

# Soil production and the soil geomorphology legacy of Grove Karl Gilbert

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## Abstract

Geomorphologists are quantifying the rates of an important component of bedrock's weathering in research that needs wide discussion among soil scientists. By using cosmogenic nuclides, geomorphologists estimate landscapes' physical lowering, which, in a steady landscape, equates to upward transfers of weathered rock into slowly moving hillslope-soil creep. Since the 1990s, these processes have been called "soil production" or "mobile regolith production". In this paper, we assert the importance of a fully integrated pedological and geomorphological approach not only to soil creep but to soil, regolith, and landscape evolution; we clarify terms to facilitate soil geomorphology collaboration; and we seek a greater understanding of our sciences' history. We show how the legacy of Grove Karl Gilbert extend across soil geomorphology. We interpret three contrasting soils and regoliths in the USA's Southern Piedmont in the context of a Gilbert-inspired model of weathering and transport, a model of regolith evolution and of nonsteady systems that liberate particles and solutes from bedrock and transport them across the landscape. This exercise leads us to conclude that the Southern Piedmont is a region with soils and regoliths derived directly from weathering bedrock below (a regional paradigm for more than a century) but that the Piedmont also has significant areas in which regoliths are at least partly formed from paleo-colluvia that may be massive in volume and overlie organic-enriched layers, peat, and paleo-saprolite. An explicitly integrated study of soil geomorphology can accelerate our understanding of soil, regoliths, and landscape evolution in all physiographic regions.

**Abbreviations:**  $+V_t$ , removals via transport; CN, cosmogenic nuclides; SCS, Soil Conservation Service; TCN, terrestrial (or in situ) cosmogenic nuclides;  $-V_t$ , inputs via transport;  $V_w$ , regolith production.

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## 1 | INTRODUCTION

Although the superficial layer of vegetable mold ... is no doubt of the highest antiquity, yet in regards to its permanence ... its component particles are in most cases removed at not a very small rate, and are replaced by others due to the disintegration of the underlying materials.

*Charles Darwin (1882)*

Part of the great intellectual fascination with soils derives from their extreme diversity and from the many scientific disciplines required to understand even a single profile. Because the soil, ecosystem, and critical zone sciences build from many disciplines (Richter & Billings, 2015), the circulation of concepts, data, and models depends on effective communication and collaboration. In this paper, we examine recent developments in geomorphology that have important implications for pedology, namely geomorphologists' research into what they call "soil production" or "mobile regolith production." The research is technical and has developed terminology, methodology, and a modeling context that has not facilitated communication among the community of Earth surface scientists. As pedologists and geomorphologists have much to contribute to each other's work, one purpose of this paper is to clarify the terminology and introduce methods and models with regard to soil and mobile-regolith production research. The potential for this research has been demonstrated in a variety of recent and important publications (Amundson, Heimsath, Owen, Yoo, & Dietrich, 2015; Dixon, Heimsath, & Amundson, 2009; Stockmann, Minasny, & McBratney, 2014; Wang et al., 2018; Yoo & Jelinski, 2016). We also wrote this paper to reinforce, if not rekindle, the soil geomorphology of Ruhe (1974) and many others (Holliday, 2006) who argued for integration of these two fundamental Earth sciences (Birkeland, 1984, 1990; Gerrard, 1981; Jungerius, 1985; McFadden & Knuepfer, 1990; Schatzl & Thompson, 2015; Zinck et al., 2016).

Since the 1990s, geomorphologists have been estimating rates of soil production in research that has important implications for pedology and the soil sciences as a whole. Soil production has a specific technical meaning that is easily misconstrued, given its similarity to terms such as soil development, soil formation, and soil evolution. Table 1 contains brief definitions of 12 commonly used terms and is intended to promote communication among scientists interested in both soils and geomorphology. Hereafter, use of the 12 terms in Table 1 is followed by a number in parentheses that refers to the definition in Table 1. Geomorphologists use soil production (9) as the estimated rate at which bedrock is physically added from below to slowly moving colluvial layers on hillslopes that are taken to be in a steady state and thus it also represents the physical lowering of bedrock by weath-

### Core Ideas

- Soil geomorphology can advance the sciences of pedology and landscape evolution.
- We propose a Gilbert-inspired conceptual model for soil and regolith evolution.
- The USA's ancient Piedmont may have many soils formed within paleo-colluvium.

ering. Soil production (9) is also known as mobile regolith production (9).

Although pedologists have discussed soil production (9) (e.g., Amundson et al., 2015; Dixon et al., 2009; Humphreys & Wilkinson, 2007; Minasny & McBratney, 2001; Schatzl & Thompson, 2015; Stockmann et al., 2014; Wang et al., 2018; Yoo & Jelinski, 2016; Yoo, Amundson, Heimsath, & Dietrich, 2006), soil production research deserves much wider attention across the soil sciences because it is highly relevant to soil formation and soil evolution (7). Cosmogenic methods that estimate rates of soil production (9) have been most commonly used on divergent, convex-up hillslopes. Here, we assert that soil geomorphology collaboration can help extend soil production research across the Earth's diverse soils and landscapes.

Soil production (9) cannot be fully appreciated without reference to Grove Karl Gilbert, the 19th-century geologist and contemporary of Eugene Hilgard and Vasily Dokuchaev. As discussed by Humphreys and Wilkinson (2007), a variety of historically contingent reasons limited Gilbert's ideas (1877, 1909) from circulating as widely as they might have. It was not until well into the 20th century before Gilbert's concepts on weathering and transport on hillslopes were closely examined at all (Culling, 1963; Jahn, 1968). Gilbert's (1877) nonlinear relationship between soil (4) depth and weathering rate was first illustrated (Figure 1) by Carson and Kirkby (1972). Even still, at the same time that Vasily Dokuchaev was studying chernozems across the steppes of Russia (in 1883), Gilbert (1877, 1909) was studying soil (4), weathering, and erosion across the United States' western deserts and mountain ranges in work that, even today, has fundamental implications not only for geomorphology but for pedology as well. Here we propose a Gilbert-inspired conceptual model of regolith evolution (12) as a broadly applicable model for the evolution of Earth's soils, landscapes, and critical zones (Brantley et al., 2017).

Overall, our objective is to rekindle collaboration between pedologists and geomorphologists in ways that benefit both disciplines. More specifically, we (i) examine recent approaches and rates of what geomorphologists call soil production (9) and consider how pedology can contribute to future soil production (9) research, (ii) evaluate the scientific

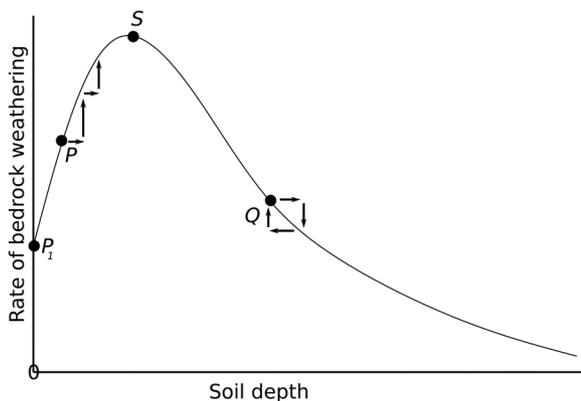
**TABLE 1** Historical and contemporary usages of soil (1–4); regolith, soil, and weathering profiles (5, 6, 8); soil formation and evolution (7); soil and mobile regolith production and the soil production function (9–11); and regolith production and evolution (11, 12) in the literature of pedologists, ecologists, engineers, and geologists

