* (2005) detected some correlation between organic aspects of wines, such as ethanol and phenol content and titrateable acidity, and the physical setting of their parent vineyards on the Niagara Peninsula, Canada.

Nevertheless, it is clear that the prevalent thinking about the role of vineyard geology in wine flavour is based on a very much simpler and more direct connection, involving inorganic vineyard geochemistry. As the fashionable image has it, a cocktail of nutrient minerals is taken up by the vine roots from the vineyard substrate and is transmitted through to the grape juice. These minerals then persist through vinification and are thus present into the wineglass, where they can be tasted. To assess this popular picture, vineyard geochemistry has to be considered.

Role of Geochemistry

Vine Nutrients

Although 88% of the vegetative matter in a vine is derived through photosynthesis from CO_2 in the air (Bourgignon, quoted in Jefford, 2002), the vineyard substrate has to provide most of the 19 or so inorganic nutrients that are essential for normal vine growth. Bedrock commonly has a crucial role in this (e.g. Pool, 2000). Although the normal weathering of most rocks will provide adequate nutrition for vines (e.g. Huggett, 2006), Wooldridge (1990) has documented differing provisions of potassium from bedrocks such as granite, sandstone and shale, and Kruckeberg (1986) showed how soils derived from serpentinite—a widespread bedrock in Californian vine-growing areas—have serious problems of nutrient balances and deficiencies. Clays are particularly important in helping provide nutrient ions. In fact, Hopkins and Huner (2004) felt that the ability of clays "to retain and exchange cations on colloidal surfaces is the single most important property of soils". Their cation exchange capacity ranges from very high values for montmorillonitic soils, such as develop from impure sandstones or volcanic deposits, to relatively low values for kaolinitic soils, typically formed over granite. The degree of weathering of the parent rock influences the depth and amount of clay material, which has been argued by Bodin and Morlat (2006) and Morlat and Bodin (2006) to influence both vine behaviour and wine character.

However, the relations in chemical composition between the growing vine and its substrate are complex and indirect (e.g. Lanyon *et al.*, 2004), with debatable correlation between soil nutritional analyses and vine performance (e.g. Gladstones, 1992; Mackenzie and Christy, 2005). Among a number of complicating factors, the different rootstocks onto which a cultivar can be grafted have differing uptake properties (Fisarakis, 2004), there is close dependence on water availability (Keller, 2005), transpiration rates (Nikolau *et al.*, 2000) and the pH of the soil (Bates *et al.*, 2002). In fact, Green *et al.* (2004) showed that the inorganic content of grapes can depend more on irrigation waters than the substrate in which the vine is growing.

The nutrients taken up by the roots are differentially partitioned among the various components of the vine (Schreiner and Baham, 2003) such that, for example, the aerial parts of the plant contain differing proportions from the roots (Brun *et al.*, 2001). As a result—importantly—"there is startlingly little correlation between relative concentrations of the elements in the substrate and in the plants" (Epstein and Bloom, 2004). And, of course, the levels of available nutrients are changed by applications of agrochemicals and can be affected by pollution. For example, anomalously high levels of copper in soils and vines due to repeated sprayings of fungicides are well known (e.g. Morgan and Taylor, 2004; Pietrzak and McPhail, 2004); high zinc concentrations in the Maribor region of Slovenia (Weingerl and Kerrin, 2000) were ascribed to the use of zinc-based fungicides. Vineyard posts made of treated timber can also contribute to the copper, chromium and arsenic content of the soil (Robinson *et al.*, 2006).

As vinification proceeds, the inorganic chemical profile of the must becomes increasingly dissimilar from that of the vineyard soils. Only a small proportion of the inorganic nutrients absorbed from the substrate is passed to the growing berries, and some of these are taken up by the yeast during fermentation and eventually dropped out as lees. Filtering and fining of the must reduces further their concentrations, and using bentonite clay as a fining agent introduces yet additional chemical complications (e.g. Castineira Gomez *et al.*, 2004). Additional changes in chemical proportions can arise from contamination in the winery, for example, from fermentation vessels, spigots and pipes (Almeida and Vasconcelos, 2003a).

An illustration of the disconnect between the chemical composition of the vineyard and the finished wine is provided by the difficulties encountered in attempting wine 'fingerprinting', that is, relating a wine to its place of origin so as to prevent fraud. Attempts have had to resort to using rare earth elements (Jakubowski *et al.*, 1999), trace elements (Taylor *et al.*, 2002), ultra-trace elements (e.g. Perez-Trujillo *et al.*, 2002), Sr^{87}/Sr^{86} isotope ratios (e.g. Almeida and Vasconcelos, 2001) and complex statistical manipulations (e.g. Fischer *et al.*, 1999), but all with debatable results. Correlations that have been detected tend to relate to pesticide use and other sources of aerial contamination rather than with the vineyard substrate (Ettler *et al.*, 2005). Analysis of the organic metabolites is showing somewhat more promise (e.g. Cliff *et al.*, 2007) but even this is problematic because the compounds largely originate during vinification. In other words, there is no obvious way in which the inorganic chemical composition of a wine corresponds with where the grapes grew, a formidable difficulty for arguing that vineyard geochemistry directly helps determine wine typicity.

Nutrient Concentrations

A further problem arises from the minuscule—and virtually untasteable—amounts of the inorganic nutrients in the finished wine. They make up only around 0.2% of a wine in total. Individual elements are typically present in amounts ranging from some tens of milligrams/l for potassium, magnesium, calcium, and sodium (e.g. Almeida and Vasconcelos, 2003b), a few hundreds of micrograms/l for iron, and down to a few tens of micrograms/l and less for metals such as aluminium, copper, lead, zinc and chromium (Cerutti *et al.*, 2005). The vapour pressures of these cations are virtually zero and consequently the concentrations are generally at levels far below human taste thresholds. For example, zinc and copper can only be sensed on the palate in amounts greater than around 3 milligrams/l, according to Zacarias *et al.* (2001), and, according to the work of Cohen *et al.* (1960), as much as 16 milligrams/l (and 62 milligrams/l for zinc) *in distilled water*. These thresholds are minimal amounts for detection; the levels at which the taste becomes recognizable is typically much higher. In contrast, some of the organic constituents occur at concentrations measured in grams/l yet, being volatile can be sensed at concentrations as low as parts per trillion. It is now well established that both the mouth-feel (e.g. Pickering and Robert, 2006; Gawel *et al.*, 2007) and organoleptic properties of wine are governed by these latter substances—a catalogue of polyphenols, volatile compounds, sugars, higher acids, etc.—almost all synthesized during fermentation and maturation (e.g. Lund and Bohlmann, 2006) and effectively 'swamping' the inorganic nutrients.

A few inorganic cations, such as iron and magnesium, together with chloride and sulphate anions, have higher detection thresholds (Cohen *et al.*, 1960) and can be present in wines at those concentrations and higher. But instead of this providing an instance of natural minerals subtly influencing flavour, such anomalous concentrations are commonly regarded as being problematic and to be avoided by winemakers. Metal ions give rise to bitter, insipid, 'off' tastes (Pereira, 1988), and their salts impart a range of undesirable sensations (Yang and Lawless, 2005). Potassium, magnesium, calcium, and aluminium can all cause turbidity and precipitation problems, and higher than normal levels of copper and iron can induce haziness. Finally, it has to be pointed out that modern treatises on wine flavour (e.g. Waterhouse and Ebeler, 1998; Clarke and Bakker, 2004) make no mention of geology; most omit discussion of inorganic elements altogether. The conclusion has to be that vineyard geology does not—certainly in any direct and demonstrated way—imbue some unique flavour to its wine.

Nevertheless, in parallel with the speculation at the end of the section on physical factors, it is conceivable that the minute quantities of inorganic nutrients in the vine can somehow influence—wholly indirectly—some of the vast array of complex metabolic reactions involved in vine growth and wine making. In any of the various stages, from influencing mycorrhizal activity around vine roots through metabolism in the vine tissues (e.g. Jackson, 2000) and eventually in the fermenting and maturing must, the inorganic elements ultimately derived from the vineyard substrate just might have crucial catalytic or retarding influences, even at minuscule concentrations. Metal ions are known to act as cofactors in some enzyme activity (e.g. Keller, 2005). Also, a wine's organoleptic properties arise from the interplay on the palate of complex aromatic molecules, and it is just possible that tiny amounts of inorganic elements play some indirect but facilitating role in this interaction. There is little supporting data on these suggestions (but see Pereira, 1988) but then detecting such effects has been beyond the reach of all but the most recent technology. Perhaps the new micro-analytical methods that are only now becoming available (e.g. Ebeler, 2001), coupled with the powerful gene-based approaches now being pursued (e.g. Qiu, 2002) may someday reveal that vineyard geochemistry does influence wine typicity and explain the battery of anecdotal evidence. However, at present this remains speculative and undemonstrated.

Geological Tastes in Wine: *Goûts de Terroir*

Even if some day a link is detected between geochemistry and wine flavour, this is not the same thing as claiming that the vineyard geology can actually be tasted. This extreme claim of a literal *goût de terroir*—for the vineyard geology to actually be discernible in the wine—pervades populist wine writings and so an examination is given below. However, this does lead to the conclusion that in addition to all the difficulties discussed in the previous section, the notion of being able to directly taste the geology is unsustainable for a number of reasons.

First, the claim is often based on an illusory precept arising from confusing three different meanings of the word 'mineral'. The rocks and soils of vineyards are made of minerals in the *geological* sense—inorganic crystalline compounds, most commonly carbonate and silicate compounds. Unfortunately, ions dissolved from them—the *nutrients* discussed in the previous sections—are also commonly referred to as minerals. In addition, it is fashionable to describe some wines as having a mineral *taste*. Yet these three different connotations are often merged together, with the result that meaning is lost. An example is the widespread claim that a mineral taste in a wine is due to the minerals in the vineyard soils—the two usages of mineral here are two different things. Thus, for example, there is no basis for popular assertions that mineral tastes are marked in wines from vineyards with conspicuously stony soils, or from vines deeply rooting into bedrock. All rocks and soils are made of geological minerals, not some more than others. Similarly, despite claims such as "Alsace has the most complex soils, which means that mineral flavours are apparent in a number of Alsace wines" (Jefford, 2000), an intricate geology does not lead to wines that have a more pronounced mineral taste.

Second, apart from sodium chloride and some rare, complex salts (Yang and Lawless, 2005), earth materials are themselves literally flavourless. Consequently, the mineral taste or 'minerality' mentioned above can have no literal meaning (and according to Goode, 2005, is almost certainly due to organic secondary metabolites produced during fermentation, possibly involving reduced sulphur compounds). Calcite, the mineral constituent of all limestones—including chalk—and the silicate 'rock-forming' minerals have no taste or smell. Thus tasting descriptions such as "minerally, rocky flavours" (http://www.thewinedoctor.com/tastingscellar/burgundy.shtml), "the pungency of fossiliferous pebbles makes Chablis stand out from other Chardonnays" (Jefford, 2002); and a "mineral, more specifically quartz" taste (http://www.wineglas.com/winereviews_white_french.html) etc., can have no literal meaning. Obviously, such phrases are, as with other tasting terms, often being used metaphorically, but if the vineyard comprises those same geological materials the scene is set for a direct causative link readily to be inferred. As an example, the wines of Priorat, Spain, are sometimes reported to taste and even smell of graphite, even though this insoluble carbon polymorph has no taste or odour. It cannot be coincidence that most tasters are probably aware that Priorat is founded on unusual schists that are rich in graphite (e.g. Dawes, 2003). Especially odd are the references in tasting notes to quartz. Besides being tasteless and odourless (and virtually insoluble at Earth's surface temperatures), quartz—silicon dioxide—is the same inert compound as the bottles and wineglasses in which the wine is being tasted.

Third, misunderstandings can arise because rocks are classified fundamentally on their geological origin, as deduced from their texture or physical structure, rather than chemically. One upshot of this is that bedrocks that are quite different in appearance can be remarkably alike chemically, with similar potential availability of nutrients. For example, patches of slaty soil around Andlau, in Alsace, France, are said to produce Riesling wines of different taste to those nearby on shale, schist, hornfels and granite (e.g. Price, 2004). The Muscadet region has recently been officially divided into sub-areas claimed to produce differing wines, depending on differing proportions of gneiss, orthogneiss, paragneiss, mica-schist, granite, etc. (Ahmed, 2007). These various lithologies may look strikingly different because of their differing geological origins—and they can give rise to soils of differing physical properties—but it is the bedrock chemistry that is usually invoked to explain taste differences and all these rock-types have roughly the same overall chemical composition.

Fourth, wines from areas known to be underlain by volcanic rocks are often ascribed a clear typicity (e.g. Óskarsson and Arnalds, 2004), sometimes involving words such as "fiery", "spicy" and "pungent" in tasting notes (e.g. http://www.hotelonlinehungary.com/hungary/wine_regions.htm). Presumably, this is a purely psychological effect, but some writers purport to be able to detect a "sense of volcanic ash in the tannin" (http://www.diamondcreekvineyards.com/diamond_creek-news12.htm) and "a taste of volcanic ash" and "deep, smoky, mineral flavors" in Piedirosso wines from the flanks of Vesuvius, Italy (http://www.thewinenews.com/octnov03/cover.asp). Indeed, Jefford (2007) went so far as to claim that in wines from the volcanic island of Santorini "you can taste the fury of the earth". Romantic though such notions are, volcanic rocks, being composed of silicates, are just as flavourless as other rocks. However, conspicuous in active volcanic regions is the smell and taste of sulphur and its compounds: perhaps this is what is being sensed in these wines? The difficulty here is that sulphur and sulphur compounds are extremely widely used chemicals in both viticulture and winemaking, as a fungicides, antiseptics, preservatives, etc., and have been for centuries (Johnson, 1998). Consequently, the majority of wines, whether from volcanic regions or not, contain sulphites, not uncommonly detectable as sulphur dioxide. Poorly made wines may smell of hydrogen sulphide. Therefore, it cannot be sulphur and its compounds that give typicity to wines from volcanic areas.

Fifth, the idea that vineyard geology can be literally tasted in the wineglass is mechanistically impossible. On top of the difficulties regarding vine nutrients—charged ions—discussed in the previous section, this notion requires the uptake and transmission into a wine of solid aggregates of entire crystalline compounds (i.e. rocks). As an illustration of the problem, some of the vineyards in the Moselle, Germany, have strikingly slaty soils and the wines, especially Rieslings, are often said to taste of slate (e.g. http://wirtschaft.fh-trier.de/ri/fell/ortfell/weinort.php?nr=7&unr=2&eTyp=n&lan=en). Geologically, slate is an aggregate of several complex silicate minerals bonded to give a characteristic aptitude for cleaving into thin sheets. It is palpably absurd that somehow in the wine there exists a cleavable, complex solid, but such an implication is apparent in popular descriptions of Moselle wines. Clearly, Moselle wines have a distinctive flavour, but unfortunately it is being expressed not by an abstract descriptor but by the name of the rock type in the vineyard, and this leads to the mistaken thought that the geology is directly responsible for this typicity.

Similar confusion follows from other geologically based tasting terms. For example, wines with an 'earthy' taste are commonly related back to geology, but in the olfactory sense the term refers not to the flavourless substrate of a vineyard but to odours of organic matter such as humus, decaying compost, mushrooms, etc. 'Acidity' is an important word in the wine lexicon, applied liberally to vineyard rocks and soils, and, of course, to wines. In the latter usage, it refers to the complex mix of mainly organic acids in wine, normally expressed as pH, titrateable acidity, fixed/volatile acidity, etc. In soils, it is usually expressed as pH; in rocks it reflects the silica content of the rock, a quite different matter. Thus, acid rocks may or may not give rise to acid wines: there is no direct connection.

Conclusions

Vineyard geology is much mentioned as an important factor in giving a wine a particular character—helping endow a typicity—but critical evaluation of its role shows that there is misunderstanding about the possible connections, resulting in its significance commonly being exaggerated. The physical setting of a vineyard, ultimately due to bedrock geology, certainly affects parameters such as airflow patterns, slope character, thermal properties and water availability, and these demonstrably influence vine growth and berry ripening. However, in practice such factors can be somewhat academic, not least because artificial wind devices, earth moving, cover crops and, especially, irrigation, commonly alter them. Nevertheless, it is conceivable that such physical factors ultimately influence the development of flavour precursors in the ripening berries, and hence in some indirect and as yet unknown way, the character of the eventual wine.

A geological role in wine typicity is most commonly ascribed to vineyard geochemistry affecting wine flavour but here any direct connection is particularly difficult to justify.

Notwithstanding the blurring of the term 'mineral' mentioned above, the popular model of nutrients being taken up by the vine from the soil and persisting to be tasted in the finished wine is untenable. The proportions that reach the fermenting must bear no apparent relation to the vineyard substrate, and they can then be further complicated by contamination and fining. Furthermore, in the final wine these inorganic nutrient ions normally exist in concentrations far below human recognition thresholds. They are 'swamped' by the organic secondary metabolites that do dominate wine flavour. Hence the plethora of anecdotes on vineyard geochemistry giving wine typicity can only arise from some highly complex and indirect mechanisms, as yet undemonstrated scientifically. It is conceivable that the inorganic geochemistry, despite being represented in the finished wine in tiny and untasteable amounts, somehow influences the biochemical pathways followed during vine-growth and vinification, but this remains speculative and unproven. Thus at our present state of understanding, the influence of vineyard geology in wine typicity is at best highly indirect, with a role much less major than its frequent mentions would suggest.

Finally, the notion of being able to actually taste the vineyard geology in the wine—a *goût de terroir*—arises partly through various misunderstandings of geological terminology and, presumably, through the sheer romance of the idea. Certainly, the vision makes good journalistic copy, and is manifestly a powerful marketing tactic, geology being one of the few factors involved in wine production that cannot be translocated or easily replicated elsewhere. However, the proposition is wholly fanciful for a number of reasons and in any literal way is scientifically impossible.

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THE INFLUENCE OF GEOLOGY ON WINE TASTE, TEXTURE AND QUALITY – AN INTERPRETATION BY SWISS GEOLOGISTS

Willi Finger[1] and Rainer Kündig[2]

INTRODUCTION

How important is the geologic factor, meaning processes, lithologies, and geomorphology, on the sensually perceptible character of wine? Other influences, such as the climate, have a critical and well-documented input on the grapes. And most importantly, the winemaker can influence the variety of tastes, aromas, and textures by traditional techniques, such as pressing, expanding and maturing the wine. For geologists, however, there is no doubt that geological conditions in the vineyards have a major impact on the growth behavior of grapevines, and therefore on quality of the wines. Sun exposure, hydrology, microclimate, soil properties, and landscape are all coupled with or are expressions of geological development and history.

In his greeting address to the 4th International Congress of Vine and Wine in 1935, the great Alpine geologist Maurice Lugeon stated that geologists, who are constantly roaming the globe, feel real satisfaction when they can apply their knowledge of the earth in comparing wines from different terroirs. Beginning in 2008, we organized and led a group of over 60 geologists and wine professionals on a voyage of discovery through the wine regions of our native Switzerland, with the objective of documenting the relationship of geology to viticulture. We did not have to travel around the world to develop our study. Switzerland is a small country blessed with a great variety of rocks and structures, with vineyards spread over a wide spectrum of soils and landscapes. Our research was, so to speak, carried out under "laboratory conditions."

Our team members were mostly geologists, all of whom are experienced and knowledgeable wine lovers, and some of whom are themselves vineyard owners and wine producers, but the team also included non-geological vineyard owners and producers. Members came from all regions of Switzerland. Over a ten-year period we visited all the wine regions of the country, and a high percentage of the vineyards in the myriad of geological situations our small nation offers. We collected data from vineyards, noting soil types, bedrock lithologies, elevations, slopes and aspects, and every natural environmental factor we felt, or were told, was critical to success of the vineyards. The results of this research were published in 2018 in our book "Stein und Wein," which was, we can proudly say, awarded the Swiss Gourmet Book Award as best publication of the year 2018.

We are honored and pleased to be asked to present this paper and to speak to the 2022 meeting of the Carolina Geological Society about our work. With the limited time allotted, it is impossible to discuss all aspects of our research, so what we present here is a small potpourri of our thoughts on the role of geology in influencing wine taste, texture, and quality.

TERROIR - NINE STEPS FROM GEOLOGY TO WINE

There are many definitions and understandings of the expression "Terroir," which is simply the French word for "earth." In the 12th century, Benedictine and Cistercian monks tried to find connections between the mother earth (Terroir) and the vines in the character of wine. In one of their cleverer methods, it is said that they dissolved soil in water and tasted it to determine the best regions for vineyards. Could this be the origin of the idea that wines acquire their tastes and character from the soils in which they are cultivated - the concept of 'goût de terroir'?

Earth and soil do, of course, play a significant role in the many present-day definitions of terroir. But limitation of the concept to bedrock and soil alone definitely falls short. Terroir includes all the natural factors of a landscape that influence the flourishing of the vines and the quality of the wine. The original definition of terroir ignored the work and skill of the winemaker, which, of course, is now part of the overarching European understanding of the term. The geological factors of time and depth, which are critical for development of the subsurface, have been somewhat overlooked until now. Geologists recognize that earth processes occur in varying time and depth intervals and interpret them accordingly. It is only logical that we as earth scientists can contribute to an understanding of the temporal and subsurface aspects of terroir. So, we have boldly added the time and depth factors to the more common terroir characteristics. Our approach to the topic of terroir in our book is thus organized around the nine themes: time, depth, topography, soil, elements, water, climate, vines and wine (Figure 1). Of course, when you participate in a wine tasting, you usually proceed in discussion and evaluation of the wines in the reverse order, starting with the wine; when you finally arrive at the geologically-influenced topics of depth and time, you may be quite overwhelmed, or, as you say in English - "out of it."

SWITZERLAND AS A WINE COUNTRY

To create a basic framework that simplifies comparisons of different wine-growing areas throughout Switzerland, we have generated a new geological map of the country by reducing the complex geology to (1) ten lithologies: conglomerates, sandstones, marls, clays, limestone, gypsum.

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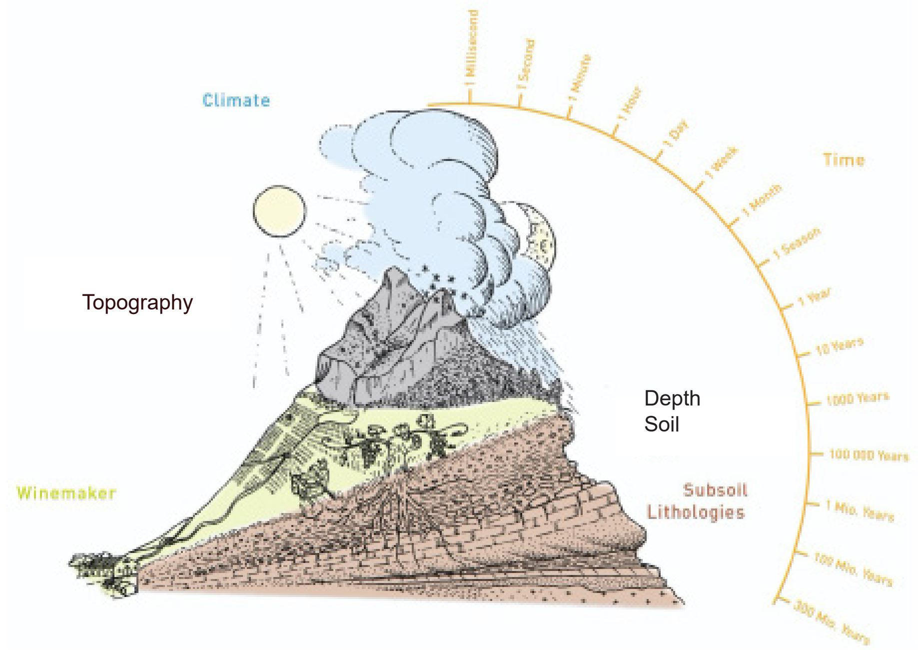

Figure 1. Traditional elements of terroir, with the additional aspects of time and depth

dolomite, slate, crystalline rocks, and volcanic rocks, and (2) four soft rock units/processes: slope, fluvial, glacial, and aeolian deposits. Each of these units has characteristics that relate to viticulture, which of course can be traced back to the complex, alpine character of Swiss geology.

With this radical reduction of Swiss geology to 14 basic units, we have created an ‘oenogeological’ map of the country. By drawing the 10 important wine-growing regions in Switzerland on this simplified base, one can see quickly differences in the composition of subsoil, both in terms of solid and unconsolidated rock. This was then our basic approach for describing the diversity of Swiss wine-growing areas in detail in the 10 regional chapters of our book.

This approach made it possible for us to quickly differentiate between geological conditions in the various regions and, importantly, to provide non-geological readers with a framework with basic geological facts, as, for example, in the comparison of wines of the same grape variety from different winemakers from different regions, or recognition that there are similarities in wines produced over debris fans, or along major folds or in a similar tectonic province. It is exciting when the character of a wine can be traced back to the subsoil of the vineyard - not with absolute certainty, but with a high degree of probability. What remains, of course, is the complex interplay of the different flavors in the wine and their subjective experience. The idea that one can taste the lithology from the wine is wishful thinking, of course, but certain characteristics, which repeat themselves and which depend strongly on the geological character of the subsoil, testify to its influence on the wine. Nevertheless, even with an understanding of rocks and minerals and the basics of tasting techniques, identification of the geological character of wines remains subjective and controversial, but it is incredibly fun.

HOW GRAPEVINES EXTRACT NUTRIENTS FROM THE SOIL

The idea that the wine-grape roots get crucial nutrients directly from rock is false.

In his well-known book on terroir and geology of French wines[3], the geologist James E. Wilson has written: *“Plants don’t eat rock per se, but sip on mineral concoctions dissolved from them. Different rocks offer different menus of mineral constituents.”* In this way, different rocks and their weathering products source different soil types, each with its own specific ‘menu’ of minerals and elements.

Deeply growing vine roots seek water and the nutrients it contains. Roots will penetrate especially deep when water and nutrients are scarce, but only when the texture of the subsoil allows it. The Swiss winemaker Benoît Dorsaz[4] has stated (personal communication): *“Even if the soil cannot*

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[3] Wilson, J. E., 1998, *TERROIR: The Role of Geology, Climate, and Culture in the Making of French Wines*: University of California Press, Berkeley, 336 pp.

[4] www.Benoit-Dorsaz.ch

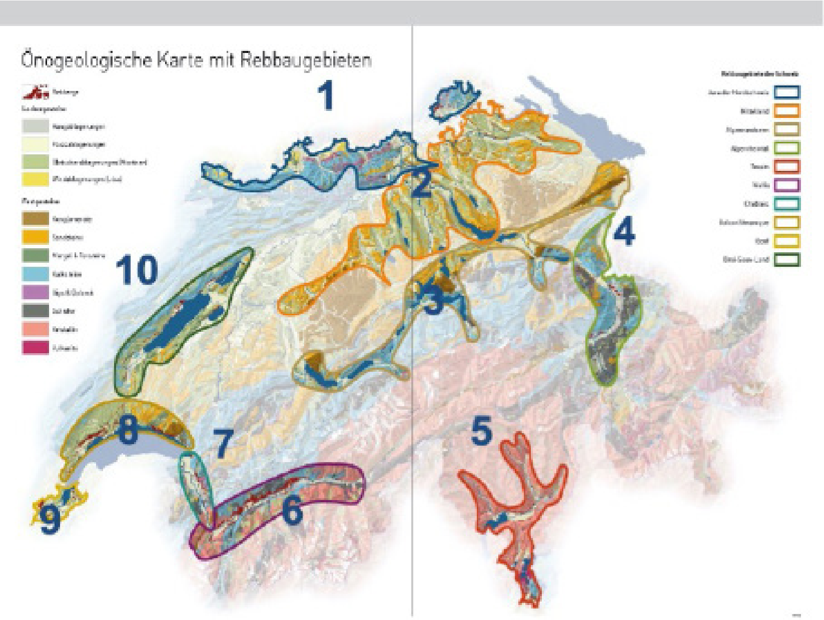

Figure 2. Simplified geological map of Switzerland (12 units) with indication of the wine-producing regions
1 Jura mountains, 2 Plateau/Midland, 3 Prealps, 4 Rhine valley/Grisons, 5 Ticino, 6 Wallis, 7 Chablais/Rhone valley, 8 Lémanique region/Lake of Geneva, 9 Geneva, 10 3-Lakes-region

store much water, the vine will seek and find moisture." And Swiss wine writer Eddy Saudan has written in a description of his experiences in the Canton of Wallis:[5] *"I have even found roots up to two meters deep, wrapping around a large stone block to find moisture even deeper."* An interesting statement can be found from North Carolina on the website of Raffaldini Vineyards[6] in an old Italian proverb that says, *"The land the farmer rejects is the land that the vineyard accepts. This implies that the less fertile and rockier the land, the more superior the wine will be as the grape vines struggle for survival by digging deeper into the soil in a never-ending search for water and critical nutrients."* And finally, another quote from James Wilson:[7] *"Grapevines by preference are deep-rooted. If conditions are favorable, their roots may go as deep as 20 feet or more. Where the bedrock is shallow and the soil thin, rooting will of necessity be shallow, making the vineplant susceptible to drought during dry spells. Light, sandy soils are easy to till and easily wetted but also dry rapidly. Heavy, clay soils are difficult to wet through and through, difficult to drain, and difficult to till. It's fairly obvious that ideal for the vineyard is a pebbly, sandy-clayey soil with considerable organic matter. Good soil structure is influenced by limy waters and the type of clay minerals."*

To relate the above concept to Switzerland and our simplified geological map, we can surmise that a soil's mineral content, especially the proportion of clay minerals, changes the further away one is from the weathering site. Also, with regard to mineral content, we have documented a dramatic and inexplicable difference in soils developed over orthogneiss and paragneiss. Soils from the latter contain a much higher proportion of plagioclase versus orthoclase and consequently a more variable supply of alkalies in the weathering minerals. From various tests in the Swiss canton of Ticino, especially in the Malcantone, we could surmise from numerous tastings that the wider abundance of elements in the wine is recognizable, not in the form of clear assignments to individual elements/minerals, but in the general perception of the wines. Wines developed on paragneiss have a full-bodied, fruity aroma, which is especially well perceived by female consumers far more than the relatively straightforward wines sourced over orthogneiss.

Metabolism plays a crucial role in the life cycle of the vine. As with humans, this includes the absorption of nutrients, the elimination of unnecessary substances and the formation of building blocks for growth. For its development, the vine needs macronutrients such as oxygen, nitrogen, phosphorus, potassium, calcium and magnesium, but also trace elements such as copper, cobalt, zinc and boron. *"Nitrogen for growth, phosphorus for health, magnesium for nutrition. and potassium for taste."* This is a rule of thumb among Swiss

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[5] https://www.walliser-weine.com/weinland-wallis
[6] https://www.raffaldini.com/Our-Estate/Vineyard
[7] Wilson, J. E., 1998, Ibid.

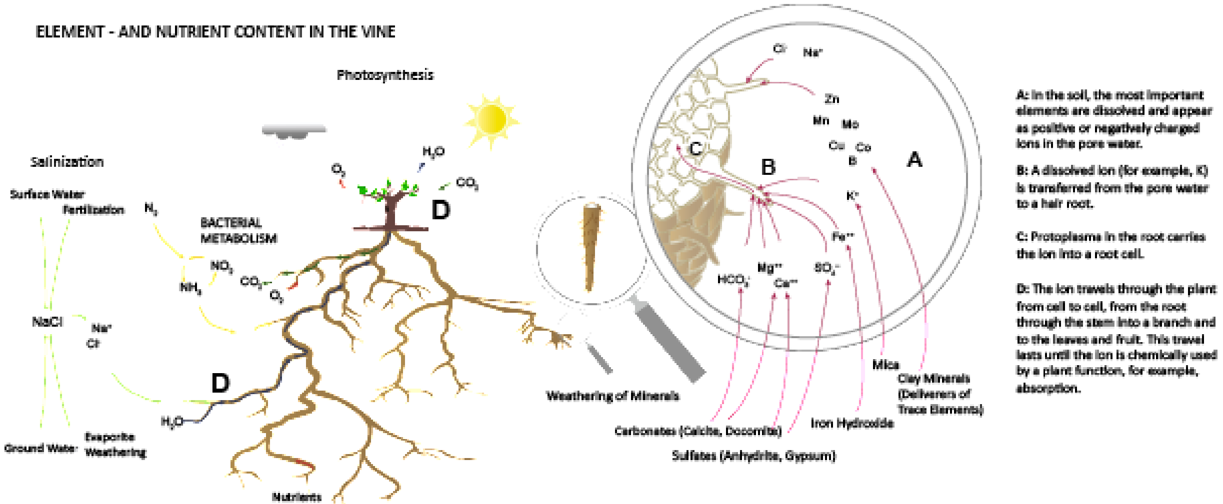

Fig 3: Absorption of elements by vine roots.

special role in the development of the vine and thus for success of the grapes and the quality of the wine. A balanced menu of nutrients is of fundamental importance for the vine's metabolism.

VINEYARD SOILS OF SWITZERLAND

Each of the basic lithologies shown on our oeno-geological map has specific properties that can be related to plant growth:

- Sandstones and the resulting sandy soils provide a multitude of elements, in particular silicon, but also sodium, potassium and calcium. However, the high silicon content typical of sandy soils is not important for the vine. On the other hand, what distinguishes sandy soils is their low carbonate and clay content. Because of their good permeability, rainwater drains quickly transporting nutrients to depth. The vine's roots must reach deep to get to the critical elements. If the growing season is short, the berries may stay small, giving the skin a relatively high proportion of the total berry. This leads to intense aroma formation.

- For limestone, the most important element is calcium. The basic rock may appear monomineralic, but in actuality, it may also contain a high percentage of impurities. During weathering, the lime dissolves to a large extent and is transported away and impurities remain in the form of clay particles. Soils developed over limestone consist of a clayey base with lime pebbles scattered through it. The clay contains the entire spectrum of the mineral nutrients required by the vine: sodium, potassium, magnesium, silicon, aluminum and trace elements. Despite the modest soil thickness, the vine can thrive from it.

- Claystones, marls and slates usually form clayey, sometimes sandy, mostly heavy soils. The clay minerals contain an almost inexhaustible reservoir of elements available to plants. In addition, there is the favorable water balance of clayey soils: large amounts of water are stored in the microscopic pores and are available to the vine at any time. The vine does not come under water stress, and elements

- Compared to other soils, the soils of crystalline rocks have a higher proportion of feldspars or alkalis and are largely free of lime. They differ in that they are rather barren and mostly shallow and have a small water reserve. Rainwater cannot carry soluble elements to depth, so that plants can benefit from it without great effort (see example of paragneiss vs orthogneiss described earlier).

- There are only very few vineyards on volcanic rocks and ultramafics in Switzerland. Well known vineyards are Zeneggen (opposite Visperterminen, VS) on serpentinite, Felsberg (Calanda) on greenschist or Vigno Porzo in Luganese on andesite and basalt from the Permian.

ELEMENTAL CONTENT IN LITHOLOGIES, SOILS AND WINES

Our research included element analysis to see if equivalent concentrations in the rock are found in the overlying soil and in the wines grown in it. Our investigations were carried out in three vineyards, one each in German-, French- and Italian-speaking Switzerland. The results were mixed and hardly demonstrative:

- Surprisingly, chemical analyzes of the wine do not reveal any clear statements about its subsurface.

- The element concentrations in the lithology/subsoil correlate well with those in the soil, but poorly with those in the wine.

- All measured elements are more highly concentrated in the lithology and soil than in wine. Because the wine is a liquid, the concentrations of elements turns out to be much smaller than in a solid.

- The principal result of this experiment has been well known by winemakers for a long time: The vine gets out of the ground only the amount of nutrients that it requires and nothing more.

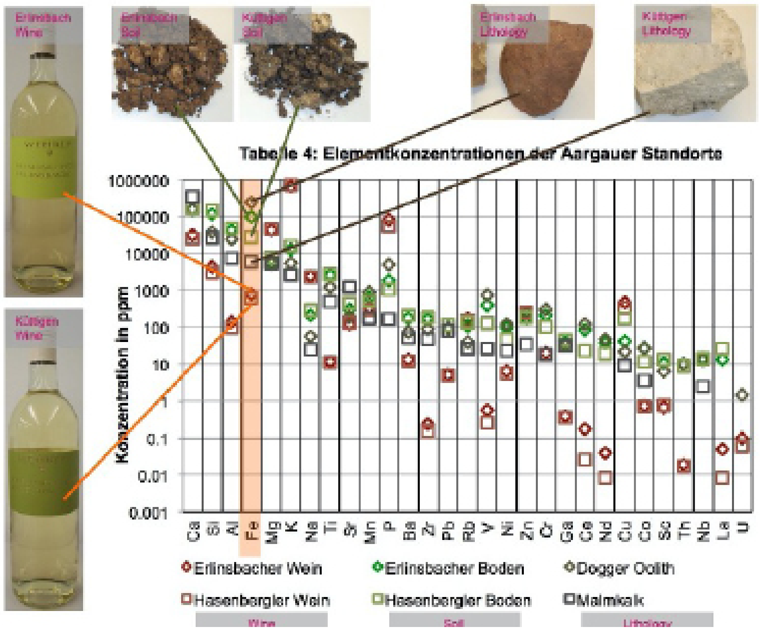

Fig. 4: Chemical composition in lithology, soil and wine (Bachelor thesis F. Donau ETHZ)

DETERMINATION OF ROCKS BY MEANS OF WINE TASTING

During tasting sessions, many participants depend on aroma wheels, which are designed to suggest terms to describe the tastes in wines. It is notable that most tasters select fruity and floral terms but very few revert to mineral aromas (petrol, flintstone, peat). This is due to the fact that few people can smell rocks.[8] We have tried to counter this fact by means of various tasting experiments. Rocks and minerals were pulverized, diluted in water and tested. Of course, this was an impossibility, given the extremely low solubility of the minerals in the water. Our experiments with various mineral waters were only marginally more successful. It is known that some branded mineral waters taste better to certain people, due to the increased element content of potassium, salt, sodium sulfate or carbonates, which can be easily ascertained from the label on the water bottle. By taking the same wine each time and adding a certain amount of the respective mineral water, the corresponding element content will be increased by factors compared to the original content. You can now try to determine this by means of a tasting. The result was, at least in our tests, sobering. Except for the very pronounced sulfate waters, there was practically no noticeable difference.

OENOGEOLOGICAL TASTINGS

Some of the "Stein und Wein" authors have been doing geology-related wine tastings for decades. As the book was being researched, the number of tastings increased. As an example, an attempt was made to discover the iron taste in a wine that grows in the immediate vicinity of an ore mine. Other approaches were made to define the much-cited lime taste in wines from the Jura mountains and the northern Alps. We tried as well to find the difference in taste between wines grown on slates of different colors, a characteristic that is often mentioned in Germany. None of these tests produced any reliable result. An explanation is found in Parr et al (2018):[9] *"First, minerals in wine are nutrient elements that are related distantly only to vineyard geological minerals. Second, mineral nutrients in wine normally have minuscule concentrations and generally lack flavour."*

The popular descriptive term minerality is being used in an increasingly inflationary manner at present. But the term is not clearly defined and, in most cases, clearly not understood by those who use it. Here is a classic example from the description of a Swiss wine: "The unique gypsum and limestone soils give the wine a typical mineral note." After reading this, we are left perplexed and wondering what a typical mineral note is.

The description of minerality is often multidimensional, relating to both aroma and taste. Even trigeminal perception[10] is invoked when dryness is mentioned in the case of white

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[8] Sun-warmed rocks and wet rocks during a summer rain do have a perceptible smell, but it is not the smell of the quartz grains of the warm or wet sandstone, but rather the predominantly organic components that are in the pores between the grains.

[9] Parr, W. V.; Maltman, A. J.; Easton, S.; and Ballester, J. Minerality in Wine: Towards the Reality behind the Myths. *Beverages 2018,* 4, 77; doi:10.3390/beverages4040077.

[10] Trigeminal taste sensations include cooling, astringency and spiciness, all tastes that fall outside of the five standard tastes. These tastes are transmitted to the brain by the fifth cranial nerve, which is the trigeminal nerve.

wines. Tart is associated with tannin and saltiness. Minerality is often invoked when juicy acidity and saltiness are in mutual interplay at the finish of a wine. For many tasters today, minerality stands generally as a descriptive term for the quality of a wine; it really does not establish any reference to soil, rocks or geological minerals. But it is a good marketing ploy to describe the finesse and complexity of a wine more precisely. Statements about texture, substance, consistency, viscosity, pleasantness, elegance, liveliness and sustainability, in short, about the character of a wine, remain subjective.

Some of these criteria can be largely correlated to the bedrock /soil (fig. 5).

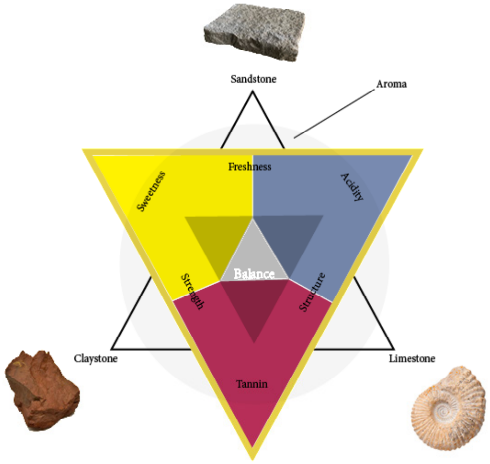

Figure 5. Perception of certain wine characteristics related to rock units.

Overall, the influencing factors for a wine can be summarized as follows:
- the climate determines the quality
- the winemaker determines the style
- the subsurface determines the character

Our fellow geologist and wine lover Alex Maltman wrote in 2019, “In summary, geology is clearly important for vine performance and, therefore, might have influence on the character and flavor of the finished wine. But its role has to be indirect, subtle and complex.”

HOW OENOGEOLOGICAL TASTINGS WORK

In our tasting experiments we used the so-called Bättig method, named after a well-known Swiss wine, viticulture and sensory expert, developed, tested and refined in countless wine tastings. The method is based on the sensations of wine in the palate changing over time, especially over the first 6 seconds. Every wine has softening and structuring properties. The prelude to a wine is usually characterized by its soft complex, which sooner or later transitions into the structural complex as the tasting time progresses. Alcohol, glycerine and any residual sugar make the wine appear softer. The soft complex can be reinforced by polysaccharides or polypeptides. The salivary and juicy acid and - especially in red wines - the drying effect of the tannins give the wine structure. The taste sensation of the acid is usually reduced within a few seconds by the neutralizing effect of the saliva. The effect of the tannins, on the other hand, lasts longer depending on the quantity and quality of the tannin.

According to this method, a tasting comprises the taste and aroma analysis of four main building blocks of a wine:

- Softness (sweetness, alcohol, glycerine): A wine is described as soft when it lacks an aggressive or young tannin taste. It is easy on the palate, or an ‘easy drinking wine.’

- Acidity: Wines that lack acidity are recognized as flat, watery, or boring. To test for acidity. Take a sip of the wine. Spit or swallow it, and let the tongue hang below the roof of the mouth and start producing saliva. The faster and greater the production of saliva, the higher the acidity.

- Tannin structure: This is recognized by a drying sensation in the mouth, sometimes extreme, like eating an unripe persimmon. The drier the mouth after taking a sip, the higher the content of tannin.

- Aroma blanket: Three types of aroma are possible. The so-called primary aroma is the typical aroma of the grape variety. Fermentation aroma is generated in the fermentation process by microbial yeast consuming sugar and off-gassing. And finally aging bouquets are aromas produced during the aging of a wine.

The focus during an oenogeological tasting is on (1) when do the perceptions of sweetness, acidity and tannin begin, (2) what intensities do they reach, and (3) how long do they persist. It is advisable to keep the wine in the mouth for at least 6 seconds in order to be aware of all the sensations.

The example shown in Figure 6 shows the general distinctions between wines from the old world (Europe) and wines from the new world (America, Australia). This type of analysis can easily be adapted to localized conditions.

EXAMPLES: SWISS ROCKS, SWISS WINES

In preparation for writing our book, various oenogeological tastings were held. One, for example, had the title “One winemaker, different soils.” Another was devoted to the topic of “Different clay content of the vineyards’ soils.” For the latter, three wines from south-eastern Switzerland were selected. The winemakers Francisca and Christian Obrecht produce, among other things, the “cuvee” [= blend] of the Monolith. Grapes for this wine come from three vineyards on three different rubble fans, rich in slate. Clay content of the soil of the three vineyards increases from north to south. The sand and lime content is almost identical in all three fans. The grapes from the three vineyards are pressed separately and

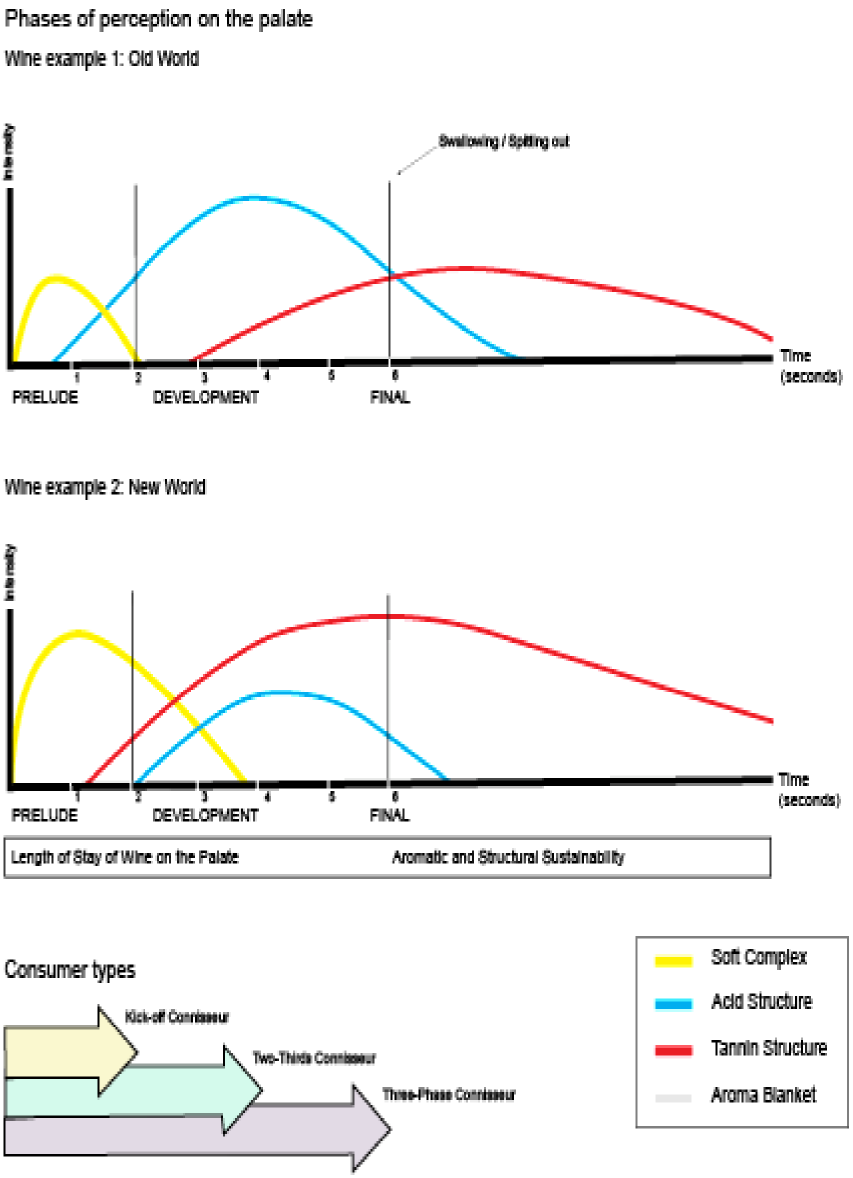

Fig. 6: Diagram of the perception of the wine over time. The graphical plot of the subjectively perceived intensity of the respective sensation structure (sweetness/soft complex, acid, tannin) in a curve can certainly be done on a table napkin and, with a little practice, shows amazing results among the participants in a tasting session. The aroma background sums up the three sensations in a playful, subjective way.

only blended at the end. It was astonishing how the different clay content of the soil was reflected in the tannin accent and expressed in the body of the three wines. In the north (low clay content of the soil) the tannin accent is not very pronounced and appears late, but the soft complex appears early and strongly. The wine from the south (high clay content of the soil), on the other hand, had a less pronounced soft complex and a fast and strong onset and long-lasting tannin perception.

