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

88 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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