Number	Terms	Definition
1	Soil, as used by pedologists, ecologists, and geologists (modified from van Es [2017])	The layers of generally loose mineral and organic material that reside on the surface of landscapes that develop from geologic and biologic materials (bedrock or sediment and organic matter) in response to physical, chemical, and biological processes; that hold and transmit solids, liquids, and gases; and that evolve over time as they support and are affected by biota and humans. Soil is composed of distinctive layers called horizons (e.g., O, A, E, B, and C horizons), which form soil profiles (6) that vary across the landscape. The base of the soil is often indistinct, disappearing into weathering rock or sediments.
2	Soil, as used by engineers	Unconsolidated material of any size above the bedrock (Hansen, 1984), be it sediment, soil (1, 2, 3), regolith (5), or mobile regolith (11).
3	Soil as used by some geomorphologists, specifically in the context of soil production (9)	Mobile regolith in transport down a slope, not including the underlying soil profile (6) and regolith (5) that is weathering in situ (in place) (Anderson & Anderson, 2010; Dietrich et al., 1995; Heimsath et al., 1997; McKean et al., 1993). Also known as hillslope colluvium, soil creep, and hillslope sediment (Daniels & Hammer, 1992). Relict rock structure is absent in this soil (3) because of movement and mixing often by biota, even though the materials are derived from the underlying weathering bedrock or sediment.
4	Soil, as in Gilbert's (1877) soil	Regolith (5), in the context of and following Gilbert (1877) and Merrill (1897). This usage of soil (4) is also found throughout the 20th century [e.g. in Carson and Kirkby (1972)], though by 1909, Gilbert was using "regolith" and "soil creep" in his studies of the convexity of hillslopes. Richter and Markewitz (1995) used soil like Gilbert (1877) as identical to regolith.
5	Regolith, used by pedologists and geomorphologists	The mantle of unconsolidated geologic material whatever its origin, whether bedrock or "drifted by wind, water, or ice" (Merrill, 1897), and weathered to any degree (Anderson & Anderson, 2010). Derived from $\rho\eta\gamma\omicron V$ ( <i>rhegos</i> ), Greek for "rug" or "blanket", and $\lambda\iota\theta\omicron V$ ( <i>lithos</i> ), meaning "stone"; it includes the soil profile (6).
6	Soil profile, used most commonly by pedologists	The vertical section of the soil (1, 3) and all its horizons, O, A, E, B, and C (Soil Science Society of America, 2008) that contrast in color, texture, structure, mineralogy, chemistry, biota, biogeochemistry, pedoturbation, and patterns of inherited rock structure. The base of the soil profile often has an indistinct boundary, blurring into the biogeochemically and physically fractured weathered geologic substratum. The solum, sometimes called "true soil", refers to the upper soil profile from the A through to the B horizons. The soil profile includes the O to C horizons.
7	Soil formation or soil evolution, used by pedologists, ecologists, and geologists	The temporal and spatial development of a soil profile (6), soilscape, or soil landscape, as a function of climatic, biotic, geomorphologic, geologic, temporal, and human factors (Buol et al., 2011; Jenny, 1941; Richter & Yaalon, 2012). Johnson and Watson-Stegner (1987) emphasize the polygenetic evolution of soil (1) and state that the processes operate to progressively and regressively alter the total depth of the profile (6) and the thicknesses of individual horizons (Johnson et al., 2005).
8	Weathering profile, used by critical zone scientists, geophysicists, geochemists, geomorphologists, and pedologists	The vertical cross-section of the regolith (5), with all its layers from the upper soil profile (6) downward through the physically, chemically, and biologically altered geologic substrata to the unweathered protolith, either sediment or bedrock [definition slightly modified from Eggleton, (2001)]. Closely related to the soil profile (6) but including all layers of initial weathering and the very beginnings of the preconditioning of protolith (St. Clair et al., 2015). Also called the belowground critical zone.
9	Soil production or mobile regolith production, as used by geomorphologists	The conversion of bedrock, saprolite, or subsoil horizons [i.e., immobile regolith (5)] to gravitationally mobile material, be it called soil (3), mobile regolith (11), or colluvium (Anderson & Anderson, 2010; Dietrich et al., 1995; Heimsath et al., 1997; McKean et al., 1993). The generation of mobile material by the detachment of nonmobile saprolite or weathered or fresh bedrock, through lateral translation and mixing. See Anderson and Anderson (2010), who used the phrase "mobile regolith production" rather than "soil production" to reduce potential confusion with definitions of soil (1, 3).

(Continues)

TABLE 1 Continued

Number	Terms	Definition
10	Soil production function (SPF), as used by geomorphologists	The quantitative dependence and relations of soil production (9) rates with local soil (3) depth (mass). The SPF may hypothetically be humped (meaning the rates reach a maximum at some finite soil depth) and can be estimated via cosmogenic nuclides analyses (Heimsath et al., 1997). The SPF is a function of rock type, climate, biota, geomorphology, and time, which govern the detachment rate of nonmobile to mobile material.
11	Regolith production and regolith production function	The conversion of bedrock or sediment into regolith (5) via physical, chemical, and biological weathering reactions. This concept was inspired by Gilbert and the regolith production function is hypothetically nonlinear, as proposed by Carson and Kirkby (1972), Gilbert (1877), and Ahnert (1998). Ahnert (1998) modeled the nonlinear function and suggested that although physical weathering rates might decline exponentially with regolith depth, chemical and biological weathering may have a decidedly humped relation.
12	Regolith evolution	Regoliths (5) evolve as they are fed from below (by weathering and regolith production) and are affected by geologic substrata, human forcings, and biotic, climatic, and geomorphologic processes that regulate the transport of the weathering products' additions and removals. Regolith evolution ebbs and flows and is characterized by dynamic equilibria and polygenesis.



**FIGURE 1** Variation in the rate of bedrock weathering with soil (4) depth, based on Gilbert's (1877) proposal of a nonlinear (humped) relationship of weathering advance and soil (4) depth and illustrated by Carson and Kirkby (1972). Soil (4) as used by Gilbert (1877) and Carson and Kirkby (1972) is identical to regolith (5) as coined by Merrill (1897) and refers to the entire blanket of weathered rock and sediment that reside on the Earth's surface. Carson and Kirkby (1972) described this as "the soil (4) thickness-rate of weathering curve." S is the depth at which rate of bedrock weathering is at the maximum because of intensity of rooting and geochemical and geophysical weathering

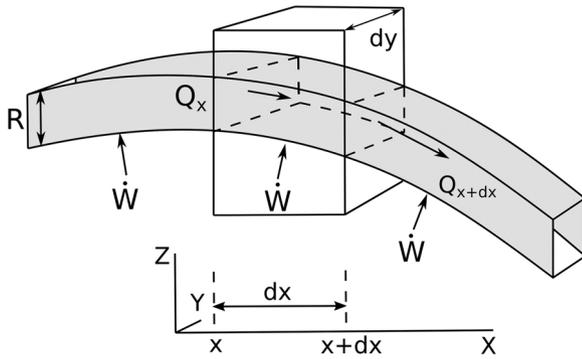
contributions of Gilbert (1877) to pedology and examine Gilbert-like ideas already seen in mainstream pedology over recent decades (Buol, Southard, Graham, & McDaniel, 2011; Johnson, 1985), and (iii) describe a conceptual model of soil and regolith evolution (7, 12) derived in part from Gilbert's ideas about weathering and transport and use this model to interpret three contrasting soils and regoliths (1, 5) at the Calhoun Critical Zone Observatory in the Piedmont of South Carolina (Richter et al., 2014).

## 2 | SOIL PRODUCTION

Gilbert (1877) was the first to propose that weathering rates may be controlled by what he called soil (4) depth and that this relationship was nonlinear or humped. Carson and Kirkby (1972) first illustrated this relationship (Figure 1) and called it "the soil (4) thickness-rate of weathering curve." Gilbert (1877) and Carson and Kirkby (1972) reasoned that the weathering rates of bedrock depend on the circulation of water, the action of plant roots, and freeze–thaw cycles. On bare rock and thin regolith (5), rooting is limited and weathering is relatively slow, as water tends to move rapidly through weathering materials. If a thin regolith (5) is in a cold environment, however, freeze–thaw cycles can greatly enhance weathering rates via frost cracking. Gilbert (1877) conceived the idea that rates of weathering are highest at intermediate soil (4) depths (Figure 1), in soils (4) that can maximize plant root–water–soil–rock interactions, especially if they are susceptible to frost damage. As regolith (5) deepens, however, weathering rates diminish as water circulates more slowly through soil and weathering profiles (6, 8) or exits the regolith (5) prior to contact with weathering fronts (Maher, 2010; Rempe & Dietrich, 2014). Gilbert's (1877) proposal for soil depth and weathering is elegant and reasonable.

Despite weathering's fundamental importance to many environmental sciences, the complexity and diversity of weathering processes have ensured that weathering rates remain very poorly quantified (Ahnert, 1998; Lebedeva & Brantley, 2013; Riebe, Hahn, & Brantley, 2017). In the 1990s, however, Gilbert's proposal (Figure 1) was finally quantitatively tested, thanks to advances in cosmogenic nuclide analyses and geochronometry (Gosse & Phillips, 2001; Lal, 1991) and to geomorphologists' insights into the mechanics of soil (3) creep. Because cosmic radiation produces long-lived

## Conservation of Mass on a Hillslope Element



**FIGURE 2** Conceptual hillslope model of Anderson and Anderson (2010) illustrating the conservation of mass of a hillslope element,  $dx$  by  $dy$  by  $r$  (length, width, and depth of hillslope element), which is related to the hillslope models of Dietrich et al. (1995), Gilbert (1909), and Heimsath et al. (1997)). Spatially uniform weathering ( $\dot{W}$ ) supplies new regolith to each hillslope element and mobile soil and mobile regolith (5). For a steady state, uniform thickness ( $R$ ) is maintained by a spatial gradient in the lateral transport of mobile regolith ( $Q_x$ ), which increases linearly with distance ( $x$ ) from the hillcrest ( $Q_x + dx$ )

cosmogenic nuclides (CNs) in the atmosphere and in minerals, Earth scientists began to track the accumulations of CN to date and estimate the rates of processes associated with bedrock exposure, glacial moraines, and marine and fluvial deposits; erosion rates at individual sites and across river basins; and soil production (9), the topic of this paper. Some CNs are stable ( $^3\text{H}$ ,  $^{21}\text{Ne}$ ) and others are radioactive, with half-lives on the order of  $10^3$  to  $10^7$  years ( $^{10}\text{Be}$ ,  $^{14}\text{C}$ ,  $^{26}\text{Al}$ ,  $^{36}\text{Cl}$ ,  $^{41}\text{Ca}$ , and  $^{129}\text{I}$ ), the timescales over which many soils, weathering profiles, and landscapes evolve. Some CNs are especially useful because they are produced within common minerals such as quartz and feldspars. The CNs produced within the atmosphere are known as meteoric CNs and those produced within minerals as terrestrial (or in situ) cosmogenic nuclides (TCNs). The production rates of TCNs decrease exponentially with depth belowground, specifically because of the density of soil or rock. Though sample preparation and analytical instrumentation are specialized and costly, the techniques have remarkable accuracy and precision (Anderson & Anderson, 2010) and a body of literature is developing that points to many potential applications for pedology (Schaeztl & Thompson, 2015).