Another winemaker experimented with the same grape varieties in geologically different areas. Although he carried out exactly the same steps at the same time during the vinification, clear differences could later be determined by tasting between his wines on lime-poor, sandy soils (simple, aromatic wine) and lime-rich soils (strong, well-structured wine with a pronounced tannin structure) and clay-rich, dense soils (strong and complex structure). The distance between the vineyards was only a few kilometers.

Another interesting experiment was made by two wine producers from Graubünden. Daniel Marugg in Fläsch (north-westernmost rubble fan, dominated by lime) pressed 500 kilograms of grapes from Irene Grünenfelder in Jenins (northeasternmost rubble fan, dominated by lime, mica and clay). Despite the different winemaking processes, the character of the wine was retained, Marugg produced a “Jeninser” [typical Jenins wine] and Grünenfelder a “Fläscher” [typical Fläsch wine].

In the following section we present some general characterizations related to the terroir of Swiss wines. The analysis is based on the experiences of the various book authors in countless tasting rounds in smaller circles or notes winemakers had collected over many years.

Strong wines from clayey soils
Heavy plastic soils develop on clays and low-lime marls. They have a high water and ion retention capacity and are rich in nutrients such as potassium, calcium, and magnesium that are available to the vine. Clay minerals are able to store the water well so that there is no vine water stress. The wines are remarkable for their strength and opulence, the fruit takes a backseat.

Well-structured wines from calcareous-clay soils
Soils in the vicinity of limestone have a clayey matrix with limestone pebbles. The presence of the pebbles gives them, in comparison to pure clayey soils, a better water permeability and a higher heat storage capacity. Limestone contains calcium and magnesium, both of which are alkaline. This increases the possibility of high acid concentrations in the grapes. The wines from limestone soils are often described as elegant, with aromatic delicacy and a distinctive acidity.

Fresh wines from light soils over sandstones and gravels
Sandstones are the basis of sandy, light and deep soils. These soils have a moderate water retention capacity but a good drainage and ventilation capacity. However, nutrients tend to be washed out and transported into the porous subsoil. The grapes ripen quickly and the berries stay small, giving the skin a large volume, which promotes intensive aroma development. The result is low-acid and low-tannin, fragrant wines with delicate fruit and a varietal expression.

Classy wines from medium-heavy slate soils
The foliation of the slates allows weathering of the rock into thin plates. The geometric arrangement of the predominantly platelet-shaped particles can, if they are stacked like roof tiles, favor surface runoff behavior of rainwater. The clay minerals can thus again absorb water. This often results in particularly fertile soils. They have a good water retention capacity and are rich in nutrients. Subtle differences in the character of the wine result from the changing proportions of sand / lime / clay. Classy, full-bodied wines arise. The acid and the tannin give a stable structure.

Wines from light gneiss soils: low in acidity, rich in tannins
Crystalline rocks in Switzerland are often synonymous with granite and gneiss, with quartz, feldspar and mica as the main components. Thin, light, stony, acidic soils with similar properties to sandy soils develop over gneiss. However, they are richer in nutrients in comparison to sandy soils because the rainwater does not carry soluble elements into deeper areas. The plant can access and benefit from these nutrients without great effort. The wines are fruity, full of aromas and low in acidity, with noticeable tannin.

WHY PERFORM OENOGEOLOGICAL TASTINGS?

Is it essential for wine lovers to know the geological subsoil on which the wine grew that is in the glass in front of them? The answer is very clear: not at all. Even if, as is done now and then, the most important possible taste components of the subsoil (rocks, shells, soil particles, fruits or other “ingredients”) are put into a glass for visualization (so-called ‘taste glasses’), it is extremely difficult for the reasons mentioned above to assign the geological-lithological aroma notes. More important still are statements such as: “I like this wine” or “I don’t like this wine, I don’t buy it anymore,” or, “It goes perfectly with today’s food.” Oenogeological tastings are more for advanced wine drinkers. Once you start doing it, you may “get hooked” on it. There are interesting table discussions during tastings, one level deeper, so to speak. The book *Stein und Wein* can be understood as a guide. It provides countless starting points for a deeper understanding of wine.

The situation is different with regard to winemakers. A good knowledge of the subsoil can help when choosing the grape variety to be planted. Our collaboration with winegrowers in Switzerland has meant that some of them switch to other varieties for certain plots. The composition of the subsoil is especially important for the selection of the rootstock.

Always pay attention; The rock should not be searched for literally in wine. Rather, the rock is representative of all the geological processes, procedures and factors that characterize a terroir and ultimately find expression in a good wine.

It takes a certain number of tastings and discussions to assign your own description to the character of the wine. Why not just try repeatedly, and then discover that you belong more to the group that prefers lime wine, or molasse[11] wines, or the pure orthogneiss wines. Or in terms of North Carolina, discover how the wines of the mountain region harmonize with the rugged backdrop of Hendersonville, and Asheville, and the Blue Ridge mountains (soil: clayey or loamy soil with mica). Are the metamorphic gneisses, schists and amphibolites (loamy surface and clayey subsoil) responsible for the bold, complex wines grown in rolling landscapes of the Piedmont region? And enjoy the muscadine wines, whose grapes grow so profusely on the sedimentary rocks of the coastal plain.

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[11] “Molasse” is the German term for sandstone, shales, and conglomerates that form as terrestrial or shallow marine deposits in front of rising mountain chains. Not to be confused with the English word “molasses.”

CONCLUSION

Thank you for the opportunity to present this short paper to your 2022 field trip. We hope it will stimulate your thinking about the true role of geology in viticulture and give you added pleasure in visiting vineyards and in consuming wines. We know the region of your field trip is hardrock country, so below we are sending you a pre-cautionary warning!

We wish you a successful and enjoyable field trip experience in the Blue Ridge mountains and would be delighted to have you join us some day in Switzerland to experience the beauty of our country and the terroir of our excellent wines.

The Short Story of North Carolina Wine's Long History

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INTRODUCTION

When the first colonists arrived on the eastern shores of America in the late 1500s, they termed the area Vinland because of the large quantities of grape vines that they saw. Alas, their enthusiasm to turn these grapes into a wine that they were familiar with back in Europe did not achieve the desired results. The grapes were probably *Vitis rotundifolia,*which is better known today as muscadine or scuppernong. One can make wine from these grapes, as many have done over the centuries, but it tends to be a sweeter wine with a different flavor profile than the *Vitis vinifera* grape that the Europeans associate with wine. Since the native grapes did not produce the type of wine the settlers wanted, they tried planting *vinifera* vines. No group matched Virginia settlers who displayed unbridled enthusiasm in this endeavor. When their efforts failed, they logically deduced that the problem lay not in the grapes but in the limited skills sets of the growers and would be wine makers. But this was flawed logic. Even after finding settlers with some winemaking experience and encouraging them to plant vines, no wine was produced. In fact a 1623 law in Virginia mandated all households to plant ten vines, and competitions were launched between 1651 and 1693 offering prizes for the best wines. There were no winners!

The problem, as scientists have discovered over the subsequent centuries, is that *vinifera* vines succumb to many diseases, all of which are evident in much of the east coast of America. Whilst it is now somewhat possible to mitigate such diseases, this knowledge was conspicuously lacking in previous centuries. The vines died before they could yield fruit.

Thomas Jefferson, an ardent believer in the benefits and joy of wine consumption, was nonetheless a forceful advocate of constant experimentation, and by the end of the 18th century, there had been some success with a domesticated native grape called Alexander. It didn't quite taste the way he perhaps wanted but at least the vines did not die. Consequently, by the 19th century, it was recognized that if wine was to be made in the eastern part of the USA, it would have to be made using native or at least hybrid grapes. And it was in North Carolina that some of these wine making experiments were yielding fruition.

In the late 18th century, the Moravians provided some of the best records on grape growing as they moved south from Pennsylvania into the Piedmont area of North Carolina and sought ways to make wine for their religious ceremonies. Their official church records bemoan the lack of adequate supplies of communion wine as well as that used in ceremonies (weddings and funerals – the latter a constant occurrence given short life expectancy). After the revolution they were cut off from imports from Europe (or it became prohibitively expensive), so if their consumption habits were to persist they had to find a way to make wine from local grapes. They appeared to do this quite assiduously, in all probability using scuppernong grapes. They clearly had the skill sets to make wine, since many had acquired winemaking skills in Europe. They merely had to discern how to manipulate the native grapes into a drinkable beverage. Given the growth of taverns where alcohol was served in some abundance, especially whiskey, which was easily made locally, wine making probably remained in the confines of local households, although there is some evidence that surpluses were sold locally. Not much is known about how the wine tasted but there are occasional anecdotal comments about it having a 'foxy' taste – whatever that might mean!

The Mother Vine, Manteo, Roanoke Island, NC. Thought to be the oldest living muscadine grape vine in the world. Source: NC State Archive.

Aside from the Moravians, others in the eastern part of the state were also making wine from white scuppernong grapes. One such individual was well-to-do planter Thomas Pettigrew who in 1835 wrote to a friend that he had been making wine for the past week.[1] The fact that he thought such an achievement merited a comment to his friend suggests that it was quite a unique event. Others around that time were also experimenting, in some cases with Catawba cultivars of which the Concord and Niagara grapes are two of the better known.

It was in Halifax County, however, that scuppernongs first flourished commercially, the initial success of which came from a schoolteacher and preacher from New York named Sidney Weller. He purchased a 400-acre farm in that county in the 1820s and eventually created a winery there in 1835. By 1840 he had 6 acres under vine, the largest vineyard in the state and second largest nationally.[2] He sold his wine from between $1 and $6 a gallon to markets as far away as New York. His wine was primarily scuppernong but he also had some Norton and a *Vitis labrusca* he named Halifax, plus he sold grapes and vine cuttings at local fairs. His enthusiasm as an advocate for winemaking was remarkable and he gave frequent presentations urging others to take up the occupation because he claimed it would be morally uplifting and a culturally respectable activity! When he died in 1854, however he was only making 40-70 barrels a year, which suggests he was better at promoting wine than he was at growing it. His vineyard was eventually purchased by the Garrett family who played a prominent role in the next chapter of the state's wine history.

During and immediately after the Civil War wine production slowed, but was quickly revitalized after transportation networks were restored in the 1870s. Also, native grapes were easy to grow and needed less routine labor, which was perfectly suited for resource-starved North Carolina. Unfortunately too many of the new breed of winemakers were adding brandy to their wine, ostensibly to kill germs and diminish spoilage but also because it enabled them to skip the fermentation process. The resulting wine made its way to the mouths of consumer more quickly but the flavor profile could be quite extreme to say the least!

Much wine production was concentrated in the eastern part of the state, but there were pockets in the Tryon area (western North Carolina) and in Valdese where Waldensian immigrants started making wine for their own consumption. With the growing popularity of grapes, agricultural land in the Sandhills area switched from lumbering to vines and fruit. The one hundred acre Tokay vineyard near Fayetteville, established in the 1840s and restored under new ownership in 1865, was reputedly the largest east of the Rockies. It primarily produced muscadines alongside thirty other varietals. When Colonel William Greene purchased it in 1879, he added more production facilities (storage casks and improved fermenting equipment) that facilitated increased volume and thoroughly professionalized the operation. At its heyday in the 1880s its annual production was 20,000-30,000 gallons of most of the major native varietals.[3]

It was the Garretts who put North Carolina on the wine map in the latter part of the 19th century. We noted earlier how Sidney Weller's Medoc vineyard was sold in 1867 to Charles Garrett, who, together with his brother, established the C.W Garrett and Company Winery. Predominantly producing scuppernong grapes, they did make wine from Concord grapes and by 1871 reported an annual production of 3,000-5,000 gallons. His son Paul entered the business in 1877 as the principal salesman, and clearly his efforts paid off since within twenty years production had increased to 175,000 gallons. Their signature wine was called Virginia Dare, named after the first English child born to settlers in the colony, and clearly this marketing ploy played well with consumers whose demand for the wine exceeded the firm's ability to produce it. A family quarrel following Charles's death led Paul to set up his own winery called Garrett and Company, and he was able to apply his marketing finesse to further expand sales in his new venture.

Many local farmers planted vines to meet the growing needs of Garrett and Co., which promised to pay a set amount per bushel of grapes. Unfortunately, not all of them had equal competence in viticulture so inevitably the quality of the finished wine varied. However, they formed a growing network of suppliers who would sustain the company for decades. Paul added juice from California grapes to his Virginia Dare as well as making a claret from Norton – all part of a growing demand for his wine, which by the turn of the century had become the most popular drink in the United States.

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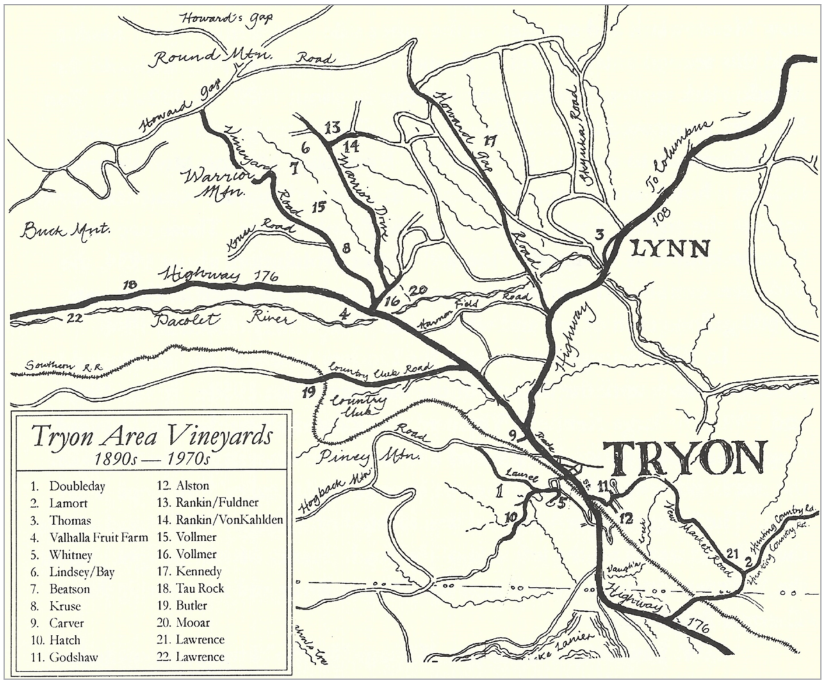
[1] Helsley, A. J., A History of North Caolina Wine (Charleston: The History Press, 2010).

[2] Nicholas Logworth's Cincinnati winery was the largest. See Taplin, Ian M., The Modern American Wine Industry (London, Routledge/Taylor & Francis), p. 43.

[3] Pinney, T. *A History of Wine in America* (Berkeley, University of California Press, 1989).



Early Tryon vineyards. From Mosseller and Pack (2001).[4] Used by permission of the author, Anna Pack Conner.

In the early 1820s, the Tryon area in western North Carolina was thought to be an ideal location (southern exposure, good climate, adequate drainage etc.) for growing grapes.[4] However, it wasn't until the latter part of the century that some of the first vineyards were planted. General Doubleday had retired to Asheville from New York and planted the Doubleday Vineyard in 1890. It consisted of 19,000 vines of sweet Niagaras and red Delaware grapes, and in 1891 he brought Alexis Lamort from France to help him with his vineyard, adding a degree of professionalism conspicuously lacking in other wine-making endeavors in the state. Several other vineyards were established in the Tryon area at this time, including Valhalla Fruit Farm (est. 1896 by George Morton), Xalapa vineyard (est. 1893 by W.T. Lindsey), and Chincora vineyard (owned by R.F. Allston). It is difficult to discern precisely what grapes they grew and how much wine was made from these grapes – anecdotal evidence suggests that the grapes were sold for table consumption rather than being made into wine. For example, there is evidence of grapes being sold to local markets and passing trains that stopped at Tryon station. Demand from the latter was significant as noted in local histories. It is apparent that many grapes from Polk County were shipped to markets in the northeast and midwest and that there were approximately 22 vineyards in the area from the late 1890s to the mid 1950's. One grower, William Lindsey, organized the Tryon Fruit Exchange at the turn of century, ostensibly to coordinate the marketing of Tryon area grapes.

When closure did come to many of these vineyards by the middle of the 20th century, it was not Prohibition that ended grape growing but probably labor shortages and the rise of more non-perishable grapes from California that were flooding the market. Some have also suggested that trains no longer stopped at Tryon station so that natural market was lost.[5] It would be another fifty years before the industry's rebirth but by then more of the grapes were made into wine rather than sold as table grapes.

INDUSTRY COLLAPSE

If we return to Paul Garrett and his success at making and selling wine, such efforts were being threatened by the growing temperance movement in state and country. Such local movements had been active since the early 1800s in part because North Carolinians (and Americans in general) were consuming large quantities of alcohol, and the social problems associated with such consumption were gaining more widespread recognition and concern. Even though much of the consumption was of hard liquor, eventually any type of alcohol (including wine) were tarred by the same brush. As the temperance movement gained pace, a 1908 referendum in North Carolina resulted in a vote of 113,612 for prohibition and 69,416 against, and the ban on the sales of 'intoxicating liquor' became law in 1909. This proved to be the death knell for the NC wine industry. Garrett and Co. moved north to New York and continued to make wine but when Prohibition became a nationwide phenomenon (the Volstead National Prohibition Act in 1920) even his

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[4] Mosseller, R. and Conner, A. P., 2001, An Artist's & Writer's Sketchbook: Chapel Hill, Tryon Publishing Co. 123 pp.

[5] Gile, J. J., "Rebirth of Vineyards," BlueridgeNow.com, Sept. 29, 2003, p. 2.

attempts to continue selling wine for medicinal purposes, and his marketing of a grape concentrate could not match his earlier successes.

When Prohibition was repealed in 1933, states still retained the right to ban or limit alcohol sales if they so wished. This is exactly what North Carolina did with a two to one margin vote. Several years later the state sanctioned local decision-making over the manufacture and sale of alcohol and in 1935 the state ratified this decision with an act that enabled the Department of Agriculture to work with farmers to facilitate grape growing and winemaking. However, it would be several more decades before any sign of a wine industry rebirth would occur.

GRADUAL REBIRTH

Muscadines: Throughout the east coast, attempts to grow grapes for wine continued in the post WWII years but with little success except with muscadines. Other grapes were small, had insufficient sugar and too much acid and the resulting wines often had an unpleasant flavor. It was clear that if wine making was to re-emerge it would be with muscadine grapes until a better understanding of the problems associated with *vinifera* was discovered.

Since the nineteenth century there had been persistent concerns over poverty in the south, especially in the rural areas. More concerted action to address this problem came in the post war years from federal agencies that directed funds to subsidiaries such as the North Carolina Relief Administration. The basic idea was to generate an interest amongst farmers to switch to grape production if a guaranteed price per ton (eventually $35) could be agreed upon and a market established. Canandaigua Wines from New York, which had earlier bought the rights to Virginia Dare, stepped up and became a buyer. But even their willingness to sign contracts with farmers was insufficient to stimulate increased production, and acreage under vines declined by two thirds between 1945 and 1964. And it is important to note that many North Carolina counties were still dry through the 1970s so whatever nascent enthusiasm there might be for growing grapes and making wine would often encounter stiff local resistance.

One company, however, decided to swim against the dry tide. In 1976 Duplin Wine Cellars opened in Rose Hill. Two years earlier Dan and David Fussell had bought 132 acres of farmland and following recommendations by the North Carolina Department of Agriculture, they planted 10 acres of muscadines. Their aim was to supply the upstate New York Market with these grapes, which were selling for $350 a ton in 1972. However, by the time their vines were mature enough to harvest grapes, the price per ton had fallen to $150 which was lower than their overall costs. In a last ditch measure to save their enterprise they decided to make wine themselves from these grapes and duly opened a small winery for that purpose – no small feat since the county where they were located (Duplin County) remained dry. It was by their own accounts a trial and error process but they nonetheless made a drinkable wine. From 20,000 gallons in 1977, 30,000 the next year and by 1979 they were making 60,000 gallons. By the 1980s they were making 200,000 gallons and were now sourcing grapes from many other local vineyards. They encouraged farmers to grow grapes to supply them and their continued growth appeared to remove whatever skepticism local farmers might have had for such a venture. However, when the preferential tax rates afforded the winery were deemed unconstitutional in 1983, their sales plummeted to just under 11,000 gallons in 1985. It was not until the mid-1990s that they recovered and were profitable again, in part because health specialists had discovered that muscadine grapes contained high levels of resveratrol that is beneficial to health. In a far cry from the Prohibitionist sentiments of yore, now drinking wine was seen as positively healthy. Duplin is currently the largest winery in the state, and at production of over 563,000 cases is the nation's 36th largest. In the past few decades numerous other muscadine wineries have been created, primarily in the eastern part of the state where the vines have traditionally flourished and where the market for sweet wine has become well established. The wine tends to be sweet and probably some of its appeal is to a population used to sweet beverages (sweet tea, sodas etc.). The real potential for growth (and ultimately industry legitimacy) however, came from individuals with a commitment to making dry wines. This would occur primarily in the central and western part of the state where altitude and climate are more favorable to *vinifera* and hybrids.

***Vinifera* and Hybrids**: As mentioned earlier, attempts to grow *vinifera* grapes in the eastern part of the United States had been fraught with failure and yet when most people think of wine, it is *vinifera* style dry wines that come to mind. However, wine historian Leon Adams perhaps best summed up the situation in this area of the country in the 1930s when he said, 'It was making the wrong kinds of wine from the wrong types of grapes for the wrong kinds of consumers in a whiskey-drinking nation with guilt feelings about imbibing in general and a confused attitude towards wine in particular.'[6] This is a fairly somber but succinct assessment of NC wine growing efforts! Attempts to address this problem continued to focus on finding ways of combating inherent weaknesses of certain varietals by breeding grapes that are more resistant to such weaknesses. One such solution appeared to lie in grafting European vines to American rootstocks with the aim of making American vines resistant to disease without compromising the quality of European varieties. Thus was borne the development of hybrid grapes, the most familiar of which today in North Carolina are Seyval Blanc and Chambourcin.

At the same time, much research at the Agricultural Experiment Station at Geneva, New York on *vinifera* growing in cold climates demonstrated the virtues of fungicide control as well as unique rootstocks more suitable to the climate in the east. Both proved effective at mitigating many of the diseases that had typically affected such vines in the past. This opened up the possibility of *vinifera* growing in North Carolina especially if vineyards were located west of the line where Pierce's disease existed. Generally speaking this would mean the central Piedmont westwards. This is precisely the region where vineyards have successfully emerged since the 1ate 1970s, with a focus upon *vinifera* and hybrid grapes.

Early pioneers with such grapes in these areas were Westbend (est. 1972), Germanton (est. 1981) and Biltmore Estate (est. 1985). They were and are very different in scale and scope but were important in the next phases of the industry's growth since they demonstrated, not without some failures, that the sort of wine that many associated with European and California wineries could be made in the state.

Westbend was truly a pioneer as the owners, Jack and Lillian Kroustalis, used money from a successful restaurant supply company and purchased 14 acres just west of Winston-Salem and planted *vinifera* vines. They struggled to get the requisite knowledge on grape growing and had to rely upon information from Cornell University. Gradually they increased production, and in 1986 they harvested 70 tons of grapes and made the decision to become a bonded winery, making and selling their own wine. They did hire an experienced winemaker, Steve Shepard who had been making wine in Ohio, and this helped establish their credibility and product quality. But it was difficult to persuade people to try the wines since they were such a novelty at the time.

The approach at Biltmore was on a different scale and they did have the virtue of being a chateau-style building that at least reminded people of France and thus wine. They were also fortunate in being able to marshal extensive resources and hire professional staff to develop the vineyard starting in 1981 when they produced 850 cases of wine from 15 acres. They spent $12 million adding more acreage in 1983 but a severe storm on the nights of 19-20 January 1985, which saw temperatures in the mountains drop to -27 degrees F, left many of the new plantings weakened or killed. Biltmore lost 65 per cent of their vineyard and for a brief time faced possible bankruptcy. Eventually they rebounded and currently produce 150,000 cases of wine with almost half sold directly from the winery. However, they had earlier realized that there was insufficient local supply of grapes to meet their ambitious production business model so most of their wine is actually produced from California grapes and is bottled there and shipped east. Only about 10 per cent of their wine (mainly whites) is produced from NC grapes.

The next growth phase, during the 1990s, saw continued investment in grape cultivation by small entrepreneurs and investors. Many took advantage of land that had been formerly tobacco farms, an industry in secular decline, which were often small (10-15 acres). Some of these were tobacco farmers who were able to acquire funds from the Golden LEAF Foundation[7] enabling them to get vines essentially free and thus diversify their crops. Others with a non-farming background brought their winery dreams to fruition following trips to France, acquiring land and planting a vineyard. Some had modest resources, whilst others were more financially secure and could embark upon their endeavor with a more professional flourish. Most importantly, it was during this period in which newcomers were able to share information and tacit knowledge with each other and collectively develop a sense of best practices. This proved better than earlier trial and error efforts that had hampered the first pioneers.

The essential story of this phase is one of a gradual increase in resources, incipient institutional support plus enthusiastic

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[6] Adams, L. D. *Wines of America*, (Boston, Houghton Mifflin, 1973), p.26.

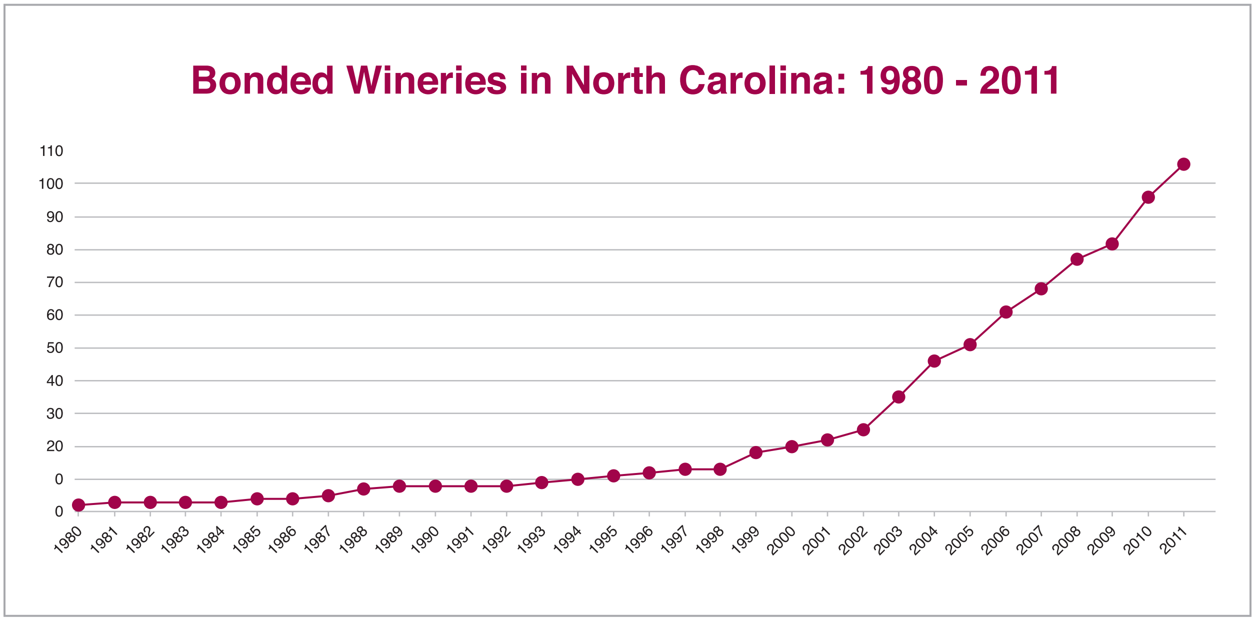
[7] The Golden Leaf Foundation was created from the settlement between the four major tobacco companies and the attorneys general on behalf of states' Medicaid systems in 1998. This was part of a class action lawsuit that targeted tobacco companies becasue of their systematic marketing of a product deemed dangeous to health.

entrepreneurship. The latter act as a precipitant of change, and identifying these individuals and their rationale for entering this industry is crucial since they were the catalyst for growth in this period. They came from a variety of backgrounds including schoolteachers, investment bankers, airline pilots, Nascar owners, and others who had made some money in another business and could use these resources to fund their 'dream' project. Some could afford professional staff but most relied upon their own labors, often learning from courses at local community colleges that were developing.

The third phase, during the first decade of the 21st century, is the period when wine-making took off in the state. In this period there was a dramatic increase in the number of wineries and the amount of land that shifted to grape cultivation. Many of the new entrants availed themselves of new institutional resources plus benefited from access to an emerging cluster of wineries from which tacit knowledge has been informally exchanged. In this phase, one has witnessed more significant investments by resource-rich individuals who were able to develop a more professional approach to grape growing that generally involved hiring a vineyard manager, winemaker and tasting room sales staff. The rapid growth during this period is indicated in the graph below of bonded wineries.

Notably during this phase was the growth of systematic information about *vinifera* best practices. Whilst muscadine producers continued to flourish, a local market for dry wines was beginning to develop, and this further encouraged new industry entrants. During this phase one begins to discern a systematic pattern in terms of ownership. Some wineries were established by individuals with extensive resources who could cross subsidize their operation from revenue streams outside of their winery. Some of these were medium-sized but many remained fairly small (2000-5000 cases). Crucially, the owners had the financial resources to maximize their attention on developing best practices and hiring professional staff to develop and often run the winery. Their goals were longer term and less constrained by profitability issues. Another group consisted of people seeking a career change but needing to be more hands-on in daily operations. They had more modest resources and scaled the winery operations accordingly. Some had sought educational training at the local community college; others relied upon contracting consulting services to furnish key activities. For this group, profitability goals were more paramount. However, it is amongst this group that winery mortality rates have been most frequent following fragile resource dependency. I will return to this shortly.

Sustained growth (a possible fourth phase) has continued in the second decade of this century with currently a total of



Source: Department of Agriculture and Consumer Affairs/NC Department of Commerce

158 bonded wineries and 31 virtual wineries plus a large number of grape growers who sell their grapes to established wineries, making the state 10th in the United States in terms of winery numbers. Some estimates based on other data sources suggest there are more than 200 wineries and many more grape growers but it has been difficult to accurately pin the numbers down. For example, there is anecdotal evidence of some grape growers not even registering their land as an agricultural enterprise, which would provide then with certain tax benefits, so this further distorts the data. And curiously, many Agricultural Extension Agency officials are unaware of who might be growing grapes in their county.

INSTITUTIONAL SUPPORT

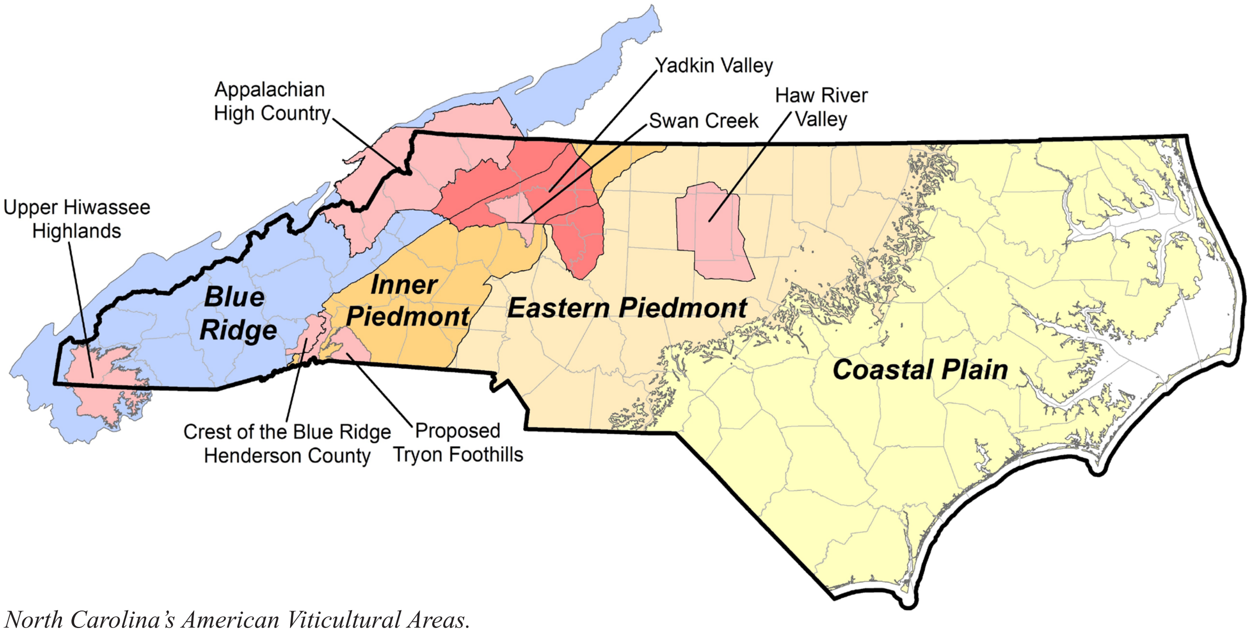
Two other important developments helped forge an identity (and legitimacy) for the incipient wine industry. The first was the establishment in 1999 of the Enology and Viticulture Program at Surry Community College (SCC). Situated in the heart of the northwest Piedmont region, where much of the growth of new wineries was occurring, and close to Shelton Vineyard from whom the initiative and funding came, the College provides training through degree and diploma/certificate courses for those interested in careers in grape growing and winemaking, with an emphasis upon viticulture (plant science, vineyard stock selection, soil and pest management as well as vine nutrition courses), the basic economics of vineyard management and layout, and oenology (the tools and techniques of winemaking). Aimed at new winery and would-be winery owners, it is at this venue that many of the small winery owners honed their initial skills.

This SCC program provides a vital missing component in the development of the industry, since it has become a vehicle for the dissemination of requisite region-specific technical knowledge – the elusive terroir factor. Both incumbents and new entrants can avail themselves, at relatively low tuition costs, of precisely the operational details that are necessary for successful start-ups and shortcut the trial and error learning that characterized industry entrants in the late 1980s and early 1990s. Furthermore, it has helped initiate knowledge and information flows that could lower transaction costs for firms.

The second development was the establishment of American Viticultural Areas (AVAs) in North Carolina, the de facto winery seal of approval. On February 7, 2003, the Yadkin Valley became an official AVA – the first one to be established in North Carolina. The application for this status was spearheaded following a two year effort by Shelton Vineyards. At that time there were six bonded wineries within the Yadkin Valley AVA. Covering close to 2,000 square miles and 1.4 million acres, it incorporates an area with a unique climate and an approximate 1200 feet elevation that seems suited to *vinifera* and hybrid production and now includes 24 wineries. Other AVAs have followed, including Swan Creek, Haw River, Appalachian High Country, Upper Hiwassee Highlands and most recently Crest of the Blue Ridge Henderson Country (with a proposed Tryon Foothills AVA in the works).

The Crest of the Blue Ridge covers 215 square miles with approximately 100 acres under vines and currently 15 commercial vineyards. Several more wineries are already in the works as this area appears attractive climatologically but it also has a discerning customer base, many of whom come up from Greenville/Spartanburg where several European multinationals have their North American headquarters. The distinguishing features of this AVA are its climate and elevation, with warm days and cool mountain nights plus the right soils and quality water.

Such AVA designations go beyond mere classification of local growing characteristics (terroir). They create a regional identity for the industry, legitimate its presence amongst oenophiles, and generate a certain 'buzz' around the firms located therein. From a production perspective, they create a local community of experience and more structured interaction in the informal knowledge exchange that occurs amongst a sub-group of wineries. Finally, AVAs are a step towards establishing a vibrant industry because they attract new entrants to the area as well as fostering growth of subsidiary and ancillary industries (suppliers to the trade, agri-tourism such as restaurants and B & B's). But above all it signifies that the state could be thought of as a serious contender in the regional wine industry, and with a grape, *vinifera*, that had proved so elusive in the past.



North Carolina's American Viticultural Areas.

CLOSURES AND NEW GROWTH

Given the demographics of winery owners who started in the late 1990s, it is almost inevitable that some would be seeking to pass on their property to heirs and if not, to sell it. This happened a decade ago with Round Peak (near Mt Airy) when the original founding couples sold to younger people. Likewise Westbend was sold following the death of one of the founders. Actual mortality rates for wineries are not excessive but over the years some early pioneers sold out. In some cases the original owners realized that the financial toll came when they struggled to sell their wine; for others they found it difficult to make the level of quality consistent, because they lacked resources to mitigate problems. One owner who struggled to make wine from Syrah grapes acknowledged that the wine was not good but he could not afford to rip out the vineyard and replant, and he continued selling the wine because he needed the income stream. Still owners were forced to realize that the often arduous agricultural labor involved was just too much for them, and it certainly lacked much of the mystical romance that they associated with owning a winery. Most of the wineries that were sold were purchased by other aspiring winegrowers but some reverted to other forms of agriculture.

One unfortunate closure was that of Rockhouse Vineyards near Tryon, developed in 1989 by Lee Griffin and Martha Cassedy. On a 200 hundred acre farm they planted 4 acres of grapes and then expanded to 10 acres. Their experience in the early years was not untypical of many new entrants, working long hours, often learning by trial and error, and balancing different jobs (including the textile machinery business that paid the bills), they produced *vinifera* wines that won competitions, but Lee's health issues forced them to close the business in 2012.

On a more positive note, other wineries in Polk County that have remained successful include Parker-Binns, started by Bob and Karen Binns when they decided to move north from retirement in Florida and acquired 40 acres with currently 12 acres under vine. Nearby is Overmountain Vineyard, founded in 2000 on land purchased in 1990 by the Lily family; Mountain Brook that was started in 2002 growing grapes for sale to other wineries and then establishing a winery in 2012 and then in 2018, under new owners, expanding both production capacity and tasting room facilities. Their current business model includes selling wine from NC grapes as well as that from California. This is similar to another winery in the area, Russian Chapel Hills Winery, which sells imported wines in addition to those made in NC. Acquired by retired businessman Andrey Medvedev in 2009 from the original founder Marvin Pack who had established the vineyard in 2004 as Green Creek vineyards, the vineyards continue to expand with additional acreage planted in 2010.

An area with recent increased growth is around Hendersonville. Several wineries, including Burntshirt Vineyards and St Paul Mountain Vineyards have been established for more than a decade. But in recent years a number of new wineries have opened including Marked Tree, Stone Ashe and Point Lookout; the latter capitalizing upon its stunning mountain location as a wedding venue. On the latter point, many winegrowers have realized that a vineyard is often a quintessential idyllic location that is perfectly suitable for weddings and corporate events. By renting out their space, wineries can develop an additional revenue stream to complement their viticulture activities as well as having a captive market for their wines.

This area in the west, part of the new Crest of the Blue Ridge AVA appears to be an attractive site for wineries, and alongside the Yadkin Valley, is where much of the dynamic growth is occurring. Contrary to some economic logic, wineries benefit from clustering or the agglomeration of sites. Rather than competing with each other, they can add to density which can attract more visitors. For example, the Hendersonville area has multiple wineries within a dozen miles of each other; likewise the Swan Creek AVA in Yadkin County has five wineries next to each other, most specializing in Italian varietals, and there are several more close by. Wineries encourage tourism, and the economic impact can be quite substantial. This is why winery owners like to encourage new entrants to set up shop nearby and such proximity can be useful for knowledge exchange and informal learning.

FINALLY, WHAT GRAPES GROW BEST IN NC?

There are two basic answers to this question, and they involve the ongoing, almost schizophrenic identity of the industry. On the one hand, muscadines flourish with little effort; they are essentially organic and grow in large clusters with high tonnage per acre. Geographically they predominate in the eastern part of the state. But the resulting wine appeals to a smaller section of the wine-drinking public, and consequently the sweet wines that are produced are often shunned by sophisticated oenophiles. However, even the most ardent of *vinifera* producers might make a muscadine wine since some claim that is where a sizable part of their sales revenue is derived.

Vitis vinifera and hybrids are often harder to grow, are more expensive, and extensive efforts at disease mitigation are necessary. However, this is where the industry has begun to establish its identity, and in the past decade it has become evident that certain varietals do quite well in the NC terrain. For reds these include cabernet franc and petit verdot (a grape that is generally used for blending in France, but that is sold as a stand-alone varietal in NC), as well as merlot. Cabernet sauvignon is often difficult to ripen given the short length of the growing season in the state. Some producers, such as Raffaldini, have been successful with Italian varietals, and in more recent years, wineries such as Shelton have made good quality Tannat. Others such as JOLO have done well with hybrids and many have found success with Chambourcin. As for whites, Chardonnay can be fairly easily made, but Viognier and Petit Manseng seem well suited to the region, as are hybrids such as Traminette and Seyval Blanc.

It has often been claimed that a wine region gains legitimacy and credibility often around a signature grape – Napa with Cabernet Sauvignon, Oregon with Pinot Noir and New Zealand with Sauvignon Blanc. There is much to be said for this claim as it puts a region on the oenophile map. North Carolina is in many respects playing catch up to Virginia but one of the benefits of being a follower rather than a pioneer is that one can discern what grows best in similar conditions. All of the above mentioned varietals grow well in Virginia, so it is not surprising that they would flourish several hundred miles to the south.

Duplin continues to dominate the industry in terms of sheer production volume, and in addition to its tasting room at its original location, has opened a very successful location in Myrtle Beach with another planned on the Gulf Coast at Pensacola. Biltmore is the most visited winery in the United States and focuses mainly upon *vinifera*, albeit from grapes grown mainly outside of the state. But the growth of boutique wineries with production in the range of 2000-7000 cases is where much of the growth is occurring, and it is from these wineries that the reputational benefits and industry legitimacy accrues. Additional AVAs like the proposed one in Polk County will only add to that image. But it always important to remember, this is not an industry for the financially faint of heart. Buying land, planting vines and then waiting 3-4 years before harvesting a significant crop and then adding additional years for red wines to age, plus the capital expenses of steel tanks and barrels, means breakeven for many such ventures is often 7-8 years after inception. One needs considerable resources to embark upon such an endeavor, and this why the wineries that are often the most successful are those whose owners have deep pockets.

Grape and Wine Education at Surry Community College

Sarah Bowman, Viticulture Instructor

The romance surrounding grapes and wine, and desire to reconnect with nature lead many aspiring grape growers and wine makers to pursue an education in viticulture and enology at Surry Community College. The college began offering viticulture and enology courses in 1999 in response to the growing need for a skilled grape and wine industry workforce. Surry Community College is located in the Yadkin Valley, North Carolina's first American Viticulture Area, where the highest concentration of vineyards and wineries were established soon after the decline of the tobacco industry. Viticulture and enology students have the option to pursue various credentials focused in grape growing, wine making, wine marketing and tasting room management. The program's facilities include the Shelton-Badgett North Carolina Center for Viticulture and Enology which houses classrooms, laboratories, the Grand Hall event space and Surry Cellars Winery. Additionally, Surry Community College has expanded their facilities to include the Sustainable Agriculture Building, which is just steps away from Surry Cellars Vineyard. The college's roughly 5-acre commercial vineyard and 1,000-case bonded winery both provide ample hands-on learning experiences for students which complement classroom instruction. Winegrowing isn't easy in the southeast, but the combination of challenges and opportunities to practice and apply solutions prepare viticulture and enology graduates for the reality of successful grape and wine production.

Grape and Wine Education at Surry Community College

Sarah Bowman

Viticulture Instructor

Carolina Geological Society Meeting

September, 2022

SURRY

Community College

Serving Surry and Yadkin Counties

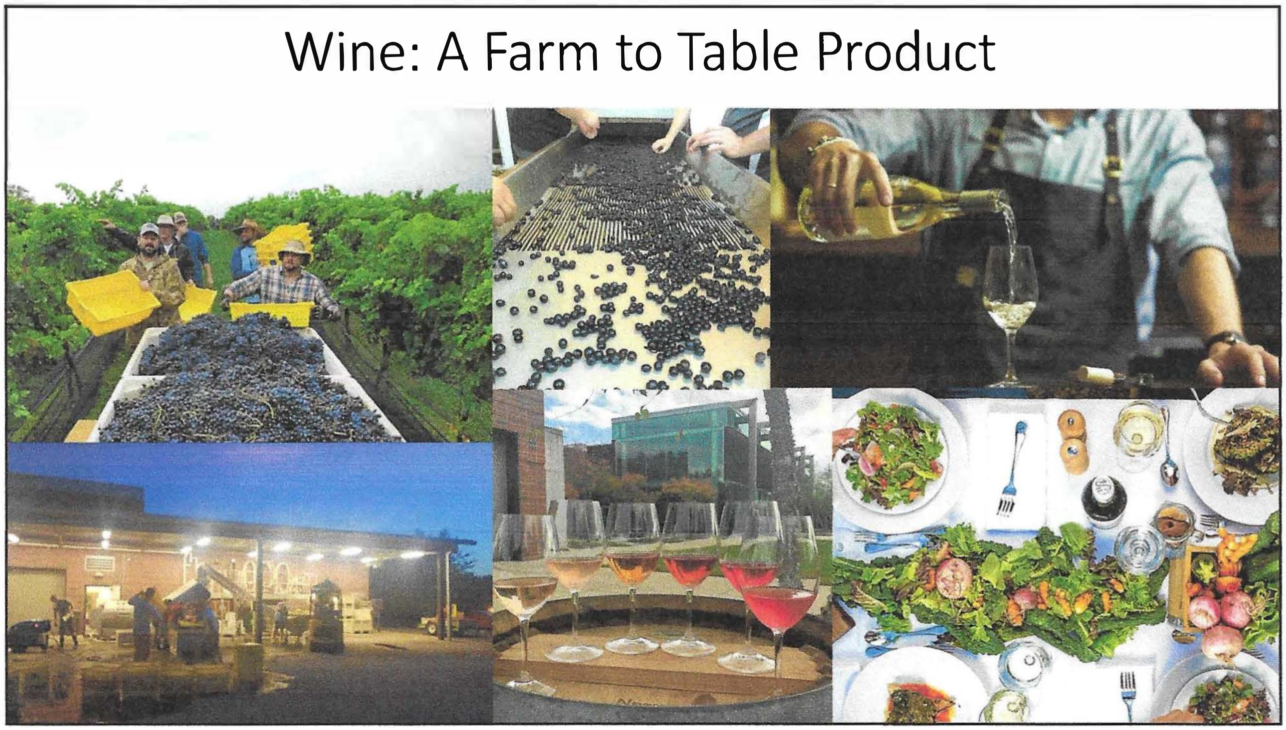
www.surry.edu

The Romance, Risks and Rewards of Grape and Wine in the Southeast

- What brings students to the Viticulture and Enology Program at Surry CC?
- What does it take to be successful in this industry?
- What impact does the grape and wine industry have?
- Where is the industry headed? What does the future hold?