To estimate soil production (9), geomorphologists apply CN analyses to estimate the physical conversion of in situ bedrock into gravitationally mobile regolith (11), reasoning that at a steady state this is equivalent to the rate of bedrock lowering (Anderson & Anderson, 2010). Figure 2 (from Anderson & Anderson, 2010) illustrates soil creep and how the rate of change in the mass of mobile regolith within a box of a hillslope element equals the rate at which

it is converted from the underlying rock, plus the mobile regolith transport inputs from upslope minus mobile regolith transport outputs downslope. An important aside is that the constant depth of mobile regolith and spatially uniform weathering rates mean that mobile regolith transport increases linearly with distance from the hillcrest. Because cosmic radiation is attenuated by the depth-dependent soil mass, the assumption of a steady system allows the concentrations of TCN in bedrock minerals in the upper immobile regolith to be used to clock the system in relation to a constant depth-dependent mass of mobile regolith (3). A steady state requires that the net erosional loss from the surface caused by the divergence of the transport rate (mass in minus mass out) matches the mass of bedrock physically introduced into mobile soil (3) from below [i.e., by soil production (9)], thus preserving soil (3) thickness through time.

Four important initial tests of how hillslope soil (3) depth affects rates of bedrock weathering are found in Dietrich, Reiss, Hsu, and Montgomery (1995), Heimsath, Dietrich, Nishiizumi, and Finkel (1997), McKean, Dietrich, Finkel, Southon, and Caffee (1993), and Small, Anderson, and Hancock (1999). McKean et al. (1993) estimated the rate of soil (3) creep on convex-up hillslopes in California via a mass-balance model that incorporated concentrations and inventories of depth-dependent, meteoric  $^{10}\text{Be}$ . The study estimated the average rate of soil production (9) to be about  $260 \text{ m Myr}^{-1}$  across the hillslope and suggested that the approach might provide an estimate of a “local soil-production rate law.” In the journal *Geology*’s Reviewer Comments, which, in 1993, were published adjacent to each paper, Robert Anderson described McKean et al. (1993) as “the first direct test of the applicability of a long-revered analysis of Gilbert’s.” (Note that most soil production studies have since used in situ produced  $^{10}\text{Be}$  rather than meteoric  $^{10}\text{Be}$ , as the production rates of in situ  $^{10}\text{Be}$  are far better constrained than those of meteoric  $^{10}\text{Be}$ .) Following Dietrich et al. (1995), McKean et al. (1993) proposed a model that predicted spatial variation in the depth of mobile soil (3) on convex slopes. They tested the model with LiDAR data and field observations of hillslope soil profiles (6) and applied the model under the assumption of a steady state. Modeling and field data suggested an exponential decline in soil production (9) with increasing soil (3) depth and gave little hint of Gilbert’s humped production function (Figure 1).

Many studies have since used CN techniques to quantify soil production (9) on slopes with contrasting lithologies and climates (e.g., Amundson et al., 2015; Anderson, 2002; Anderson & Anderson, 2010; Decker, Niedermann, & De Wit, 2011; Dixon et al., 2009; Gabet & Mudd, 2009; Heimsath et al., 1997, 1999, 2000, 2005; Larsen et al., 2014; Lebedeva & Brantley, 2013; Riebe et al., 2017; Riebe, Kirchner, Granger, & Finkel, 2001; Riggins, Anderson, Anderson, & Tye, 2011; Roering, Marshall, Booth, Mort, & Jin, 2010; Small et al.,

1999; Wang et al., 2018; West et al., 2013; Wilkinson & Humphreys, 2005; Yoo & Jelinski, 2016; Yoo et al., 2006). Many of these studies examined the shape of the soil production function (10) but no consensus has arisen. For example, Heimsath et al. (1997) coupled two independent field-based methods to estimate rates of soil production (9) vs. hillslope curvatures and vs. in situ TCN  $^{10}\text{Be}$  and  $^{26}\text{Al}$  in bedrock sampled immediately below mobile soil (3). With the assumption of a steady state, the  $^{10}\text{Be}$  and  $^{26}\text{Al}$  data supported an exponential decline in the rate of soil production (9) with increasing hillslope soil (3) thickness, much like the previous description of Dietrich et al. (1995). In contrast, Small et al. (1999) used TCN  $^{10}\text{Be}$  and  $^{26}\text{Al}$  analyses high in the Wind River Mountains of Wyoming to examine the importance of frost weathering and concluded that mobile regolith at a depth of  $\sim 90$  cm had weathering rates nearly twice that on bare rock surfaces, thereby supporting Gilbert's century-old humped weathering rate proposal.

Soil (1) time is perhaps the most elusive of the soil-forming factors. Given that the studies discussed above began to quantify rates of bedrock weathering and thus natural soil formation (7), rates that hitherto have been very poorly resolved, this research is fundamental to understanding not only landscape evolution but also to constraining soil formation (7). The details of the soil production (9) literature, including its focus on soil (3) depth as the controller of bedrock weathering, suggest many opportunities for pedologists to help expand this research through investigations of the weathering processes themselves as they respond to depth. Indeed, these opportunities are already being explored (Amundson et al., 2015; Anderson, Anderson, & Tucker, 2013; McFadden, 2013; Persico, McFadden, Frechette, & Meyer, 2011; Wang et al., 2018; Yoo & Jelinski, 2016).

### 3 | WHAT PEDOLOGY CAN ADD TO SOIL PRODUCTION RESEARCH

Across large fractions of the Earth's surface, gravity mobilizes regolith (5) in colluvial processes governed by the interplay of regolith strength and applied stress (i.e., between resistance and force) (Carson & Kirkby, 1972). The stress–strength interplay depends on slope curvature, length, and steepness; freeze–thaw; moisture dynamics; animal activity; vegetative rooting; seismicity; and the evolving structure and strength of soil (1), regolith (5), and bedrock (Anderson & Anderson, 2010; Schaetzl & Thompson, 2015). Mobile regoliths are mixtures of mineral particles and organic matter that range in size from colloids to boulders and they move at rates ranging over many orders of magnitude. Displacement and movement may be continuous or periodic and involve creeps, slumps, slides, flows, and heaves. Most mobile regolith dates from the Pleistocene to the present. Although

regolith moves and rests, it weathers chemically, biologically, and physically while individual soil (1) features and horizons form, persist, and are erased.

Many pedogenic pathways are possible, as hillslope soils (1, 4) form during the downslope movement and mixing of materials as individual particles and in bulk (Graham, Daniels, & Buol, 1990). Soil production research began by focusing on soil (3) depth as a primary control on the soil production function (10). We envision, however, that quantifying the depth-dependent rates of soil production is the first step and that quantifying the evolution of the entire regolith is the goal.

Soil production (9) research is moving beyond the depth-dependence of weathering rates (Figure 1). Soil production (9) studies have increasingly focused on how regolith processes interact and control weathering and transport; in other words, how processes transform and weaken bedrocks and convey materials to the soil (1, 3, 11). A process-based example is the model of Anderson et al. (2013) that investigates climatic controls on hillslope evolution via frost-related processes that convert bedrock into regolith, and mobilize regolith and soil (1, 3, 11). Via models, the authors demonstrate strong aspect-dependent differences in hillslope and soil evolution (3, 7). A second process study is that of Dixon et al. (2009), who compared chemical and physical weathering rates in 30 soil-saprolite profiles (6) that ranged from 200 to 3000 m elevation in the Southern Sierras and estimated that chemical weathering rates within saprolite averaged 75% of the rates of soil production ( $54$  vs.  $74 \text{ Mg km}^{-2} \text{ yr}^{-1}$ ). Pedologists can help quantify the process rates of pedoturbation and soil creep and the shear strengths and stresses, and can extend estimates of weathering to include not only the physical conveyance of saprolite into mobile regolith but also the many biogeochemical weathering processes throughout the entire regolith. Process research is key to future work, which was part of an argument made by Ahnert (1998) suggesting that although mechanical weathering may decline exponentially with regolith thickness, chemical and biological weathering may give the thickness–weathering function its nonlinear humped shape (Figure 1). In contrast, mechanical weathering was proposed to contribute to the nonlinear thickness–weathering function by Eppes and Keanini (2017) because of the role that moisture plays in bond-breaking in rock and soil, a conclusion supported by Amit, Gerson, and Yaalon (1993) in hyperarid landscapes where salt-shattering peaked in the regolith at a depth of 20 cm.

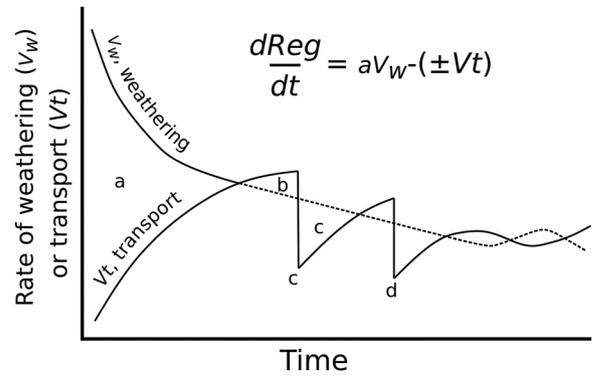
Soil production research marks a fundamental achievement for geomorphology. The approach, however, estimates a component of weathering and has been, to date, mainly applicable to a portion of the Earth's surface, namely to mobile soils (3) found on divergent convex-up hillslopes that can be taken to be in a steady state. To extend soil production research, pedologists can formally describe soil and weathering profiles (6, 8)

and greatly enrich soil production inquiries into environmental reconstruction (Eppes & McFadden, 2008; McFadden, 2013; Richter & Yaalon, 2012). Pedologists can help extend soil production research across complex landscapes and many more climates, vegetation types, pedoturbation processes, tectonic regimes, lithologies, and soils (e.g., Amundson et al., 2015; Heimsath, Fink, & Hancock, 2009; Wang et al., 2018; Wilkinson & Humphreys, 2005; Yoo et al., 2011). For example, all 12 soil orders in the USDA’s *Keys to Soil Taxonomy* (Soil Survey Staff, 2014) are found on hillslopes, including youthful A over C horizon Entisols, Inceptisols with weak Bw horizons, self-swallowing Vertisols, grassland-derived Mollisols, Gelisols dominated by permafrost that freeze and thaw in many ways, loess-accretionary and paleoclimatic Aridisols, volcanic-ash laden Andisols, peat-accumulating Histosols, and even soil orders with well-developed B horizons (i.e., the Spodosols, Alfisols, Ultisols, and Oxisols). Soil scientists bring their experience of soil features, processes, and extreme diversity to soil production research. Viewed in this way, pedologists and geomorphologists can learn much together about how landscapes function and evolve and how soil profiles and regoliths (5, 6) are distributed across complex terrain.

Two studies in particular demonstrate how pedologists can make special contributions to studies of soil production (9). Nichols et al. (2007) in the Mojave Desert used TCNs in soil and weathering profiles (6, 8) that included several buried paleosols to reconstruct cycles of stability, erosion, and deposition over ~70,000 yr. In a second example, Persico et al. (2011) described and interpreted hillslope soil and weathering profiles (6, 8) derived from aplite and granite in the Sandia Mountains of New Mexico. Significantly, soil profiles (6) from aplite but not from granite developed 1- to 2-m-thick argillic B horizons that stabilized hillslopes and contributed to preventing “attainment of a steady state balance between soil production and downslope transport” (Persico et al., 2011).

#### 4 | REGOLITH EVOLUTION

Pedogenesis was historically conceived as a process of soil maturation toward soil steady-states. This linear concept of soil formation toward a stable endpoint is deeply entrenched in pedology and it can perhaps best be seen in Marbut (1928), who advanced the mature, normal, and zonal soil as one on gently sloping land in a steady state relative to regional climate and biota. Nikiforoff (1949) described a mature soil as “a steady stage of its parent material adjusted to its environment” and one in which “the time factor has no significance.” Although Butler (1958) maintained that time would always remain as a major soil-forming factor, it has only been in recent decades that a new generation of pedological research has embraced the idea that nearly all

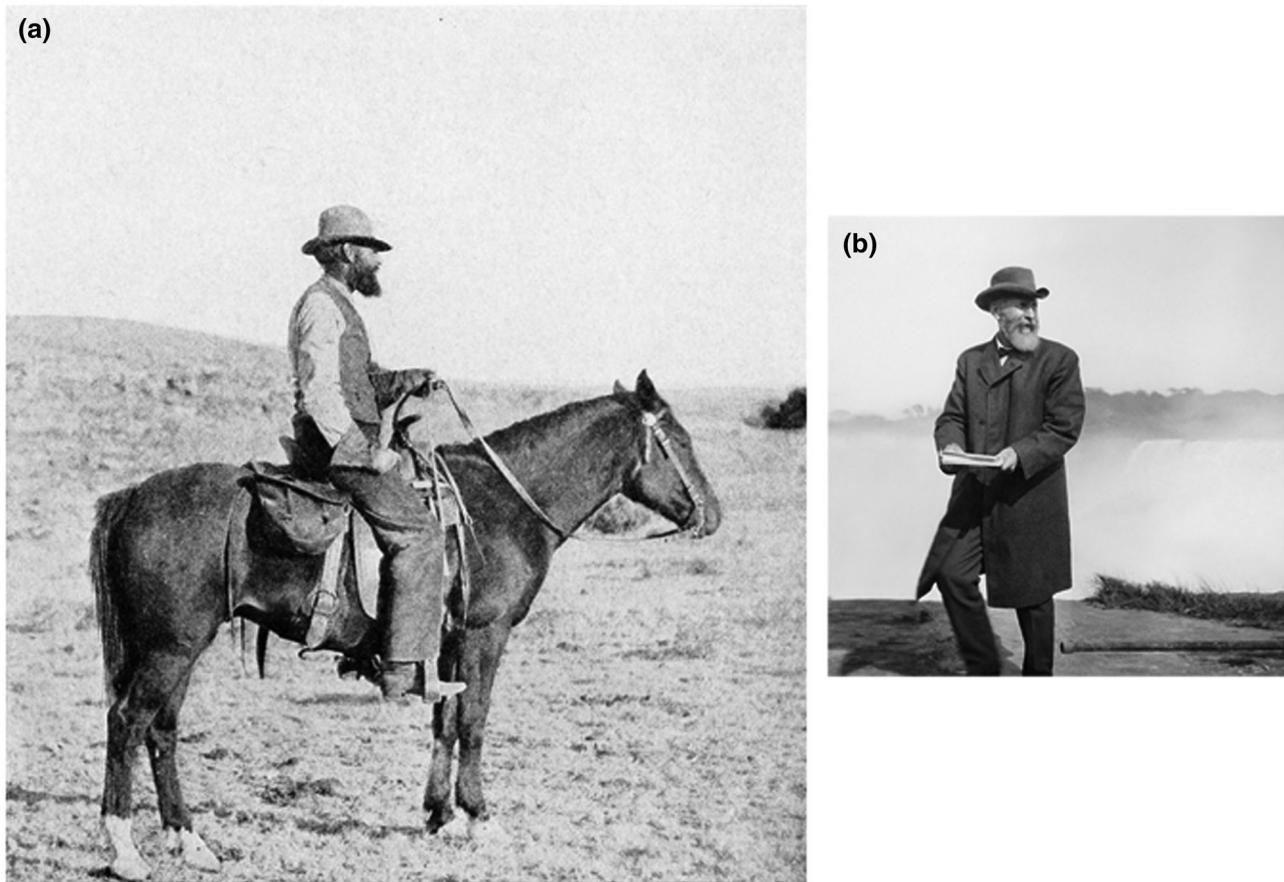


**FIGURE 3** Regolith evolution as a modified presentation of Crozier’s (1986) “waste production”, as in regolith production (12), illustrating temporal changes in accumulated regolith (5) depth as a result of contrasting rates of weathering and transportation. (a) The gradual buildup of regolith, (b) a period of net removal, (c) major colluvial deposition ( $-V_t$ ), and (d) pronounced and sudden aeolian deposition, all of which contribute to regolith production (12). The equation is discussed in the text

soils (1) have polygenetic histories to their formation (Buol et al., 2011; Chadwick, Nettleton, & Staidl, 1995; Richter & Yaalon, 2012; Schaetzl & Thompson, 2015). The implication is that most soil profiles and regoliths (5, 6) are archival and evolutionary products of pedogenic processes that have ebbed and flowed on time scales that range from  $<100$  to  $>10^6$  yr.

Of great interest and entirely understudied are how soils and regoliths have evolved throughout the Pleistocene in response to cyclic climatic, biotic, and geomorphic forcings, in approximately 20, 40, and 100 millennia (Shepard, Pelletier, Schaap, & Rasmussen, 2018). Soils, regoliths, and critical zones are subject to cyclic variations in atmospheric deposition of water, dust, and solutes; plant rooting and organic decomposition; soil animal activity; pedoturbation; fire effects; redox reactions and chemical leaching; and weathering reactions and erosion. These cyclic forcings alter soil organic matter, organomineral complexes, secondary minerals, structural aggregates, clay films, the soil’s surface area, soil pans, and pore networks. Soils and regoliths (1, 5) are intrinsically unsteady systems that are fundamentally contingent on their pedogenic history. Soils are thus polygenetic paleosols with physical, chemical, and biological features that form, persist, and are eventually erased (Buol et al., 2011; Chadwick et al., 1995; Richter & Yaalon, 2012; Yaalon, 1983). The exceptional soil and regolith (1, 5) is monogenetic and were hypothetically formed under the influence of a single set of relatively constant pedogenic processes. Busacca and Cremaschi (1998) called such soils *Vetusols*.

Given that most soils and regoliths (1, 5) have polygenetic histories, the evolution of soil and weathering profiles (6, 8) provides the basis for our conceptual model of regolith evolution (12). Figure 3 illustrates that although bedrock



**FIGURE 4** Mr. Gilbert on “Billy” and at Niagara Falls. Over many summers in the 1870s, Gilbert worked with the Wheeler and Powell geological surveys. John Wesley Powell, Charles Dutton, Gilbert and others would return to the East in winter to share and develop their findings and ideas and to write reports (Stegner, 1954)

weathering and regolith (5) removal may have a tendency to converge, as if in dynamic equilibrium, the regolith (5) is an open system connected to the wider environment that controls regolith (5) imports and exports via climate, biota, tectonics, and gravity. We thus do not bind regolith evolution (12) to a steady state (Figure 3); indeed, regolith evolution (12) embraces the nonsteady state, the lack of an endpoint, and evolutionary change (Johnson & Watson-Stegner, 1987).