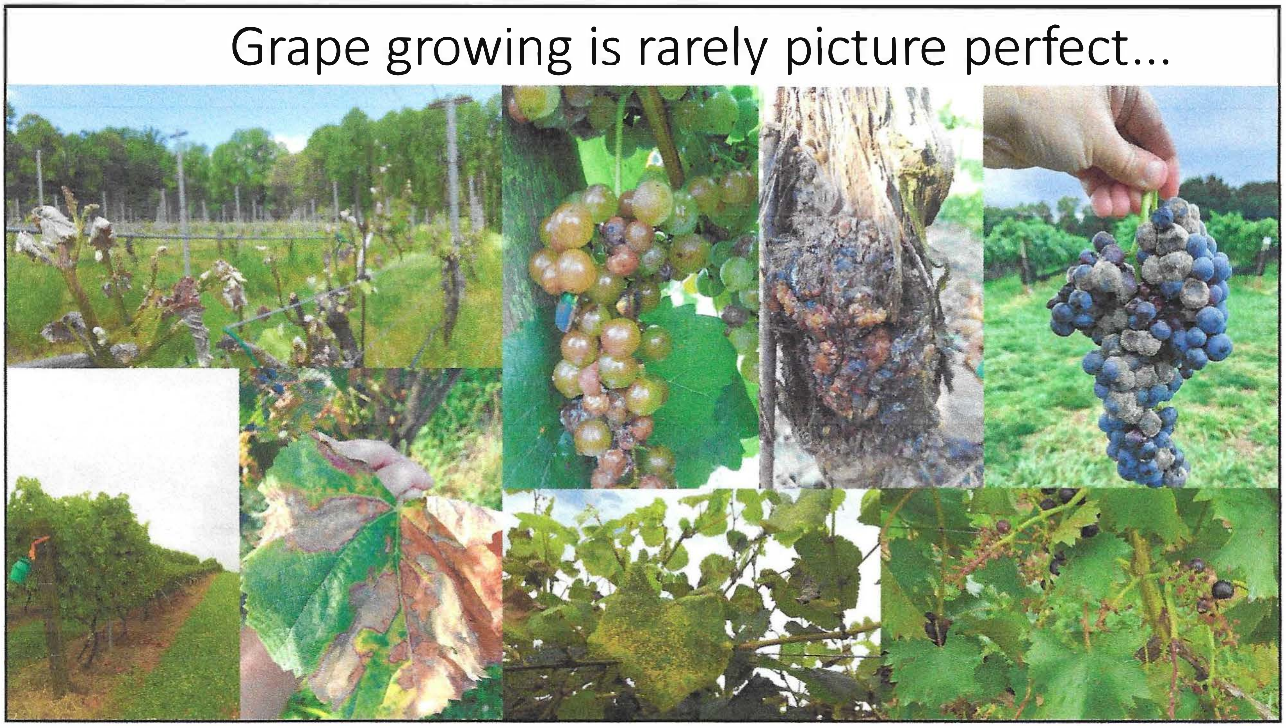
Viticulture: To care for the vine

- Site and variety selection
- Site preparation and trellis construction
- Planting and training
- Pruning
- Canopy management
- Yield estimation and control
- Pest and disease control
- Water and nutrient monitoring
- Many hours of hand labor and tractor time
- Harvest

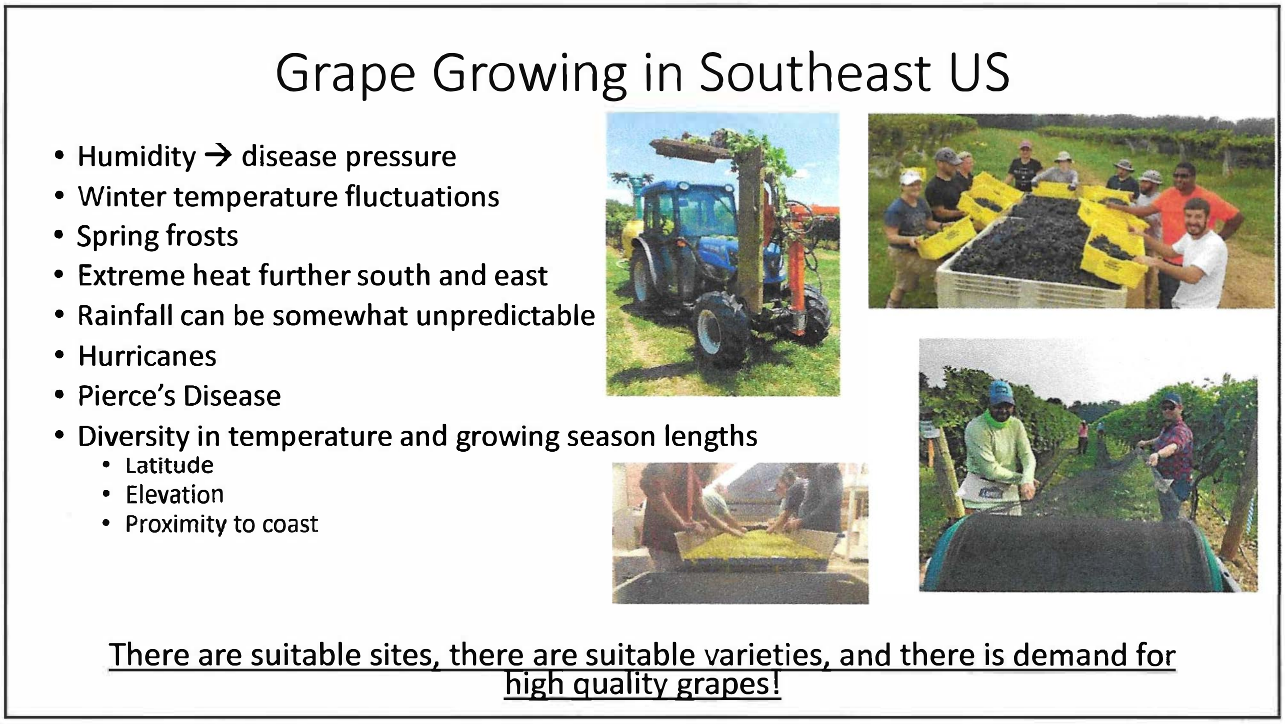


Wine: A Farm to Table Product

Picture perfect, right?



Grape growing is rarely picture perfect...



Grape Growing in Southeast US

- Humidity → disease pressure
- Winter temperature fluctuations
- Spring frosts
- Extreme heat further south and east
- Rainfall can be somewhat unpredictable
- Hurricanes
- Pierce's Disease
- Diversity in temperature and growing season lengths
  - Latitude
  - Elevation
  - Proximity to coast

There are suitable sites, there are suitable varieties, and there is demand for high quality grapes!

Risks Associated with Grape Growing

- Weather:
    - Winter low
    - Temperature swings (January thaws)
    - Late frost in spring, early frost in fall
    - Drought, flood
    - Cool and cloudy weather
    - Extreme heat
    - Humidity
    - Wind
    - Tornados
    - Hurricanes
    - Hail
    - Rain near harvest time

- Pests
    - Weeds
    - Disease
    - Virus
    - Nematodes
    - Insects
    - Birds
    - Mammals

- Equipment
    - Breakdown
    - Learning curve
    - Specialized
    - Expensive

- Labor
    - Shortage
    - Expensive
    - Reliability
    - Skill

- Changing Market

- Competition

- Start-up costs

- Economy of scale

- 8 to 15 years before profit

Truths

- Grape production is capital intensive. Long-term investment
- Need a Business Plan!
    - Why are you on this mission? What do you aim to accomplish? How will you get the work done? How will you pay for it? Tell me about your product. Who will you sell it to? How will you sell it?
- Hard physical labor
- Risky
- Equipment must match size of operation→ economy of scale
- Markets change
- Planning and efficiency are a must!
- Experience and best management practices are key!
- Record keeping and book keeping is critical!!!
    - Measure performance/productivity → adapt/adjust to reach goals

…your location reduces or promotes risks

So does your variety selection and management

Rewards of Grapes and Wine

- High value crop
- Economic development
- Cultural development
- Opportunity to sustainably farm
- Opportunity for scientific and technological advancement

FULL ECONOMIC IMPACT OF NORTH CAROLINA WINE AND WINE GRAPES 2016

$1.97 Billion

Frank and Rimerman, 2017

Surry Viticulture and Enology Students

- Many are non-traditional
- Looking for career change or change in lifestyle
- Interested in reconnecting with land and nature
- Some have family ties to farming
- Aspire to utilize sustainable farming practices
- Diverse goals:
  - Enter workforce during/after graduation
  - Own and operate vineyard/winery
  - Retirement project
  - Hobby scale operation

SCC Viticulture and Enology Program

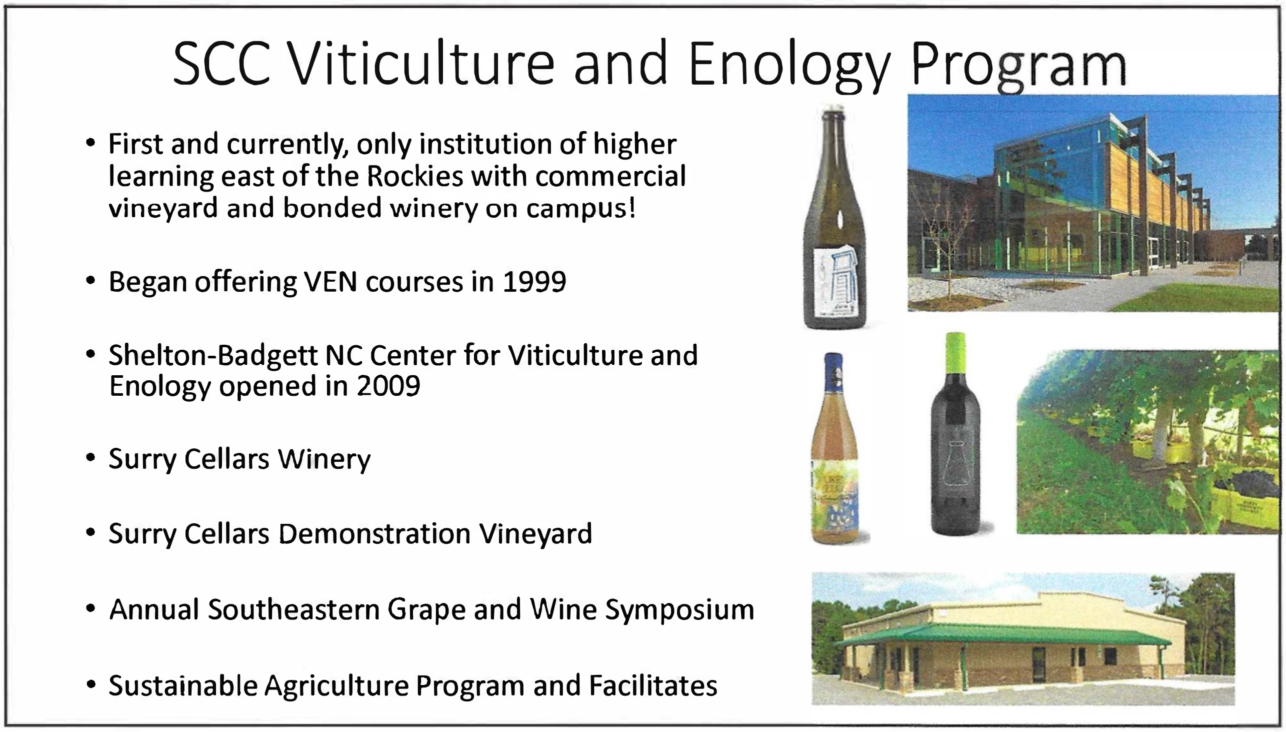
The Viticulture and Enology curriculum is designed to prepare individuals for various careers in the grape growing and wine making industry. Classroom instruction, laboratory and field applications of viticulture/enological principles and practices are included in the program of study.

Credential Options:

Associates Degree or Diploma in Viticulture and Enology

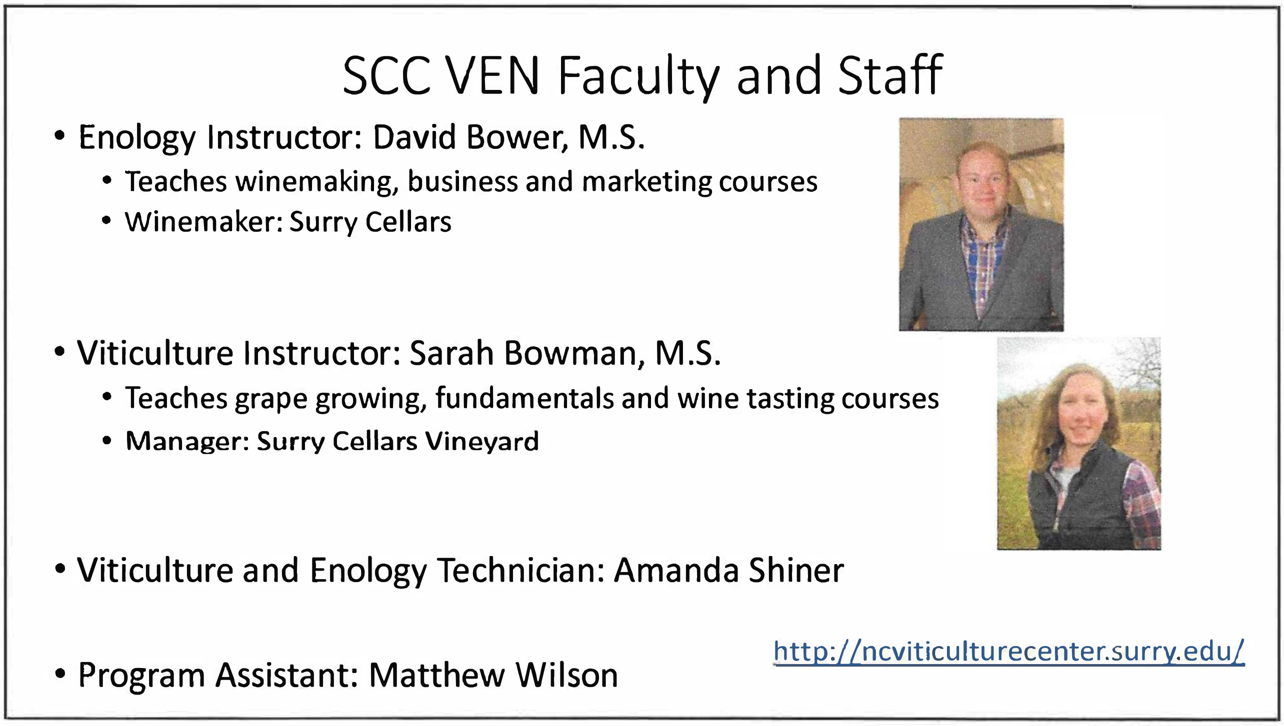
Certificates in: Viticulture, Enology, Marketing, Tasting Room Operations

Graduates should qualify for positions in vineyards, wineries, and in related areas of sales and services. Graduates in viticulture will also be certified as North Carolina Private Pesticide Applicators.



SCC Viticulture and Enology Program

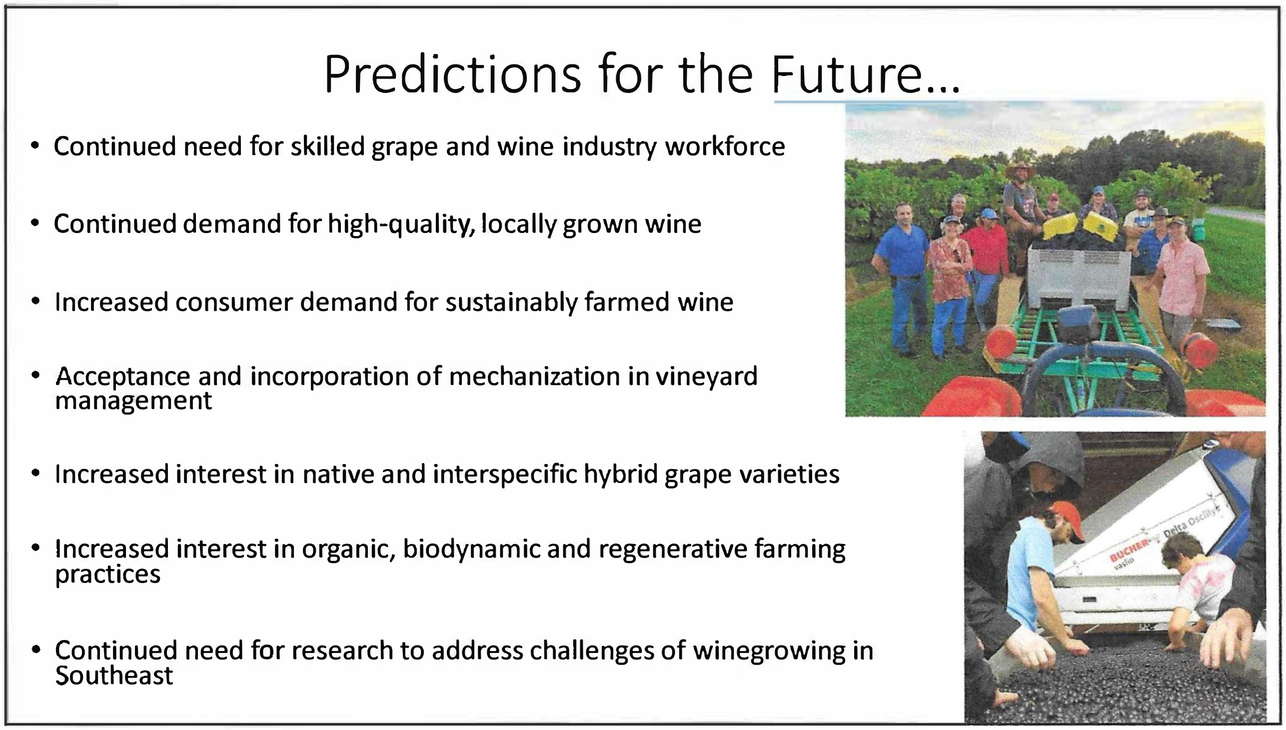
- First and currently, only institution of higher learning east of the Rockies with commercial vineyard and bonded winery on campus!
- Began offering VEN courses in 1999
- Shelton-Badgett NC Center for Viticulture and Enology opened in 2009
- Surry Cellars Winery
- Surry Cellars Demonstration Vineyard
- Annual Southeastern Grape and Wine Symposium
- Sustainable Agriculture Program and Facilitates



SCC VEN Faculty and Staff

- Enology Instructor: David Bower, M.S.
    - Teaches winemaking, business and marketing courses
    - Winemaker: Surry Cellars
- Viticulture Instructor: Sarah Bowman, M.S.
    - Teaches grape growing, fundamentals and wine tasting courses
    - Manager: Surry Cellars Vineyard
- Viticulture and Enology Technician: Amanda Shiner
- Program Assistant: Matthew Wilson

http://ncviticulturecenter.surry.edu/



Predictions for the Future…

- Continued need for skilled grape and wine industry workforce
- Continued demand for high-quality, locally grown wine
- Increased consumer demand for sustainably farmed wine
- Acceptance and incorporation of mechanization in vineyard management
- Increased interest in native and interspecific hybrid grape varieties
- Increased interest in organic, biodynamic and regenerative farming practices
- Continued need for research to address challenges of winegrowing in Southeast

A Preliminary Analysis of North Carolina's Winegrape Cultivars: Their Geographic Distribution and Climatic Characteristics

Mark Hoffmann[1] and Joseph Forrest[2]

Introduction

North Carolina has been well endowed with complex topographic and climatic patterns that provide myriad growing conditions for winegrapes, including most of the important European cultivars (*Vitis vinifera*), as well as hybrid varieties (crosses between two or more *Vitis* species), native American varieties (*Vitis aestivalis*, and *Vitis labruscana*), and muscadines (*Vitis rotundifolia*). The state ranked number seven in the United States for its 2021 wine production,[3] and is one of the fastest growing viticultural areas of eastern North America. The growing eminence of North Carolina as a wine-producer is demonstrated by the presence of six federally designated American Viticultural Areas, with a seventh presently under consideration by the US Department of the Treasury.

The general pattern of winegrape cultivar distribution in the state has long been suggested by the Viticulture Site Suitability map published in 2001 by the NC Dept. of Agriculture and Consumer Services. This work divided the state into four zones based on environmental characteristics and recommended winegrape varieties that would be most appropriate for each (Figure 1). We are not aware that any further work has been carried out to document and verify these recommendations, or to modify them based on the last 20 years of wine-growing experience in the state. The map appeared most

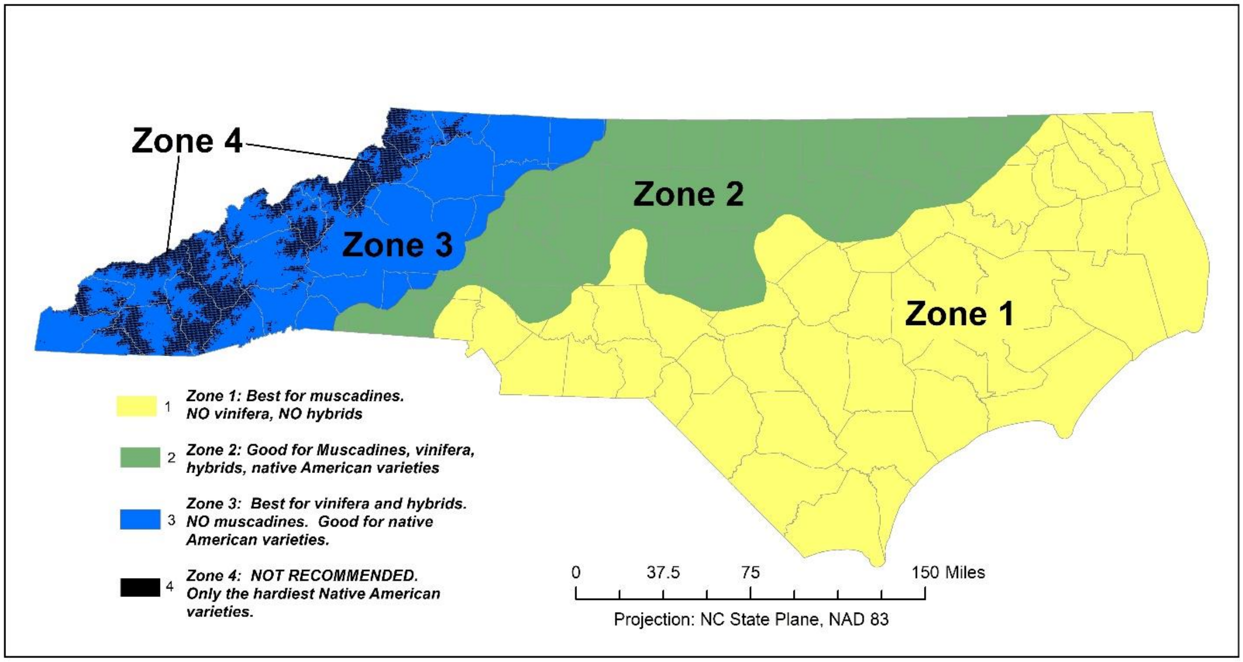


Figure 1. Viticulture Site Suitability in North Carolina.

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[3] https://winesvinesanalytics.com/statistics/winery/

recently in the 2015 *North Carolina Winegrape Growers Guide*[4] unchanged from its original publication. An early, preliminary review of the map suggested to us that some grapes are being grown successfully outside of the zones in which they are considered appropriate, or grapes are being grown in some zones that are not optimal for their geographic setting, specific climate characteristics, and local disease and pest pressure. A primary goal of this analysis is, therefore, to test the reliability of the Site Suitability mapping by (1) identifying North Carolina's presently active vineyards and vineyard-wineries, and (2) determining what cultivars these active operations are growing, and how they relate to the Site Suitability recommendations.

Viticulture is a complex science governed by many environmental aspects, the totality of which are expressed in the French term "terroir," which attempts to relate all natural and human factors that contribute to successful cultivation of winegrapes and production of quality wines. Our goal is not to analyze the total terroir aspects of North Carolina; we restrict ourselves in this study to climate, specifically to some aspects of regional temperature conditions, which we feel are the most important determinants of grape and wine quality. After all, temperature determines the time of annual onset of vine growth, length of the growing season, mean temperature of the growing season, amount of heat accumulated by grapes prior to harvest, and the risk of late spring and early frost events. These temperature factors are easily understood and are important for selecting vineyard sites and winegrape cultivars for initial and replacement plantings. To relate North Carolina's cultivars to a framework of temperature factors, we have developed four regional models to illustrate and define the above-mentioned temperature regimes across the state.

In addition to describing the overall cultivar distribution patterns in North Carolina, we discuss the implications of climate change for North Carolina's viticultural future and make recommendations of winegrape cultivars for new and replacement plantings.

Methodology

To identify active vineyards and their cultivars, we researched websites and publications of organizations that represent the state's wine producers, the most important of which are the NC Winegrowers Association,[5] the NC Grape and Wine Council,[6] and the NC Muscadine Grape Association.[7] For vineyards that are not members of these groups, we did more in-depth online searches of specific counties or geographic areas. We also conducted telephone interviews with County Extension Agents, Chambers of Commerce, and with individual vineyard owners.

After assembling a list of active vineyards, we researched each one online to ascertain the types of grapes they grow. Most vineyards list grape types on their websites as an indication of the styles of wines they are producing, or of varieties they have for sale. Since our goal has been to correlate cultivars with specific geographic sites, we only consider grapes that are grown at a vineyard with a discernible latitude-longitude location. Wineries that only make wines from purchased grapes are not included in the analysis. Vineyards that grow and sell their grapes are included. Many vineyard-wineries not only grow their own grapes but purchase grapes as well from other vineyards; in these cases, we have attempted, by phone conversations with the winegrowers, to exclude the purchased grapes and to include the grapes grown on site. We did not try to get information on the acreages of each grape type. We rank our listing of

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[4] Polling, Barclay and Sarah Spayd. 2015. *The North Carolina Winegrape Growers Guide*: Raleigh, NC State Extension.

[5] https://www.ncwinegrowers.com/

[6] https://www.ncwine.org/

[7] https://www.ncmuscadinegrape.org/

cultivars by the number of vineyards that grow them, which is the "frequency of planting." A frequency of '10' means that 10 vineyards in a geographic area list this grape variety as one they grow. We cannot confirm that our frequency numbers indicate anything about the acreage that a particular grape variety occupies.

Using physical addresses, we located the identified vineyards on Google Earth or on imagery from the National Agricultural Imagery Program (NAIP).[8] Since this analysis was meant to be quick and preliminary, we did not digitize the planted vineyard blocks; instead, we manually placed a centroid point among the visible planted blocks as the latitude-longitude location of the vineyard. To assign a physical characteristic, such as elevation or a climate value, we generated a one-mile buffer around each centroid point and extracted values from our climate models to the buffered area. Extracted values were then averaged and assigned to the location.

We feel we have identified a majority of the vineyards and vineyard-wineries that are presently operational, but there is a high probability that we have missed some; this is especially true for the coastal plain region where there are likely to be a number of muscadine vineyards that do not belong to the statewide organizations, or do not advertise via a website. Nevertheless, our evidence suggests that the predominance of the principal muscadine varieties will not likely change based on data from additional vineyards. The websites of a few vineyards and vineyard-wineries (3-5 in number) do not list the grape types they grow, and we have not been able to reach the winegrowers, despite numerous attempts. These operations are mainly in the Yadkin Valley, the area of the largest concentration of vineyards and vineyard-wineries in the state. Lack of data from this small group of vineyards will not materially change our interpretations.

To develop models for temperature characteristics, we utilized data from the National Centers for Environmental Information (NCEI),[9] and the Prism Climate Group at Oregon State University.[10] The models for Mean Length of Growing Season, and the Spring and Fall frost indices are based on the 1981-2010 climate normals generated by the NCEI. Unfortunately, climate normals for 1991-2020 have not yet been released by the NCEI. The models for Mean Growing Season Temperature and for Growing Degree Days are based on the gridded 1991-2020 climate normals from the Prism Climate Group at Oregon State University.[10] Processing of data and generation of maps utilized ESRI's ArcGIS software and its Spatial Analyst extension.[11]

Geographic Distribution of Vineyards and Cultivars

Our research identified 158 active vineyards and vineyard-wineries that fit our analysis criteria (Figure 2), and 125 distinct cultivars being grown in North Carolina (Appendix 1 and Appendix 2). To test the reliability of Viticultural Site Suitability (Figure 1), we show the distribution of cultivars on that map, followed by the distribution on a physiographic map of North Carolina, and finally on a map of North Carolina's American Viticultural Areas.

Viticulture Suitability Zones. The Viticulture Site Suitability (VSS) map of North Carolina (Figure 1) was published originally in 2001[12] with the purpose of recommending the general types of winegrapes that

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[8] https://www.usgs.gov/centers/eros/science/usgs-eros-archive-aerial-photography-national-agriculture-imagery-program-naip

[9] https://www.ncei.noaa.gov/

[10] https://www.prism.oregonstate.edu/

[11] https://www.esri.com/en-us/arcgis/products/arcgis-desktop/overview

[12] Polling, Barclay and Sarah Spayd, eds. 2015. *The North Carolina Winegrape Grower's Guide*: Raleigh, NC State Extension.

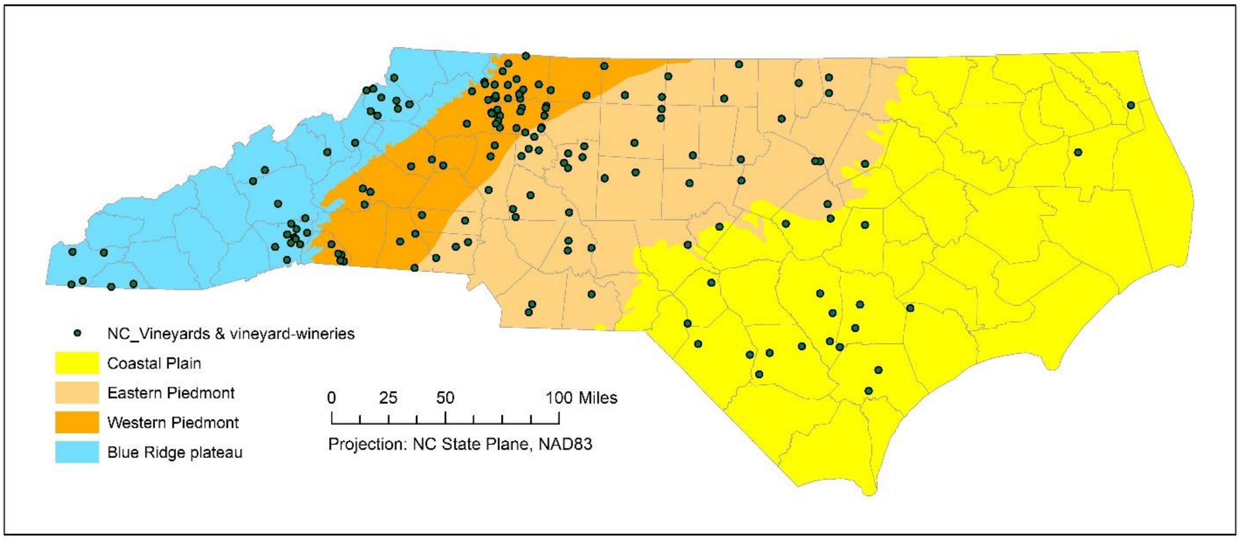

Figure 2. Location of North Carolina vineyards and vineyard-wineries active as of July 2022.

are appropriate in each of four zones across the state. Since publication of the map, there have been two recalculations of US climate normals[13] that affect interpreted climate patterns of the state and possibly boundaries of the original suitability zones, suggesting that the 2001 boundaries require updating. An additional weakness of the 2001 map is the definition of Zone 3, which combines the western Piedmont with the Blue Ridge plateau. Combination of these two physiographic features masks the profound elevational difference between them and gives a false impression of the varieties of grapes appropriate in both. Finally, the map does not recognize the cold-hardy hybrids that have been developed in the last

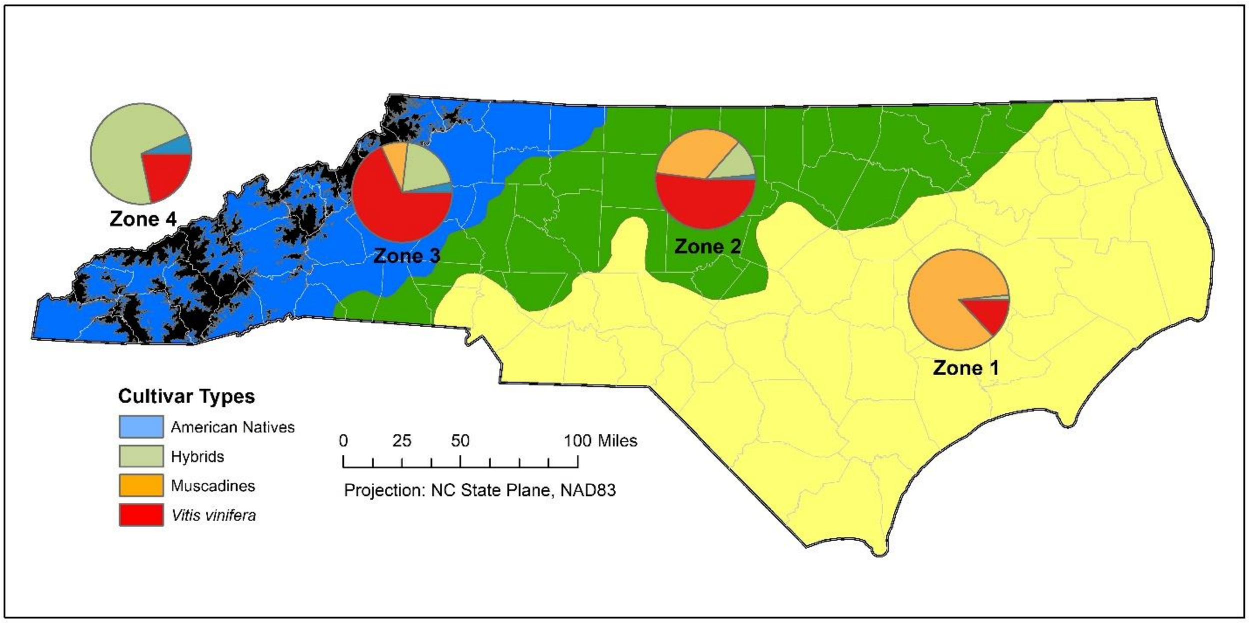

Figure 3. Winegrape cultivar types presently growing in North Carolina Viticulture Site Suitability zones.

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[13] The US National Centers for Environmental Information (NCEI) calculates climate normals every ten years. The latest normals that are publicly available are for the period 1981-2010.

twenty years that have allowed viticulture to thrive in the northern states and that could be appropriate cultivars for the higher elevations of the Blue Ridge plateau.

Figure 3 illustrates our interpretation of winegrape species distribution in the 2001 Viticulture Suitability Zones. Specific cultivars are summarized for each zone in Appendix 1.

Muscadine varieties dominate Zone 1, with plantings become fewer moving westward across Zones 2 and Zone 3, and non-existent in Zone 4. *Vitis vinifera* cultivars are relatively rare in Zone 1, but are abundant in Zone 2, and are the most frequent plantings in Zone 3; plantings are considerably reduced in Zone 4. Hybrid cultivars are rare in Zone 1 but increase in frequency to the west, becoming the dominant varieties in Zone 4. Native American varieties are relatively rare in Zones 1, 2 and 3, and are at their most prominent in Zone 4, where they still constitute only a small number of plantings.

Despite The VSS's recommendations against *Vitis vinifera* and hybrids in Zone 1, we found 16 *vinifera* cultivars in 16 plantings in the zone, and 2 hybrid cultivars in 2 plantings. In Zone 3 where muscadines are specifically not recommended, we found 21 muscadine cultivars being grown in 54 plantings. Zone 4 is recommended for only the hardiest America native cultivars. Our research indicates 16 *vinifera* cultivars in the zone, 33 hybrids, and only 2 native American cultivars. Finally, native American cultivars are recommended for Zone 2, 3, and 4 but we found only three native American cultivars in 21 plantings throughout the state.

***Zonation of Physiographic Regions**:* North Carolina comprises four major physiographic regions: coastal plain, eastern Piedmont, western Piedmont, and Blue Ridge plateau, each distinguished by differences in elevation, topography, and climate. The distribution of wine-grape cultivars in the physiographic regions is shown in Figure 4. Specific cultivars planted in each are summarized in Appendix 2.

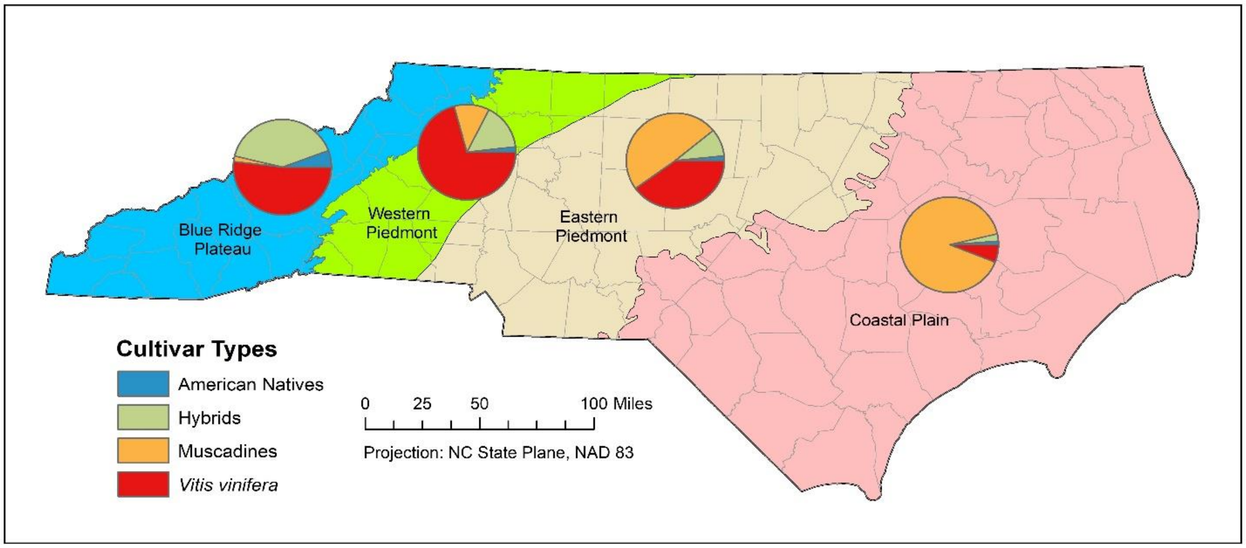

Figure 4. Winegrape cultivars presently growing in North Carolina's four major physiographic provinces.

The dominant varieties on the coastal plain are muscadines, with only a smattering of *vinifera* plantings, a few hybrids and a single native American variety. Going west into the eastern Piedmont, *vinifera* cultivars become increasingly important, as do hybrids; muscadine plantings decrease, and native

American varieties remain insignificant. In the western Piedmont, *vinifera* cultivars become the most frequently planted varieties; hybrids increase in numbers, with muscadine plantings decreasing significantly. On the Blue Ridge plateau, *vinifera* plantings are still dominant, with hybrid having increased significantly, muscadines are rarely planted, and native American varieties have achieved their greatest number of plantings, which are relatively insignificant.

American Viticultural Areas: The American Viticultural Area program (commonly referred to as the "AVA" program), is administered by the Tax and Trade Bureau (TTB) of the US Department of the Treasury. The program began in 1978 and to date has resulted in the designation of 266 AVAs in the United States, Applications for an AVA are made by the winegrowers of a region. The most important part of an AVA petition is a description of the area's natural environmental characteristics that influence viticulture and an explanation of how these characteristics differ from those of surrounding areas. There are now six AVAs in North Carolina, and a seventh (Tryon Foothills) is under review by the TTB (Figure 4).

Figure 4 and Appendices 3, 4, and 5 summarize the cultivar types in North Carolina AVA's. We include the Dahlonega Plateau AVA of north Georgia in this analysis, as it contrasts so sharply with the adjacent Upper Hiwassee Highlands AVA of North Carolina and north Georgia.

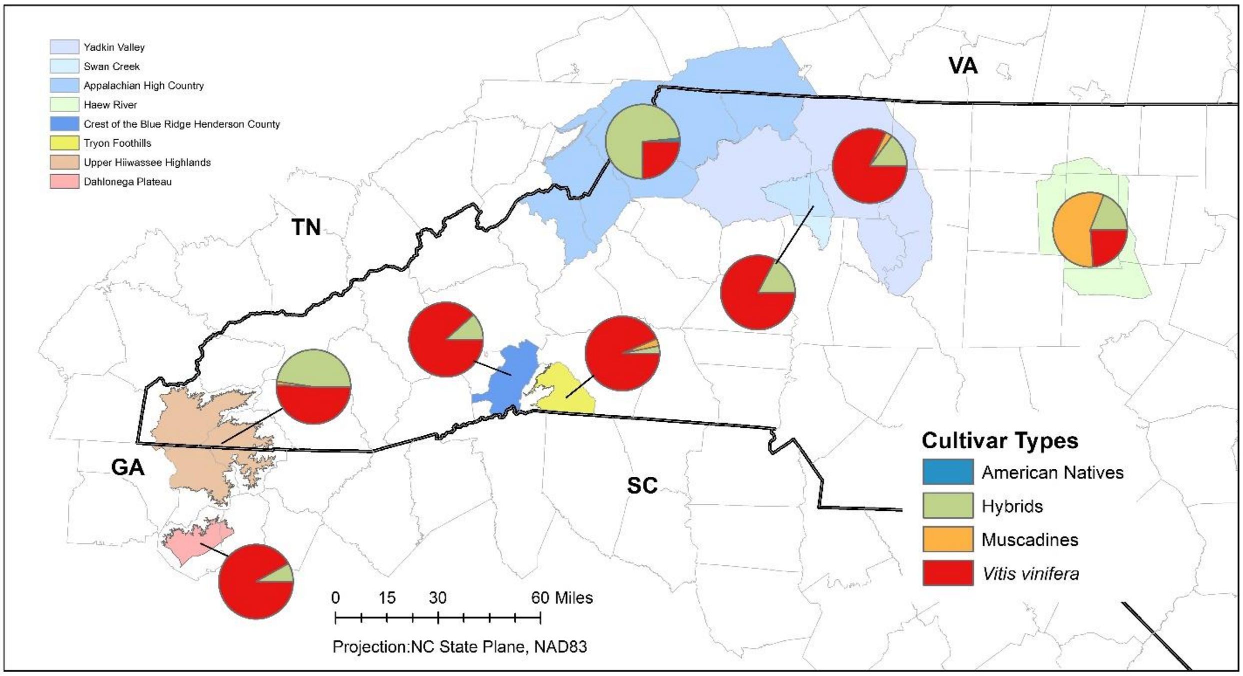

Figure 5. Cultivar distribution in the American Viticultural Areas of North Carolina and north Georgia.

In the Haw River AVA, muscadines are the dominant cultivars, but *vinifera* and hybrids are also well-represented. In the Yadkin Valley and Swan Creek AVAs, *vinifera* and hybrids are the predominant cultivars, with a few plantings of muscadines and native American varieties. In the adjacent Appalachian High Country AVA, hybrid plantings dominate, with *vinifera* and a few plantings of native American varieties. In the proposed Tryon Foothills AVA, the predominant cultivars are *vinifera* with a very small number of hybrid plantings and a single planting of muscadines. The adjacent Crest of the Blue Ridge Henderson County AVA is predominantly planted in *vinifera* cultivars, but with a significant number of hybrid plantings. The Upper Hiwassee Highlands AVA of southwestern North Carolina and north Georgia is approximately half *vinifera* and half hybrids, but with a small number of muscadine plantings. Finally, the Dahlonega Plateau of north Georgia is planted predominantly in *vinifera* varieties with a small number of hybrid plantings.

Summary of Cultivar Distribution

The 125 cultivars under cultivation in North Carolina can be classified as follows: 56 are *vinifera*, 30 are hybrids, 38 are muscadines, and three are native American varieties. Table 1 lists the 36 most frequently planted cultivars that are planted in five or more vineyards. Of these, 16 *vinifera* cultivars occur in 373 plantings, followed by 13 muscadine cultivars in 172 plantings, 5 hybrid cultivars in 85 plantings, and 3 native American cultivars in 21 plantings. The grapes that have attained a worldwide reputation and claim to be the most desired by wine-drinkers are the seven *vinifera* cultivars known as the 'Noble Grapes.' They include the red cultivars Cabernet Sauvignon, Merlot, Pinot Noir, and Syrah, and the white cultivars Chardonnay, Sauvignon Blanc, and Riesling. All the noble varieties are grown in North Carolina, though Pinot Noir was found in only one vineyard. The other six are commonly planted in the state.

Geographically, *vinifera* cultivars are dominant in the western Piedmont, with 233 out of a total of 341 plantings, the most frequently planted being Merlot, Chardonnay, Cabernet Sauvignon, Cabernet Franc, Viognier, and Syrah. *Vinifera* grapes are also important in the eastern Piedmont, where they are present in 101 out of a total of 247 plantings. The most frequently planted are Merlot, Cabernet Sauvignon, Cabernet Franc, Chardonnay, Syrah, and Sauvignon Blanc. On the Blue Ridge plateau, *vinifera* grapes comprise 96 of 167 plantings, with the dominant cultivars being Cabernet Franc, Riesling, Cabernet Sauvignon, Chardonnay, Vidal Blanc, Merlot, and Grüner Veltliner. On the coastal plain, there are a total of 81 plantings, of which *vinifera* cultivars comprise five, with Cabernet Franc, Cabernet Sauvignon, Syrah, Tempranillo, and Viognier comprising one planting each.

The predominance of *vinifera* plantings in North Carolina is in many ways a miracle. In the 1970's when Jack Kroustakis decided to start a vineyard and winery in Lewisville, NC, he was told by grape experts that it was impossible to grow European grapes in North Carolina. Mr. Kroustakis persisted and opened North Carolina's first bonded vineyard-winery (Westbend Vineyards) in 1988 and became the state's first winegrower to successfully cultivate *vinifera* grapes and make wine from them. The persistence of North Carolina winegrowers and their willingness to take risks have made *vinifera* cultivars the predominantly planted winegrapes in the state and thus have advanced North Carolina's status as a serious wine-producing region.

The second most frequently planted cultivars in North Carolina are muscadines, which are the most frequently planted grapes on the coastal plain, with an estimated 72 out of a total of 81 plantings. The most important cultivars are Carlos, Noble, Triumph, Supreme, and Tara. In the eastern Piedmont, muscadines comprise slightly less than half of all cultivar plantings with 121 of a total of 247 plantings, with Noble, Carlos, Magnolia, Nesbitt, Triumph, Tara, Ison, Supreme, and Fry being the most frequently planted. In the western Piedmont, muscadines form 37 out of 335 total plantings, with Noble, Carlos, Tara, Triumph and Scuppernongs being the most frequently planted. On the Blue Ridge plateau, there are three plantings of muscadine out of a total of 167 total plantings. The cultivars are Katuah Muscadines and Katuah Scuppernongs and an unspecified muscadine cultivar. The Katuah varieties are cold-hardy cultivars developed by Jewel of the Blue Ridge Vineyard in Marshall, NC.