We modify Crozier’s (1986) transport equation of rate change in regolith depth ( $\frac{dReg}{dt}$ ) to represent regolith evolution (12), which includes both regolith production ( $V_w$ ) (11), removals via transport ( $+V_t$ ), and inputs via transport ( $-V_t$ ):

$$\frac{dReg}{dt} = aV_w - (\pm V_t), \quad (1)$$

where *Reg* is thickness of the entire regolith (5) and the entire weathering profile (8);  $V_w$  is the weathering rate (rate of physical and biogeochemical weathering), also known as regolith production (Anderson, 2002);  $a$  is a coefficient of expansion or contraction following weathering, and  $\pm V_t$  is the rate of transportation-related removal ( $+V_t$ ) or deposition ( $-V_t$ ).

In Figure 3, the step functions in the trajectory of regolith evolution (12) represent inputs of loess, volcanic detritus, or mass movement deposition of colluvium or other sediments from higher up the slope. In the next section, after describing Gilbert’s (1877) ideas about weathering and transportation and linking them to pedology, we revisit regolith evolution in Figure 3 and Equation (1) by examining three contrasting soils and regoliths (1, 5) in the Calhoun Critical Zone Observatory of the Southern Piedmont.

## 5 | GILBERT’S WEATHERING AND TRANSPORTATION

At precisely the time that Darwin (1882), Hilgard (1860), and Dokuchaev (1967) were conceiving of soil (1) in new and creative ways, Grove Karl Gilbert (1877) wrote about soil (4), weathering, and erosion in his *Report on the Geology of the Henry Mountains* (Figure 4). Gilbert described land sculpture (what today we call landscape evolution), as the overcoming of the forces of cohesion by agents that weather indurated rock and that transport the weathered products via water,

wind, and glaciers. The Henry Mountains report was written after extraordinarily demanding field work over several years and is one of a series of magnificent field surveys about the geology of the American West (Pyne, 1980; Stegner, 1954). In the report on the Henry Mountains, Gilbert (1877) wrote with wonder,

Over nearly the whole of the earth's surface, there is a soil, and wherever this exists we know that conditions are more favorable to weathering than to transportation. Hence ... the conditions which limit transportation are those which limit the general degradation of the surface.

What might seem but a simple statement of mass balance is a profound statement about the dynamics of Earth's surface. From the tropics to the tundra, weathering gains have outpaced transportation losses across the planet's diverse landscapes, climates, lithologies, vegetative assemblages, and geomorphologies. An important fraction of mineral particles and solutes liberated from rocks by weathering accumulate in nearly all landscapes to build soils. After being transported, particles tend to be deposited on their journey to the ocean. The result is that a strikingly small proportion of Earth's land surface is exposed bare rock. Buol et al. (2011) recently estimated that bare rock covers about 1.4% of the Earth's terrestrial surface and soils of all kinds blanket about 98.6%.

Gilbert used the word "soil" (4) differently from how the word "soil" is used today (Table 1), such as in his sweeping statement, "Over nearly all of the earth's surface, there is a soil..." We take Gilbert's soil (4) to be identical to Merrill's (1897) regolith (5), meaning the entire weathering profile (8). Soil (1) today (van Es, 2017) is typically taken to be the upper volumes of the regolith (5) (the A, B, and C horizons), although some researchers periodically use soil to mean regolith (Carson & Kirkby, 1972; Nikiforoff, 1959; Richter & Markewitz, 1995). Regolith (5) includes the entire profile of partly unconsolidated or partly weathered material derived from a wide range of geological substrata, including all that is "drifted by wind, water, or ice" (Merrill, 1897). Regolith (5) is rock that Anderson and Anderson (2010) said "is weathered to any degree," and is taken from  $\rho\eta\gamma\omicron V$  (*rhegos*) in Greek, meaning "rug" or "blanket" and  $\lambda\iota\gamma\omicron V$  (*lithos*), meaning "stone".

Gilbert (1877) understood that as bedrock disintegrates and is loosened and opened with fractures and pores, the liberated materials are potentially transported by pedoturbation, gravity, ice, wind, and water. Gilbert also understood that the weathering of rock into particles and solutes occurred by physical, chemical, and biological means and that transportation losses of weathering products can be by dissolution and/or suspension. Net erosion (a part of  $V_t$  in Eq. [1] and Figure 3) means more is lost by transport than is gained; hence

physical transport has a positive gradient. Importantly, Gilbert also recognized that weathering varied greatly with lithology and climate and that weathering responded to transport. Transport was also seen to range widely, depending on weathering, climate, vegetation, lithology, and geomorphology.

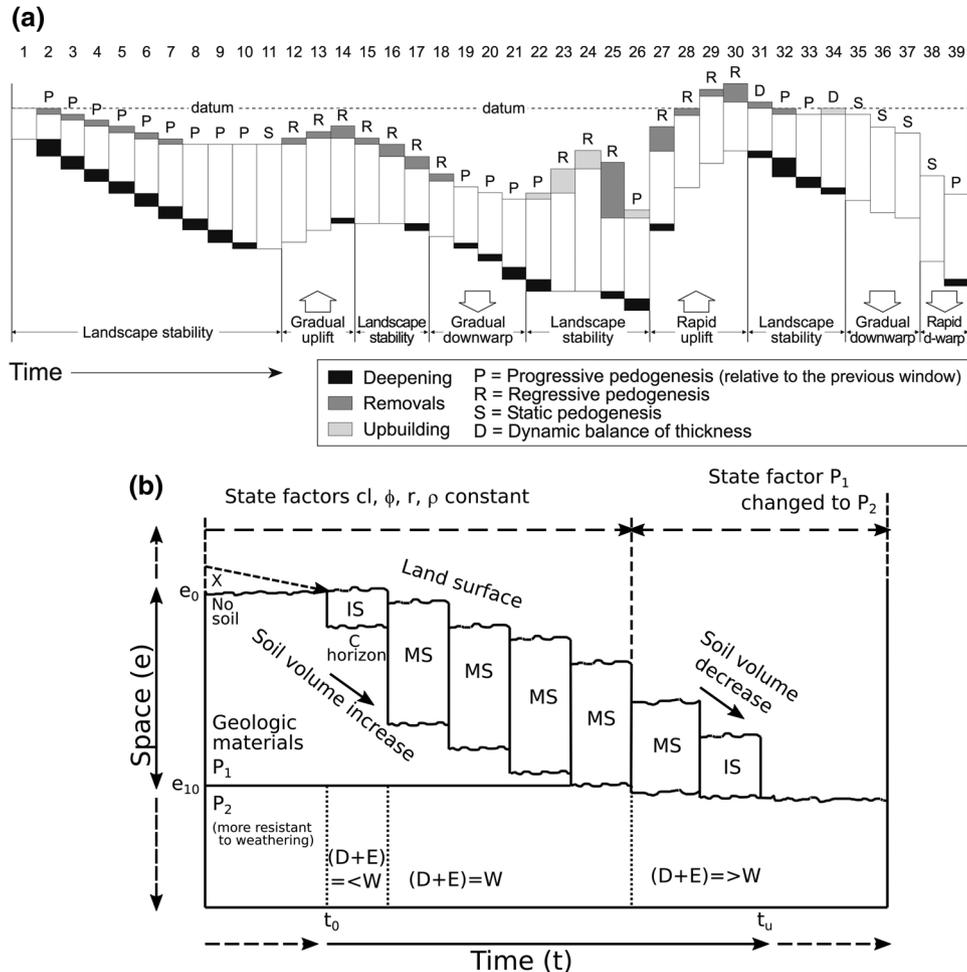
In the article "Denudational Balance of Slopes" (first published in Polish in 1954), Jahn (1968) (first published in Polish in 1954) made use of both Gilbert's Henry Mountains report and Gilbert's (1909) paper on hilltop convexity and may have been the first to use the word "production" to describe how "waste" (i.e., regolith) accumulates "when waste production proceeds at a higher rate than the action of denudation." Soon thereafter, in *Hillslope Form and Process* Carson and Kirkby (1972) illustrated Gilbert's proposed relationship between soil (4) depth and the rate of bedrock weathering (Figure 1), using the term soil (4) as had Gilbert. Today, soil (1, 3) and regolith (5) are the most widely used definitions in the geomorphology and pedology communities.

Remarkably, Gilbert's (1877) ideas on weathering, transport, and soil depth began to circulate in the mid- to late-20th century, first among geomorphologists and more recently among pedologists (Humphreys & Wilkinson, 2007). The delay among the latter resulted from most soil scientists being focused on soil profiles (6), soil profile classification, and agronomy (Humphreys & Wilkinson, 2007; Johnson, Domier, & Johnson, 2005; Paton, Humphreys, & Mitchell, 1995; Tandarich, Darmody, Follmer, & Johnson, 2002). Despite this history, considering how well Gilbert (1877, 1909) articulated the processes and feedback involved in soil (4), weathering, and transport, he deserves much wider recognition and even a place in the pantheon of scientists who first conceived of soils (1), as systems worthy of study, including Darwin (1882), Hilgard (1860), and Dokuchaev (1967).

## 6 | GILBERT-LIKE IDEAS IN PEDOLOGY

Although Gilbert is not well known to most pedologists (Humphreys & Wilkinson, 2007), two distinguished pedologists, Don Johnson and Stanley Buol, both advanced pedological ideas in the late 20th century that share much with Gilbert's ideas of weathering, transportation, and soil and regolith evolution (7, 12). Johnson's and Buol's formulations (Figure 5) appear to be independent of Gilbert (1877), although Johnson (1985) cites Jahn (1968) in the context of soil depth and is thus linked to Gilbert via Jahn (1968). The Johnson–Buol models are both described by these authors as being soil (1) models, although they can also be conceived to be models of soil and regolith evolution.

In Johnson's concept of soil (Figure 5a), he refers to weathering's advance into the unweathered material as deepening, which counteracts removals from erosion, mass wasting,



**FIGURE 5** Pedological models of soil formation (7) and regolith production (12) used by (a) Johnson (1985) and (b) Buol et al. (2011), conceptual models that parallel Gilbert's (1877) ideas that soils (4) are the net products of weathering gains exceeding transportation losses. In (b), Buol et al. (2011) indicates that IS is "immature soil", probably an Entisol or Inceptisol; MS is a "mature soil", probably an Alfisol or Ultisol; D is dissolution and loss by solutes in runoff; E is erosion loss; and W is weathering gain

and leaching. Significantly, Johnson (1985) includes soil (1) upbuilding from sediments of allochthonous origin from the atmosphere and from upslope, and from plant-derived organic matter. Johnson was particularly intrigued by the incorporation of imported materials such as aeolian inputs and human artifacts, by bioturbation, and by the thickening and thinning of individual horizons over time (Johnson et al., 2005). Johnson uses soil profile (6) depth and horizon thickness to illustrate progressive and regressive pedogenesis, meaning the increase or decrease, respectively, in soil (3) depth and horizon thickness (Figure 5a). Johnson's (1985) model also includes landscape uplift and subsidence to account for the vertical relations to the original datum. Johnson details his pedogenic pathways in Johnson and Watson-Stegner (1987).

In parallel with Johnson (1985), in several editions of *Soil Genesis and Classification*, Buol et al. (2011) illustrated what they called a "conceptual soil continuum of space and time" (Figure 5b). The Buol model also illustrates how the soil's surface moves vertically relative to a datum, namely down-

ward without geologic uplift caused by weathering's advance and transportation's losses. Time is on the horizontal axis and space (soil depth and volume) on the vertical. The site is indicated to be on a gentle slope – formed directly from the underlying bedrock – from which erosion, dissolution, and leaching remove weathering products. Two types of geologic material are illustrated below the soil profile (6): a readily weatherable upper unit and a lower unit that is more resistant to weathering. Time at  $t_0$  represents the moment after a catastrophic event such as glacial ice scouring or a landslide that has removed all previous regolith (5). At time  $t_1$ , a soil has formed as gains from weathering outpace the losses from transport. This initial soil contains a relatively simple profile, an Entisol with an organic-enriched A over a C horizon, as the soil has not yet had enough time to form a B horizon. As the profile accumulates depth and clay-sized minerals in a Bt horizon, an Alfisol or Ultisol develops with A–Bt–C horizons (from  $t_2$  to  $t_5$ ). At  $t_6$ , the weathering advance has encountered the more resistant bedrock and rates of weathering slow and

are not able to keep pace with transport losses that continue to lower the soil surface. The soil profile thins and the A horizon envelops the former Bt horizon and thus the soil transitions back to an Entisol with a profile of A–C horizons ( $t_7$ ). In Figure 5b, Buol et al. (2011) illustrated a soil that, because of variations in the bedrock, evolves from a transport-limited A–Bt–C horizon to a shallow, weathering-limited Entisol with an A–C profile. According to Carson and Kirkby (1972), Gilbert (1877) was the first to describe weathering- and transport-limited landscapes, endmembers that are fundamental to our understanding of soil, hillslope, and regolith development.

Although Johnson, Buol, and 100 yr of pedology have added enormously to our understanding of soils as complex, highly diverse, and polygenetic systems, the striking comparability yet apparent independence of the Johnson–Buol models illustrated in Figure 5, relative to the ideas of Gilbert (1877) reinforces our support for Gilbert being much more widely read and recognized in the science of pedology.

## 7 | REGOLITH EVOLUTION ON THE SOUTHERN PIEDMONT

To demonstrate the relevance of Gilbert's insights for pedology, we examine three contrasting soil and weathering profiles (6, 8) at the Calhoun Critical Zone Observatory in the South Carolina Piedmont (Richter et al., 2014). Our intent is to consider soil and regolith evolution (12) from the perspective of weathering and transport,  $V_w$  and  $V_t$ , (Figure 3, Eq. [1]):

- (i) a residual regolith with an Ultisol soil (34°36'24.804'' N, 81°43'25.662'' W) that was directly inherited from underlying granitic gneiss with the regolith (5) derived from  $V_w \gg |-V_t|$  (i.e., regolith largely from weathering rather than deposition),
- (ii) a mixed regolith with an Ultisol soil (34°48'29.9232'' N, 81°53'53.4552'' W) that has formed within a thick paleo-colluvium with a regolith (5) derived from both  $V_w$  and  $-V_t$  (i.e., a regolith from weathering and deposition), and
- (iii) a alluvial depositional regolith with an Entisol soil (34°37'8.3712'' N, 81°41'27.2472'' W) formed within historic legacy sediments with a regolith (5) derived from  $|-V_t| \gg V_w$ .

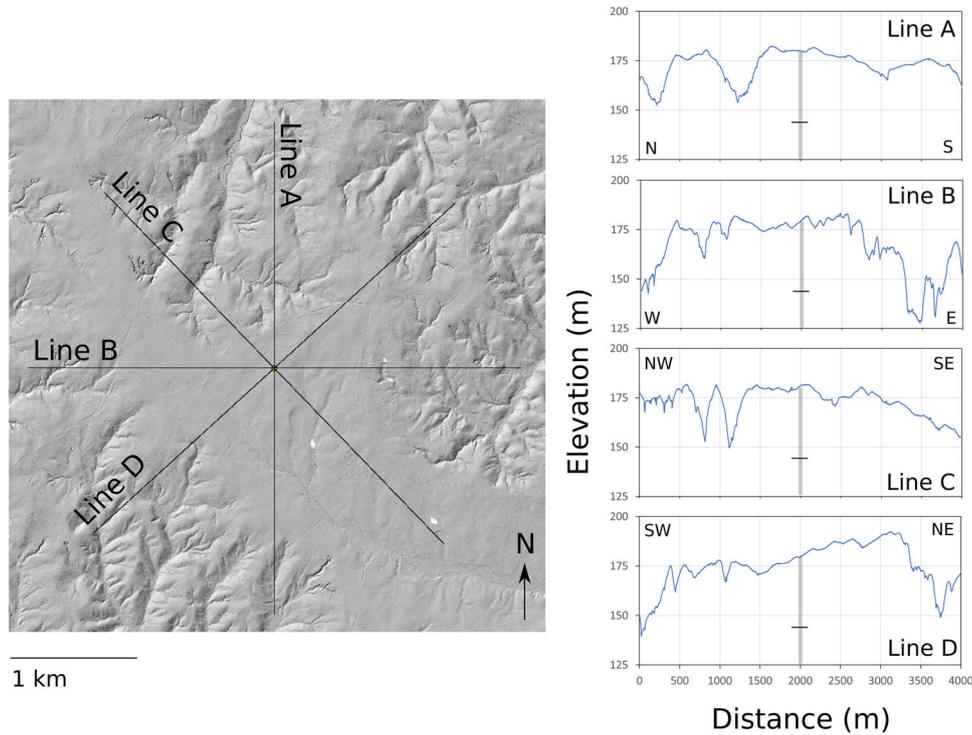
### 7.1 | Residual regolith from $V_w \gg |-V_t|$

In the Southern Piedmont, broad, low-curvature, and ancient interfluves (Brecheisen, 2018) have regolith (5) that is weathered to tens of meters in depth (Bacon, Richter, Bierman, & Rood, 2012; Holbrook et al., 2019; Pavich, 1989). The coring site for this deeply weathered regolith (5) was selected (Bacon et al., 2012) for its geomorphic stability and low geologic