Cultivars	Species	Frequency	Elevation (Ft)		MGSL (Days)		MGST (F°)		MGDD (F°Days)		LSFrost (Date)		FFFrost (Date)	
			Low	High	Low	High	Low	High	Low	High	Early	Late	Early	Late
Merlot	VV	53	524	2820	173	212	66	70	3176	4340	4/2	4/24	10/17	11/2
Cabernet Franc	VV	50	14	3172	157	239	61	71	2411	4595	3/25	5/3	10/9	11/20
Cabernet Sauvignon	VV	48	14	3238	157	239	61	71	2411	4595	3/25	5/3	10/9	11/20
Chardonnay	VV	47	451	3172	157	212	61	70	2411	4300	4/4	5/3	10/9	11/2
Carlos	M	38	14	1288	182	239	68	73	3869	4865	3/25	4/20	10/21	11/20
Noble	M	37	19	1288	182	227	68	73	3869	4865	3/26	4/20	10/21	11/9
Chambourcin	H	34	356	3172	157	214	61	71	2411	4432	4/3	5/3	10/9	11/4
Petit Verdot	VV	31	451	3443	163	208	61	70	2466	4340	4/6	4/30	10/12	11/1
Viognier	VV	23	14	2187	176	239	65	71	3288	4595	3/25	4/24	10/18	11/20
Traminette	H	23	14	3431	158	239	61	71	2481	4595	3/25	5/2	10/10	11/20
Riesling	VV	20	700	3443	163	199	61	70	2466	4251	4/12	4/30	10/12	10/26
Seyval Blanc	H	16	500	4067	154	213	59	70	2031	4285	4/3	5/5	10/8	11/3
Norton-Cynthiana	AN	16	64	3252	162	223	62	72	2634	4670	3/29	4/29	10/12	11/8
Syrah	VV	15	14	1149	179	239	67	71	3721	4595	3/25	4/22	10/19	11/20
Nesbitt	M	15	151	1021	187	220	69	72	4009	4746	3/30	4/18	10/23	11/6
Pinot Grigio/Gris	VV	14	451	3172	157	212	61	70	2411	4300	4/4	5/3	10/9	11/2
Muscadine (Unspecified)	M	14	3	2186	179	233	65	72	3233	4739	3/27	4/22	10/20	11/15
Sangiovese	VV	13	451	3237	159	212	61	70	2481	4285	4/4	5/1	10/10	11/2
Magnolia	M	13	121	1288	189	220	68	73	3948	4865	3/30	4/17	10/24	11/6
Petit Manseng	VV	12	695	2217	173	212	65	70	3233	4275	4/4	4/26	10/17	11/2
Tara	M	12	108	393	196	220	68	72	3948	4796	3/30	4/13	10/27	11/6
Triumph	M	12	19	286	187	225	69	72	4009	4832	3/29	4/18	10/23	11/9
Malbec	VV	11	587	2217	173	208	65	70	3263	4340	4/6	4/24	10/17	11/1
Vidal Blanc	VV	11	356	3443	157	214	61	70	2411	4410	4/3	5/3	10/9	11/4
Supreme	M	11	36	1288	196	228	68	72	3948	4814	3/28	4/13	10/27	11/9
Sauvignon Blanc	VV	10	700	2337	178	206	65	70	3176	4340	4/8	4/22	10/19	10/31
Catawaba	AN	7	356	3252	162	214	62	70	2634	4410	4/3	4/30	10/12	11/4
Montepulciano	VV	6	451	2199	172	195	65	69	3260	4094	4/13	4/26	10/16	10/26
Fry (Unspecified)	M	6	414	937	187	213	69	71	4009	4534	4/3	4/18	10/23	11/3
Ison	M	6	133	1021	196	213	69	72	4157	4692	4/3	4/14	10/28	11/3
Lane	M	6	108	806	196	220	70	72	4326	4796	3/30	4/13	10/27	11/6
Scuppernong	M	6	121	1021	199	220	69	73	4122	4845	3/30	4/12	10/26	11/6
Chardonel	H	6	14	2238	183	239	65	71	3375	4595	3/25	4/21	10/21	11/20
Doreen	M	5	19	951	182	225	68	72	3869	4832	3/29	4/20	10/21	11/9
Summit	M	5	181	937	187	215	69	71	4009	4618	4/1	4/18	10/23	11/3
Marquette	H	5	1221	3443	162	201	61	69	2466	4035	4/10	4/30	10/12	10/30

Table 1: The 36 most frequently planted winegrape cultivars in North Carolina. MGSL=Mean Growing Season Length; MGST=Mean Growing Season Temperature; MGDD=Mean Growing Degree Days; LSFrost=Last Spring Frost; FFFrost=First Fall Frost.

Hybrids are the third most frequently planted cultivars in North Carolina. On the Blue Ridge plateau, they comprise 68 out of a total of 167 plantings. The most frequently planted are Seyval Blanc, Catawba, Chambourcin, Marechal Foch, and Marquette. In the western Piedmont, there are 52 hybrid plantings out of a total of 335 plantings. Chambourcin and Traminette are the most frequently planted. In the eastern Piedmont, there are 21 hybrid plantings out of a total of 247. The most frequently planted are Traminette, Seyval Blanc, and Chardonel. On the coastal plain, there are only two plantings of hybrids, one each of Traminette and Chardonel.

The most surprising of the cultivars are the native American varieties, which were highly recommended by the 2001 Site Suitability mapping. We found only three cultivars – Norton-Cynthiana, Concord, and Sunbelt - in this category and in very limited geographical distribution. There are six plantings of Norton-Cynthiana in each of the western Piedmont and the Blue Ridge plateau, three plantings in the eastern Piedmont and one planting on the coastal plain. There are three plantings of Concord on the Blue Ridge plateau and one planting in the eastern Piedmont. There is one planting of Sunbelt in the eastern Piedmont.

To compare cultivars in North Carolina's AVAs, refer to Appendices 3, 4, and 5. We have divided the AVAs into three categories based on geographic location. The Northern Tier (Appendix 4) consists of the Appalachian High Country, Yadkin Valley, Swan Creek and Haw River AVAs, and the areas have been aligned in the table with the adjacent AVAs in their geographic positions from west to east. The Central Tier of AVAs (Appendix 5) includes the Crest of the Blue Ridge Henderson County and the proposed Tryon Foothills. The Southern Tier comprises the Upper Hiwassee Highlands and the Dahlonega Plateau AVAs.

Regional Temperature Models for Vineyard Site Evaluation and Cultivar Selection

Mean Length of Growing Season: The length of a vineyard site's growing season is defined as the number of days between the last spring frost and the first fall frost, based on a temperature of 32°F. To produce quality wine, grapes should be fully ripe at time of harvest. Determining the mean length of growing season is an important metric for selecting a vineyard site, and for deciding on the appropriate grapes to plant. Many authors have suggested ranges of growing season length for optimum ripening of grapes. Average values fall between 170-190 days.[14] A minimum growing season of 165 days is essential.[15] Sites with 165-180 days may be marginal. A growing season of 180 days or greater is preferable.

To generate our model of Growing Season Length, we utilized 284 NCEI weather monitoring stations throughout North Carolina and within a 75-mile buffer around the state's boundaries (Figure 6).[16] These stations all have mean values of the length of growing season based on the NCEI 1981-2010 climate normals. As might be expected, growing season length varies with topography, with the lower elevations of the coastal plain having the longest growing season, the central parts of the state having intermediate lengths, and the higher elevations of the western part of the state having the shortest season.

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[12] https://glossary.wein.plus/maturity-date

[14] Jones, Gregory. 2015. Climate, Grapes, and Wine: Terroir and the Importance of Climate to Winegrape Production. https://www.guildsomm.com/public_content/features/articles/b/gregory_jones/posts/climate-grapes-and-wine

[15] Jordan, T. D., R. M. Pool, T. J. Zabadal, and J. P. Tompkins. 1980. Cultural Practices for Commercial Vineyards. Cornell University, College of Agriculture and Life Sciences: Ithaca, New York. Miscellaneous Bulletin 111.

[16] Values from the NCEI 1980-2010 Climate Normals found on website of the National Centers for Environmental Information: https://www.ncei.noaa.gov/.

To generate a more complete interpretation of length of growing season, we have converted the observed values shown in Figure 6 into an indiscrete, continuous field model (Figure 7) using an Inverse Distance Weighted interpolation. From the resulting model, we have assigned estimated Mean Growing Season Lengths to each of the active vineyards, using an average of all modeled values within a 1-mile radius of a vineyard's manually assigned center point. Our estimated length of growing season throughput North Carolina ranges from 134 days on the highest peaks of the Blue Ridge plateau to 283 days at the lowest

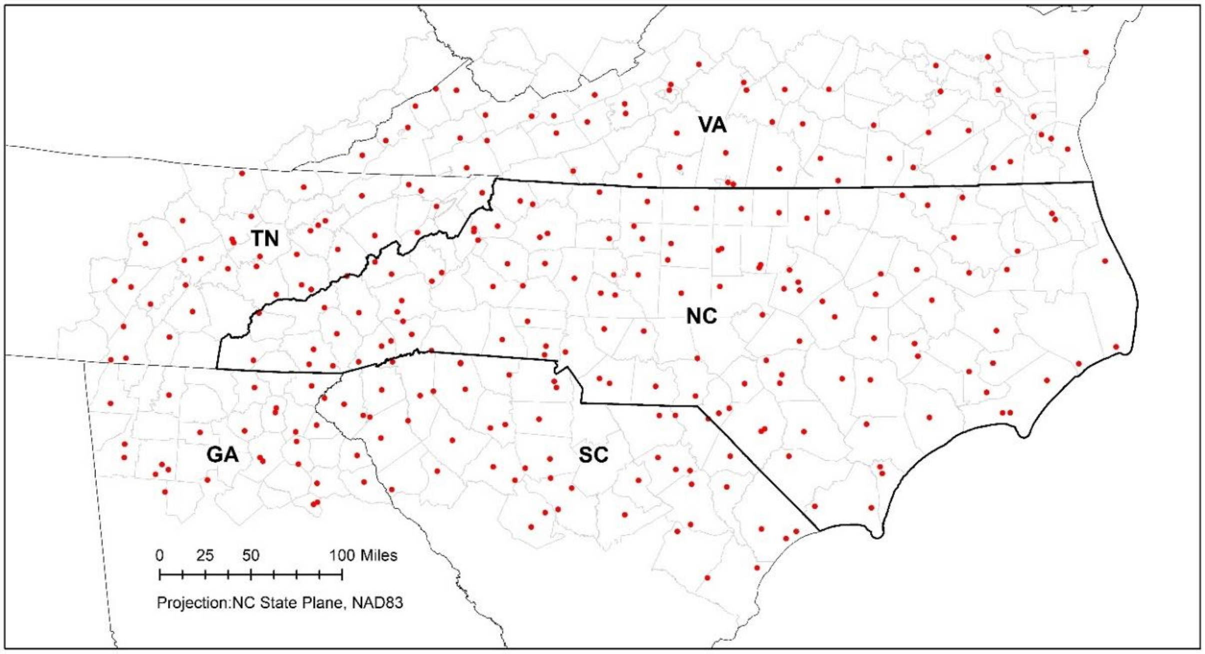


Figure 6. Locations of NCEI weather stations used to generate models of mean growing season length and last spring and first fall first dates.

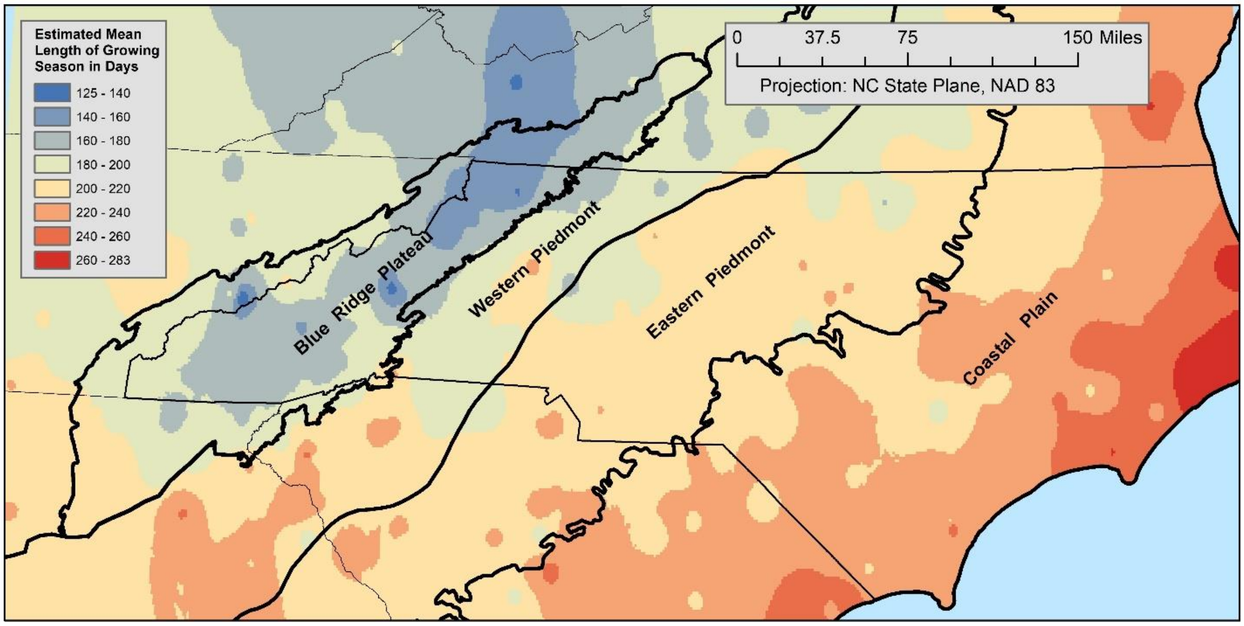
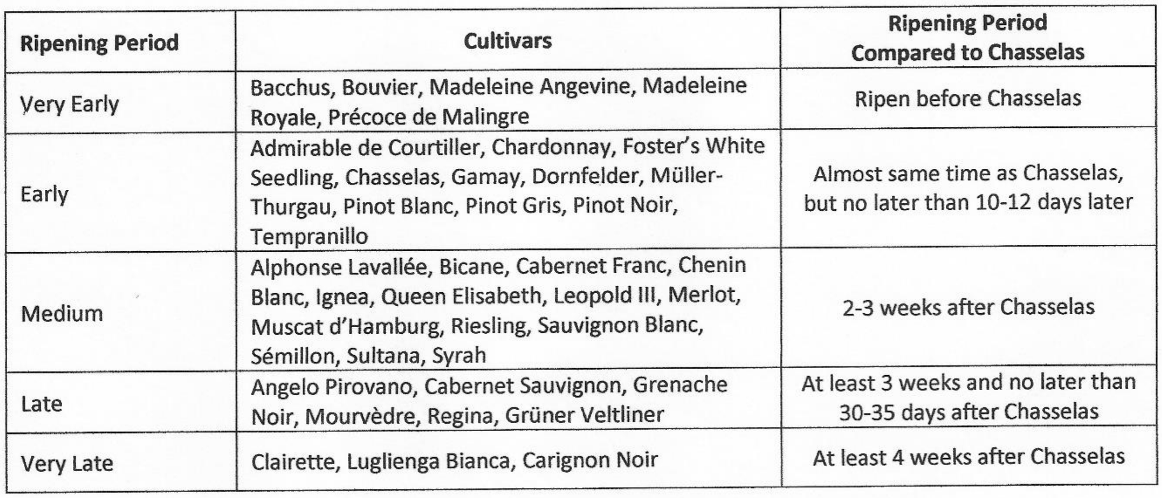


Figure 7. Estimated mean growing season length in days.

elevations of the coastal plain. The estimated mean length of growing season for North Carolina's active vineyards ranges from 154 to 239 days. Since grape varieties vary in their rates of maturation, it is essential that the winegrower plant grapes that will ripen during the vineyard site's growing season. To get an idea of the ripening times of some grape cultivars, we can look at the work of the French ampelographer Victor Pulliat, who in the late 19th century devised a classification of cultivar ripening that is still used today. This scheme is based on the winegrape Chasselas Doré (The most widely grown wine-grape in Switzerland) as the reference variety against which other varieties are compared. The classification breaks the ripening period into five broad periods. Table 2 summarizes typical cultivars in each period.



Ripening Period	Cultivars	Ripening Period Compared to Chasselas
Very Early	Bacchus, Bouvier, Madeleine Angevine, Madeleine Royale, Précoce de Malingre	Ripen before Chasselas
Early	Admirable de Courtiller, Chardonnay, Foster's White Seedling, Chasselas, Gamay, Dornfelder, Müller-Thurgau, Pinot Blanc, Pinot Gris, Pinot Noir, Tempranillo	Almost same time as Chasselas, but no later than 10-12 days later
Medium	Alphonse Lavallée, Bicane, Cabernet Franc, Chenin Blanc, Ignea, Queen Elisabeth, Leopold III, Merlot, Muscat d'Hamburg, Riesling, Sauvignon Blanc, Sémillon, Sultana, Syrah	2-3 weeks after Chasselas
Late	Angelo Pirovano, Cabernet Sauvignon, Grenache Noir, Mourvèdre, Regina, Grüner Veltliner	At least 3 weeks and no later than 30-35 days after Chasselas
Very Late	Clairette, Luglienga Bianca, Carignon Noir	At least 4 weeks after Chasselas

Table 2. The winegrape ripening classification of Victor Pulliat.

Mean Growing Season Temperature: Quality wine production is generally limited worldwide to mean growing season temperatures in the range of 55-70°F.[17] The Grapevine Climate/Maturity Groupings chart of Prof. Gregory Jones (Figure 8) shows optimal mean growing season temperatures for some of the best-known winegrape cultivars based on four temperature ranges (cool, intermediate, warm, and hot) that occur in vineyard climates worldwide. Though the cultivars on the chart can be grown outside of the optimal ranges, they tend to produce the best wines in the temperature ranges shown. The classification can be used to suggest cultivars that might be appropriate for new vineyards or for new plantings in areas with similar growing season temperatures.

Unfortunately, the Jones Maturity Groupings chart illustrates only *vinifera* varieties and tells us nothing about hybrid, muscadine, or native American grapes that are also important to North Carolina. By plotting the mean growing season temperatures of the *vinifera* grapes growing in the state on the Jones chart, we can surmise that many of the *vinifera* grapes planted in North Carolina may be in areas that are too warm for their ripening characteristics (See Figure 8).

Using the Prism Climate Group's gridded 1991-2020 temperature normals, we have generated a model of Mean Growing Season Temperature for North Carolina (Figure 9). All four of Jones's Maturity Groupings

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[17] Jones, Gregory. 2015. Climate, Grapes, and Wine: Terroir and the Importance of Climate to Winegrape Production: Guildsomm.com https://www.guildsomm.com/public_content/features/articles/b/gregory_jones/posts/climate-grapes-and-wine

occur in the state, with the cool, Intermediate, and Warm regions in the western Piedmont and the Blue Ridge plateau, and the Hot areas in the eastern Piedmont and Coastal Plain.

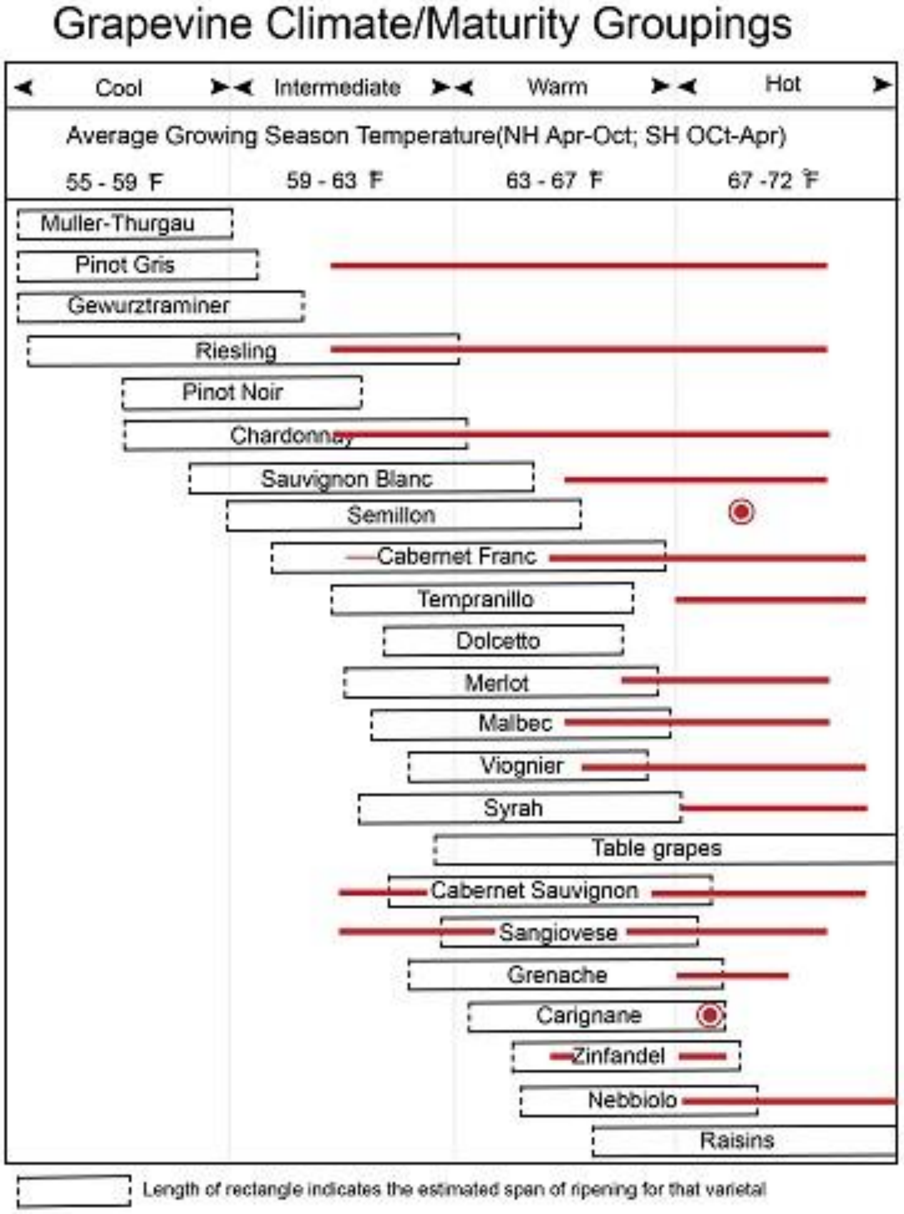

Figure 8. Climate-Maturity Groupings based on mean growing season temperatures at which each variety is known to ripen and produce high to premium quality wine in the world's benchmark regions. Dashed line at the end of the bars indicates that some adjustments may occur as more data becomes available, but changes of more than +/-0.4-0.8°F are highly unlikely. The figure and research behind it are a work in progress and are used with permission of the author, Dr. Gregory Jones.

The heavy red lines represent the mean growing season temperature ranges for *vinifera* presently under cultivation in North Carolina. Two encircled red points represent the value for cultivars in which there is only one planting.

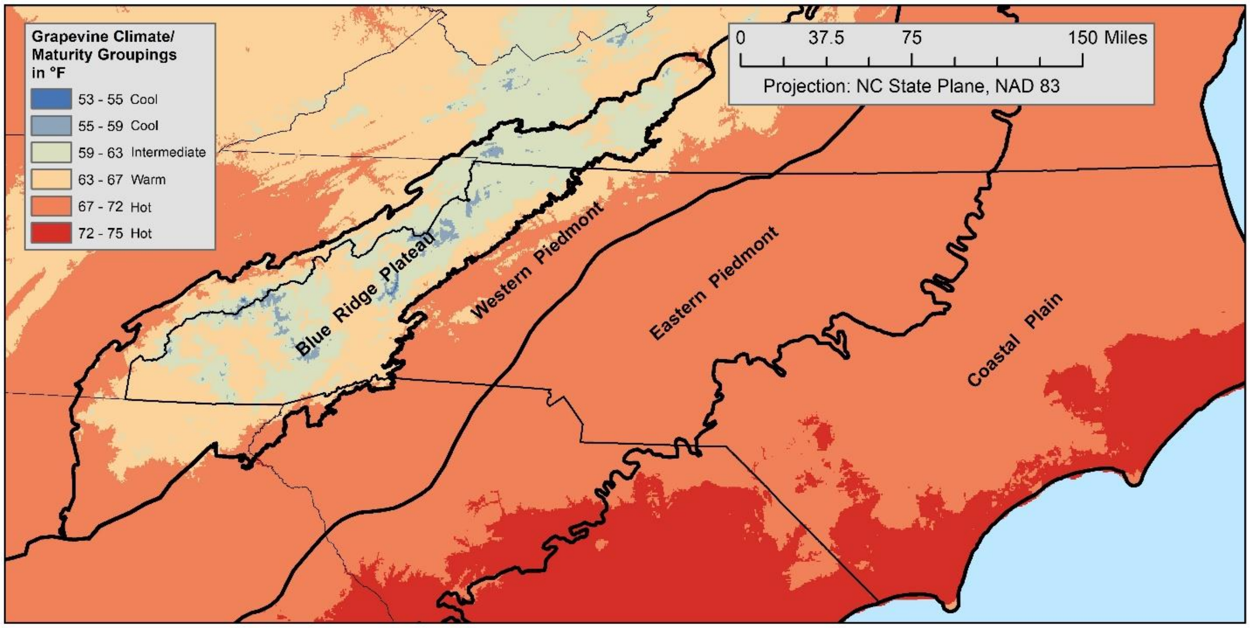

Figure 9. Mean growing season temperature. Data from Prism Climate Group gridded 1991-2020 climate normals.

Growing Degree Day Zonation: Plants begin their annual growth cycle when the mean daily temperature reaches a critical base value, which in the case of grapes is generally assumed to be 50°F (10°C). In the northern hemisphere this level is normally attained in April, with the growth cycle then extending, on average, through October. The ability of a plant to reach full maturity is based on the amount of heat to which the plant is exposed over the growing season. Agronomists estimate the accumulated heat by calculating and summing heat units called Growing Degree Days (GDD).

The technique of GDD zonation was popularized in viticulture by Amerine and Winkler in their renowned classification of California vineyards published in 1944. They divided the state's viticultural areas into five categories known as 'Winkler Regions'[20] based on their ranges of GDD units and assigned grapes to them based on the varieties' optimal development. Recent work in the western US[21] and Australia[22] suggests a lower limit of 1500 F° units for Region I and an upper limit of 4900 F° units for Region V. Further work has

GDD in F° Units	GDD Zones	Climate Condition
< 1500	Too cold	Cooler ↕ Warmer
1500 - 2000	Zone Ia	
2000 – 2500	Zone Ib	
2500 – 3000	Zone II	
3001 - 3500	Zone III	
3500 – 4000	Zone IV	
4000 - 4900	Zone V	
> 4900	Too warm	

Table 2. Growing Degree Day zones.

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[20] We use the term "GDD zones" rather "Winkler regions" since the California classification is presently under recalculation.

[21] Jones et al., *Spatial analysis of climate in winegrape growing regions in the United States.*

[22] Hall, A., and G. V. Jones. 2010*. Spatial analysis of climate in wine-growing regions of Australia*. Aust. J. Grape Wine Res. Do:10.1111/j.1755-0238.2010.00100.x.

divided Region I into a Region Ia, for early ripening cultivars, mainly hybrids, and Region Ib for early ripening cultivars, mainly *V. vinifera* (Table 2).

Our model (Figure 10) indicates the highest GDD values for North Carolina occur on the coastal plain and decrease westward, with intermediate values in the eastern and western Piedmont regions, and the lowest values on the Blue Ridge plateau. All five Winkler regions occur in North Carolina, with a total range Of 1237 – 4900 GDD units. The range of GDD units for active North Carolina vineyard sites is 1939 – 4722.

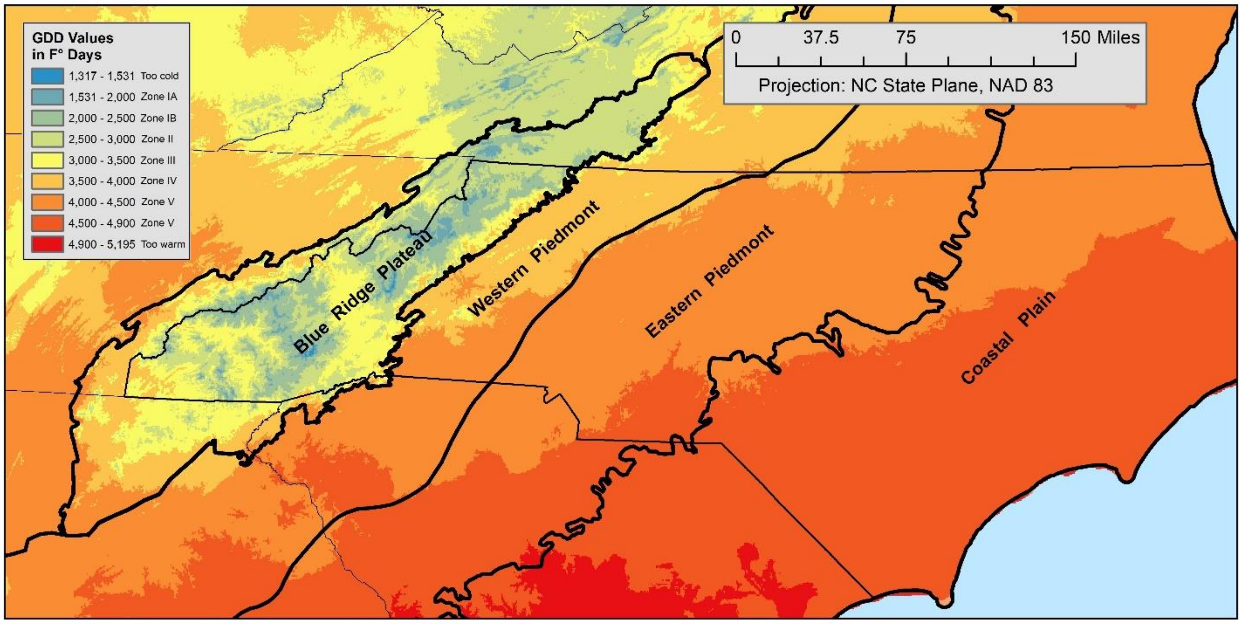

Figure 10. Growing Degree Day zonation. Temperature data from the Prism Climate Group gridded 1991-2020 climate normals.

The geographic areas in which these vineyards are located, including AVAs and non-AVA areas, are found in all defined GDD zones (Table 1). Zone I (below 2500 GDD) was found exclusively in the Appalachian High Country AVA and the very highest peaks of the Blue Ridge plateau. The GDDs of zone I can be compared to those of winegrowing regions of the Rhine Valley or the Champagne region of France.

The majority of vineyards in NC are in zones III, IV, and V. Vineyards of zone III are in higher elevations of the Crest of the Blue Ridge Henderson County AVA, as well as in the Upper Hiwassee Highlands. This zone can be compared with growing regions of the Rhone Valley. Vineyards in zone IV and V are in the Yadkin Valley, Swan Creek, and Haw River AVAs, as well as most Piedmont vineyards outside of AVAs. The average GDD of Zone IV can be compared with regions in Spain and Italy. Approximately 54% of investigated vineyards were in regions that accumulate an average of 4000 or greater GDD (zone V) units, which surprisingly includes the vineyards in the proposed Tryon Foothills AVA, which is located at the base of the Blue Ridge escarpment. The GDD accumulation in this region can be compared to winegrowing regions in North Africa.

Though it is interesting to make the above comparisons with international viticulture areas, it is important to keep in mind that the Winkler index was developed for the Mediterranean and semi-arid climates of California, and not for the warm and mixed humid climate of North Carolina. Therefore, GDD zone analysis should be seen as one of many climatic characteristics that contributes to the overall *terroir* conditions of North Carolina. While the GDD index might recommend certain cultivars for optimal ripening, North Carolina's low winter temperatures, late spring frosts, humid climate and high average annual precipitation can be highly limiting factors for sustainable vineyards. For example, cultivars such as Riesling, Pinot Noir, Pinot Grigio, Zinfandel, Malbec or even Chardonnay are recommended for Zones I and II. Of these, Riesling, Malbec, and Chardonnay are found frequently in North Carolina vineyards in GDD zones IB to V. All areas of western North Carolina can be affected by frequent late spring frost and freeze events, which make the growing of early bud-breaking cultivars (e.g., Chardonnay) challenging. Summer humidity and heavy rainfalls facilitate the spread of foliar and fruit diseases and hinder development of microclimates under the canopies. That is an especial problem in cultivars with tight clusters and thin berry skins (e.g., Riesling). Such cultivars are usually harvested before desired maturity, because of extensive deterioration in the vineyard. On the other hand, cultivars such as Cabernet Franc and Merlot are not recommended for Zones IV and V but produce well in those zones in North Carolina. Cultivars such as Montepulciano or Sangiovese are challenging but can be successfully grown in the state's Zones IV and V.

Spring and Fall Frost Indices: Unexpected late spring or early fall frost events are a great danger to winegrapes, especially when bud break,[25] veraison,[26] or harvest occurs during frost-prone periods. Winegrowers should therefore consider the risk of frosts when selecting a vineyard site and in choosing specific cultivars for a site.

Our model utilized the NCDC 1981-2010 climate normals from the 284 weather-monitoring stations in Figure 6 and is based on the average dates for the last spring frost event, and the first fall frost event.[27] Using an Inverse Distance Weighted interpolation, we converted the discrete data points into continuous field data models (Figures 12 and 13). The colored areas on the map represent mean ranges of dates in which spring or fall frost events can be expected. In the low elevations of the coastal plain the latest spring frost events can be expected from March 2 to April 7, in the eastern Piedmont from March 29 to April 25, in the western Piedmont from March 29 to April 25, and on the Blue Ridge plateau from April 16 to May 23. The first fall frost on the coastal plain can be expected from October 25 to December 13, in the eastern Piedmont from October 19 to November 8, in the western Piedmont from October 19 to November 15 and on the Blue Ridge plateau from September 27 to October 25.

Climate Change and Viticulture in NC

Establishment of a vineyard and winery is often a multi-million-dollar enterprise that requires a minimum vision of two decades into the future. Climate change therefore plays a major role in today's selection of grape cultivars and vineyard sites that will withstand rapidly changing weather patterns that are predicted

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[25] Bud Break typically begins when the mean daily temperature in the vineyard reaches or exceeds 50°F. At that point, buds on the vines begin to swell, and shoots and leaves emerge.

[26] Veraison is the onset of grape ripening or the last stage in the vine growth cycle. The berries begin to change physically and chemically. The skins change color, the berries soften, flavor compounds begin to develop, sugar content increases, and acid level decreases. Veraison is a sign that harvest time is near.

[27] The average date for these events as published in the NOAA datasets is the so-called "50% probability date for a 32°F frost event."

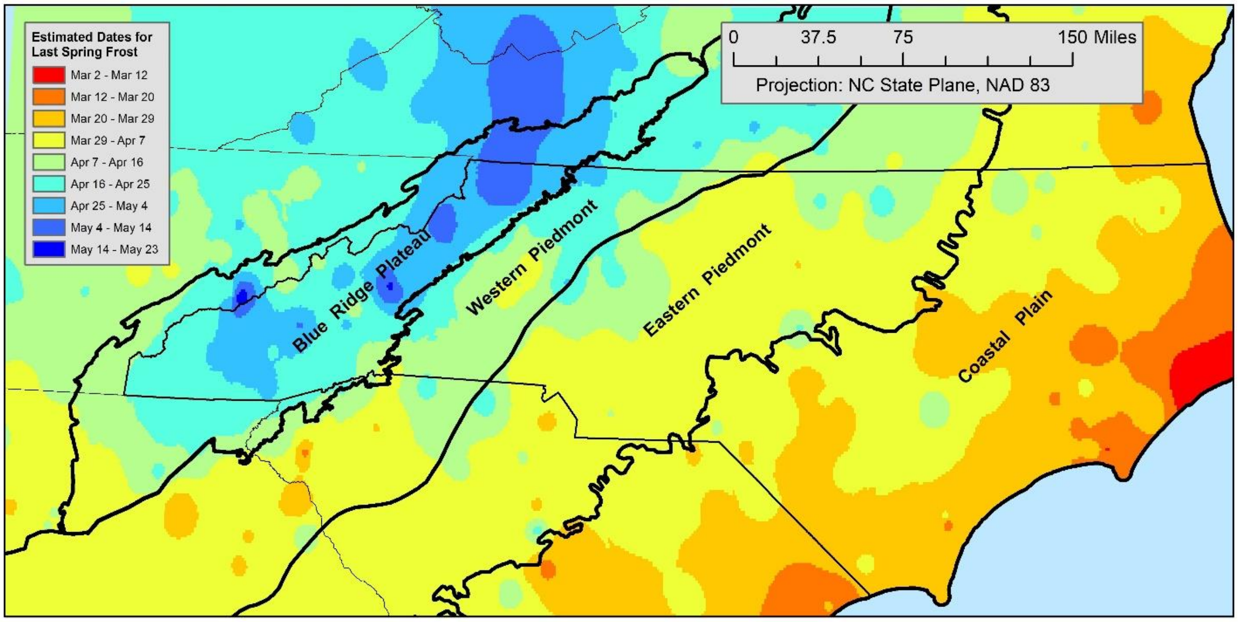

Figure 12. Estimated dates for last spring frost event based on 32°F. Modeled using the 284 NCEI weather stations shown in Figure 6.

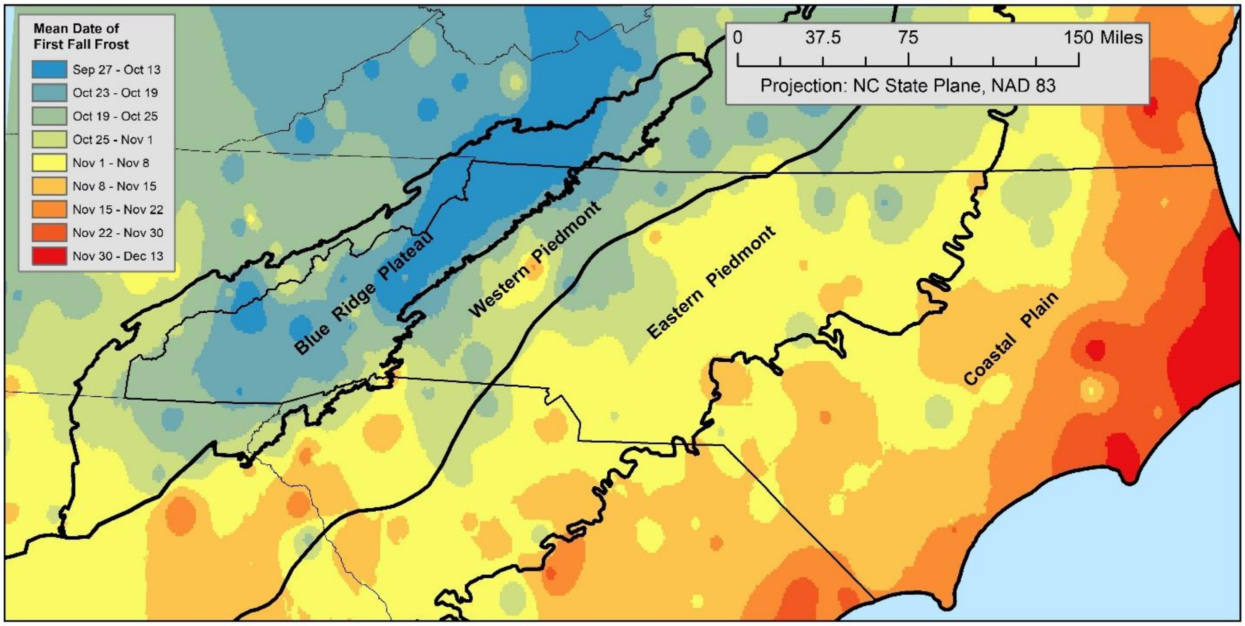

Figure 13. Estimated dates for first fall frost event based on 32°F. Modeled using the 284 NCEI weather stations shown in Figure 6.

for the future in the southeastern US. The Fourth National Climate Assessment projects an increase of warmer nights (temperatures greater than 75°F) in most parts of NC to 30-50 nights per year by 2050, a drastic change of 100-200% to the current 30-year average.[28] At the same time, increased heavy rainfalls will cause more flooding and erosion of vineyard soils, an already existing problem in the Southeast.[29]

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[28] https://nca2018.globalchange.gov/

[29] Wolf, T., Smith, A. and G. Gisie. 2020: *Floor Management Strategies for Virginia Vineyards*. Virginia Cooperative Extension.

Increased rainfalls will also hinder optimal vineyard management and spray programs, most likely increasing severity of pathogens in vineyards across North Carolina. By the end of the 21st century, a shift of plant hardiness zones is projected, with most of the Piedmont and southern foothills of the state shifting into plant hardiness zone 8b (currently 8a). This shift is projected for the whole state of NC, including the mountain regions.[30] Under this scenario, vector-borne diseases for humans as well as for plants (such as Pierce's Disease) will be more common and be found in areas which had low incidence in the past. Extreme weather events such as tropical storms, flooding, and droughts are expected to increase in the coming 30 years in the southeast. The number of heavy rainfalls, spring frosts and droughts in NC has been problematic for vineyards already in the recent past and has widely affected the grape-growing industry, especially in the past 5 years. It is unclear what effects those changes will have on grape maturity and grapevine performance in North Carolina. However, winegrape varieties already struggling to perform under current humid, hot, and wet conditions will likely be problematic for new vineyard plantings.

Winegrape Cultivar Recommendations for NC

The choice of cultivars is always a complex decision. A profitable North Carolina vineyard needs to be established based on climatic conditions, as well as a sound business model and attention to customer preferences. Temperature aspects discussed in this study are only a few among many factors in this very complex equation, and as mentioned above, other climatic factors such as precipitation, humidity, and diurnal temperature range will affect cultivar performance as well. In Table 3, we have followed Poling and Spayd (2015)[34] and developed an overview of recommended, more challenging cultivars, and in Table 4 we present cultivars not recommended for North Carolina. These recommendations are certainly not complete, but we believe that we cover most of the commonly used winegrape cultivars. We do not cover muscadine cultivars in this list, but we believe that under current climate projections, muscadine production will become feasible in areas of North Carolina that were historically too cool. Cultivars that are thin-skinned, tight-clustered or not very cold hardy are not recommended for any growing region in North Carolina. Those encompass most Italian and Spanish *V. vinifera* cultivars, especially Pinot Grigio and Pinot Noir. While there are small plantings of both currently in North Carolina, those cultivars require well selected sites and intensive management and are at high risk for severe cold damage. Less well-known *Vitis vinifera* cultivars such as Mourvèdre, Petit Verdot, or Petit Manseng perform well in North Carolina due to late bud break, mid-season ripening and loose cluster structure. French-American hybrids generally have a higher chance of success in North Carolina. Cultivars such as Chambourcin, Vidal Blanc, Traminette, and Chardonel are known throughout the North Carolina industry as cultivars with good growing and ripening qualities and are increasingly used in all winegrape growing regions in the state. Cultivars such as Frontenac and Seyval Blanc are receiving increasing interest throughout the North Carolina grape and wine community.

Another challenging and widely grown cultivar in North Carolina is Riesling, which is commonly harvested in NC based on rot incidence and not on berry chemistry, often resulting in low yields and low berry quality. Newer hybrid Pierce's Disease resistant winegrape cultivars, released in 2019 by the University of California-Davis breeding program, could have potential for the future viticulture industry in North

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[30] Carter, L., A. Terando, K. Dow, K. Hiers, K.E. Kunkel, A. Lascurain, D. Marcy, M. Osland, and P. Schramm, 2018: Southeast. In Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II [Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 743–808. doi: 10.7930/NCA4.2018.CH19

[34] Poling, B. and Spayd, S. 2015. *The North Carolina Winegrape Grower's Guide*. 196pp. North Carolina Cooperative Extension. https://content.ces.ncsu.edu/north-carolina-winegrape-growers-guide

Carolina and are presently being tested in a trial in the Yadkin Valley AVA. The red cultivars are Camminare Noir, Paseante Noir, Errante Noir, and the whites are Ambulo Blanc and Caminante Blanc. Other hybrid wine-grape cultivars, such as Enchantment and Opportunity, released in 2016 by the University of Arkansas breeding program might have potential, but are not widely planted in North Carolina at this time.

Cultivars	Color	Harvest Season	Yield Potential	Zone
Vitis vinifera cultivars. Also called European wine-grapes. Cultivars are based on crossings between European grapevines. *V. vinifera* cultivars are commonly grafted to American rootstocks to control grape phylloxera, nematodes, and vigor.				
Cabernet Franc	Red	Late	High	II-V
Viognier	White	Early	Moderate	I-III
Merlot	Red	Mid	High	III-IV
Syrah	Red	Late	High	III-IV
Sangiovese	Red	Late	High	IV-V
Montepulciano	Red	Mid-Late	Moderate	IV-V
Petit Verdot	Red	Late	Very High	II-V
Petit Manseng	White	Late	High	I-IV
French-American hybrids. Cultivars that derived from crosses between *V. vinifera* and American genetics. Less popular but good wine making qualities and better adapted.				
Chambourcin	Red	Mid-Late	Very High	II-V
Traminette	White	Mid	Moderate-High	I-IV
Chardonel	White	Early	High	I-IV
Vidal Blanc	White	Early	High	I-IV
Seyval Blanc	White	Early	High	II-V
Native Ameican cultivars. Grapes of native American origin that are not Muscadine (*Vitis rotundifolia*) grapevines. Mainly based on *V. labruscana* or *V. aestivalis* .				
Norton-Cynthiana	Red	Late	Low	I-III
Niagara	White	Mid	High	I-III
Catawba	Red	Mid	High	I-III
Sunbelt	Red	Mid	High	I-III

Table 3. Recommended cultivars for North Carolina.

Emergence of the Appalachian High Country AVA is an interesting and surprising development due to the high elevation of the terrain with its shorter growing season, and higher incidence of late spring and early fall frosts. Proper site selection is extremely important in this region for successful establishment of a vineyard. Sites should be located in rain-shadows, provide good airflow and have sufficient sun exposure, combined with appropriate choice of cultivars to increase potential for success. Development in recent years of very cold-hardy cultivars for use in the upper Midwest and New England has opened the possibility of growing grapes routinely at elevations exceeding 3000 feet. Though a number of early pioneering vineyards in the Appalachian High Country have permanently closed, there is an emerging group of younger entrepreneurs and investors that is taking up the challenges of opening this new viticultural province.

Cultivars	Color	Harvest Season	Yield Potential	Zone	Challenges
Vitis vinifera cultivars. Also called European wine-grapes. Cultivars are based on crossings between European grapevines. *V. vinifera* cultivars are commonly grafted to American rootstocks to control grape phylloxera, nematodes, and vigor.					
Chardonnay	White	Early	Moderate	II-IV	Frost damage
Cabernet Sauvignon	Red	Very Late	High	III-IV	Ripening & vigor
Riesling	White	Early	Moderate	I-IV	Bunch rot
Grüner Veltliner	Wwhite	Mid	Moderate	I-III	Bunch rot
Gewürztraminer	White	Mid	Moderate	I-III	Bunch rot
Sauvignon Blanc	White	Mid	Moderate	III-IV	Bunch rot
Tannat	Red	Mid	Moderate	III-IV	Low demand
French-American hybrids. Cultivars that derived from crosses between *V. vinifera* and American genetics. Less popular but good wine making qualities and better adapted.					
Blanc du Bois	White	Mid-Late	High	IV-V	Low demand
Black Spanish (Lenoir)	Red	Early	High	IV-V	Ripening
Native Ameican cultivars. Grapes of native American origin that are not Muscadine (*Vitis rotundifolia*) grpevines. Mostky based on *V. labruscana* or *V. aestivalis* .					
Concord	Red	Early	High	III-V	Uneven ripening

Table 4. Wine-grape cultivars that are challenging in North Carolina.

Conclusions

North Carolina has a wide range of climate zones and provides the potential environment for a wide variety of grape cultivars. Growing season lengths in the state will accommodate very early to very late-ripening grape varieties. Our mean growing season temperatures span the range in which quality wine production occurs worldwide. Heat accumulation as measured by Growing Degree Days cover the entire spectrum of the Winkler Regions/GDD Zones. However, all areas of the state suffer from the risks due to late spring and early fall frost events, heavy and frequent rain falls, droughts that promote early bud break, and high humidity in summer with resulting year-round disease pressure. And on top of all these limitations, there are the catastrophic weather events such as hurricanes and tornadoes, and concomitant landslides.

We have stressed the relationship of climate to topography and feel there is a strong correlation of winegrape varieties to North Carolina's four major physiographic regions. Climate change is likely to increase average length of the growing season, mean growing season temperature and GDD values, and parts of North Carolina's mountains will become more interesting for future cultivation of *vinifera* and muscadines. The complex geomorphology and climate conditions of western North Carolina (especially the western Piedmont and Blue Ridge plateau regions) provide especial opportunities for growth of many different wine-grapes. Cultivars such as Chardonnay, Merlot, Malbec and Riesling are grown in larger quantities in western North Carolina but are challenging to manage. Other European cultivars, such as Petit Verdot, or French-American hybrids such as Chambourcin, Vidal Blanc, Chardonel or Seyval Blanc, have become increasingly prominent in the western part of the state, due to their better performance and less intensive management. Moreover, western NC has significant plantings of native American cultivars such as Norton-Cynthiana.

When using the information in this study, it is important that the reader be aware of its imperfections. Though we have tried to be as complete as time would allow, we know there are vineyards missing and some vineyards that are included may now be out of business. We certainly have missed some cultivars that are presently under cultivation, and may have included others that are no longer planted.

A second caveat concerns our use of computer models. These depend on many assumptions and interpolation of values between widely-spaced data points. Though they may suggest important trends, models are never totally correct. The complex topography of North Carolina presents myriad geomorphic situations that hide subtle climate conditions that are not detected at the resolution of today's digital elevation models and gridded climate data. High resolution lidar that the state is presently collecting can be a game-changer, if the data is made easily available to the public for research.

Our primary goal in this study has been to provide a preliminary framework of North Carolina's winegrape geography. To make proper recommendations for future cultivars in North Carolina, it is important to know which cultivars are being grown at the present time and how successful these are in the individual vineyard sites. Though it may not be perfect, our analysis is a beginning towards this goal. Major improvement will be the addition of digital vineyard blocks, acreages of each cultivar type in those blocks, and an assessment of the success of individual cultivars. These enhancements will give a truer accounting of the importance of the various cultivars in North Carolina's viticultural future.

APPENDIX 1: Alphabetical listing of cultivars in NC Viticulture Suitability Zones

Key to Abbreviations		
NC Viticulture Suitability Zones		**Abbreviation**
		Zone 1
		Zone 2
		Zone 3
		Zone 4
Grape Variety	*Vitis vinifera*	VV
	Hybrid	H
	Muscadine	M
	American Native	AN

Cultivars	**Frequency**	**Variety**	**Zone 1**	**Zone 2**	**Zone 3**	**Zone 4**
Aglianico	1	VV	1			
Albariño	2	VV			2	
Albemarle	1	M	1			
Arandell	3	VV			3	
Aromella	1	H			1	
Assyrtiko	1	VV	1			
Ayapi	1	VV	1			
Baco Noir	1	H			1	
Barbera	3	VV		1	2	
Black Beauty	1	M		1		
Cabernet Franc	51	VV	1	15	33	2
Cabernet Sauvignon	48	VV	1	16	29	2
Carignan	1	VV		1		
Carlos	38	M	22	12	4	
Carménère	1	VV		1		
Catawba	7	H		1	4	2
Cayuga White	4	H			4	
Chambourcin	34	H		13	20	1
Chardonel	6	H	1	3	2	
Chardonnay	48	VV		15	31	2
Cinsault	1	VV		1		
Concord	4	AN		1	1	2
Corot Noir	4	H			3	1
Cowart	3	M		2	1	
Crimson Cabernet	1	H		1		
Darlene	3	M	2	1		
Dixie Red	3	M		1	2	
Doreen	5	M	2	2	1	
Dornfelder	1	VV			1	
Farrer	1	M		1		
Fleurtai	1	VV		1		
Frontenac	1	H				1
Frontenac Gris	1	H				1
Fry (unspecified)	6	M	1	4	1	
Fry (Black)	1	M	1			
Fry (Early)	2	M	2			
Fry (Late)	2	M	2			
Fry (White)	2	M	2			
Golden Muscat	1	H				1
Granny Val	1	M	1			
Grenache	4	VV		3	1	

APPENDIX 1: Alphabetical listing of cultivars in NC Viticulture Suitability Zones

Cultivars	Frequency	Variety	Zone 1	Zone 2	Zone 3	Zone 4
Grüner Veltliner	4	VV			3	1
Hall	1	M	1			
Hunt	2	M		1	1	
Ison	6	M	2	3	1	
Itasca	2	H		1		1
Jumbo	4	M		3	1	
Katuah Muscadine	1	M			1	
Katuah Scuppernong	1	M			1	
La Crosse	1	H				1
Landot Noir	2	H			1	1
Lane	6	M	5	1		
Lemberger	2	VV			2	
Léon Millot	1	VV			1	
Magnolia	13	M	6	6	1	
Malbec	11	VV		6	5	
Malvasia Bianca	2	VV	1		1	
Marechal Foch	4	H				4
Marquette	5	H			3	2
Marsanne	1	H			1	
Mavron	1	VV	1			
Merlot	53	VV		19	34	
Montepulciano	6	VV		2	4	
Moschofilera	2	VV	1		1	
Mourvedre	3	VV		2	1	
Muscadine (unspecified)	14	M	2	10	2	
Muscat	2	VV		1	1	
Muscat Canelli	2	VV			2	
Muscat Ottonel	1	VV			1	
Nebbiolo	3	VV	1	1	1	
Negroamaro	2	VV	1		1	
Nesbitt	15	M	8	5	2	
Niagara	1	H			1	
Noble	37	M	18	14	5	
Noiret	2	H				2
Norton-Cynthiana	16	AN	1	3	11	1
Pam	4	M	1	2	1	
Paulk	4	M	4			
Petit Manseng	12	VV		2	10	
Petit Pearl	1	H				1
Petit Sirah	1	VV		1		
Petit Verdot	31	VV		10	20	1
Pinot Grigio/Gris	14	VV		7	6	1
Pinot Noir	1	VV				1
Pinotage	1	VV			1	
Prairie Star	1	H			1	
Ravat 34	1	H			1	
Regent	4	H		1	3	
Ribolla Gialla	1	VV	1			
Riesling	21	VV		4	15	2
Rkatsiteli	1	VV		1		
Robert S. Lee	1	M	1			
Roditis	1	VV	1			

APPENDIX 1: Alphabetical listing of cultivars in NC Viticulture Suitability Zones

Cultivars	Frequency	Variety	Zone 1	Zone 2	Zone 3	Zone 4
Roussanne	1	VV		1		
Sagrantino	1	VV			1	
Sangiovese	13	VV		4	8	1
Saperavi	1	VV			1	
Sauvignon Blanc	10	VV		5	5	
Scarlet	3	M		3		
Scuppernong	6	M	2	3	1	
Semillon	1	VV			1	
Seyval Blanc	16	H		2	8	6
St. Croix	2	H			1	1
Soreli	1	H		1		
Southern Home	2	M	1	1		
Steuben	2	AH				2
Sugargate	1	M		1		
Summit	5	M	2	2	1	
Sunbelt	1	M	1			
Supreme	11	M	6	4	1	
Sweet Jenny	2	M		2		
Syrah	15	VV	1	8	6	
Tannat	4	VV		1	3	
Tara	12	M	5	5	2	
Tempranillo	3	VV	1		2	
Thiakon	1	VV	1			
Touriga Nacional	1	VV			1	
Traminette	24	H	1	6	13	4
Triumph	12	M	8	3	1	
Valvin Muscat	1	AH		1		
Vermentino	4	VV		2	2	
Vidal Blanc	12	VV		3	6	3
Villard Noir	1	H			1	
Viognier	23	VV	1	11	11	
Welder	1	M		1		
Xynesteri	1	VV		1		
Zinfandel	4	VV			4	

APPENDIX 2: Alphabetical listing of cultivars in NC physiographic provinces

Key to Abbreviations		
Physiographic Provinces		**Abbreviation**
Coastal Plain		CP
Eastern Piedmont		EP
Western Piedmont		WP
Blue Ridge Plateau		BRP
Blue Ridge Escarpment		BRE
Grape Varieties	*Vitis vinifera*	VV
	Hybrid	H
	Muscadine	M
	American Native	AN

Cultivars	Frequency	Variety	CP	EP	WP	BRP	BRE
Aglianico	1	VV		1			
Albariño	2	VV			2		
Albemarle	1	M		1			
Arandell	3	VV			3		
Aromella	1	H				1	
Assyrtiko	1	VV		1			
Ayapi	1	VV		1			
Baco Noir	1	H				1	1
Barbera	3	VV			3		
Black Beauty	1	M		1			
Cabernet Franc	51	VV	1	9	27	14	3
Cabernet Sauvignon	48	VV	1	9	28	10	
Carignan	1	VV			1		
Carlos	38	M	16	18	4		
Carménère	1	VV		1			
Catawba	7	H		1		6	3
Cayuga White	4	H			3	1	
Chambourcin	34	H		8	20	6	
Chardonel	6	H	1	2	1	2	1
Chardonnay	48	VV		9	30	9	
Cinsault	1	VV			1		
Concord	4	AN		1		3	2
Corot Noir	4	H			3	1	
Cowart	3	M		2	1		
Crimson Cabernet	1	H		1			
Darlene	3	M		3			
Dixie Red	3	M		1	2		
Doreen	5	M	1	3	1		
Dornfelder	1	VV				1	1
Farrer	1	M		1			
Fleurtai	1	VV		1			
Frontenac	1	H				1	1
Frontenac Gris	1	H				1	1
Fry (unspecified)	6	M	1	4	1		
Fry (Black)	1	M	1				
Fry (Early)	2	M		2			
Fry (Late)	2	M	1	1			
Fry (White)	2	M	2				
Golden Muscat	1	H			1	1	
Granny Val	1	M	1				
Grenache	4	VV		2	2		
Grüner Veltliner	5	VV				5	1

APPENDIX 2: Alphabetical listing of cultivars in NC physiographic provinces

Cultivars	Frequency	Variety	CP	EP	WP	BRP	BRE
Hall	1	M	1				
Hunt	2	M		1	1		
Ison	6	M	1	4	1		
Itasca	2	H		1		1	1
Jumbo	4	M		3	1		
Katuah Muscadine	1	M				1	
Katuah Scuppernong	1	M				1	
La Crosse	1	H				1	1
Landot Noir	2	H			1	1	
Lane	6	M	4	1	1		
Lemberger	2	VV				2	
Léon Millot	1	VV				1	1
Magnolia	13	M	2	10	1		
Malbec	11	VV		3	7	1	
Malvasia Bianca	2	VV		1		1	
Marechal Foch	4	H				4	
Marquette	5	H			1	4	1
Marsanne	1	H			1		
Mavron	1	VV		1			
Merlot	53	VV		10	36	7	
Montepulciano	6	VV		2	3	1	
Moschofilera	1	VV		1	1		
Mourvedre	3	VV		1	2		
Muscadine (unsp.)	14	M	1	8	4	1	
Muscat	2	VV		1	1		
Muscat Canelli	2	VV			2		
Muscat Ottonel	1	VV				1	1
Nebbiolo	3	VV		2	1		
Negroamaro	2	VV		1	1		
Nesbitt	15	M	5	7	3		
Niagara	1	H			1		
Noble	37	M	12	20	5		
Noiret	2	H				2	
Norton-Cynthiana	16	AN	1	3	6	6	1
Pam	4	M	1	2	1		
Paulk	4	M	3	1			
Petit Manseng	12	VV		1	8	3	
Petit Pearl	1	H				1	1
Petit Sirah	1	VV		1			
Petit Verdot	31	VV		5	20	6	1
Pinot Grigio/Gris	14	VV		5	7	2	
Pinot Noir	1	VV				1	
Pinotage	1	VV				1	1
Prairie Star	1	H			1		
Ravat 34	1	H				1	
Regent	4	H		1	1	2	
Ribolla Gialla	1	VV		1			
Riesling	21	VV		2	8	11	1
Rkatsiteli	1	VV		1			
Robert S. Lee	1	M	1				
Roditis	1	VV		1			
Roussanne	1	VV		1			
Sagrantino	1	VV			1		
Sangiovese	13	VV		4	7	2	

APPENDIX 2: Alphabetical listing of cultivars in NC physiographic provinces

Cultivars	Frequency	Variety	CP	EP	WP	BRP	BRE
Saperavi	1	VV				1	
Sauvignon Blanc	10	VV		3	5	2	
Scarlet	3	M		3			
Scuppernong	6	M	2	2	2		
Semillon	1	VV			1		
Seyval Blanc	16	H		2	3	11	2
St. Croix	2	H			1	1	
Soreli	1	H		1			
Southern Home	2	M	1	1			
Steuben	2	H				2	
Sugargate	1	M		1			
Summit	5	M	1	3	1		
Sunbelt	1	M		1			
Supreme	11	M	5	4	2		
Sweet Jenny	2	M		2			
Syrah	15	VV	1	5	9		
Tannat	4	VV		1	3		
Tara	12	M	4	5	3		
Tempranillo	3	VV	1		2		
Thiakon	1	VV		1			
Touriga Nacional	1	VV			1		
Traminette	24	H	1	4	13	6	4
Triumph	12	M	6	4	2		
Valvin Muscat	1	H			1		
Vermentino	4	VV		2	2		
Vidal Blanc	12	VV		2	1	9	3
Villard Noir	1	FAH				1	
Viognier	23	VV	1	7	12	3	
Welder	1	M		1			
Xynesteri	1	VV		1			
Zinfandel	4	VV			2	2	

APPENDIX 3: Alphabetical listing of cultivars in American Viticultural Areas

<table>
<tr><th colspan="3">Key to Abbreviations</th></tr>
<tr><th colspan="2">AVA Name</th><th>Abbreviation</th></tr>
<tr><td colspan="2">Yadkin Valley</td><td>YV</td></tr>
<tr><td colspan="2">Swan Creek</td><td>SC</td></tr>
<tr><td colspan="2">Appalachian High Country</td><td>AHC</td></tr>
<tr><td colspan="2">Crest of the Blue Ridge Henderson County</td><td>CBRHC</td></tr>
<tr><td colspan="2">Tryon Foothills (proposed AVA)</td><td>TF</td></tr>
<tr><td colspan="2">Upper Hiwassee Highlands</td><td>UHH</td></tr>
<tr><td colspan="2">Dahlonega Plateau</td><td>DP</td></tr>
<tr><td colspan="2">Haw River</td><td>HR</td></tr>
<tr><td rowspan="4">Grape Varieties</td><td><i>Vitis vinifera</i></td><td>VV</td></tr>
<tr><td>Hybrid</td><td>H</td></tr>
<tr><td>Muscadine</td><td>M</td></tr>
<tr><td>American Native</td><td>AN</td></tr>
</table>

Cultivars	Frequency	Variety	YV	SC	AHC	CBRHC	TF	UHH	DP	HR
Albariño	3	VV	1					1	1	
Arandell	3	VV	3	1						
Aromella	1	H						1		
Baco Noir	1	H				1				
Barbera	3	VV	3							
Black Beauty	1	M								1
Cabernet Franc	47	VV	21	3	1	8	3	6	3	2
Cabernet Sauvignon	46	VV	22	3	2	5	5	3	4	2
Carignan	1	VV	1							
Carlos	4	M	2							2
Catawba	6	H			2	1		3		
Cayuga White	3	H	3	1						
Chambourcin	31	H	17	3	1	1	1	7	2	2
Chardonel	9	H	1			1		4	1	2
Chardonnay	49	VV	26	5	1	5	3	3	5	1
Cinsault	1	VV	1							
Concord	3	AN			2			1		
Corot Noir	3	H	2	1	1					
Cowart	1	M								1
Crimson Cabernet	1	H								1
Darlene	1	M								1
Doreen	1	M	1							
Dornfelder	1	VV				1				
Frontenac	1	H			1					
Frontenac Gris	1	H			1					
Fry (unspecified)	2	M								2
Golden Muscat	1	H			1					
Greco di Tufo	1	VV							1	
Grenache	4	VV	4							
Grüner Veltliner	6	VV				5		1		
Ison	1	M								1
Itasca	1	H			1					
Jumbo	2	M								2
La Crosse	1	H			1					
Landot Noir	1	H			1					
Lemberger	2	VV				2				
Léon Millot	1	VV				1				
Magnolia	2	M								2
Malbec	12	VV	6			1	2		3	
Malvasia Bianca	1	VV				1				
Marechal Foch	4	H			4					
Marquette	3	H			2			1		

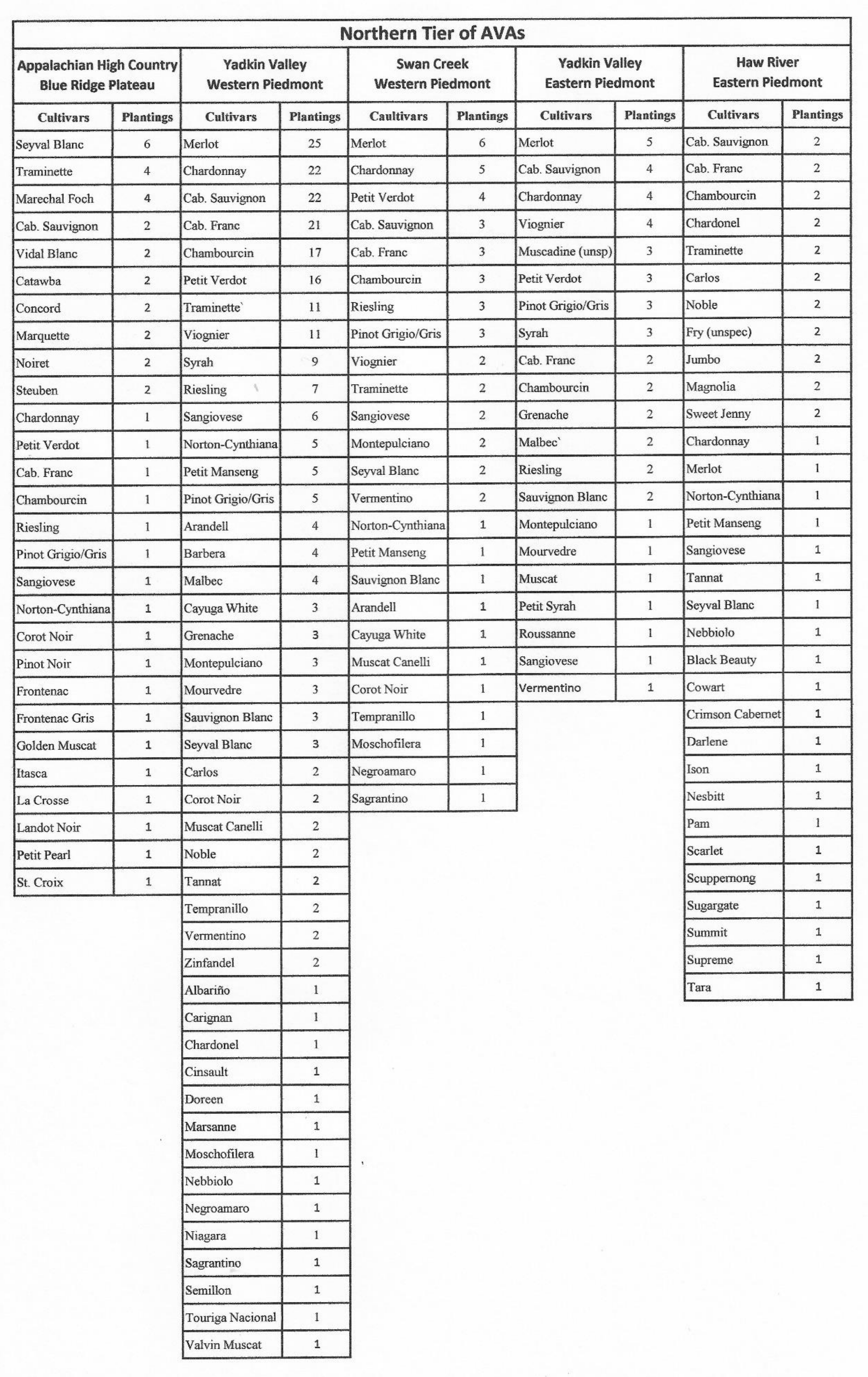
APPENDIX 3: Alphabetical listing of cultivars in American Viticultural Areas

Cultivars	Frequency	Variety	YV	SC	AHC	CBRHC	TF	UHH	DP	HR
Marsanne	2	H	1						1	
Merlot	48	VV	30	6		6	5	1	5	1
Montepulciano	4	VV	4	2						
Moschofilera	1	VV	1	1						
Mourvedre	4	VV	3						1	
Muscadine (unspecified)	5	M	3				1	1		
Muscat	3	VV					1		2	
Muscat Canelli	3	VV	2	1					1	
Muscat Ottonel	1	VV				1				
Nebbiolo	3	VV	1						1	1
Negroamaro	1	VV	1	1						
Nesbitt	1	M								1
Niagara	1	H	1							
Noble	4	M	2							2
Noiret	2	H			2					
Norton-Cynthiana	17	AN	5	1	1	2		5	3	1
Pam	1	M								1
Petit Manseng	12	VV	5	1		1	2	1	2	1
Petit Pearl	1	H			1					
Petit Sirah	2	VV	1						1	
Petit Verdot	27	VV	16	4	1	4	3	1	2	
Pinot Blanc	1	VV							1	
Pinot Grigio/Gris	12	VV	8	3	1		1	2		
Pinot Meunier	1	VV							1	
Pinot Noir	3	VV			1				2	
Pinotage	1	VV				1				
Ravat 34	1	H						1		
Regent	2	H				1		1		
Riesling	23	VV	9	3	1	6		4		
Roussanne	2	VV	1						1	
Sagrantino	1	VV	1	1						
Sangiovese	12	VV	7	2	1			1	2	1
Saperavi	1	VV				1				
Sauvignon Blanc	11	VV	5	1		2	2		2	
Sauvignon Gris	1	VV							1	
Scarlet	1	M								1
Scuppernong	1	M								1
Semillon	1	VV	1							
Seyval Blanc	19	H	3	2	6			8	1	1
St. Croix	1	H			1					
Steuben	2	H			2					
Sugargate	1	M								1
Summit	1	M								1
Supreme	1	M								1
Sweet Jenny	2	M								2
Symphony	1	VV						1		
Syrah	14	VV	12						2	
Tannat	6	VV	2				1		2	1
Tara	1	M								1
Tempranillo	2	VV	2	1						
Teroldego	1	VV							1	
Touriga Nacional	6	VV	1					1	4	
Traminette	24	H	11	2	4	3		2		2
Valvin Muscat	1	H	1							
Vermentino	3	VV	3	2						
Vidal Blanc	14	VV			2	6		4	2	
Villard Noir	2	H						2		

APPENDIX 3: Alphabetical listing of cultivars in American Viticultural Areas

Cultivars	**Frequency**	**Variety**	**YV**	**SC**	**AHC**	**CBRHC**	**TF**	**UHH**	**DP**	**HR**
Viognier	22	VV	15	2		1	1	1	4	
Zinfandel	4	VV	2			1		1		

APPENDIX 4: Listing of cultivars by frequency of planting in northern tier of AVAs



Northern Tier of AVAs									
Appalachian High Country Blue Ridge Plateau		Yadkin Valley Western Piedmont		Swan Creek Western Piedmont		Yadkin Valley Eastern Piedmont		Haw River Eastern Piedmont	
Cultivars	Plantings	Cultivars	Plantings	Caultivars	Plantings	Cultivars	Plantings	Cultivars	Plantings
Seyval Blanc	6	Merlot	25	Merlot	6	Merlot	5	Cab. Sauvignon	2
Traminette	4	Chardonnay	22	Chardonnay	5	Cab. Sauvignon	4	Cab. Franc	2
Marechal Foch	4	Cab. Sauvignon	22	Petit Verdot	4	Chardonnay	4	Chambourcin	2
Cab. Sauvignon	2	Cab. Franc	21	Cab. Sauvignon	3	Viognier	4	Chardonel	2
Vidal Blanc	2	Chambourcin	17	Cab. Franc	3	Muscadine (unsp)	3	Traminette	2
Catawba	2	Petit Verdot	16	Chambourcin	3	Petit Verdot	3	Carlos	2
Concord	2	Traminette`	11	Riesling	3	Pinot Grigio/Gris	3	Noble	2
Marquette	2	Viognier	11	Pinot Grigio/Gris	3	Syrah	3	Fry (unspec)	2
Noiret	2	Syrah	9	Viognier	2	Cab. Franc	2	Jumbo	2
Steuben	2	Riesling	7	Traminette	2	Chambourcin	2	Magnolia	2
Chardonnay	1	Sangiovese	6	Sangiovese	2	Grenache	2	Sweet Jenny	2
Petit Verdot	1	Norton-Cynthiana	5	Montepulciano	2	Malbec`	2	Chardonnay	1
Cab. Franc	1	Petit Manseng	5	Seyval Blanc	2	Riesling	2	Merlot	1
Chambourcin	1	Pinot Grigio/Gris	5	Vermentino	2	Sauvignon Blanc	2	Norton-Cynthiana	1
Riesling	1	Arandell	4	Norton-Cynthiana	1	Montepulciano	1	Petit Manseng	1
Pinot Grigio/Gris	1	Barbera	4	Petit Manseng	1	Mourvedre	1	Sangiovese	1
Sangiovese	1	Malbec	4	Sauvignon Blanc	1	Muscat	1	Tannat	1
Norton-Cynthiana	1	Cayuga White	3	Arandell	1	Petit Syrah	1	Seyval Blanc	1
Corot Noir	1	Grenache	3	Cayuga White	1	Roussanne	1	Nebbiolo	1
Pinot Noir	1	Montepulciano	3	Muscat Canelli	1	Sangiovese	1	Black Beauty	1
Frontenac	1	Mourvedre	3	Corot Noir	1	Vermentino	1	Cowart	1
Frontenac Gris	1	Sauvignon Blanc	3	Tempranillo	1			Crimson Cabernet	1
Golden Muscat	1	Seyval Blanc	3	Moschofilera	1			Darlene	1
Itasca	1	Carlos	2	Negroamaro	1			Ison	1
La Crosse	1	Corot Noir	2	Sagrantino	1			Nesbitt	1
Landot Noir	1	Muscat Canelli	2					Pam	1
Petit Pearl	1	Noble	2					Scarlet	1
St. Croix	1	Tannat	2					Scuppernong	1
		Tempranillo	2					Sugargate	1
		Vermentino	2					Summit	1
		Zinfandel	2					Supreme	1
		Albariño	1					Tara	1
		Carignan	1						
		Chardonel	1						
		Cinsault	1						
		Doreen	1						
		Marsanne	1						
		Moschofilera	1						
		Nebbiolo	1						
		Negroamaro	1						
		Niagara	1						
		Sagrantino	1						
		Semillon	1						
		Touriga Nacional	1						
		Valvin Muscat	1						

APPENDIX 5: Listing of cultivars by frequency of planting in central and southern tiers of AVAs

Central Tier of AVA's				Southern Tier of AVA's			
Crest of the Blue Ridge HC Blue Ridge Plateau		**Tryon Foothills Western Piedmont**		**Upper Hiwassee Highlands Blue Ridge Plateau**		**Dahlonega Plateau Western Piedmont**	
Cultivars	**Plantings**	**Cultivars**	**Plantings**	**Cultivars**	**Plantings**	**Cultivars**	**Plantings**
Cab. Franc	8	Merlot	5	Seyval Blanc	8	Chardonnay	5
Merlot	6	Cab. Sauvignon	5	Chambourcin	7	Merlot	5
Cab. Sauvignon	5	Cab. Franc	3	Cab. Franc	6	Cab. Sauvignon	4
Vidal Blanc	6	Chardonnay	3	Norton-Cynthiana	5	Viognier	4
Riesling	6	Petit Verdot	3	Vidal Blanc	4	Touriga Nacional	4
Chardonnay	5	Sauvignon Blanc	2	Riesling	4	Cab. Franc	3
Petit Verdot	4	Petit Manseng	2	Chardonel	4	Norton-Cynthiana	3
Grüner Veltliner	4	Malbec	2	Cab. Sauvignon	3	Malbec	3
Traminette	3	Chambourcin	1	Chardonnay	3	Chambourcin	2
Norton-Cynthiana	2	Viognier	1	Catawba	3	Vidal Blanc	2
Sauvignon Blanc	2	Pinot Grigio/Gris	1	Pinot Grigio/Gris	2	Petit Verdot	2
Lemberger	2	Muscadine (unsp)	1	Traminette	2	Petit Manseng	2
Catawba	1	Tannat	1	Villard Noir	2	Sangiovese	2
Chambourcin	1	Muscat	1	Merlot	1	Sauvignon Blanc	2
Viognier	1			Petit Verdot	1	Tannat	2
Petit Manseng	1			Petit Manseng	1	Muscat	2
Malbec	1			Viognier	1	Pinot Noir	2
Zinfandel	1			Muscadine (unsp)	1	Syrah	2
Chardonel	1			Grüner Veltliner	1	Seyval Blanc	1
Regent	1			Zinfandel	1	Chardonel	1
Baco Noir	1			Regent	1	Albariño	1
Dornfelder	1			Concord	1	Muscat Canelli	1
Léon Millot	1			Marquette	1	Mourvedre	1
Malvasia Bianca	1			Sangiovese	1	Marsanne	1
Muscat Ottonel	1			Touriga Nacional	1	Nebbiolo	1
Pinotage	1			Albariño	1	Petit Sirah	1
Saperavi	1			Aromella	1	Roussanne	1
				Ravat 34	1	Greco di Tufo	1
				Symphony	1	Pinot Blanc	1
						Pinot Meunier	1
						Sauvignon Gris	1
						Teroldego	1

Stop 1. North Pacolet River Valley, Highway 176, Polk County

Objectives. The purpose of this stop is to observe debris flow impacts from the May 18, 2018 storm and to highlight landslide responses and landslide mapping in Polk County by the North Carolina Geological Survey (NCGS) and Appalachian Landslide Consultants (ALC) in the wake of the storm. Connections between the Blue Ridge Escarpment (BRE), landslides, and thermal belts related to viticulture will also be discussed. This stop description is adapted from Wooten et al., (2019) with information from Bauer et al., 2019a and 2019b. It includes additional information from the completed landslide hazard mapping for Polk County.

Leaders: Rick Wooten,[1] Bart Cattanach,[2] Joseph Forrest[6]

Authors: Rick Wooten[1], Bart Cattanach[2], Jesse Hill[3], Corey Scheip[4], Tommy Douglas[1], David Korte[2], Jennifer Bauer[5], Joseph Forrest[6]

Affiliations: [1]North Carolina Geological Survey (retired), [2]North Carolina Geological Survey,
[3]Eskay Mining Corp., [4]BGC Engineering, [5]Appalachian Landslide Consultants, PLLC. [6]Retired Geologist

Location: Latitude 35.224358°, Longitude -82.284164°, 3161 U.S. Highway 176, Tryon, Polk County, North Carolina, Saluda 7.5minute quadrangle.

Background. A two-year interval of increased landslide activity in western North Carolina began abruptly on May 18, 2018, when a convective storm along the BRE triggered at least 240 debris flows and debris slides that resulted in a fatality, destroyed homes, and severely damaged infrastructure. Shortly after this event, the N.C. General Assembly reinstated funding for the NCGS landslide hazards program. The NCGS and their contractor Appalachian Landslide Consultants, PLLC (ALC) completed landslide hazard mapping in Polk County in February 2021. As of that date the completed Polk County landslide inventory consisted of 920 landslide initiation points, 685 landslide polygons (~2.22 km^2), and 287 undifferentiated landslide deposit polygons (~19.9 km^2).

Geomorphic and Geologic Setting. In Polk County, southwestern North Carolina, past and recent landslide activity is concentrated along the BRE, where there is as much as 400 m of topographic relief and slopes are typically >20° (Figures 1-1, 1-2). Structurally controlled, incised valleys, or reentrants, such as the Green River and North Pacolet River valleys are zones of focused landslide activity on the Escarpment (Wooten et al., 2022a); as they are in other locations in western North Carolina (Wooten et al., 2008a,b; Gillon et al. 2009; Wooten et al, 2016; Hill, 2018; Wooten and Witt, 2018; Wooten et al., 2022b). Western Polk County is located in the eastern slopes of the Columbus Promontory, a landform situated between the Brevard fault zone and the Blue Ridge Escarpment (Figure 1-2). Here the Eastern Continental divide is located up to 20km west of the crest (abrupt, high relief slope break) of the BRE.

Across the valley from Stop 1, the south slopes of Little Warrior Mountain are underlain by late Proterozoic to early Paleozoic metasedimentary and meta-igneous rocks of the lower Tallulah Falls Formation. Originally mapped as the amphibolite of the lower Mill Spring complex by Davis and Yanagihara (1993), these rocks have since been correlated with the lower Tallulah Falls Formation (Bream, 2002; Cattanach, this guidebook). Traverses along several of the scoured 2018 debris flow tracks reveal an interlayered sequence of biotite gneiss-metagraywacke, felsic gneiss, hornblende gneiss and amphibolite. These rocks are within the Mill Spring thrust sheet which overlies rocks of the Sugarloaf Mountain thrust sheet exposed primarily on the south side of the North Pacolet River Valley (Figure 1-3A). Rocks within the

Stop 1. North Pacolet River Valley, Highway 176, Polk County

Sugarloaf thrust sheet are dominated by biotite gneiss-metagraywacke and schist of the Upper Tallulah Falls Formation

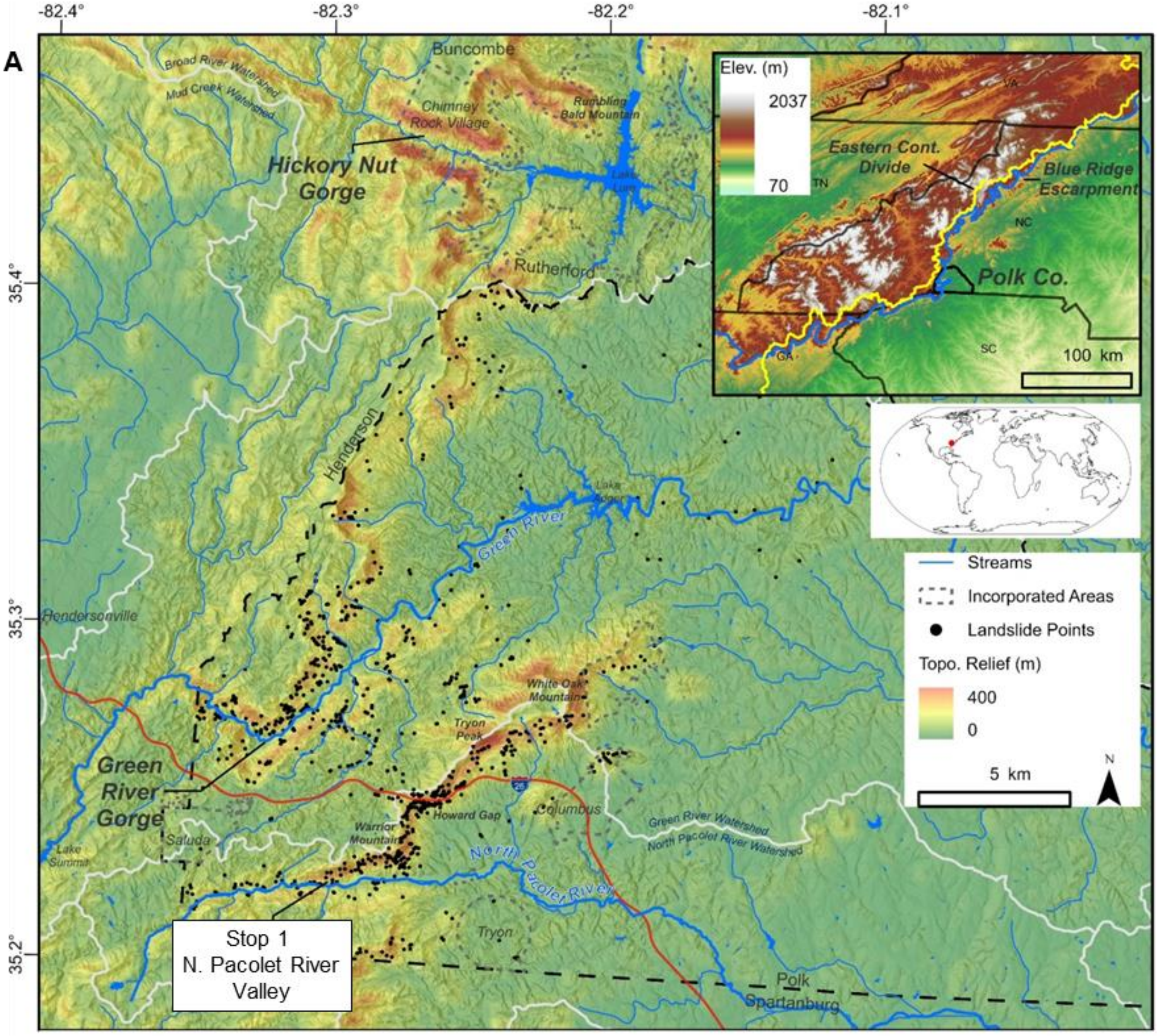


Figure 1-1. Topographic relief map of the Blue Ridge Escarpment (BRE) region of western Polk County and southern Rutherford County, N.C. In this vicinity, the crest (abrupt, high relief slope break) of the BRE is separated from the Eastern Continental Divide by up to 20 km (see inset). The Green River and North Pacolet Rivers incise across the BRE and form reentrants to the mountain front. These high relief zones (up to 400 m local relief) disproportionately contribute to landslide hazards in the region. Adapted from Wooten et al., 2022a).

In this section of the North Pacolet River Valley foliation generally dips at low to moderate angles primarily towards the ENE; however, its undulatory nature results in considerable variation in dip direction (Figure 1-3B). Rose diagrams and lower hemisphere stereonets (contoured poles to planes) show the orientations of joints measured within Polk County, within Polk Co. landslides, and within slides that occurred during the May 2018 storms. These steeply dipping joint sets strike parallel to the W-E-trending Pacolet River Valley and the SW-NE-trending Green River Gorge.

Stop 1. North Pacolet River Valley, Highway 176, Polk County

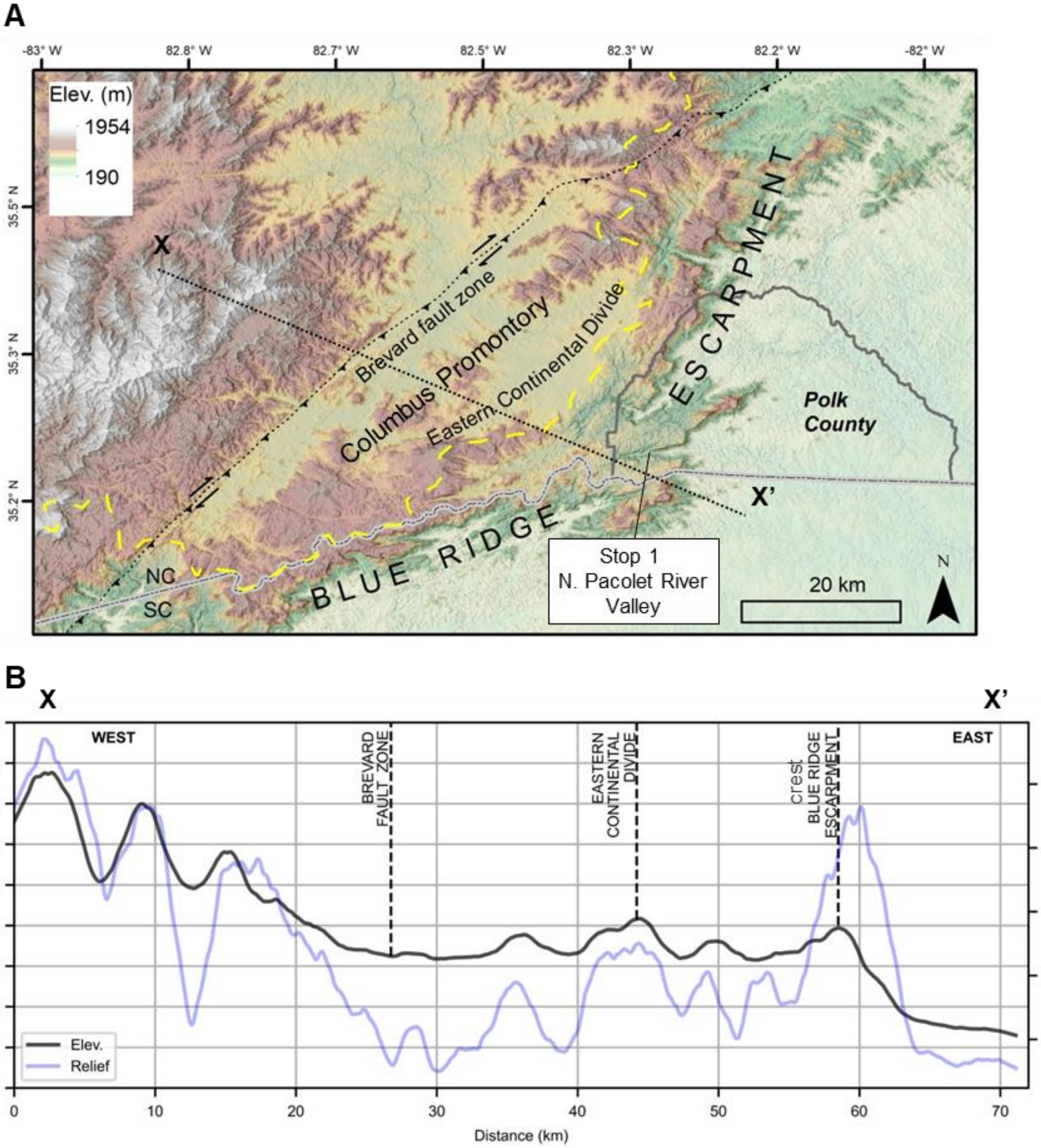


Figure 1-2. A. Map of the Columbus Promontory and the Blue Ridge Escarpment (BRE) near Polk County, NC. Note how the continental divide (yellow line) is west of the BRE crest (abrupt, high relief slope break). **B**. Stacked profiles of elevation and local relief across the Columbus Promontory. Local relief at the BRE is similar to the Blue Ridge Mountains found west of the Brevard Fault Zone. Local relief values were computed for 500m^2 kernels in 3m increments along the profile line. Both profiles were smoothed with a 1 km filter. Adapted from Wooten, et al., 2022a).

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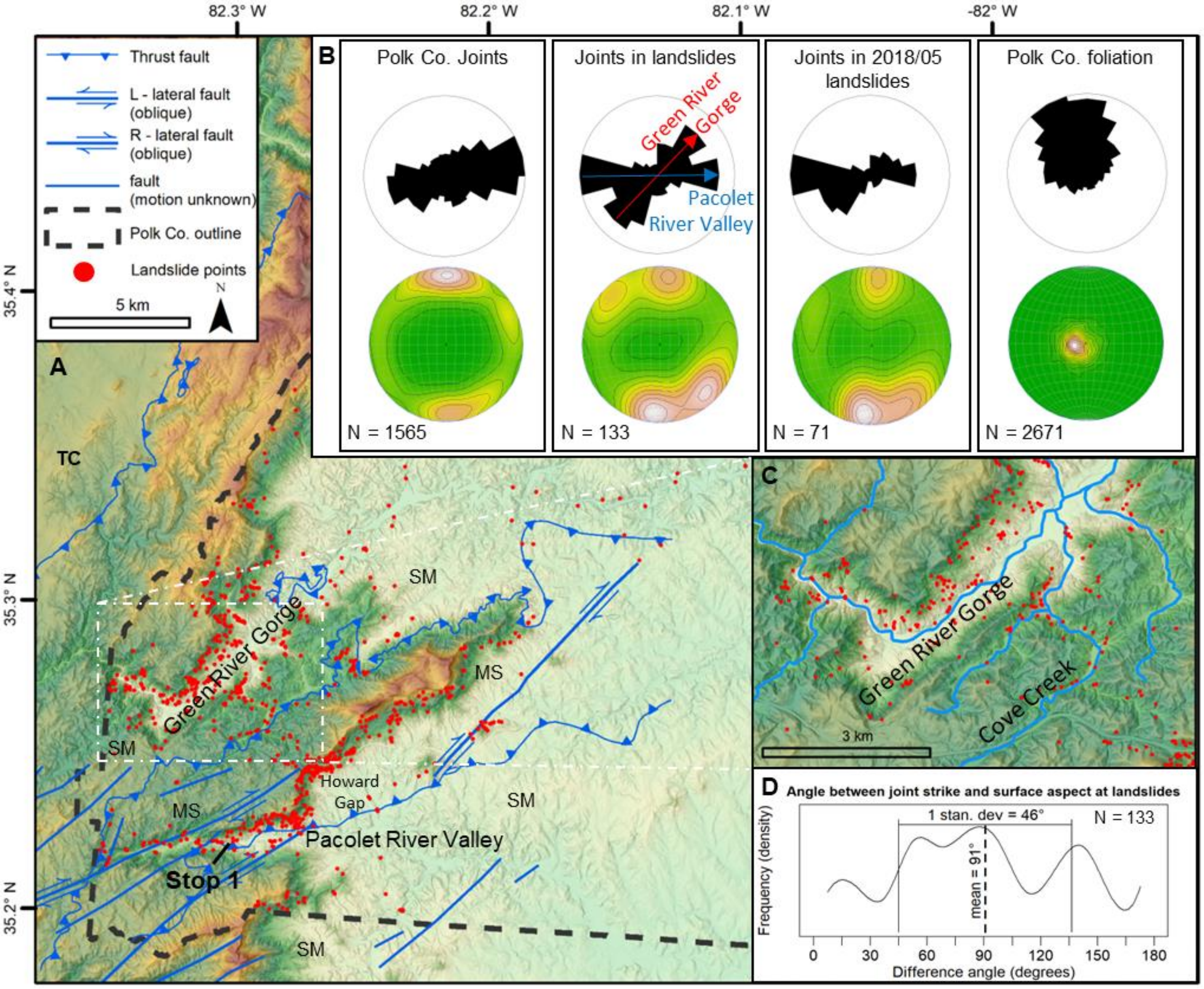

Figure 1-3. A. Map of western Polk County showing landslide initiation locations (red points) and previously mapped faults (blue lines). Faults modified from Garihan et al. (1993), and Davis and Yanigahara (1993). Thrust sheets: MS = Mill Spring, SM = Sugarloaf Mountain, TC = Tumblebug Creek. **B**. Rose diagrams and lower-hemisphere stereonets (contoured poles to planes) of joints measured within Polk County, within Polk Co. landslides, and within slides that occurred during the May 2018 storms. These steeply dipping joint sets strike parallel to the W-E-trending (blue arrow) Pacolet River Valley and the SW-NE-trending (red arrow) Green River Gorge. The foliation dips gently and consistently towards east-northeast. **C.** Inlay map of the Green River Gorge and its tributary Cove Creek, where numerous May 2018 slides and flows occurred within a rectilinear drainage network that parallels NW-SE-striking, and NE-SW-striking joint sets. **D.** Frequency plot of minimum angle between joint strike and topographic aspect at landslides, with a mean value = 91°, consistent with abundant high-angle joints that acted as back-release failure surfaces at landslide initiation zones and within debris slides and flows. Modified from Wooten et al., 2022.

2018 Debris Flow Impacts – North Pacolet River Valley. Beginning at approximately 6:00 p.m. on the evening of May 18, 2018, a sequence of severe thunderstorms produced as much as 200 mm (7.9 in) of rainfall over a 3 to 4-hour period in Polk County (NCEI, 2018; Bauer et al., 2019). Figures 1-4 and 1-5 show rainfall in formation for the storm event from the National Weather Service Greenville-Spartanburg Weather Forecast Office. Subsequent landslide hazard mapping determined that this storm system along the BRE triggered >240 debris flows and slides, resulting in one fatality and damage to homes and roads.

Stop 1. North Pacolet River Valley, Highway 176, Polk County

A cluster of these debris flows initiated on the south-facing slopes of Little Warrior Mountain on the evening of May 18, 2018 (Figure 1-6). At around 9:00 p.m. the Case home, located near the base of the mountain, was initially hit by a debris flow from the eastern drainage above their home. Mrs. Case was unable to leave the home due to health complications, and Mr. Case assisted her into a detached garage next to the home. He then left, wading through the mud trying to get help, when a second debris flow from the western drainage behind the home hit the garage. Mr. Case tried to return to the house to get to his wife but was unable to do so.

The North Carolina State Emergency Operation Center tasked NCGS geologists to assist Polk County Emergency Management to determine if slopes above the home were stable enough for the Urban Search and Rescue (USAR) team to enter the impacted area to locate Mrs. Case. Shortly after daybreak on May 19, NCGS geologists arrived at the incident response staging area, to be briefed by the State and County Emergency Managers and integrated into the local Incident Command System for task assignments (FEMA, 2017). Rain had subsided, allowing the Broad River Volunteer Fire Department (BRVFD) to begin UAS flights. Emergency Management (EM) teams and the NCGS conducted the following stages of activities (refer to Figure 1-6 A-D):

1. The BRVFD conducted UAS reconnaissance flights (optical cameras), and the NCGS made initial field observations of site conditions.
2. The NCGS assessed foot-access to the damaged home and area stability, and coordinated with EM responders for spotter locations and escape routes for the USAR team in the event of further debris flow activity during their entry into the damage zone.
3. UAS (thermal imaging) pinpointed Ms. Case’s location in the wreckage. The USAR team quickly found her, but sadly she was not alive, and they recovered the fatality without incident.
4. The EM responders and the NCGS conducted an expanded search and rescue, and damage assessment of the 1 km-long corridor along U.S. 176 damaged by flooding and blocked by debris flows.