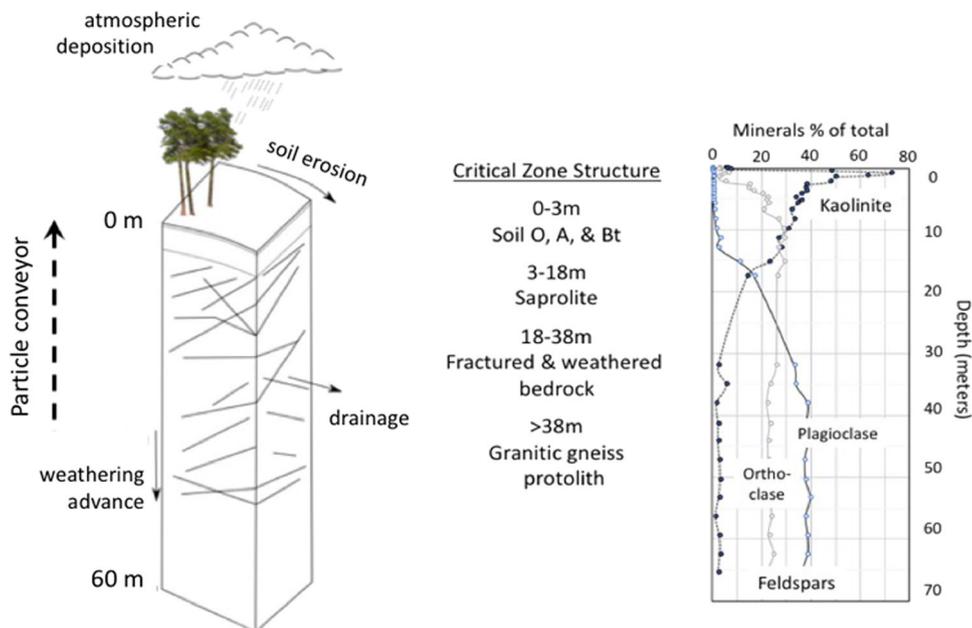
erosion rates (Figure 6). Although the rates of weathering and transportation today are very low (Richter & Markewitz, 2001), weathering over time has outpaced transport losses and the accumulated regolith is about 38 m in depth (Holbrook et al., 2019), a regolith that totals nearly 70 Mg m<sup>-2</sup> in mass (Figure 7). The profile has an advanced weathering state with near-complete dissolution of plagioclase to ~12-m depth, with the deepest evidence of weathering at about 38 m (Holbrook et al., 2019). To quote the metaphor from Dokuchaev and Targulian (Richter & Yaalon, 2012), “soils are a mirror and memory of the landscape”, and this soil and weathering profile (6, 8) mirrors and contains the memory of an ancient landscape that, overall, is transport-limited.

The soil profile (6) is classified as a residual Cataula series (Lance Brewington, USDA-NRCS, personal communication, 2011), a soil formed directly from underlying bedrock. The Cataula series is in the taxonomic class of fine, kaolinitic, thermic Oxyaquic Kanhapludults and is mapped on more than 150,000 ha of upland interfluves and upper hillslopes in the Southern Piedmont, mainly in South Carolina and Georgia ([www.websoilsurvey.nrcs.usda.gov](http://www.websoilsurvey.nrcs.usda.gov), accessed 9 Oct. 2019). The soil, with its saprolite and fractured weathered bedrock, is understood to be formed in place, as is the central concept for most upland soils across the Southern Piedmont (Buol et al., 2011; Daniels, Buol, Kleiss, & Ditzler, 1999). At the same time, pedoturbation and eluviation–illuviation have thoroughly mixed particles that make up the A, E, and Bt horizons. Even on these broad, low-curvature, low-slope landforms, we suspect that mineral particles of the solum (0–3 m) are somewhat displaced from the C-horizon saprolite immediately below. It remains for future soil geomorphologists to estimate the rates of pedoturbation and such hypothetical particle movement. We are far more certain about the in situ weathering history of the C-horizon saprolite between 3 and 18 m, given its lithic structural inheritance and that of the fractured bedrock from 18 to 38 m depth that remains attached to the unweathered protolith itself (Holbrook et al., 2019).

We are well informed about this regolith (5), which we have long considered to be weathered in place (Bacon et al., 2012; Holbrook et al., 2019; Richter & Markewitz, 1995, 2001; St. Clair et al., 2015). For example, inventories of meteoric <sup>10</sup>Be within this weathering profile [ $2 \times 10^{12}$  atoms cm<sup>-2</sup> (Bacon et al., 2012)] help demonstrate its very great age, >2 to 3 million years. In more than 10 ha that surround the 65-m-deep borehole, many dozens of boreholes have been hand-augered 5 to 8.5 m in depth (Brecheisen, 2018; Richter & Markewitz, 1995); biological, chemical, and physical properties have been analyzed for the solid samples from most of these boreholes (Austin, Perry, Richter, & Schroeder, 2018; Bacon et al., 2012; Billings et al., 2018; Callahan, Richter, Coleman, & Hofmockel, 2006; Holbrook et al., 2019; Richter & Billings, 2015; Richter & Markewitz, 1995, 2001; Richter et al., 2014; St. Clair et al., 2015).



**FIGURE 6** A LiDAR slope map of the Calhoun Critical Zone Observatory, near Cross Keys and Sedalia, SC. Here, we show the broad, low-curvature, nearly level interfluvium and the location of the residual regolith and the 65-m-deep borehole. On the right, 4000-m-long elevational transects are illustrated with the vertical borehole shown as a vertical line with a horizontal crosshatch at the base of the regolith at 38 m, the base of the fractured weathering granitic gneiss bedrock. Nearly all of this landscape is eroded, much of it seriously so. Nearly every channel in the LiDAR image is deeply incised or gullied as a result of historical agriculture



**FIGURE 7** Diagram of a residual regolith (5) and its soil (1) with materials derived mainly from weathering in place ( $V_w$  in Eq. [1]). The residual, transport-limited Ultisol soil and weathering profile (6, 8) are formed directly from the underlying bedrock. The figure at the left is a conceptual model of the weathering profile, illustrating weathering advance and transport losses, and thus regolith production (12). The horizons of the soil and weathering profile (6, 8) are given in the middle of the figure and the depth dependence of the feldspar weathering fronts are illustrated on the right, with nearly all plagioclase exhausted by weathering at 12 m in the C horizon saprolite (Holbrook et al., 2019)

The soil profile's O, A, E, and Bt horizons together total about 3 m in thickness and the C horizon saprolite extends from 3 to 18 m. Above about 12 m, total porosity averages >40%, pH and base saturation are extremely low (<4.5 and <10%, respectively), and plagioclase (Ab74) is completely exhausted by weathering dissolution. Between 12 and 18 m, however, in the lower saprolite, porosity diminishes from >40 to 10%, pH increases from <4.5 to 6, base saturation, increases from <10 to 100%, and plagioclase increases from nearly 0 to about 20% of the bulk mineral mass. Between 18 and 38 m, the bedrock is physically fractured and is geochemically most weathered within the fractures. The patterns of geophysical and geochemical data appear to be closely coincident throughout the weathering profile (Holbrook et al., 2019).

Dissolution losses from this regolith today are remarkably low, given the dilute alkalinity and base cations ( $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ , plus  $\text{K}^+$ ) in soil waters that average <40  $\mu\text{mol}_c \text{L}^{-1}$  down through to 6 m deep in the Bt and upper C soil horizons (Markewitz, Richter, Allen, & Urrego, 1998). Many of the Ca, Mg, and Na silicates such as plagioclase, chlorite, and epidote have been completely exhausted by chemical weathering by the time the regolith (5) is fed into the upper 10 m of the weathering profile (8) (i.e., the upper saprolite C horizons) (Holbrook et al., 2019). The dilute solute concentrations throughout at least the upper 6 m (Markewitz et al., 1998; Richter & Markewitz, 2001) indicate that ongoing weathering reaction rates are very slow above the weathering fronts for minerals such as plagioclase and biotite in the upper 12 m of the regolith (5). The low solute concentrations in soil waters also indicate that aeolian dust inputs that have been periodically added to this ancient profile in the past have limited impacts on ongoing weathering reactions today. This regolith is in an advanced state of weathering (Richter & Markewitz, 2001) and is currently a slowly evolving biogeochemical system. The soil and weathering profile is an excellent example of a transport-limited endmember of regolith production and evolution (11, 12) in which  $V_w \gg V_t$  [Eq. (1)].

## 7.2 | Mixed regolith from both $V_w$ and $-V_t$

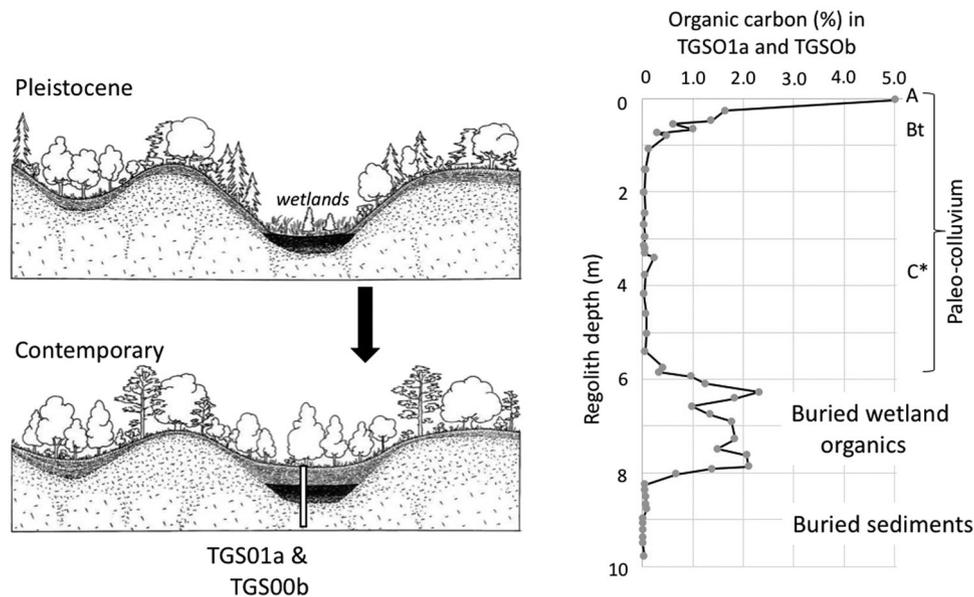
Like the residual Cataula soil and regolith (1, 5) illustrated in Figure 6 and Figure 7, an Ultisol soil with an A–Bt–C profile has formed high in the Piedmont landscape within a regolith with a far different soil geomorphic history from that of the residual regolith. This regolith is mixed in that its materials are derived from both transported colluvium and from weathering in place (from  $-V_t$  and  $V_w$ ). The site is ~3 km southwest of Pauline, SC, and is entirely within a Cecil series mapping unit in the Spartanburg County Soil Survey. The Cecil series is in the taxonomic class of fine, kaolinitic, thermic Typic Kanhapludults and is one of the most exten-

sive soil series on the Southern Piedmont, covering about 2.5 million ha ([www.websoilsurvey.nrcs.usda.gov](http://www.websoilsurvey.nrcs.usda.gov), accessed 9 Oct., 2019). The Cecil series is North Carolina's official state soil (Tennesen, 2014) and is conceived to be formed from saprolite derived from the bedrock below (i.e., from in situ weathering).