During the response activities following the May 18 storms, Subtropical Storm Alberto formed in the southern Gulf of Mexico and was forecast to deliver heavy rainfall to southwestern NC over the period of May 28-31. NCGS and ALC geologists identified areas impacted by the May 18 debris flows, and those with potential for future movement, and communicated this to the State and Polk County EM responders. Meteorologists with the National Weather Service, Greenville-Spartanburg SC Weather Forecast Office visited the damage area and met with the EM response team to discuss potential impacts from Subtropical Depression Alberto, which was forecast to deliver heavy rainfall to southwestern North Carolina over the period of May 28-31. Polk County EM issued a voluntary evacuation based on potential rainfall, landslide impact areas, and existing damage to local roads that could impede local traffic and hamper emergency vehicle access. Fortunately landslides during Alberto caused minimal damage in the North Pacolet River Valley; however, significant landslide damage occurred in neighboring McDowell and Rutherford Counties.

Stop 1. North Pacolet River Valley, Highway 176, Polk County

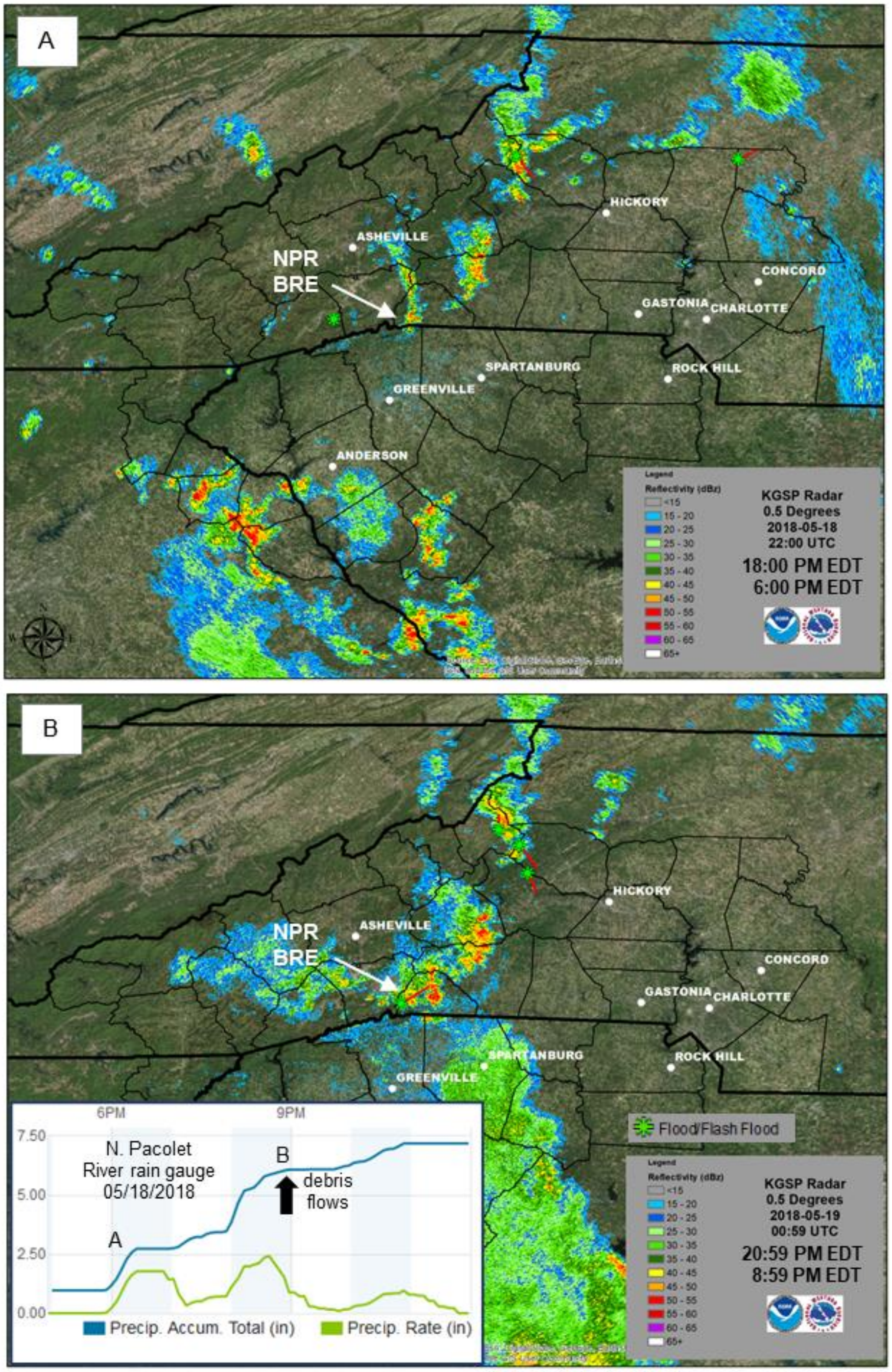

Figure 1-4. Rainfall information for the May 18, 2018 storm from the National Weather Service Greenville-Spartanburg, SC Weather Forecast Office. **A.** Flood event summary radar loop image from 18:00 (6:00 PM) EDT, May 18, 2018. Arrow points to the North Pacolet River – Blue Ridge Escarpment area of western Polk County. **B.** Event radar loop image from 20:59:00 (8:59 PM) EDT, May 18, 2018 indicating the flood/flash flood conditions in the NPR-BRE area coincident with debris flows. **Inset:** Weather Underground cumulative rainfall plot for the N. Pacolet River rain gauge on the evening of May 18, 2018. Points A and B respectively coincide with the approximate times of the radar images in Figs. A. and B above. Source: http://weather.gov/gsp/20180517-20180518_flood_eventSum; accessed 2022/07/24.

Stop 1. North Pacolet River Valley, Highway 176, Polk County

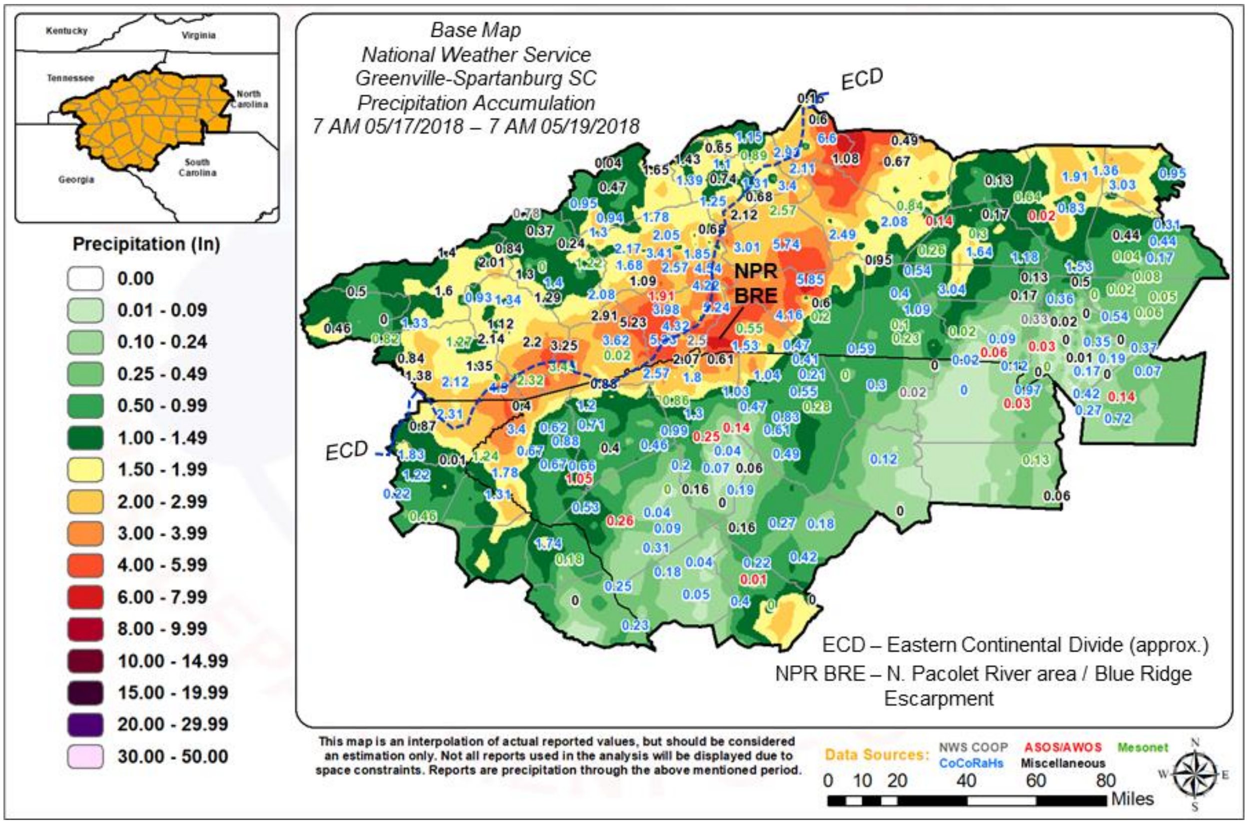

Figure 1-5. Precipitation accumulation map for the storm-flood event from 7:00 AM May 17 – 7:00 AM May 19, 2018 from the National Weather Service Greenville-Spartanburg, SC Weather Forecast Office. Approximate location of the Eastern Continental Divide (ECD) added for reference. In North Carolina the ECD generally coincides with the crest of the Blue Ridge Escarpment. One of the highest rainfall accumulations (6.00-7.99 in; 152-203 mm) coincides with the area of concentrated debris flow activity in the North Pacolet River area and adjacent Blue Ridge Escarpment in western Polk County. Source: http://weather.gov/gsp/20180517_20180518_flood_eventSum; accessed 2022/07/24.

Stop 1. North Pacolet River Valley, Highway 176, Polk County

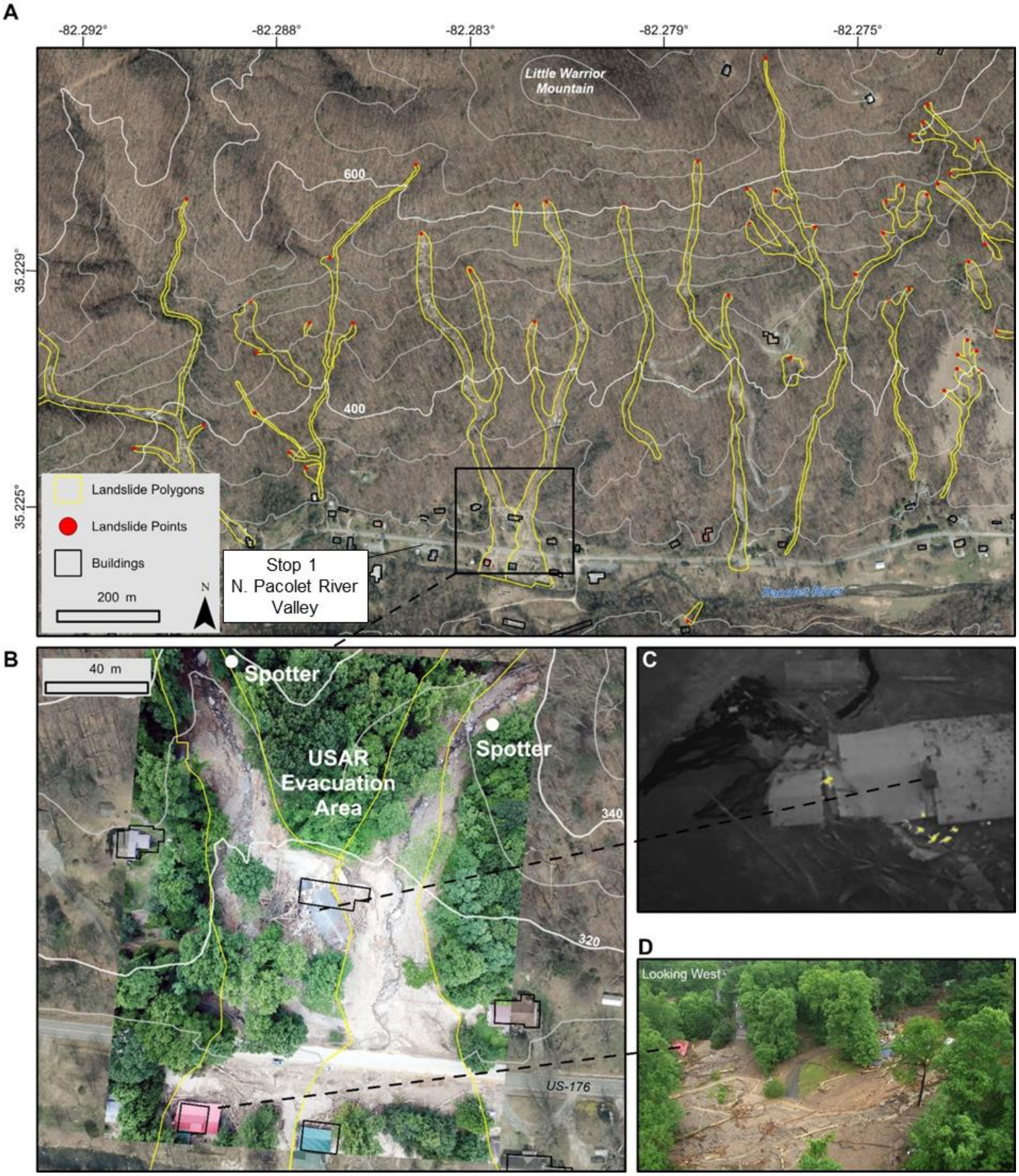

Figure 1-6. A. Debris flows triggered by the May 18, 2018 storm originated on the steep south-facing slopes of Little Warrior Mountain on the north side of the Pacolet River Valley. Coalescing debris flows channelized and deposited material to the valley floor. 2019 orthophotography base map. Contour interval = 40m. **B.** Location of search and rescue operations and fatality. Black outlines show the location of buildings prior to the debris flows. June 8, 2018 uncrewed aerial systems (UAS) image courtesy of the NC Geodetic Survey. 2019 orthophotography base map. Contour interval = 10m. **C.** Thermal UAS image of rescue personnel (bright areas) during search operations. May 19, 2018 UAS image courtesy of the Broad River Fire Department. **D.** UAS image from May 19, 2018 showing debris flow deposits along US-176. View looking west. May 19, 2018 UAS image courtesy of the Broad River Fire Department. Adapted from Wooten et al., 2022a.

Stop 1. North Pacolet River Valley, Highway 176, Polk County

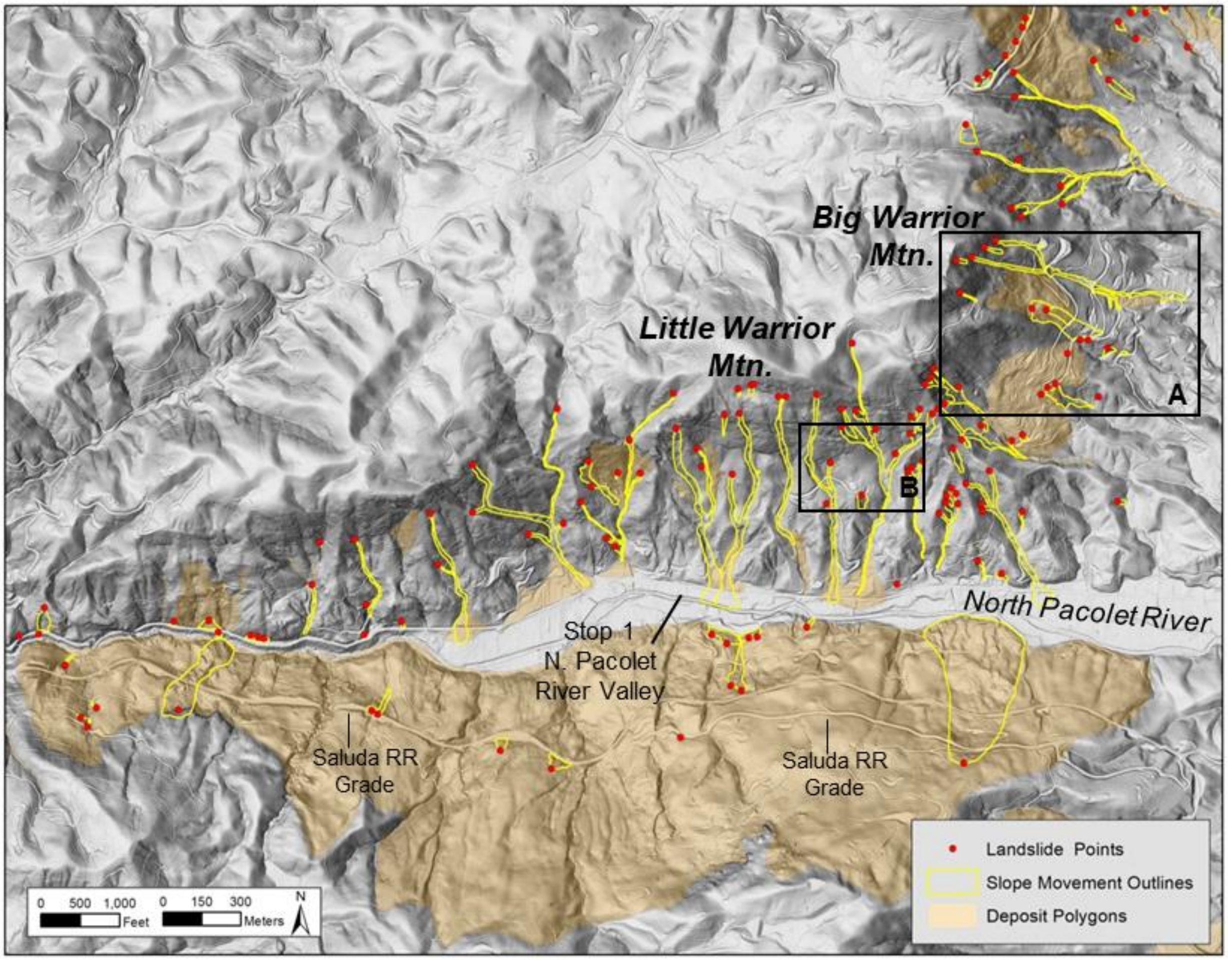

Figure 1-7. Lidar shaded relief map of the Pacolet River Valley showing mapped landslide features. Insets A and B correspond roughly to inset locations shown on Figure 1-8, and to locations shown in detail in Figures 1-9 and 1-10.

Mountains, Weather, Landslides and Viticulture. The effects of interactions between mountains and weather are evident in the influence of the former on precipitation and air temperatures. Prime examples of these interactions occur along the North Carolina segment of the BRE where orographic enhancement of rainfall related to landsliding is common (Wooten et al, 2016 and references therein), and where thermal belts occur on slopes where minimum average temperatures are higher than at either the bases of the slopes or the summits (Cox and Hutt, 1923). Here in the North Pacolet River Valley we can see evidence of both phenomena as well as areas of past and present viticulture (Figures 1-8, -9, -10, -11).

The extreme precipitation event of May 18, 2021, that was focused on the BRE in Polk County triggered over 240 landslides, the vast majority of which were concentrated on the steep slopes of the North Pacolet River and Green River Valleys (Figure 1-1). The spatial frequency and areal extents of some of the individual debris flows and debris slides from this event are shown in Figures 1-6A and 1-7. Orographic forcing of rainfall along the BRE in North Carolina is identified by greater rainfall totals as compared to the surrounding regions for the major landslide-triggering storms of July 15–6, 1916 (Scott, 1972; Witt, 2005), and August 10–17, 1940 (U.S. Geological Survey 1949; Witt and Wooten, 2018; Wooten and Witt, 2018); and for the May 18, 2018 storm in Polk County (Figure 1-5). It is noteworthy that the highest average rainfalls for the 1913-1916 period (heavily influenced by the July 15-16, 1916 tropical cyclone) shown in

Stop 1. North Pacolet River Valley, Highway 176, Polk County

Figure 1 in Cox and Hutt (1923) occurred in a zone concentrated along the BRE that included their Tryon study site. In North Carolina and Virginia the BRE is an area of frequent landslide activity (Witt and Wooten, 2015; Wooten, et.al, 2016, Wooten and Witt, 2018). High relief, steep slopes, and the dissected nature of the BRE, in combination with its orographic influence on rainfall, make it susceptible to debris flows.

The four temperature recording stations for the Tryon study site in the four-year investigation into thermal belts by Cox and Hutt (1923) were located on Warrior Mountain (Figures 1-8, 1-11). In their study temperature recording Station 2, located in a vineyard, was generally considered to be in the most favorable location for the thermal belt at the Tryon site, owing in part to temperature inversions and the moderating effect of downslope breezes on freezing temperatures. This moderating effect was also reflected in the longer growing season for the midslope Stations 2 and 3 at 223 and 220 days respectively, in comparison to 200 days for Station 1 at the valley floor, and 197 days for Station 4 near the summit. Figure 1-9 shows a detailed view of an area where finely terraced slopes are visible in the lidar shaded relief map (top) that were forested as in the 2019 orthophotography (bottom). It is possible some of the relict terracing on these slopes corresponds with the locations of vineyards reported at Stations 2 and 3.

Figures 1-9 and 1-10 illustrate some of the 2018 debris flows and debris slides that impacted areas of present-day hillslope development, as well as areas of current and possibly past viticulture. Damage to the hillslopes and roads in the Meadowlark Drive area was significant (Figure 1-9), and additional information on these slope failures can be found in Bauer et al., 2019a, and 2019b. Although damage to the present-day Tau Rock vineyard was relatively minor (Figure 1-10), there was severe damage to the roads accessing the property. Finely terraced slopes visible in the lidar shaded relief map (Figure 1-10 top), which were forested as in the 2019 orthophotography (Figure 1-10 bottom), are possibly remnants of earlier viticulture at the former Lee-Tau Rock vineyard.

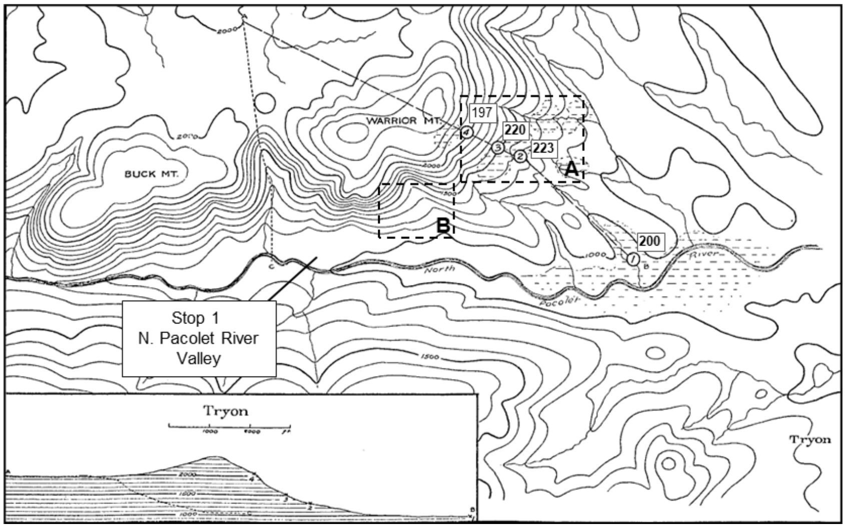

Figure 1-8. Map excerpt from Figure 21 in Cox and Hutt (1923) showing the four Tryon station locations (circled numbers) on the southeast slopes of Warrior Mountain. Length of growing season (days) for the 1913-16 study period are given beside each station (from Figure 78 in Cox and Hutt). Note that the two midslope station have longer growing seasons the either the upper or lower stations. In 1923 Stations 1 and 2 are reported to be in vineyard which coincides with the approximate area of the terraced slopes located in inset A (above and in Figure 1-7) and shown in detail in Figure 1-9. Inset B (above and in Figure 1-7) coincides with the area of the present-day Tau Rock vineyard shown in detail in Figure 1-10.

Stop 1. North Pacolet River Valley, Highway 176, Polk County

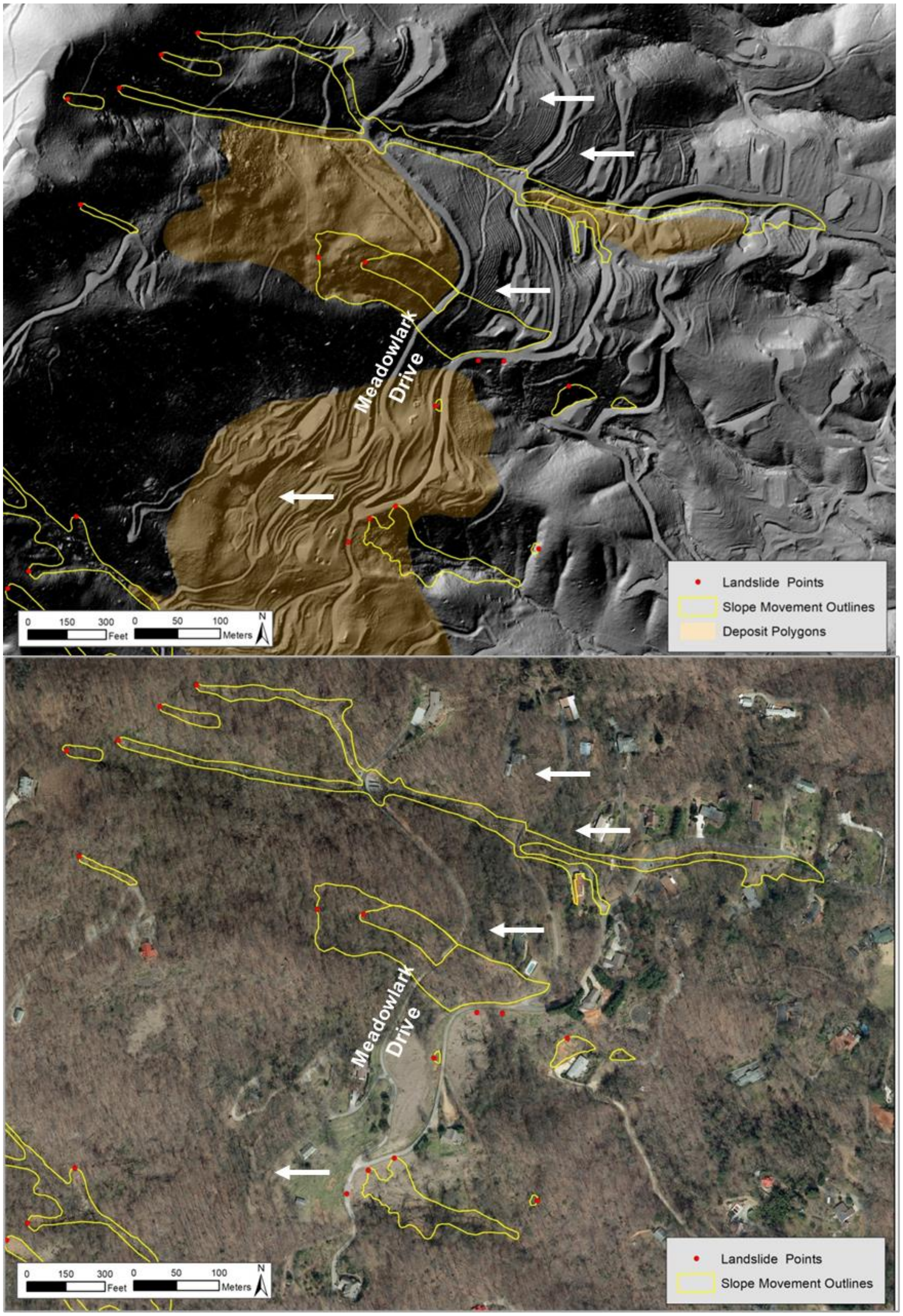

Figure 1-9. Mapped landslide features in the area of inset A in Figures 1-7 and 1-8. White arrows point to representative locations of finely terraced, forested hillslopes that may be former vineyards in the vicinity of Tryon stations 2 and 3 in Cox and Hutt (1923). **Top**. Lidar shaded relief base map. **Bottom**. 2019 orthophotography base map.

Stop 1. North Pacolet River Valley, Highway 176, Polk County

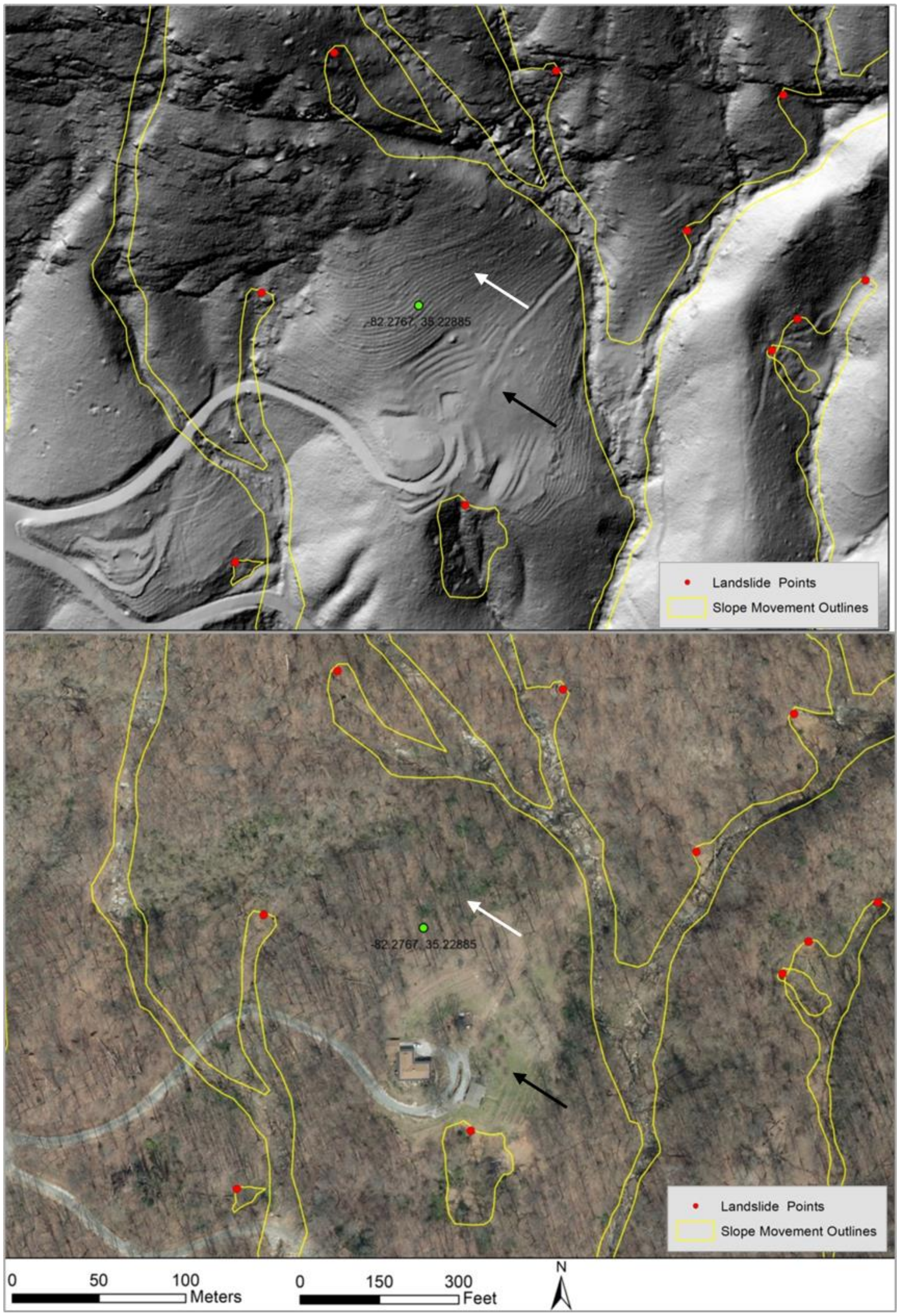

Figure 1-10. Detailed views of mapped 2018 landslide features in the area of inset B in Figures 1-8 and 1-9 that are part of the present-day Tau Rock vineyard. White arrows point to representative locations of finely terraced, forested hillslopes that may be former vineyards. Black arrows point to a current vineyard location. **Top**. Lidar shaded relief base map. **Bottom**. 2019 orthophotography base map.

Stop 1. North Pacolet River Valley, Highway 176, Polk County

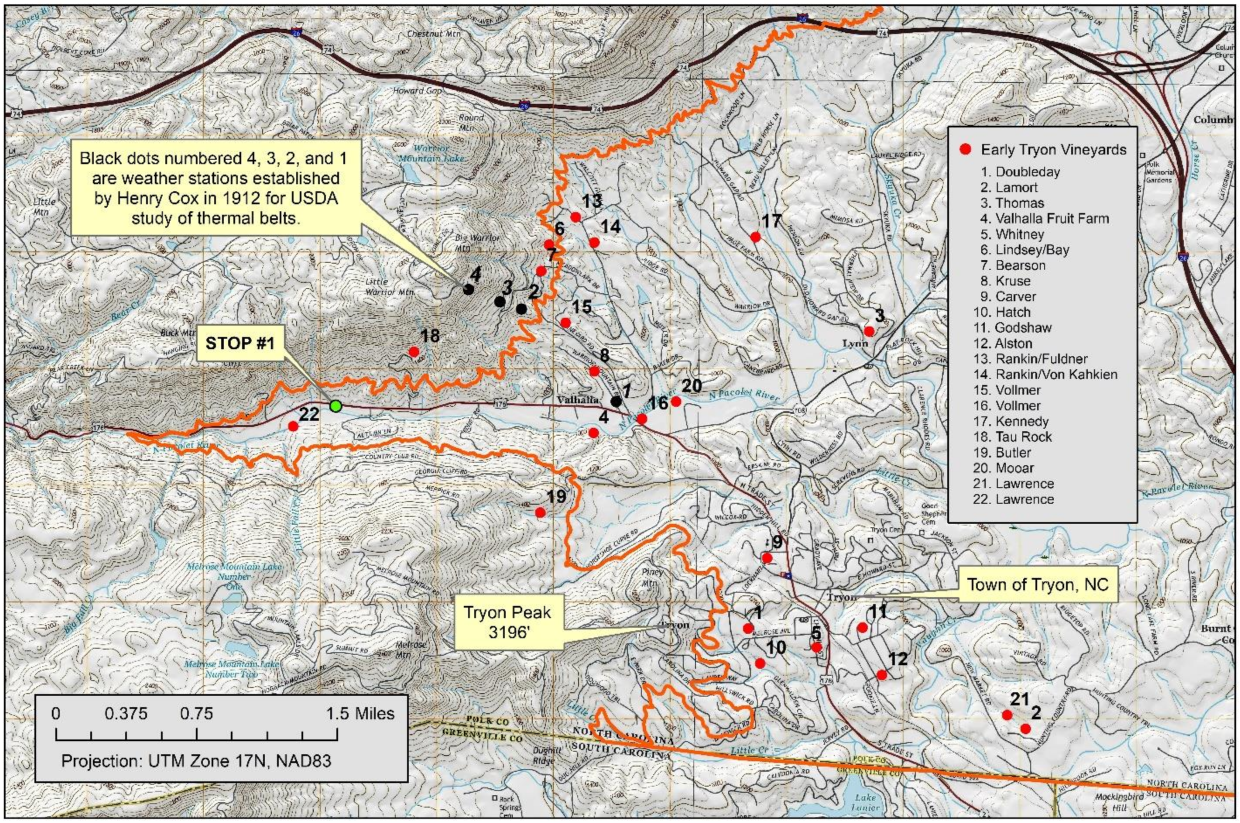

Figure 1-11. Location of early Tryon area vineyards near Stop #1 and location of Cox's weather stations on Big Warrior Mountain. Red outline is boundary of the proposed Tryon Foothills American Viticultural Area (AVA). The source of the vineyard locations is the map published in the book *Tryon: An Artist's and Writer's Sketchbook*, Ronald Mosseller and Anna Pack Conner.

Viticultural Significance of Stop #1. The viticultural significance of the Stop #1 site has already been alluded to in prior sections of this description (Cox study of thermal belts, recognition of possible vineyard terracing by high-resolution lidar), but now is the time to expand on the topic as we prepare to visit our first vineyard. From about 1890 till the 1950's the area around Tryon, NC was one of the major grape-growing regions of the US east coast. The map in Figure 1-11 shows the location of 22 of the vineyards that existed during that period. Two of these were close to the Stop #1 site. The Lawrence vineyard (#22) grew Concord, Niagara and Delaware varieties, and was very close to the spot where we will park the buses for Stop #1. The Tau Rock Vineyard (#18) was a 20-acre operation on the slope of Little Warrior Mountain, near the Stop #1 site. There is still a small vineyard at the old Tau Rock site, but it is no longer a commercial operation. All of the other vineyards are gone and but not forgotten. The modern-day viticultural revival that is occurring in Polk County now has heightened interest in the vineyards of the past.

It is difficult to pin down the exact years when grapes were first planted in Tryon, but they were produced as a cash crop as early as the 1820's (Mosseller and Conner, 2001). After the Civil War, grape cultivation and wine production prospered in Polk and Buncombe Counties (Helsley, 2010), and by the 1890's, Polk County was a center of viticultural activities in western North Carolina, with the third highest number of vineyards of any county in North Carolina.

Stop 1. North Pacolet River Valley, Highway 176, Polk County

We cannot mention all of the names that were associated with grape cultivation in Tryon's grape and wine heydays, so we have selected a few of the more prominent and interesting characters that played major roles in promoting Tryon grapes. General Ulysses Doubleday, brother of General Abner Doubleday, who reportedly fired the first shot in defense of Fort Sumter, and who was the recognized inventor of baseball, founded a vineyard in Tryon in the 1890's (Vineyard #1 on Figure 1-11). He was responsible for bringing the French winemaster Alexis Lamort to Tryon to help with development of his vineyard. Lamort was instrumental in assisting other winegrowers, and eventually started his own vineyard (#2 on Figure 1-11) and winery. After Ulysses's death, his son Harold and Sydney Lanier, Jr., son of the southern poet and Johns Hopkins University professor Sydney Lanier, took over and ran the Doubleday operation. Harold also headed the Pacolet Grape Juice Co., which produced a popular carbonated grape drink during the summer season.

Another influential individual who moved to Tryon to recover his failing health was George Morton, an Ohio horticulturalist. He established a 40 acre vineyard named Valhalla Fruit Farm (#4 on Figure 1-11) in the Pacolet Valley and just east of the Stop #1 site. His wife operated the popular Pacolet Tea Room and ran the Pacolet Post Office.

Finally, we should mention William Lindsey from Kentucky, who developed a 30-acre vineyard on the slope of Big Warrior Mountain. Lindsey was an avid promoter of the Tryon area and was very influential in popularizing the grapes up and down the east coast. In a 1919 article in the Polk County News, he stated "From Washington to Miami the cry is the same: Give me Tryon grapes."

Much of the success of Tryon grapes is related to the trains that stopped in Tryon on their runs between Greenville and Asheville in the earlt to mid twentieth century. Vendors with basket of grapes met these trains and sold their wares to passengers through the windows. The fame and popularity of the Tryon grapes was spread up and down the east coast and even to other areas of the country. The Waldorf-Astoria Hotel in New York City even featured the grapes on it menu. The saying was that "Grapes were to Tryon as beer was to Milwaukee." But the popularity of the grapes began to dwindle in the 1940's. With the Second World War raging, there was reduced labor available to maintain the vineyards, train service was slowly suspended as the steam engines gave way to diesels, and California was rapidly overtaking the east coast with its more interesting and less expensive grape varieties and *vinifera* wines. By the 1950's, Tryon vineyards were on an unstoppable decline.

Tragic though it is, Stop #1 has an important lesson for residential siting and modern-day viticulture, and that is the risk and danger of high slope locations. Might landslides have affected the vineyards that were located on the steep slopes of Warrior Mountain and added to the decline of viticulture in the area? Perhaps detailed analysis of the high-resolution lidar would offer some clues as to whether the early vineyards were affected by landslides. With the high density of slide events that have been mapped on Warrior Mountain, and the number of vineyards that were operated there, it seems unlikely that some were not damaged.

The story of the early Tryon area vineyards is fascinating, and for those who wish to read more about it, we recommend the books by Mosseller and Conner (2001) and Helsley (2010) referenced in this stop description. But, it is now time to move on to the modern era of viticulture and our first modern-era vineyard – Parker-Binns Vineyard in Mill Spring.

Stop 1. North Pacolet River Valley, Highway 176, Polk County

Summary. The May 18, 2018 storm triggered 241 landslides in western Polk County in one of the largest landslide events in NC in the last 80 years with respect to landslide density (spatial frequency). Comparable events occurred in September 2004 and in August 1940. Rainfall from tropical cyclones Frances and Ivan during September 6-17, 2004 triggered approximately 400 landslides in western NC (Wooten et al., 2016) with 254 of these recorded in the NCGS landslide geodatabase, and distributed over a 12-county region. During August 13-17, 1940, remnants of a tropical cyclone delivered heavy rainfall, triggering over 2,000 debris flows and debris slides over a 1,197 km^2 area of Watauga County (Wooten et al., 2008b). Although the 1940 storm produced an order of magnitude greater number of landslides in Watauga County than the 2018 Polk County storm, the maximum landslide density from the 1940 event (20.7 landslides/km^2) was approximately half of the observed maximum density from the 2018 event (38.9 landslides/km^2). Fortunately, because of the localized nature of the May 18, 2018 storm, the 241 landslides were limited to a 67 km^2 area of western Polk County along the BRE.

Debris flows in the Pacolet valley are not a new occurrence. There is evidence of multiple debris flow deposits within the scoured stream banks of the debris flows that impacted the Case home. Landslide mapping has also documented extensive debris deposits along the slopes of the North Pacolet River Valley (Figure 1-7) indicative of many past landslide events. Although relatively narrow and shallow, debris flows can cause significant damage and even fatalities because of long run out distances and proximity of residences to the drainages. Consequently, debris flows and other types of landslides, can pose threats to hillslope development, viticulture and other types of agricultural activities on steep slopes.

While the post-May 18 emergency response and pre-Alberto planning was well organized and interdisciplinary, the public awareness about landslide hazards in the valley was lacking because the landslide hazard mapping had not been undertaken. As this tragic event exemplifies, continued mapping, communication with stakeholders and awareness is necessary to save lives. To make landslide information available to the public, the NCGS in partnership with the National Environmental Modeling and Assessment Center (NEMAC) at UNC-Asheville developed a suite of online tools to examine landslide hazards in North Carolina. Data on over 5,000 landslides are now publicly available at: http://mapviewer.landslidesncgs.org, and http://landslidesncgs.org. Additional landslide data are available on ALC's landslide website and map viewer at: https://appalachianlandslide.com.

Acknowledgements. The leaders and authors would like to thank the residents of the Pacolet Valley for sharing their stories, heartbreaks, and community during the days and months following the May 18 event. We would also like to thank the Polk County Emergency Management Department, the National Weather Service Greenville-Spartanburg office, the N.C. Forest Service, and the N.C. Geodetic Survey for their support and sharing information and data during this event response. Nick Bozdog, Sierra Isard, and Rebecca Latham assisted with post-event data collection.

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Stop 2. Parker-Binns Vineyards & Winery, Mill Spring, NC

Figure 2-1. Parker-Binns Vineyards in Mill Spring, NC. Hatched areas outline vineyard blocks.

Objectives. Our first vineyard stop will be Parker-Binns Vineyards, which is located in the western Piedmont physiographic province and in the proposed Tryon Foothills AVA. From the vineyard we will have an excellent view of the Blue Ridge escarpment. We will compare and contrast the proposed AVA with the already established and adjacent Crest of the Blue Ridge Henderson County AVA, which lies directly to the west and is quite different in character from the Tryon Foothills region. Mr. Cory Lillberg, the vineyard manager, will give us an overview of the history and present-day operation of the vineyard, following which we will have presentations on the regional geological setting of the field trip area, and origin, geomorphology, and development of the Blue Ridge escarpment. There will, of course, be an opportunity to taste wines, these produced from grapes grown on soils formed in mafic rocks.

Background. The vineyard was started in 2008 by Bob and Karen Binns who had spent their careers in the food and beverage industry. After several years of retirement, they were bored and decided they needed something else to do. Specifically, they dreamed of establishing a vineyard in the foothills region of North Carolina, which turned out to be on a tract in Mill Spring, NC. The property was cleared, and the initial planting was done in 2008. Now 14 years later, Parker-Binns Vineyards & Winery is an established part of the Polk County wine scene with many awards for the quality of its wines.

Stop 2. Parker-Binns Vineyards & Winery, Mill Spring, NC

General Description.

Location:	Lat. 35.318047 Long. -82.117734 (Tasting room)
USGS Topo Quad (7.5-minutes):	Pea Ridge, NC
Address:	2275 Whiteside Road, Mills Spring, NC 28756
Founder(s):	Bob Binns and Karen Binns
Vineyard Management:	Cory Lillberg
Winemaker:	Justin Taylor

Viticultural Characteristics.

First Plantings:	2008
Vineyard size:	8.1 acres
Elevation:	1014 feet (mean elevation of vineyard blocks, which range from 980'to 1059')
Slope of vineyard blocks:	19° mean value (34.4%). Range of all blocks 9-34° (15.8-67.5%)
Aspects of vineyard blocks:	

Aspects	Azimuths	Percentage
North	0-22.5°	0
Northeast	22.5-67.5°	0
East	67.5-112.5°	0
Southeast	112.5-157.5°	1.3
South	157.5-202.5°	34.1
Southwest	202.5-247.5°	12.1
West	247.5-292.5°	27.1
Northwest	292.5-337.5°	25.4
North	337.6-360.0°	0

GDD (F° units):	4035 (Winkler region/GDD zone V)
Mean annual temp:	59.3°F
Mean growing season temp:	69°F. 'Hot' category of Grapevine Climate/Maturity Groupings.
Mean annual frost free days:	302
Est. length of growing season (days):	200
Mean annual precipitation:	55.7 inches
Mean growing season precipitation:	33.1 inches
Mean solar radiation ($MJm^{-2}day^{-1}$):	15.37
Est. last spring frost (mean date):	April 12
Est. first fall frost (mean date):	October 29
Grape varieties:	Cabernet Franc, Cabernet Sauvignon, Chambourcin, Chardonnay, Malbec, Merlot, Muscat, Petit Manseng, Petit Verdot, Tannat.
Wine Styles:	Red and white estate varietals and blends, rosé, white grape and blackberry dessert wines.

Viticultural Setting. Parker-Binns is part of the proposed Tryon Foothills AVA, the application for which was submitted to the US Dept. of the Treasury on August 21, 2021. At the present time there are five vineyards in the proposed AVA, four of which have wineries[1] and a fifth[2] that sells its grapes but does not produce wines. Elevations in the proposed AVA range from 712' to 1656', with a mean elevation of 988'.

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[1] Parker-Binns, Overmountain, Mountain Brook, and Russian Chapel Hill.

[2] Red Bell Run.

Stop 2. Parker-Binns Vineyards & Winery, Mill Spring, NC

The mean annual temperature of the AVA has a narrow range of 59-60°F, and the mean annual growing season temperature ranges from 68-70°F placing the AVA in the "Hot" category of the Grapevine Climate/Maturity Groupings. The Growing Degree Day zones of the AVA place the area solidly in GDD Zone (Winkler Region) V, with a small area in the South Mountains along the northeast margins of the AVA in GDD Zone IV. The five most commonly planted grapes in the AVA are all European *vinifera*: Merlot, Cabernet Sauvignon, Cabernet Franc, Chardonnay, and Petit Verdot.

Geological/Geomorphic Setting. Parker-Binns Vineyard is located in the western Piedmont physiographic province (Inner Piedmont geological province), approximately seven miles east of the base of the Blue Ridge escarpment, which can be seen to the west from the grounds of the vineyard (Figure 2-3). Parker-Binns Vineyards is located on the Pea Ridge 7.5-minute quadrangle, just east of Davis's and Yanigahara's 1993 mapping. It is underlain by amphibolites and hornblende gneisses. These mafic rocks project into Davis's lower Mill Spring group of the Mill Spring thrust sheet, here tentatively correlated with the lower Tallulah Falls Formation. They would thus be considered either a) fragments of oceanic crust, b) volcanic rocks deposited contemporaneously with clastic sediments, c) intrusions into the sedimentary pile and underlying oceanic crust, or d) some combination of the above. Cobble- and gravel-sized samples can be seen on the grounds around the tasting room, and the soil is a dark red (Figure 2-3), reflecting its mafic composition. Deeply weathered outcrops can be viewed in nearby ditches but we ask that you refrain from hammer use in order to minimize erosion. A pile of excavated saprolite and soil along the entrance road east of the tasting room is representative of the weathered mafic bedrock that underlies the vineyard.

Figure 2-2. Sunset over the Blue Ridge escarpment seen from Parker-Binns Vineyard.

Stop 2. Parker-Binns Vineyards & Winery, Mill Spring, NC

Figure 2-3. Saprolite and soil pile along entrance road to Parker-Binns Vineyard.

The North Carolina Geological Survey mapped the Pea Ridge quadrangle as part of the USGS-sponsored STATEMAP program (Cattanach et al, 2016). Nearby foliations are undulatory, striking NNW-SSE and gently dipping to the NE and SW. Approximately 1 kilometer east of this stop, outcrops of quartzite within the amphibolite raise the possibility that some of these rocks may belong in the stratigraphically higher Poor Mountain Formation, but that is a story for a future trip.

Soils. The vineyard blocks at Parker-Binns are located on two soil series: Pacolet and Cecil. Other soil series that occur in the immediate vicinity of the vineyard include Madison. For detailed descriptions of soils, go to USDA-NRCS Official Soil Series Description View By Name and type in name of series.

Series	Map Unit	Description
Pacolet	PaC2	Pacolet sandy clay loam 8-15% slopes, moderately eroded
Pacolet	PaD2	Pacolet sandy clay loam 15-25% slopes, moderately eroded
Cecil	CeB2	Cecil sandy clay loam 2-8% slopes, moderately eroded
Madison	MaC2	Madison sandy clay loam 8-15% slopes, moderately eroded

Stop 2. Parker-Binns Vineyards & Winery, Mill Spring, NC

Both the Pacolet and the Cecil series are normally derived from the weathering of felsic igneous and high-grade metamorphic rocks, but at Parker-Binns, they have obviously formed from the weathering of **mafic rocks.**

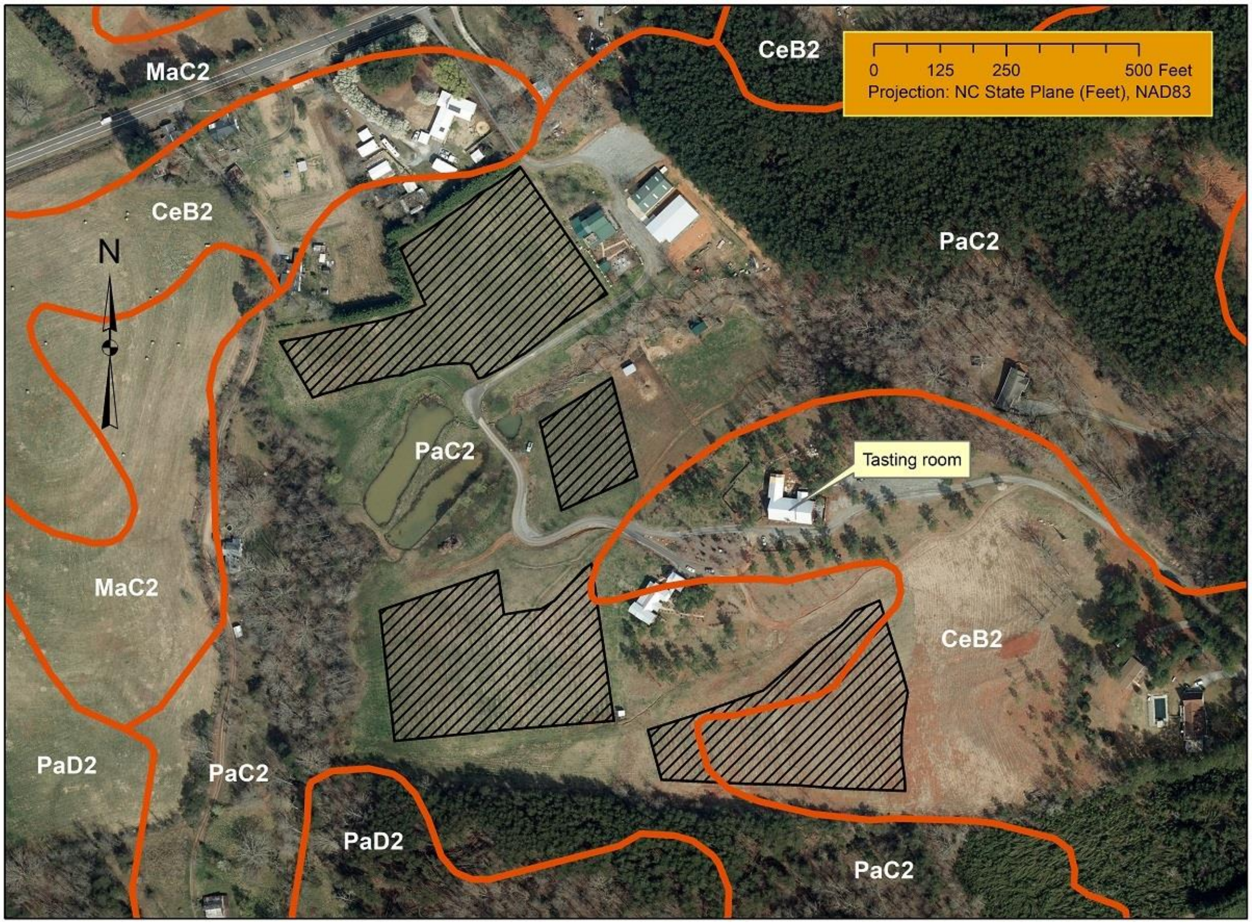

Figure 2-4. Soils of the Parker-Binns Vineyard. Hatched areas outline vineyard blocks. Red lines are soil unit boundaries.

References.

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Stop 3. Marked Tree Vineyard, Flat Rock, NC

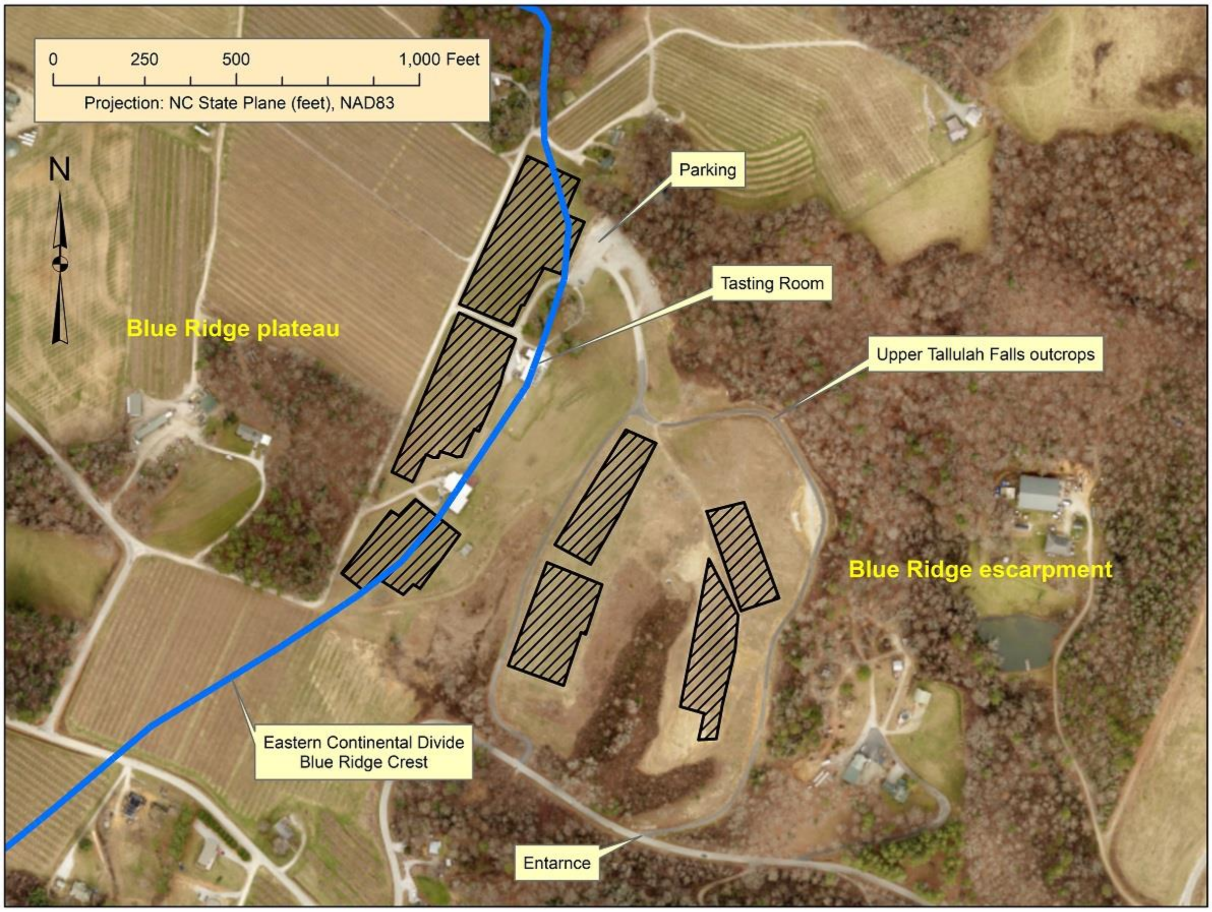

Figure 3-1. Marked Tree Vineyards. Hatched areas outline vineyard blocks. Eastern Continental divide/Blue Ridge crest passes through tasting room and divides the vineyard between the Blue Ridge plateau to the west and Blue Ridge escarpment to the east.

Objectives. At Marked Tree Vineyards (Figure 3-1), we have moved from the western Piedmont physiographic province to the Blue Ridge plateau and the Blue Ridge escarpment. We have also moved from the proposed Tryon Foothills AVA to the Crest of the Blue Ridge Henderson County (CBRHC) AVA. We will again compare and contrast the differences in these two environments. The founders and owners will give us an overview of the vineyard history and operations, after which we will explore (1) the breaching of the proto-Blue Ridge crest by the Broad and Green Rivers, (2) the differences this creates in the vineyard soils, and (3) the geomorphic development of the Hickory Nut gorge by stream capture. A wine tasting will consist of Marked Tree's estate-grown *vinifera* grapes and perhaps one hybrid variety.

Background. Marked Tree Vineyards was founded in 2015 by Lance Hiatt and Tim Parks, architecture and business graduates, respectively, from Tulane University. Lance was the architect of the tasting room.

In April 2022, the newspaper USA Today nominated 20 new US wineries for its annual 10 Best New American Wineries for 2022. Two vineyards on the east coast (Marked Tree and Stone Ashe, both of which are on our itinerary) were among the nominees, the other 18 wineries were all on the west coast. On July 29th, USA Today announced that Marked Tree had won fifth place among the 10 Best New Wineries.

Stop 3. Marked Tree Vineyard, Flat Rock, NC

General Description.

Location:	Lat. 35.316755 Long. -82.364419 (Tasting room)
USGS Topo Quad (7.5-minute):	Cliffield Mountain, NC
Address:	623 Deep Gap Road, Flat Rock, NC 28731
Founder(s):	Lance Hiatt, Tim Parks
Vineyard Management:	Lance Hiatt, Tim Parks
Winemaker(s):	Justin Taylor, Mark Frizolowski, Dane Dressler

Viticultural Characteristics.[1]

First Plantings:	2016
Vineyard size:	10 acres
Elevation:	2303 feet (mean elevation of vineyard blocks, which range from 2250 to 2355 feet)
Slope of vineyard blocks:	22.2° mean value (40.8%). Range of all blocks 9-34° (15.8-67.5%)
Aspects of vineyard blocks:	

Aspects	Azimuths	Percentage
North	0-22.5°	0
Northeast	22.5-67.5°	0
East	67.5-112.5°	13.5
Southeast	112.5-157.5°	15.9
South	157.5-202.5°	16.5
Southwest	202.5-247.5°	20.3
West	247.5-292.5°	28.8
Northwest	292.5-337.5°	5.0
North	337.6-360.0°	0

GDD (F° units):	3375 (Winkler region/GDD zone III)
Mean annual temp:	55.8°F
Mean growing season temp:	65°F. 'Warm' category of Grapevine Climate/Maturity Groupings.
Mean annual frost free days:	300
Est. length of growing season (days):	195
Mean annual precipitation:	59.7 inches
Mean growing season precipitation:	35.8 inches
Mean solar radiation ($MJm^{-2}day^{-1}$):	15.02
Est. last spring frost (mean date):	April 12
Est. first fall frost (mean date):	October 29
Grape varieties:	Cabernet Franc, Petit Verdot, Grüner Veltliner, Chardonel, Vidal Blanc, Muscat Ottenel
Wine Styles:	Red and white estate-grown varietals and blends

Viticultural Setting. Marked Tree Vineyards is located in the Crest of the Blue Ridge Henderson County (CBRHC) AVA, which was established by the Department of the Treasury on July 18, 2019. Mean elevation of the AVA is 2362', with a range of 1394' to 4396'. The mean annual temperature of the AVA is 55.5°F , with a range of 51.7°F to 57.9°F. The mean growing season temperature is 65°F, placing it in the 'Warm'

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[1] To view sources of data for Viticultural Characteristics and Soils, go to Appendix 1 at end of guidebook.

category of Grapevine Climate/Maturity Groupings. The mean Growing Degree Day value of the AVA is 3315 placing it in GDD zone (Winkler Region) III. Mean length of growing season is 195 days, based on a temperature of 32°F.

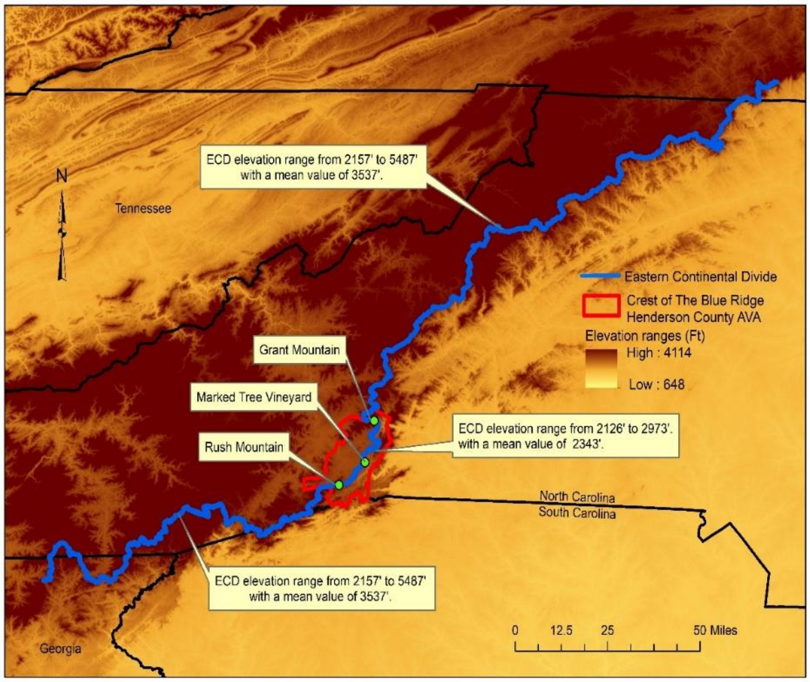

Figure 3-2. Elevation ranges along the ECD from southern Virginia to northern Georgia.

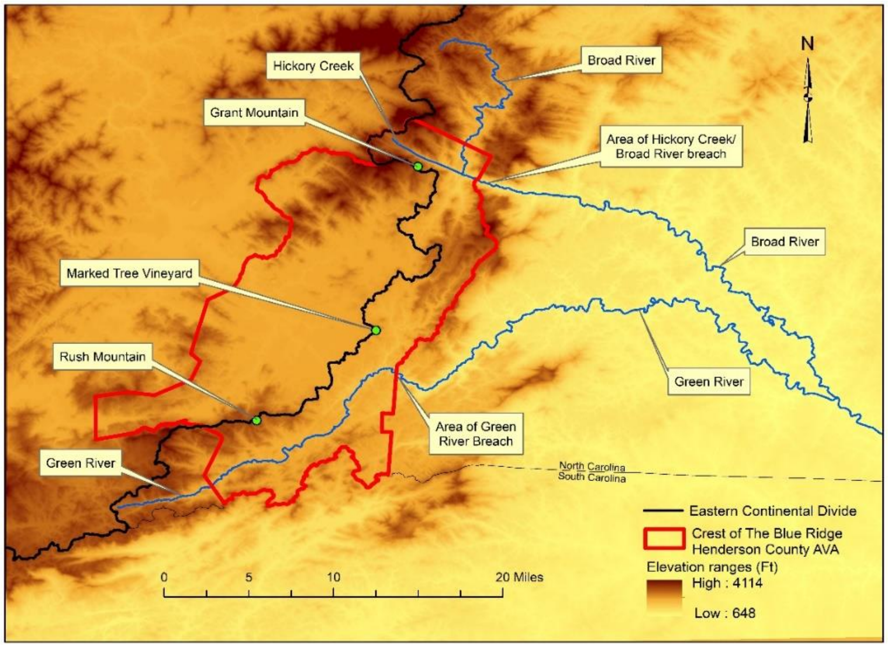

Figure 3-3. Breaching of the proto-Blue Ridge crest by the Broad River-Hickory Nut Creek system, and by the Green River.

Geomorphic Setting. The eastern continental divide (ECD) at Marked Tree is certainly not what one would expect of a major divide; here it looks more like a subtle speed bump in a quiet residential neighborhood. But it is real and marks the top of the Blue Ridge escarpment. Figure 3-2 illustrates the trace of the divide from southern Virginia to northern Georgia. The 'descent' in the elevation of the ECD that we see at Marked Tree begins on the north at Grant Mountain in the Bat Cave quadrangle and on the south at Rush Mountain in the Zirconia quadrangle. Elevations south of Rush Mountain to north Georgia range from 2157 to 5492 feet, with a mean value of 3537 feet. North of Grant Mountain to southern Virginia, elevations range from 2545 to 5918 feet, with a mean value of 3569 feet. The divide between these two points has an elevation range of 2126 to 2973 feet, with a mean value of 2412 feet. Figure 3-3 presents a more detailed view of the lower-elevation section of the ECD. The frontal peaks of the escarpment, which are most likely the proto-Blue Ridge crest, as suggested By Rick Wooten at Stop 1, have been breached in two places: Just east of Grant Mountain by the Broad River-Hickory Nut Creek tributary system where it crosses the boundary between Henderson and Polk Counties and to the south by the Green River where it transects the same county boundary. Prince (2012) mentioned these examples in his Carolina Geological Society paper that is reprinted in this year's guidebook and suggested that the mechanism for their headward erosion is steam capture, which has resulted in retreat of the ECD/Blue Ridge crest to the west and reestablishment at a lower and less conspicuous elevation. An example of how the process works is shown in Figure 3-4 for development of the Hickory Nut Gorge .

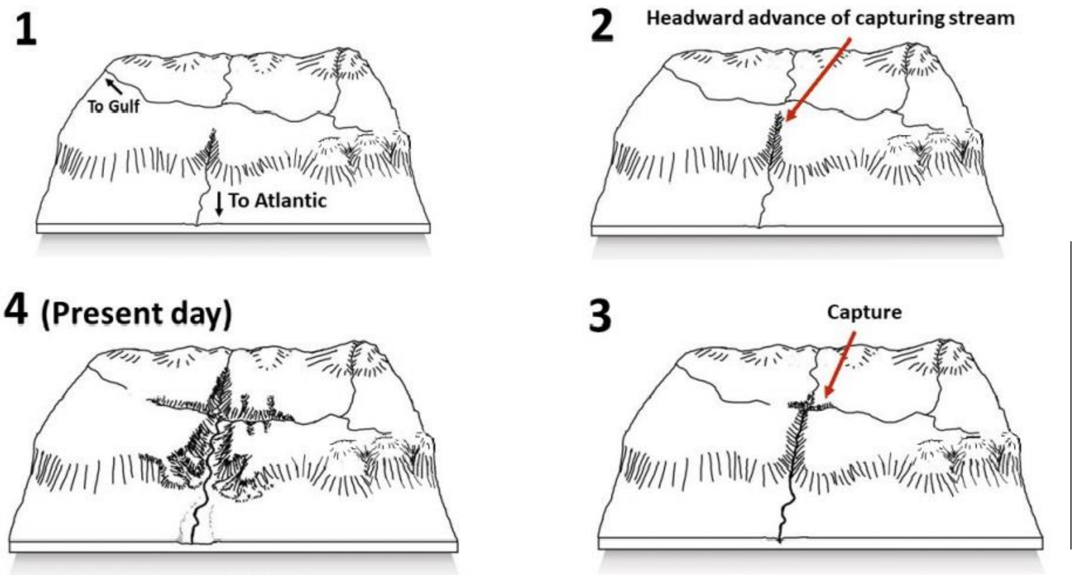

Figure 3-4. Conceptual model of Hickory Nut Gorge development following capture of the ancestral, Gulf of Mexico-draining Rocky Broad River. 1. Headward erosion of an Atlantic-draining Broad River erodes into the Blue Ridge escarpment, utilizing a topographic lineament. 2. Headward advance of the Atlantic headwater approaches the Gulf-draining ancestral Rocky Broad River. 3. Capture occurs when the Atlantic headwater erodes into and intersects the ancestral Rocky Broad, diverting it to the steep Blue Ridge escarpment and to the Piedmont, ~300 m below. Rapid incision begins. 4. The present-day gorge system reflects ongoing incision and retreat of gorge walls as upland topography within the captured basin is consumed and eroded to Piedmont elevations. Note inheritance of pre-capture drainage pattern in the modern gorge due to strong structural control of river networks. After Prince (2022).

Streams on the western side of the divide are perched on a low gradient plateau while streams on the eastern side drain down into the Piedmont. The resulting asymmetry allows for capture of the western rivers by the eastern rivers resulting in migration of the escarpment to the west. This mechanism has been used to explain why a mountain range as old as the Appalachians can retain its high relief (Johnson, 2020), although other mechanisms may also be active (Gallen et al., 2013). Soils are likely more stable west of the divide where incision has not yet increased relief and produced the potential energy required for erosion. Approximately half of the Marked Tree vineyard blocks are in this more stable portion of the site and likely retain better A horizons (i.e., topsoil) compared with the eastern side of the site which is likely more eroded due to the intervening stream valley (Figure 3-1)

Soils. The vineyard blocks at Marked Tree are planted in two major soil series (Figure 3-5: Hayesville and Evard. (Figure 3-5). Tate, Edneyville, and Ashe series also occur in the immediate vicinity of the vineyard blocks. For detailed descriptions of soils, go to USDA-NRCS Official Soil Series Description View By Name and type in name of series.

Series	Map Unit	Description[2]
Hayesville	HyB	Hayesville loam 2-7% slopes
Hayesville	HyC	Hayesville loam 7-15% slopes
Evard	EwE	Evard soils 15-25% slopes
Evard	EwF	Evard soils 25-45% slopes
Tate	TeB	Tate fine sandy loam 2-7% slopes
Tate	TeC	Tate fine sandy loam 7-15% slopes
Edneyville	EdF	Edneyville fine sandy loam 25-45% slopes
Edneyville	EdE	Edneyville fine sandy loam 15-25% slopes
Ashe	AhF	Ashe stony sandy loam 25-45% slopes

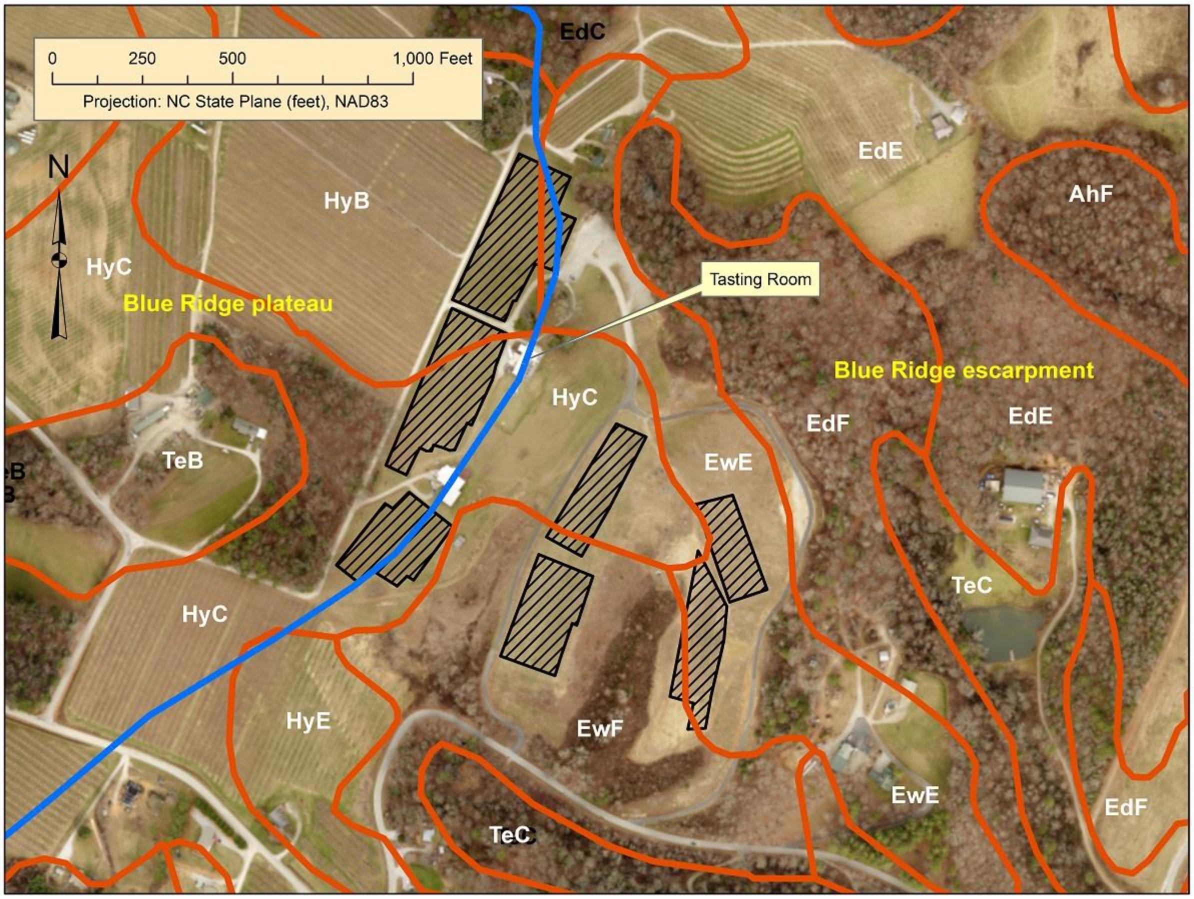

Figure 3-5. Soils of the Marked Tree Vineyard. Hatched areas outline vineyard blocks. Red lines are soil unit boundaries.

References.

Gallen, S.F., Wegmann, K.W., and Bohnenstieh, D.R., 2013, Miocene rejuvenation of topographic relief in the southern Appalachians: GSA Today, v. 23, p. 4–10, doi:10.1130/GSATG163A.1.

Johnson, B., 2020, Stream capture and the geomorphic evolution of the Linville Gorge in the southern Appalachians, USA: Geomorphology, v. 368, p. 107360, doi:10.1016/j.geomorph.2020.107360.

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[2] To view ranges of soil components (sand, clay, and silt), see soil texture classification diagram in Appendix 1.

Stop 3. Marked Tree Vineyard, Flat Rock, NC

Prince, P., 2022, Overview of geomorphic features and evolution of the Blue Ridge Escarpment, topography and stream capture: Stop 1 Field Trip Description, *in* Eppes, M, ed., Hickory Nut Gorge: A Natural Laboratory to Advance Our Understanding of Progressive Rock Failure: Geol. Soc. America, Penrose Conference Field Trip Guide, June 22, 2022.

Stop 4. St. Paul Mountain Vineyards & Appalachian Ridge Cidery

Figure 4-1. St. Paul Mountain Vineyard & Appalachian Ridge Cidery. Hatched areas outline vineyard blocks.

Objectives. Our last stop of day 1 will be at St. Paul Mountain Vineyards and Appalachian Ridge Cidery (Figure 4-1). The founder and owner, Mr. Alan Ward, will lead a conversational trek through the vineyard and the orchard, and the newly completed winery/cidery. Following the trek, we will have talks on (1) the history of viticulture in North Carolina, (2) the viticulture program at Surry Community College, (3) the climate patterns affecting viticulture in the southern Appalachians, and (4) grape varieties grown in North Carolina. Be sure to try the estate-grown European *vinifera* wines and Normandy-style hard ciders.

Background. Alan Ward grew up on the vineyard/cidery property, which has been in the Ward family for many generations. He is an avid conservationist, a vocal advocate of sustainable agriculture, and an accomplished speaker who delights in talking about his love of the mountains and farming. Alan has a valid claim of responsibility for revival of interest in viticulture in this beautiful area of the Blue Ridge plateau; St. Paul Mountain was the first modern-day vineyard in Henderson County and is the oldest and one of the largest vineyards in the Crest of the Blue Ridge Henderson County AVA.

General Description.

Location:	Lat. 35.356185 Long. -82.408172 (Tasting room)
USGS Topo Quad (7.5-minutes):	Hendersonville, NC
Address:	588 Chestnut Gap Road, Hendersonville, NC 28792
Founder(s):	Alan Ward
Vineyard Management:	Barbara Walker

Stop 4. St. Paul Mountain Vineyards & Appalachian Ridge Cidery

Viticultural Characteristics.[1]

First Plantings:	2008
Vineyard size:	15.3 acres (10 total blocks). Additional 20 acres at satellite vineyard in Edneyville, NC, not included in this description.
Elevation:	2165 feet (mean elevation of vineyard blocks, which range from 2129 to 2202 feet)
Slope of vineyard blocks:	15.9° mean value (28.5%). Range of all blocks 2.7-37.0° (4.7-75.4%)
Aspects of vineyard blocks:	

Aspects	Azimuths	Percentage
North	0-22.5°	9.7
Northeast	22.5-67.5°	6.1
East	67.5-112.5°	1.6
Southeast	112.5-157.5°	1.1
South	157.5-202.5°	0.7
Southwest	202.5-247.5°	15.5
West	247.5-292.5°	45.9
Northwest	292.5-337.5°	15.5
North	337.6-360.0°	3.9

GDD (F° units):	3288 (Winkler region/GDD zone III)
Mean annual temp:	55.6°F
Mean growing season temp:	65°F. 'Warm' category of Grapevine Climate/Maturity Groupings.
Mean annual frost-free days:	298
Est. length of growing season (days):	192
Mean annual precipitation:	58.0 inches
Mean growing season precipitation:	34.7 inches
Mean solar radiation ($MJm^{-2}day^{-1}$):	15.07
Est. last spring frost (mean date):	April 15
Est. first fall frost (mean date):	October 25
Grape varieties:	Cabernet Franc, Cabernet Sauvignon, Chardonnay, Grüner Veltliner, Merlot, Petit Verdot, Riesling, Vidal Blanc
Wine Styles:	Red and white estate-grown varietals and blends, rosé, sparkling rosé, apple and fruit ciders, apple, and fruit brandies

Geological Setting. St. Paul Mountain Vineyards is located on a granitic body interpreted to be part of the Table Rock Plutonic Suite. Many Table Rock Plutonic Suite bodies are intruded into the Henderson Gneiss. Age of the Henderson Gneiss is Late Ordovician, and the Table Rock Plutonic Suite is Late Ordovician to Early Silurian in age. The Henderson Gneiss has a crystallization age of 447 Ma (Moecher et al, 2011). A body correlated with the Table Rock Suite has a reported crystallization age of 435 Ma (T. W. Stern and J. W. Horton, unpublished US Geological Survey data, 1984). Davis (1993) and Lemmon (1973) show that the contacts between the bodies are concordant and parallel with regional Acadian/Neoacadian F2 foliation. Outcrops of the granitic gneiss can be seen along an orchard trail east of the Appalachian Ridge Cidery.

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[1] To view sources of data for Viticultural Characteristics and Soils, go to Appendix 1 at end of guidebook.

Stop 4. St. Paul Mountain Vineyards & Appalachian Ridge Cidery

Soils. St. Paul Mountain vineyard blocks are located on three soils series: Hayesville, Edneyville, and Codorus (Figure 4-2). Other soil series that occur in the immediate vicinity of the vineyard property include Bradson, Tate, Ashe, and Hatboro. For detailed descriptions of soils, go to USDA-NRCS Official Soil Series Description View By Name and type in name of series.

Series	Map Unit	Description[2]
Hayesville	HyB	Hayesville loam 2-7% slopes
Hayesville	HyC	Hayesville loam 7-15% slopes
Edneyville	EdE	Edneyville fine sandy loam 15-25% slopes
Codorus	Co	Codorus loam (arkaqua)
Bradson	BaB	Bradson gravelly loam 2-7% slopes
Bradson	BaC	Bradson gravelly loam 7-15% slopes
Tate	TeC	Tate fine sandy loam 7-15% slopes
Ashe	AhF	Ashe stony sandy loam 15-45% slopes
Hatboro	Ha	Hatboro loam

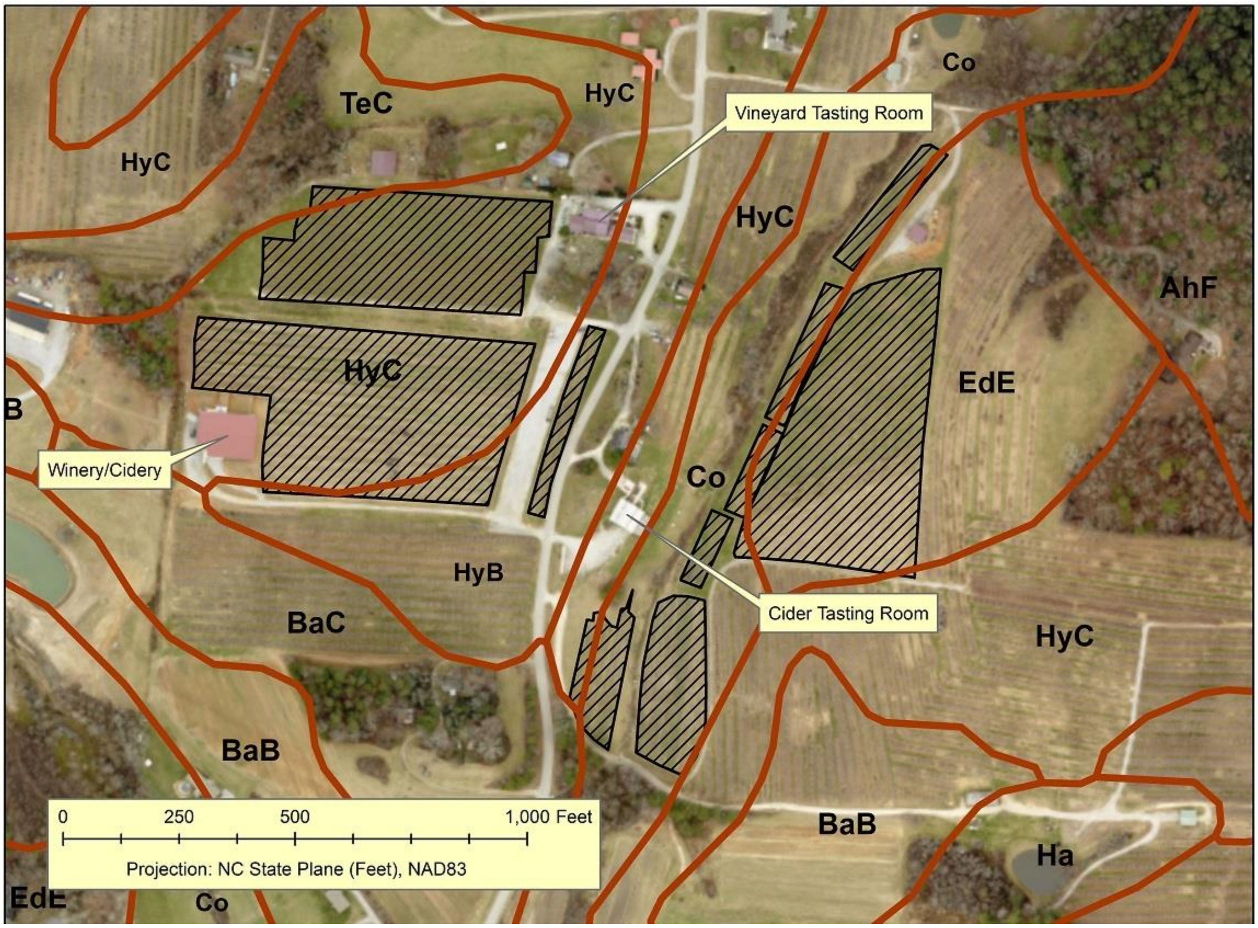

Figure 4-2. Soils of the St. Paul Mountain Vineyard and Appalachian Ridge Cidery. Hatched areas outline vineyard blocks. Red lines are soil unit boundaries.

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[2] To view ranges of soil components (sand, clay, and silt), see soil texture classification diagram in Appendix 1.

Stop 4. St. Paul Mountain Vineyards & Appalachian Ridge Cidery

Geomorphic Setting. The lowest elevation portions of the property are likely formed on overbank or alluvial deposits, having received fluvial inputs from Wolfpen Creek at some point. The higher elevation portions of the site have a more uncertain geomorphic setting. Some of the flat fields may be located on Pleistocene fluvial terraces that formed from downcutting in trunk streams. However, most of the vineyard blocks appear to be on an interfluve between the two headwater streams. Low relief on these streams likely minimized erosion over the past 200 years, increasing the quality of topsoil at the site.

References.

Davis, T. L., 1993. Geology of the Columbus Promontory, western Inner Piedmont, North Carolina, Southern Appalachians, *in* Hatcher , R. D. Jr., and Davis, T. L. , eds, Studies of Inner Piedmont geology with a focus on the Columbus Promontory: North Carolina Geological Survey, Carolina Geological Society Guidebook, p. 17-43.

Lemmon, R. E., 1973. Geology of the Bat Cave and Fruitland quadrangles and the Origin of the Henderson Gneiss, Western North Carolina [Ph.D. dissertation]: Chapel Hill, North Carolina, University of North Carolina, 145 p.

Moecher, D., Hietpas, J., Samson, S., and Chakraborty, S., 2011. Insights into southern Appalachian tectonics from ages of detrital monazite and zircon in modern alluvium: Geosphere, v. 7, No. 2, p. 1-19.

Stop #5: Stone Ashe Vineyards, Hendersonville, NC

Figure 5-1. Stone Ashe Vineyards. Hatched areas outline vineyard blocks.

Objectives. The recently opened Stone Ashe Vineyards (Figure 5-1) underwent an extensive vetting process by a soil scientist and a horticulturalist to determine its suitability for growing European *vinifera* grapes on steep mountain slopes. Mr. Hudson Little, the vineyard manager, will give us an overview of the process, which included the digging of 35 backhoe soil pits and boring of numerous auger cores, and will discuss recommendations that resulted from the evaluation. We will discuss the pros and cons of steep-slope and north aspect vineyards. Due to shortage of personnel, we will not be able to do traditional wine tastings, but glasses and bottles of wine will be available for purchase.

Background. Stone Ashe Vineyards was founded by Dr. Craig and Mrs. Tina Little of Charleston, SC, and opened in 2021. On July 29, 2022, USA Today announced that the vineyard had won its prestigious "#1 Best New American Winery of 2022," competing with 19 other vineyards, most of which were located on the west coast.

General Description.

Location:	Lat. 35.39532 Long. -82.40948 (Tasting room)
USGS Topo Quad (1:24K):	Fruitland, NC
Address:	736 Green Mountain Road, Hendersonville, NC 28792
Founder(s):	Craig and Tina Little
Vineyard Management:	Hudson Little

Stop #5: Stone Ashe Vineyards, Hendersonville, NC

Viticultural Characteristics.[1]

First Plantings:	2014
Vineyard size:	8.6-9.0 acres in 10 blocks
Elevation:	2423 feet mean elevation of vineyard blocks, which range from 2305 to 2520 feet
Slope of vineyard blocks:	41.4° mean value (88.2%). Range of all blocks 22.5-54.4° (41.4-139.7%)
Aspects of vineyard blocks:	

Aspects	Azimuths	Percentage
North	0-22.5°	11.05
Northeast	22.5-67.5°	34.21
East	67.5-112.5°	39.47
Southeast	112.5-157.5°	8.95
South	157.5-202.5°	4.74
Southwest	202.5-247.5°	0
West	247.5-292.5°	0
Northwest	292.5-337.5°	0
North	337.5-360.0°	1.58

GDD (F° units):	3176 (Winkler region/GDD zone III)
Mean annual temp:	54.9°F
Mean growing season temp:	65°F. 'Warm' category of Grapevine Climate/Maturity Groupings.
Mean annual frost-free days:	296
Est. length of growing season (days):	188
Mean annual precipitation:	57.3 inches
Mean growing season precipitation:	34.8 inches
Mean solar radiation ($MJm^{-2}day^{-1}$):	14.88
Est. last spring frost (mean date):	April 17
Est. first fall frost (mean date):	October 23
Grape varieties:	Cabernet Franc, Cabernet Sauvignon, Merlot, Petit Verdot, Sauvignon Blanc
Wine Styles:	Red and white varietals, red and white blends, left and right bank Bordeaux blends

Geological Setting. Stone Ashe Vineyard is located within the Tumblebug thrust sheet in the same granitic body of the Table Rock Plutonic suite seen Saturday at Stop #4 (St. Paul Mountain). Large colluvial boulders of the granitoid can be seen in the drainage ditch behind the tasting room. Outcrops can be viewed in the ditch along the entrance road. A body correlated with the Table Rock Plutonic Suite has a reported crystallization age of 435 Ma (T. W. Stern and J. W. Horton, unpublished US Geological Survey data, 1984).

Viticultural/Geomorphic Setting. Stone Ashe is located on the Blue Ridge plateau in the Crest of the Blue Ridge Henderson County AVA. The most striking characteristic of the vineyard is the high angle concave slopes of the vineyard blocks (Figures 5-2 and 5-3). The siting of the blocks on these steep slopes was purposeful, to replicate the characteristics of vineyards that the Littles grew to admire in their travels and vineyard visits in the USA and Europe. The slopes do pose risks of landslides and safety during mechanical maintenance procedures, for which specialized equipment has been developed. The steep slopes also

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[1] To view sources of data for Viticultural Characteristics and Soils, go to Appendix 1 at end of guidebook.

require that the row orientation within the blocks be parallel to the aspect of the slopes. This allows best air flow through the blocks for drying after rainfalls, for drainage of surface run-off, and for safer mechanical maintenance work. The site of the vineyard on the northeast flank of Green Mountain suggests that the vineyard property is subject to thermal belt temperature inversions, with cool evening air flowing down the northeast flank of Green Mountain and displacing warmer air from the valley of Mill Creek, which runs parallel to Green Mountain Road (Figure 5-3).

Figure 5-2. View to the east of Stone Ashe Vineyards showing high-angle slopes of vineyard blocks.

The WNW-trending linear ridgelines and valleys at Stone Ashe have an alignment similar to Hickory Nut Gorge where Hickory Creek has incised into the Blue Ridge Escarpment (see Stop 3, Fig. 3-3; and Stop 7 Fig. 7-1). This lineament swarm extends approximately 14.25 km (8.9 miles) to the WNW and includes the

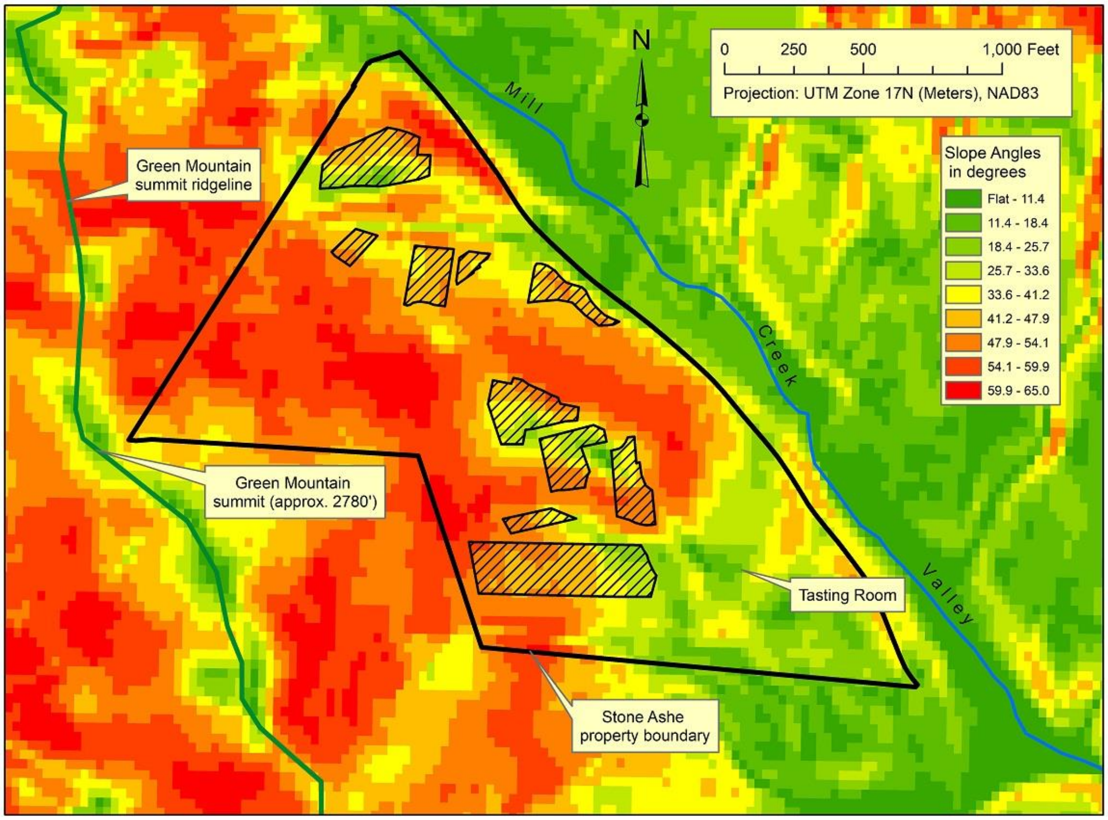

Figure 5.3. Slope map of the Stone Ashe vineyard blocks.

WNW-striking Mills Gap fault zone. Post-orogenic brittle fractures and lineaments in this region are consistent with this WNW trend (Wooten et al, 2022).

Soils. The vineyard blocks at Stone Ashe are planted in three soil series: Edneyville, Brevard, and Tusquitee (Figure 5-4). Other series that have been mapped in the immediate vicinity of the vineyard include Ashe, Tate, Tusquitee, Edneyville, Hayesville, and Bradson. For detailed descriptions of soils, go to USDA-NRCS Official Soil Series Description View By Name and type in name of series.

Series	Map Unit	Description[2]
Edneyville	EdF	Edneyville fine sandy loam 25-45% slopes
Edneyville	EdE	Edneyville fine sandy loam 15-25% slopes
Brevard	BrE	Brevard loam 15-25% slopes
Tusquitee	TsE	Tusquitee loam 15-25% slopes
Ashe	AhF	Ashe stony sandy loam 25-45% slopes
Ashe	AhG	Ashe stony sandy loam 45-70% slopes
Tate	TeB	Tate fine sandy loam 2-7% slopes
Tate	TeC	Tate fine sandy loam 7-15% slopes
Tusquitee	TsC	Tusquitee loam 7-15% slopes
Hayesville	HyE	Hayesville loam 15-25% slopes
Hayesville	HyC	Hayesville loam 7-15% slopes
Bradson	BaB	Bradson gravelly loam 2-7% slopes

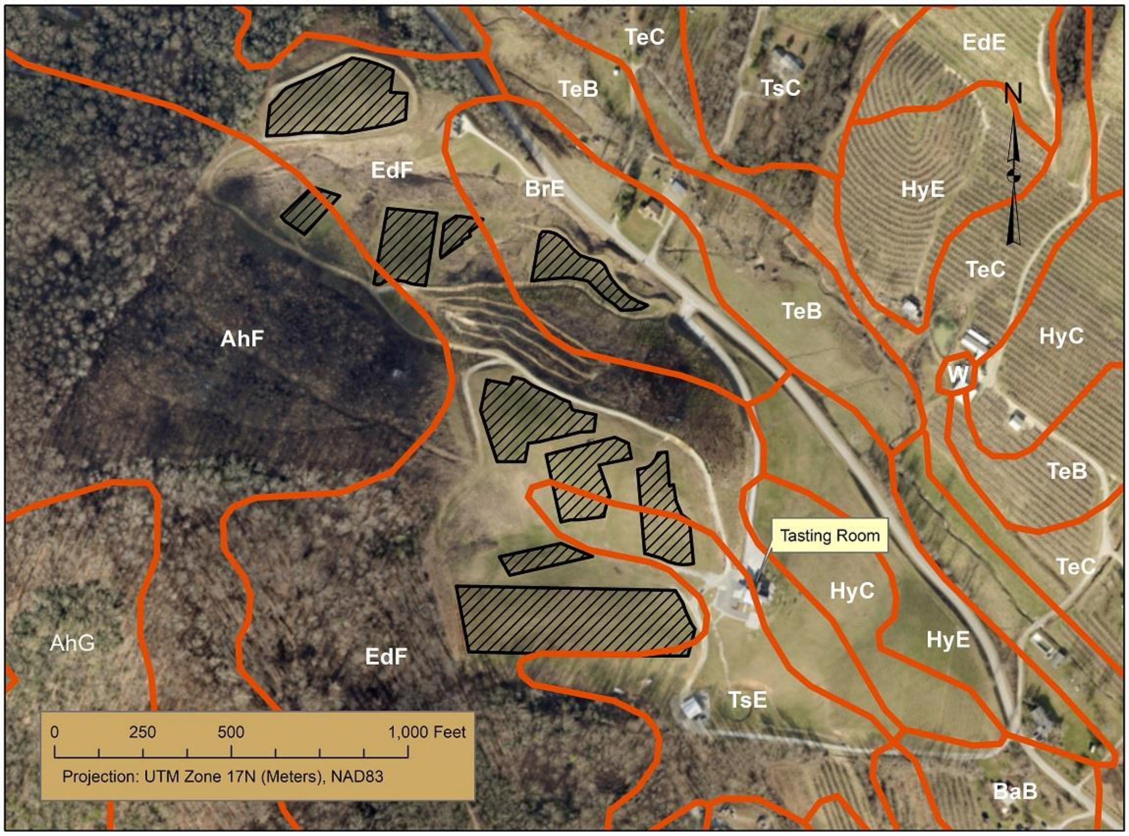

Figure 5-4. Soils of the Stone Ashe Vineyard. Hatched areas outline vineyard blocks. Red lines are soil unit boundaries.

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[2] To view ranges of soil components, see soil texture classification diagram in Appendix 1.

Stop #5: Stone Ashe Vineyards, Hendersonville, NC

The Stone Ashe vineyard blocks are located on a mix of gravity driven sedimentary deposits, which differentiates them from the other vineyards we have seen. Specifically, they are on a mixture of colluvium and alluvial fan deposits that form as a result of erosion from Green Mountain, on whose east slope they are located. For this reason, these soils are sandier and rockier than others that we have visited. Abandoned roads upslope of the site are visible in some images, which indicates that logging was common in the area. The site of the vineyard blocks likely experienced both erosion and received sediment from upper slopes. Human alteration of this relatively steep site likely influences the soils that are visible today.

Reference.

Wooten, R.M., Korte, D.M., Hill, J.S., Cattanach, B.L., Bauer, J.B., Prince, P., Waters-Tormey, C., Scheip, C.M., 2022, *in* Eppes, M.C., ed., Hickory Nut Gorge: A Natural Laboratory to Advance Our Understanding of Progressive Rock Failure, PRF2022-Progressive Failure of Brittle Rocks, Geological Society of America-Penrose Conference Field Trip Guide, 52p

Stop #6: Biltmore Estate Vineyards, Asheville, NC

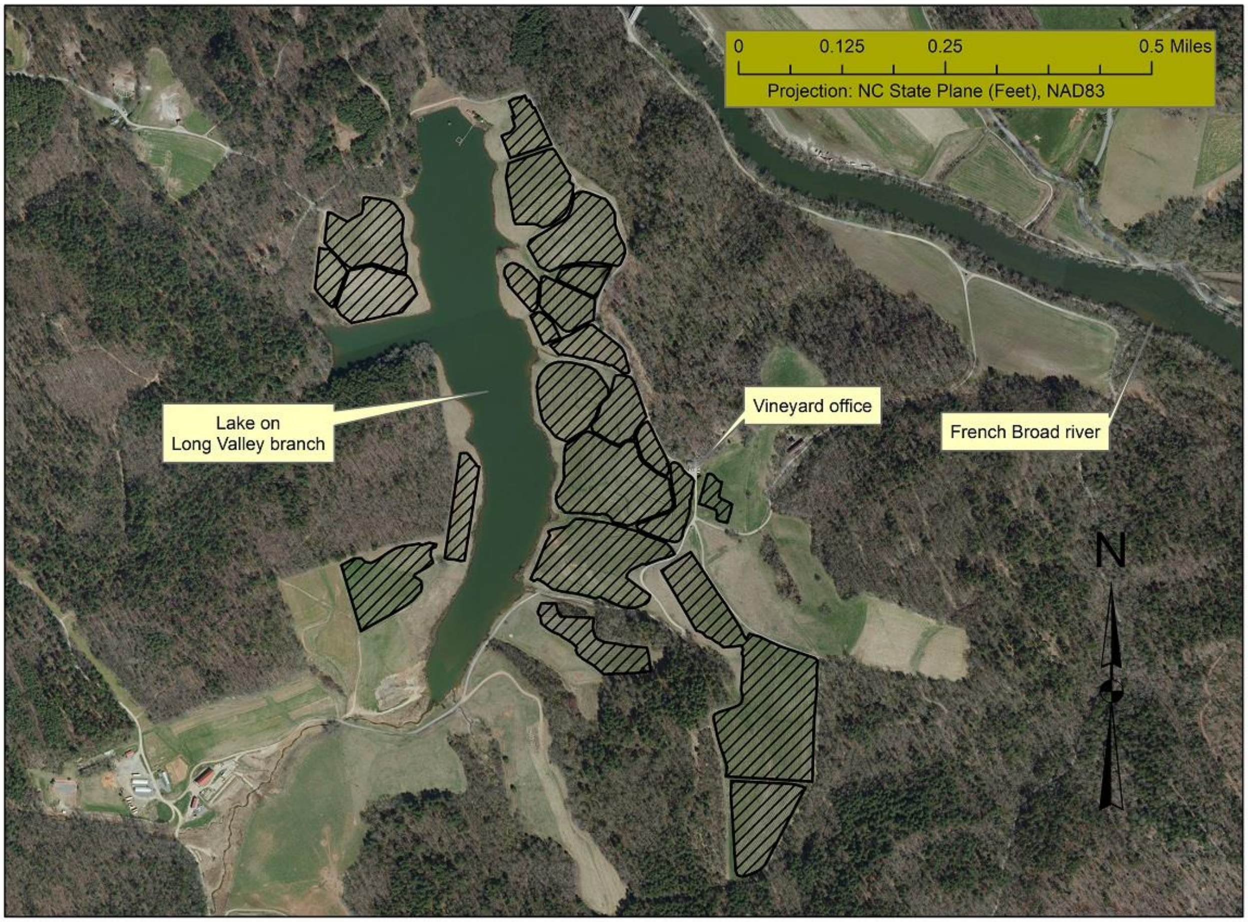

Figure 6-1. Biltmore Estate Vineyard. Hatched areas outline vineyard blocks.

Objectives. Though the winery at Biltmore Estate is well known and is a popular attraction for visitors to the Biltmore House, the vineyards are not open to the public. That we have been allowed to visit them and to hear about them from the vineyard staff is a great honor and a once-in-a-lifetime opportunity. The management staff will give us an overview of the interesting history and development of the site, which is the largest vineyard on the Blue Ridge plateau. We will discuss the setting along the French Broad River in the Asheville basin and its significance, and we will compare and contrast the location with the two AVAs we have visited previously. As a special treat, The Biltmore staff has graciously invited us for a pouring of their wines as we conclude our field trip at this last stop.

Background. The present Biltmore vineyard was the dream of Mr. William A. V. Cecil, the great-grandson of the founder of Biltmore Estate, George Washington Vanderbilt, who was himself a lover and collector of wines. In 1971, Mr. Cecil planted a small vineyard of French-American hybrid grapes near Biltmore House. The grapes were harvested and wine was made but Mr. Cecil was not satisfied with the outcome and sought advice from researchers at the University of California at Davis. At that time there was uncertainty about the suitability of *vinifera* grapes for the North Carolina climate. But the UC-Davis researchers assisted Mr. Cecil with advice on the latest viticultural technologies.

In the late 1970's, Mr. Cecil moved the vineyard to its present location on the west side of the estate and planted *vinifera* grapes. In 1977, he traveled to France and persuaded the noted wine-master Philippe

Stop #6: Biltmore Estate Vineyards, Asheville, NC

Jourdain to come to Asheville and oversee the development of Biltmore vineyards and winery. This turned out to be a masterful decision, as Jourdain played a major role in building a sustainable vineyard and winery that would become the Biltmore Estate Wine Company.

In the decades since its founding, Biltmore has grown and tested numerous grape varieties. Five vinifera cultivars have proven to be well-suited for the terroir of the Blue Ridge plateau and are the grapes we see today in the vineyard. Management continues to evaluate other varieties in a special test vineyard near the Winery. To expand its portfolio and craft the highest quality wines, Biltmore Estate Wine Company partners with select growers in North Carolina, California, and Washington.

General Description.

Location:	Lat. 35.54151, Long. -82.58096 (Vineyard office)
USGS Topo Quad (7.5-minutes):	Asheville, NC
Address:	702 Brevard Road, Asheville, NC 28806
Founder(s):	William A. V. Cecil
Vineyard Management:	Philip Oglesby
Winemaker:	Sharon Fenchak

Viticultural Characteristics.[1]

First Plantings:	circa 1977 at the present site
Vineyard size:	50 acres
Elevation:	2088 feet mean elevation of vineyard blocks, which range from 2030 to 2170 feet
Slope of vineyard blocks:	21.4° mean value (39.2%). Range of all blocks 0.84-42.1° (1.5-90.4%)
Aspects of vineyard blocks:	

Aspects	Azimuths	Percentage
North	0-22.5°	6.53
Northeast	22.5-67.5°	13.92
East	67.5-112.5°	18.69
Southeast	112.5-157.5°	11.36
South	157.5-202.5°	14.36
Southwest	202.5-247.5°	14.66
West	247.5-292.5°	8.88
Northwest	292.5-337.5°	7.22
North	337.6-360.0°	4.38

GDD (F° units):	3350 (Winkler region/GDD zone III)
Mean annual temp:	55.5°F
Mean growing season temp:	65°F. 'Warm' category of Grapevine Climate/Maturity Groupings.
Mean annual frost free days:	298
Est. length of growing season (days):	194
Mean annual precipitation:	46.6 inches
Mean growing season precipitation:	27.6 inches
Mean solar radiation ($MJm^{-2}day^{-1}$):	15.24

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[1] To view sources of data for Viticultural Characteristics and Soils, go to Appendix 1 at end of guidebook.

Stop #6: Biltmore Estate Vineyards, Asheville, NC

Est. last spring frost (mean date):	April 14
Est. first fall frost (mean date):	October 25
Grape varieties:	Cabernet Franc, Cabernet Sauvignon, Chardonnay, Merlot, Petit Manseng
Wine Styles:	Red and white varietals, red and white blends

Viticultural/Geomorphic Setting. Biltmore Vineyards is located on the Blue Ridge plateau in the Asheville basin (Bent Creek-French Broad River watershed). Due to the orographic effect of the Blue Ridge escarpment, the basin is the driest region of North Carolina, with a mean annual precipitation of around 37 inches. The mean growing season precipitation of the Biltmore vineyard is 27.6 inches, which is considered sufficient for the grapes being grown. The lake on Long Valley branch is used rarely for irrigation and is mainly for watering new planted vines and for frost control. The predominance of convex slopes in the vineyard (Figure 6-2 and Figure 6-3) is in stark contrast to the concave slopes we saw at Stone Ashe Vineyards.

Figure 6-2. Biltmore Estate vineyard looking southeast at convex slopes of vineyard blocks. Biltmore House in the upper left corner with stretch of French Broad River below it.

Geological Setting. Biltmore Estate vineyard is located north of the Brevard zone in the eastern Blue Ridge geological province. Bedrock is primarily metawacke with lesser amounts of schist and minor amphibolite (Miller and Fryer, 2008). These rocks are mapped as part of the Ashe Metamorphic Suite and are considered to be correlative with the upper Tallulah Falls formation further to the southwest and to the southeast in the Inner Piedmont (Hatcher et al, 1997).

Stop #6: Biltmore Estate Vineyards, Asheville, NC

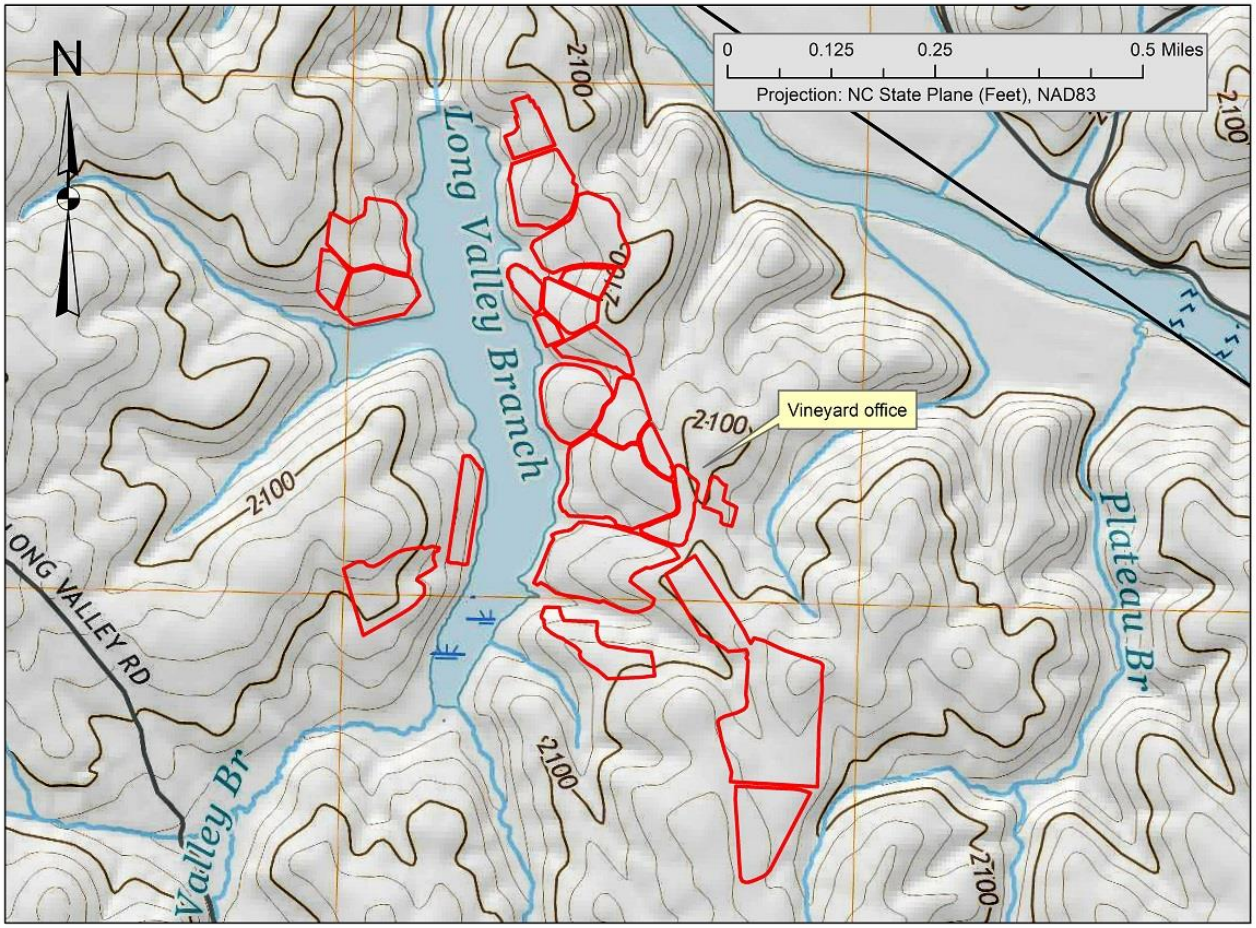

Figure 6-3. Hillshaded topographic view of the Biltmore Estate vineyard illustrating the predominantly convex slopes of the vineyard blocks, which are shown in red outlines.

Soils. Vineyard blocks at Biltmore vineyard are planted on two soil series: Evard-Cowee complex and Clifton (Figure 6-4). Other series in the immediate vicinity of the vineyard include: Tate, Udorthents, Iotla, Udorthents-Urban Land Complex, Biltmore, Rosman, Hemphill, Tate-Urban Land Complex, and French. The soils designated as “complexes” are areas in which two or more series are so similar and intermixed,

Series	Map Unit	Description[2]
Evard-Cowee complex	EwD	Evard-Cowee comolex, basin, 15-30% slopes, stony
Evard-Cowee complex	EwC	Evard-Cowee complex, basin, 8-15% slope, stony
Cllifton	CsC	Clifton sandy loam, 8-15% slopes
Clifton	CsB	Cliftpon sandy loam, 2-8% slopes
Tate	TaC	Tate loam, basin, 8-15% slopes
Tate	TaB	Tate loam, basin 2-8% slopes
Udorthents	Ud	Udorthents, loamy
Udorthents-Urban land complex	UfB	Udorthents-Urban land complex, 0-5% slopes, occasionally flooded
Biltmore	BeA	Biltmore loamy sand, 0-3% slopes, occasionally flooded
Rosman	RsA	Rosman fine sandy loam, 0-3% slopes, occasionally flooded
Hemphill	HpA	Hemphill loam, 0-3% slopes, rarely flooded
Tate-Urban Land complex	TmB	Tate-Urban land complex, 2-8% slopes
French	FrA	French loam, 0-3% slopes, occasionally flooded

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[2] To view ranges of soil components (sand, clay, and silt), see soil texture classification diagram in Appendix 1.

or in such small areal extent that it is impractical or impossible to map them separately. For detailed descriptions of soils, go to USDA-NRCS Official Soil Series Description View By Name and type in name of series.

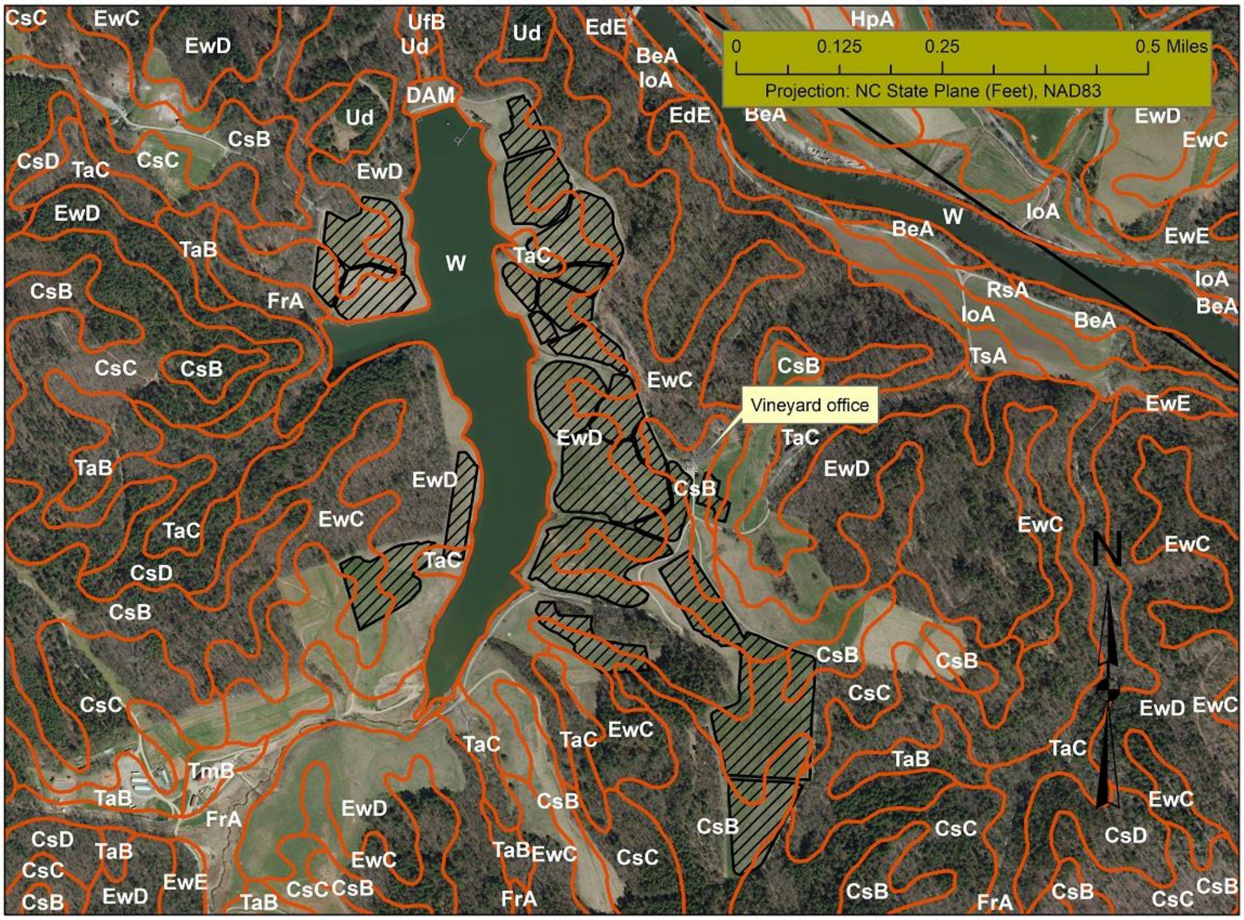

Figure 6-4. Soils of the Biltmore Estate Vineyard. Hatched areas outline vineyard blocks. Red lines are soil unit boundaries.

Biltmore vineyard blocks lie in a variety of landscape positions; most are on colluvial surfaces adjacent to the reservoir. These sites may have experienced erosion and/or received sediment from uplands. The southern and northwestern-most sites are slightly different and lie on interfluves that have likely been eroded since Euro-American settlement.

References.

Miller, W. M.,and Fryer, K.H., 2008, Bedrock Geologic Map of the Asheville 7.5-minute Quadrangle. Buncombe County, North Carolina: North Carolina Geological Survey Geologic Map Series 14, 1:24,000-scale.

Hatcher, R. D., Jr., 2002, An Inner Piedmont Primer, *in* Hatcher , R. D., Jr., and Bream, B. R., eds., Inner Piedmont geology in the South Mountains-Blue Ridge Foothills and the southwestern Brushy Mountains, central-western North Carolina: North Carolina Geological Survey, Carolina Geological Society annual field trip guidebook, p. 1-18.

Stop #7: Burntshirt Mountain High Vineyard, Bat Cave, NC

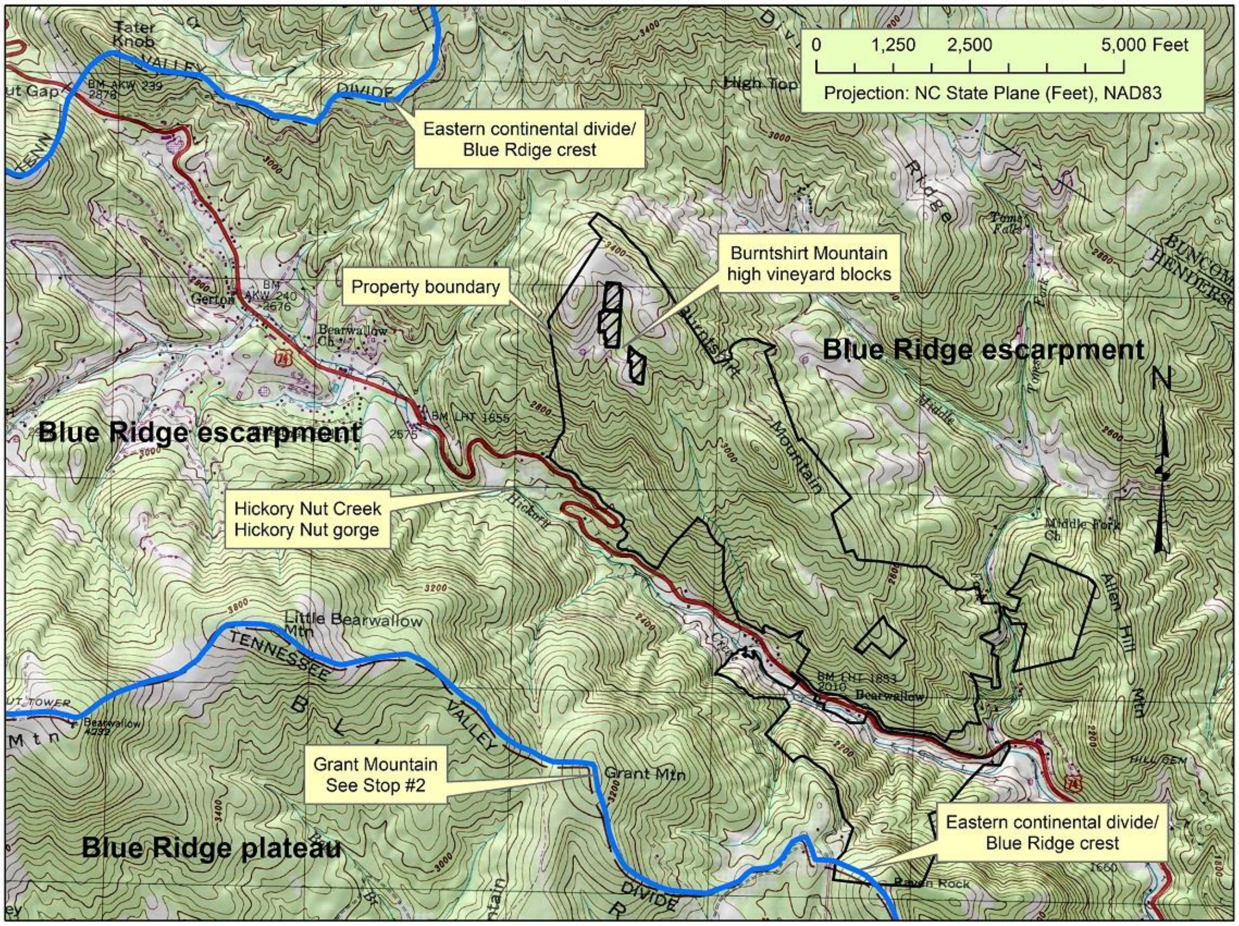

Figure 7-1. Hillshaded topographic view of Burntshirt high satellite vineyard on Burntshirt Mountain.

Objectives. The high Burntshirt vineyard (Figure 7-1) is one of the most beautiful settings in eastern America, with a spectacular view of the Blue Ridge plateau and escarpment, just south of the summit of Little Pisgah Mountain (on the Black Mountain 7.5-minute topo sheet). We had hoped to offer a special visit to the high vineyard, but recent inspection of the road to the site indicated that the route had suffered major degradation due to heavy rainfall during the spring months and would be difficult to navigate safely. Our normal activity buses would not be able to make the frequent hairpin turns along the road, which is a private dirt-gravel road for most of the way. Please do not attempt to visit this site without permission or unaccompanied; it is private property, on a hazardous road, with poor to non-existent cell phone reception, and a locked gate. Mr. David Fleming, manager of Burntshirt Vineyards, has graciously agreed to speak to us about the high vineyard during our Friday evening social hour and dinner.

Background. The high vineyard on Burntshirt Mountain is part of the Burntshirt Vineyard located at 2695 Sugarloaf Road in Hendersonville, NC. Founded by owners Lemuel and Sandra Oates, the vineyard at Sugarloaf Road and the high satellite vineyard began as a business to grow and sell grapes. On realizing the quality of their fruit, the Oates decided to start a winery and bottle their estate-grown wines. The two locations have a total of 39 acres of grapes under cultivation – 30 acres on Sugarloaf Road and nine acres on Burntshirt Mountain.

Stop #7: Burntshirt Mountain High Vineyard, Bat Cave, NC

General Information.

Location:	Long. -82.328551, Lat. 35.480105
Address:	2164 Gerton Hwy., Bat Cave, NC 28710
Founders/Owners:	Lemuel and Sandra Oates
Vineyard Mgmt:	David Fleming
Winemaker:	David Fleming

Viticultural Characteristics.[1]

First Plantings:	???
Vineyard Size:	Nine acres
Elevation:	3337 feet (mean elevation of vineyard blocks, which range from 3289-3413 feet)
Slope of vineyard blocks:	22.9° mean value (42.2%). Range of all blocks Flat-38.0° (0-78.1%)
Aspects of vineyard blocks:	

Aspects	Azimuths	Percentage
North	0-22.5°	0
Northeast	22.5-67.5°	0
East	67.5-112.5°	0.4
Southeast	112.5-157.5°	20.0
South	157.5-202.5°	21.4
Southwest	202.5-247.5°	52.9
West	247.5-292.5°	4.9
Northwest	292.5-337.5°	0.4
North	337.6-360.0°	0

GDD (F° units):	3057 (Winkler region/GDD zone III)
Mean annual temp:	54.3°F
Mean growing season temp:	64°F. 'Warm' category of Grapevine Climate/Maturity Groupings.
Mean annual frost-free days:	294
Est. length of growing season (days):	184
Mean annual precipitation:	61.0 inches
Mean growing season precipitation:	36.7 inches
Mean solar radiation ($MJm^{-2}day^{-1}$):	14.75
Est. last spring frost (mean date):	April 19
Est. first fall frost (mean date):	October 21
Grape varieties:	Riesling, Cabernet Franc, Chardonnay, Traminette, Vidal Blanc, Grüner Veltliner
Wine Styles:	Red and white estate varietals and blends, dry rosé, blended and varietal dessert wines, apple wine

Viticultural/Geomorphic Setting. The Burntshirt high vineyard is in the Blue Ridge escarpment in the Crest of the Blue Ridge Henderson County AVA. At 3400 feet of elevation, the property is the highest vineyard in the AVA and one of the highest in eastern North America. As such, a major issue is the danger of late spring and early fall frosts. Nevertheless, the vineyard blocks have an excellent southern aspect and

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[1] To view sources of data for Viticultural Characteristics and Soils, go to Appendix 1 at end of guidebook.

protection from cold winds by the peculiar wrap-around top of Burntshirt Mountain, which almost encases the vineyard blocks and forms a natural south-southeast-trending "drainage chute." Could this "cirque-like" feature be the head of a landslide? Situated between higher elevations to the north and lower elevations in the valley of Hickory Nut Creek, the high vineyard is ideally situated for thermal belt temperature inversions, a situation that would offer further protection from cold air developed during the spring and early fall. According to the owners the site's main problem is not climate or weather but bears, 12 of which have been seen on wildlife cameras mounted in the vineyard. Despite its elevation, the temperature-related characteristics of the site are not radically different from the lower elevation areas of the Blue Ridge plateau.

The distinct WNW-trending linear ridgelines and valleys here (Figure7-1) are within a lineament swarm related to post-orogenic brittle fractures in this region as exemplified by Hickory Nut Gorge (Wooten et al, 2022).

Geological Setting. The high-elevation Burntshirt Vineyard is located in the Henderson Gneiss (Figure 7-2) within the Tumblebug thrust sheet. The Henderson gneiss is one the largest plutonic bodies in the southeast and has a crystallization age of approximately 447 Ma (Moecher et al., 2011). The large granitic to granodioritic body was originally termed the "Henderson augen[2] gneiss." It received this designation because of its characteristic K-feldspar porphyroclasts that have been rounded into ovoid shapes by high temperature ductile deformation.

Figure 7-2. Henderson gneiss atop Burntshirt Mountain. Car key for scale.

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[2] "Augen" is the German word for "eyes."

Stop #7: Burntshirt Mountain High Vineyard, Bat Cave, NC

Soils. The three vineyard blocks on Burntshirt Mountain are located on two soil series: Tusquitee and Porters (Figure 7-3). Other series that occur in the immediate vicinity of the vineyard include Ashe, Ashe-Rock outcrop complex, Evard, Tusquitee, and Edneyville. For detailed descriptions of soils, go to USDA-NRCS Official Soil Series Description View By Name and type in name of series.

Series	Map Unit	Description[3]
Tusquitee	TuE	Tusquitee stony loam, 15-25% slopes
Tusquitee	TuF	Tusquitee stony loam, 25-45% slopes
Tusquitee	TuC	Tusquitee stony loam, 7-15% slopes
Porters	PoE	Porters stony loam, 15-25% slopes
Porters	PoF	Porters stony loam, 25-45% slopes
Ashe	AhG	Ashe stony sandy loam, 45-70% slopes
Ashe	AhF	Ashe stony sandy loam, 25-45% slopes
Evard	EwE	Evard soils, 15-25% slopes
Ashe-Rock outcrop complex	ArG	Ashe-Rock outcrop complex, 15-70% slopes
Edneyville	EdE	Edneyville fine sandy loam, 15-25% slopes
Edneyville	EdF	Edneyville fine sandy loam, 25-45% slopes

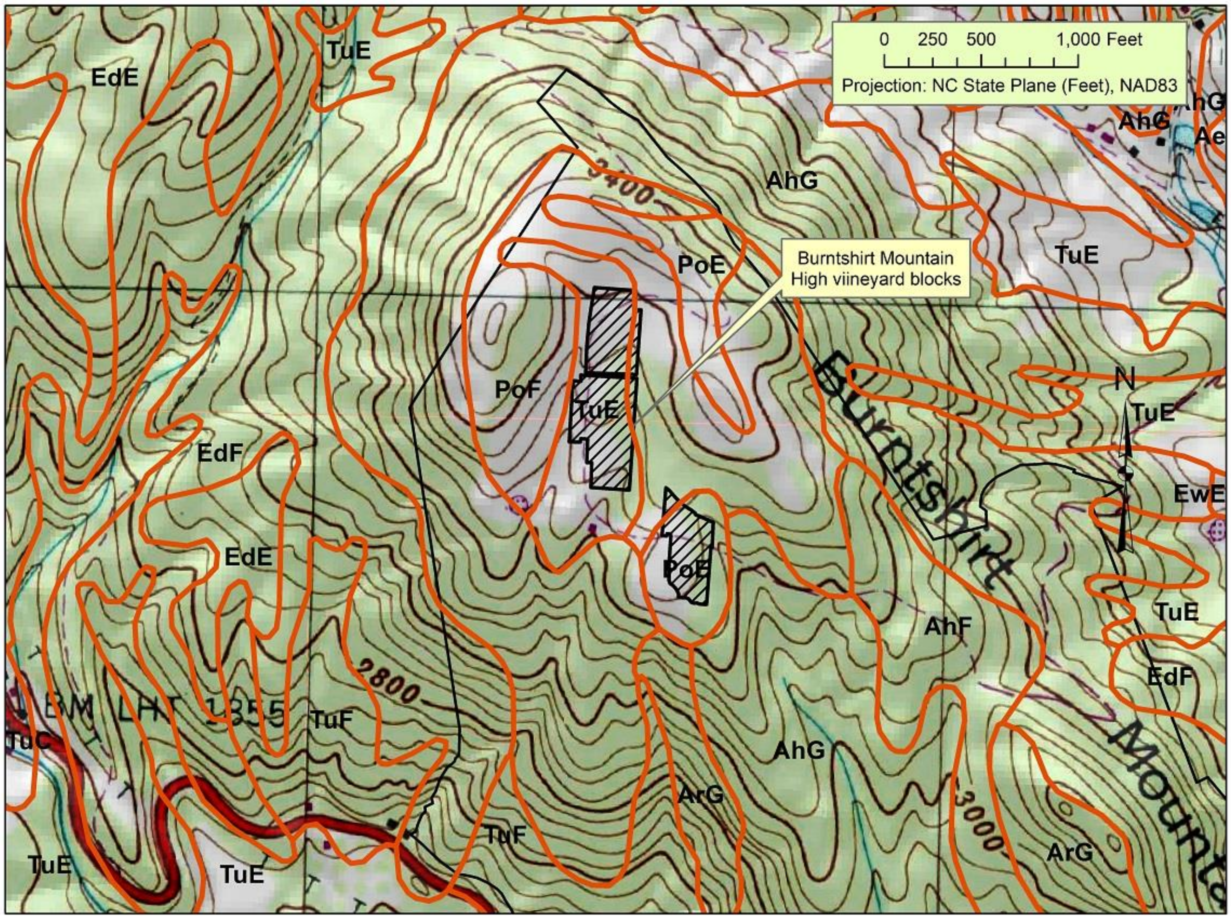

Figure 7-3. Soils of the Burntshirt high vineyard. Hatched areas outline vineyard blocks. Red lines are soil unit boundaries.

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[3] To view ranges of soil components (sand, clay, and silt(, see soil texture classification diagram in Appendix 1.

Stop #7: Burntshirt Mountain High Vineyard, Bat Cave, NC

Location of the vineyard blocks at or near the top of Burntshirt Mountain will have an impact on the thickness and stone content of the soils there. Soils on mountaintops tend to be thin because they erode faster than parent material can weather, at least relative to downslope soils, which may thicken as a result of downslope movement. We would expect the depth to saprolite or bedrock here to be less than at lower angle slopes. Soils will be rocky due to slow weathering and/or cobble excavation from tree throws. Small, ground level patches of Henderson gneiss are exposed throughout the Burntshirt vineyard blocks and attest to the thinness and stoniness of the soils.

Reference.

Wooten, R.M., Korte, D.M., Hill, J.S., Cattanach, B.L., Bauer, J.B., Prince, P., Waters-Tormey, C., Scheip, C.M., 2022, *in* Eppes, M.C., ed., Hickory Nut Gorge: A Natural Laboratory to Advance Our Understanding of Progressive Rock Failure, PRF 2022 - Progressive Failure of Brittle Rocks, Geological Society of America-Penrose Conference Field Trip Guide, 52p.

Appendix 1. Notes on Sources of Vineyard Characteristics and Soils

Introduction.
For each vineyard stop, we have assembled or calculated a standard set of characteristics, including data on soils. Some of the data is derived directly from online sources, while other characteristics are derived from calculations, estimates, or interpretations by the authors based on terrain or climate datasets from the US Geological Survey,[1] National Centers for Environmental Information,[2] the Prism Climate Group at Oregon State University,[3] or the Web Soil Survey site of the US Dept. of Agriculture.[4]

Viticultural Characteristics.

First Plantings:	Information provided by winegrowers or from vineyard websites.
Vineyard size:	Calculated from vineyard block outlines interpreted by author using ArcGIS Spatial Analyst extension, or from data supplied by winegrower.
Elevation:	Derived from USGS Digital Elevation Models (DEMs) using ArcGIS Spatial Analyst extension.
Slope of vineyard blocks:	Calculated from USGS DEMs using ArcGIS Spatial Analyst extension.
Aspects of vineyard blocks:	Calculated from USGS DEMs using ArcGIS Spatial Analyst extension.
GDD (F° units):	Calculated from Prism Climate Group gridded temperature normals (1991-2020) using ArcGIS Spatial Analyst extension.
Mean annual temp:	From Prism Climate Group 1991-2020 temperature normals.
Mean growing season temp:	Calculated from Prism Climate Group 1991-2020 temperature normals using ArcGIS Spatial Analyst extension.
Mean annual frost free days:	From National Centers for Environmental Information (NCEI) 1981-2010 climate normals.
Est. length of growing season (days):	Estimated by Inverse Distance Weighting of NCEI 1981-2010 climate normals using ArcGIS Spatial Analyst extension.
Mean annual precipitation:	From Prism Climate Group 1991-2020 gridded climate normals.
Mean growing season precipitation:	Calculated from Prism Climate Group 1991-2020 gridded climate normals using ArcGIS Spatial Analyst extension.

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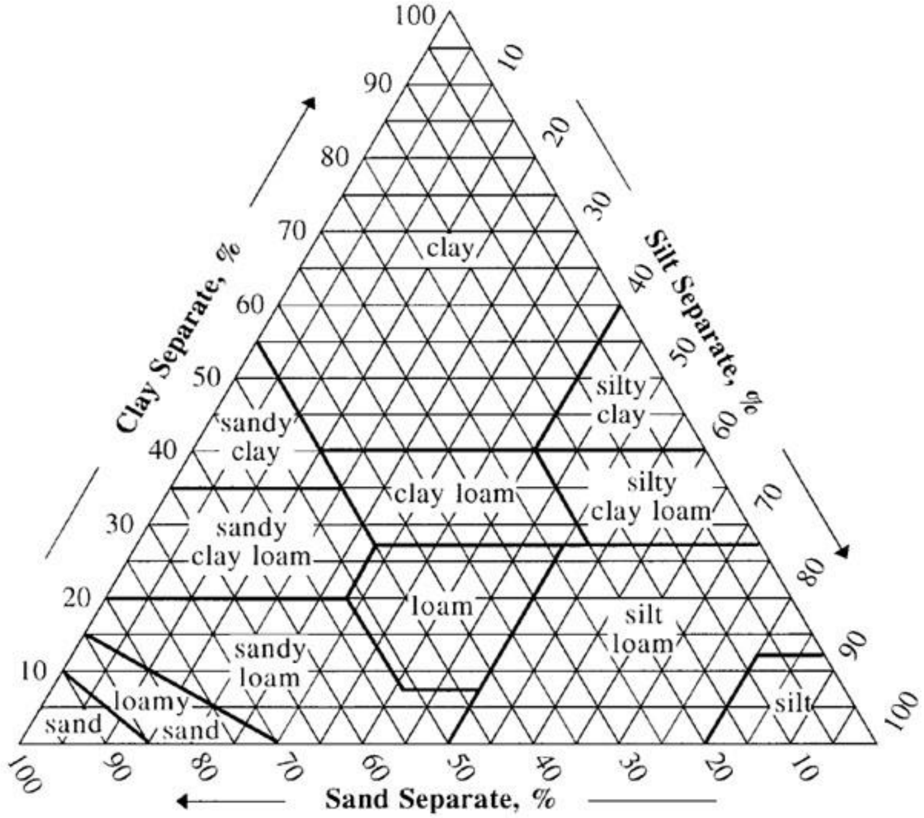
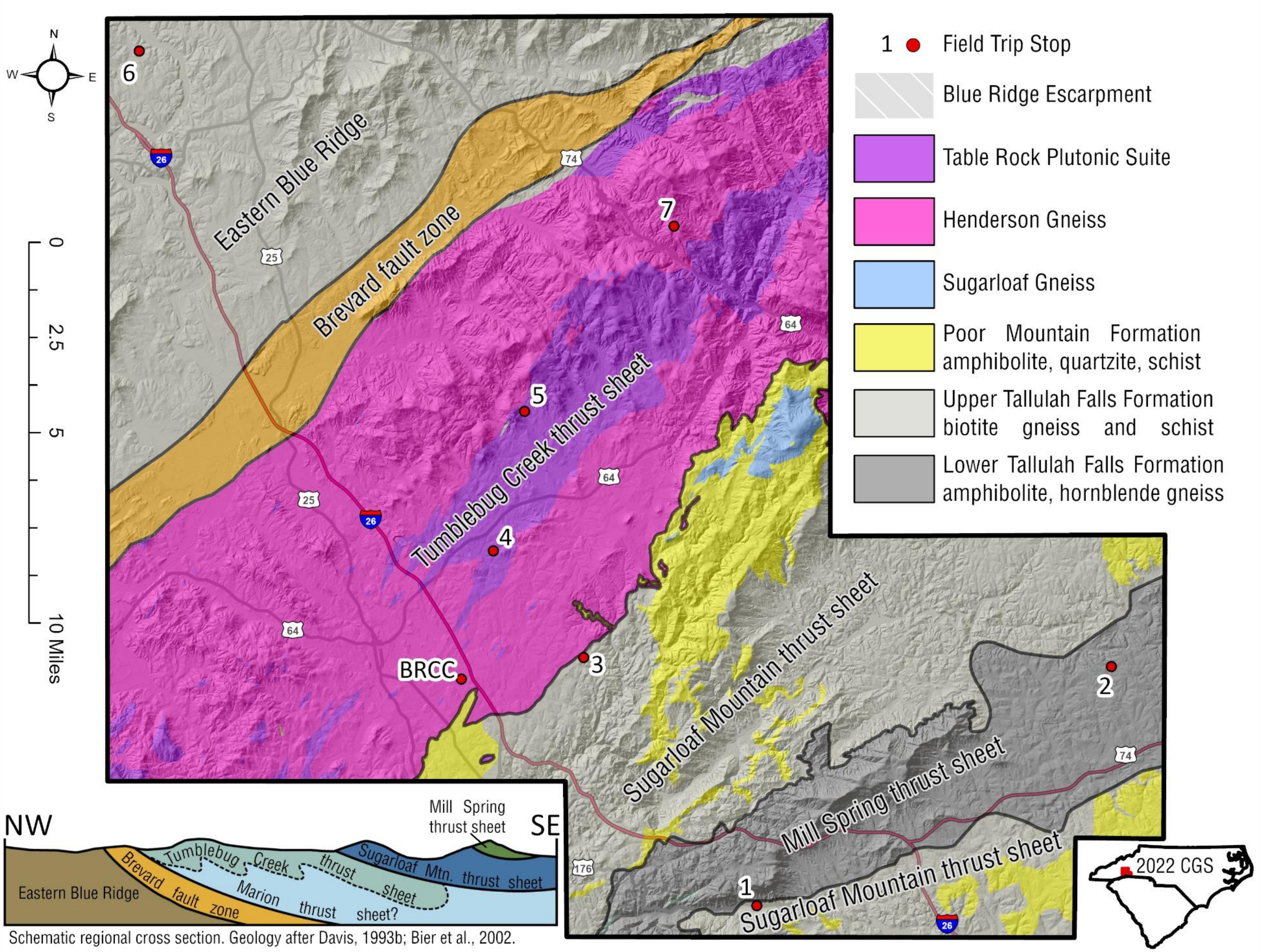
[1] 1 meter Digital Elevation Models (DEMs) - USGS National Map 3DEP Downloadable Data Collection - Catalog
[2] https://www.ncei.noaa.gov
[3] https://www.prism.oregonstate.edu
[4] https://websoilsurvey.nrcs.usda.go

Appendix 1. Notes on Sources of Vineyard Characteristics and Soils

Mean solar radiation ($MJm^{-2}day^{-1}$):	From Prism Climate Group 1991-2020 gridded climate normals.
Est. last spring frost (mean date):	Estimated by Inverse Distance Weighting of NCEI 1981-2010 climate normals using ArcGIS Spatial Analyst extension.
Est. first fall frost (mean date):	Estimated by Inverse Distance Weighting of NCEI 1981-2010 climate normals.
Grape varieties:	From vineyard websites and conversations with winegrowers.
Wine Styles:	From vineyard websites and conversations with winegrowers.
Soils Data:	All soil data is from the online Web Soil Survey site of the US Dept of Agriculture.



USDA Soil Texture Classification Diagram.



Schematic regional cross section. Geology after Davis, 1993b; Bier et al., 2002.