This surprising mixed regolith profile (from  $-V_t$  and  $V_w$ ) was first exposed in the 1930s by a massive agricultural gully that grew to be nearly 10 m deep at the gully head (Cain, 1944). By 2018, the gully was <6 m deep as a result of regolith sloughing and detritus that included a complete wood-frame house with contents that was pushed into the gully in the 1970s or early 1980s. However, within a 20-m horizontal distance from today's gully head, a less eroded soil profile contains an illuvial clay-enriched Bt horizon with a red 10R hue (characteristic of a Cecil soil) that we interpret to have formed entirely within the massive colluvium (Figure 8). The deep paleo-colluvium is itself mixed but is also stratified with several horizontal deposits of quartz gravel and is entirely devoid of lithic features inherited from weathering bedrock. The mineralogy of the 6-m-deep colluvium is dominated by kaolinite and quartz and is devoid of plagioclase. The advanced weathering state of this paleo-colluvium and its contemporary soil horizons suggest that the colluvium is composed of material that was preweathered while in at least one previous soil and weathering profile (6, 8).

Perhaps most remarkable is that this upland Piedmont regolith, specifically the 6-m-deep paleo-colluvium, overlies (has buried) an organic-enriched sandy deposit 2 m thick (Figure 8). This layer contains  $^{14}\text{C}$ -dead soil organic matter, charcoal, tree trunks up to 30 cm in diameter, and plant macrofossils including acorns (*Quercus* spp.) and hickory (*Carya* spp.) nuts (Eargle, 1946). The organic-enriched layer that resides at a depth of ~6 to ~8 m also contains abundant *Abies* and *Picea* pollen (Cain, 1944; Deb Willard, US Geological Survey, personal communication, 2019). We attribute the organic matter to be from a paleo-wetland that resides above what we believe to be a paleo-saprolite of unknown depth and age.

Presumably, one or more ancient excursions in climate and vegetation set in motion the erosion and deposition of this massive volume of colluvium. To geologically date these colluvial events, quartz and K-rich feldspar grains taken from the 4-m depth were measured for their optical and infrared stimulated luminescence and estimated to have been buried for ~109,000 yr before the present (Michelle Nelson, Utah State University Luminescence Laboratory, personal communication, 2019). Overall, this second profile's stratigraphy, sedimentology, and pedology indicate a regolith system in a far from steady state. We assume the paleo-colluvial materials to have originated upslope from their present positions, that they are a part of a process of valley filling (Figure 8), and that the colluvium was derived from the upper meters of a highly



**FIGURE 8** Diagram of a mixed regolith (5) and soils (1) derived from both regolith production ( $V_w$ ) and inputs via transport ( $-V_t$ ) in Eq. [1] (from weathering gains and colluvial deposition). On the left is Eargle's (1946, 1977) concept of the Piedmont landscape's development during the late Pleistocene near Greer, SC. Two stages of landscape development are illustrated on the left. One is a deeply weathered landscape with wetland peats, residual weathering profiles (8), and cool temperature vegetation. The second is a landscape in which colluvium has migrated into valley bottoms, burying former wetlands and diminishing surface relief. On the right is organic C in an Ultisol soil (1) and its underlying regolith (from cores TGS01a and TGS00b) formed in the paleo-colluvium (with A, Bt, and C\* horizons) that overlies buried organic-matter-enriched sediments that reside over low organic matter sediments. The C\* horizon has an asterisk, as we do not yet know if the paleo-colluvium includes one or multiple depositional events and thus paleosols may yet be discovered in the C\*

weathered, plagioclase-free regolith (5), perhaps not unlike that of the upper 10 to 12 m of the residual regolith with the Cataula series soil illustrated in Figure 6 and Figure 7.

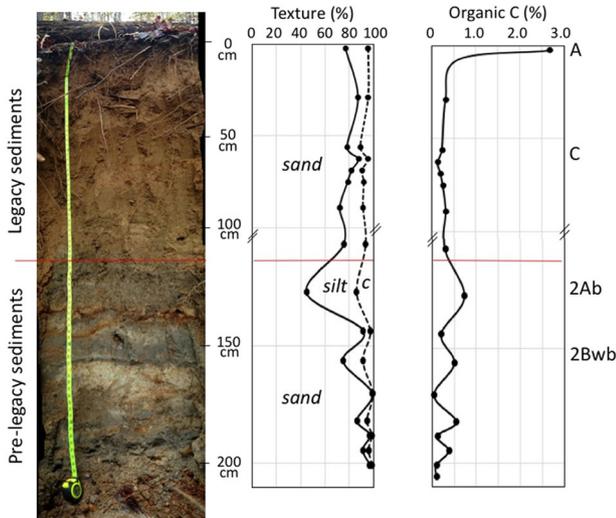
In the 1930s, the Soil Conservation Service (SCS) systematically studied soil erosion and gully development across the Southern Piedmont in efforts that included the Civilian Conservation Corps (Eargle, 1946); Hans Albert Einstein, the son of Albert (Ettema & Mutel, 2014); and Carl O. Sauer (2009), efforts that led to new ideas and data about the Southern Piedmont paleo-colluvium and its important relations to Piedmont soils and geomorphic surfaces (Eargle, 1940, 1946, 1977; Sharpe, 1938). Dozens of localities with regolith containing paleo-colluvium were sampled and mapped in the upper Piedmont of North and South Carolina, many of which had buried organics (Cain, 1944; Eargle, 1940, 1946, 1977; Sharpe, 1938). We agree with these 1930s scientists that these regoliths tell the story of ancient filled valleys and buried wetlands. These early SCS observations and ideas about regional landscapes contrast with the long and persistently held paradigm that the Piedmont is a region largely characterized by deep residual regoliths with soils directly inherited from the underlying bedrock (Buol et al., 2011; Coffey & Hearn, 1901; Daniels et al., 1999; Pavich, 1989; Richter & Markewitz, 2001). Although Eargle (1940) and Sharpe (1938) were well aware of this conflict, except for a paper by Eargle (1940) in *Science* magazine, the SCS's

studies were not widely circulated. World War II quickly and completely terminated the SCS's research on the region's paleo-colluvium and very little of these spectacular data are circulating today (Terry Ferguson, personal communication, 2019). The paradigm that the Piedmont regolith is largely an in situ weathering product (Hunt, 1986) has remained largely in place from the time of the first soil surveys (Coffey & Hearn, 1901).

Ongoing research, in association with Wofford College and the Calhoun Critical Zone Observatory, is reconstituting historic SCS data and marshalling new evidence (Figure 8) to reconstruct a history of the Southern Piedmont's regoliths derived from in situ weathering (Figure 7) and from mixed and transported origins (Figure 8). The Pauline, SC, regolith illustrated in Figure 8 is an excellent example of landscape evolution and mobile regolith in a far from steady state, a biogeochemical system derived from materials from both  $V_w$  and  $-V_t$  (Equation (1)).

### 7.3 | Depositional regolith from $|-V_t| \gg V_w$

We conclude by examining an alluvial regolith with a legacy sediment overlay (James, 2013) because these so clearly illustrate the opportunities for soil geomorphology to produce new insights about regolith evolution. Profiles composed of



**FIGURE 9** Diagram of a sedimentary regolith (5) and its soils (1) with materials almost entirely from transport ( $-V_i$  in Eq. [1]). On the left is a photograph of profile XHBr-6'', with over 1 m of coarse-textured legacy sediments that are low in organic carbon, well oxidized. The profile has a buried Ab horizon at about 117 cm deep with redox-active buried Bwb horizons that overlie quartz-rich coarse sand, pebbles, and cobbles at >210 cm. The middle panel illustrates the profile to be a sandy loam (clay-sized particles in all samples were <15%). The right-hand panel depicts organic C, which, except for the redeveloping A horizon, is <1%, with notable variability in the buried prelegacy sediment

transported materials can also demonstrate the reach of Gilbert's accomplishment. The contemporary Piedmont soil forming in this alluvium (Figure 9) is derived from sedimentation greatly accelerated by human activities, a process of great interest to Gilbert (1917) and one about which he made seminal contributions (James, Phillips, & Lecce, 2017).

By the late 1700s, farming began accelerating soil erosion in the Southern Piedmont (Happ, 1945; Ireland, Sharpe, & Eagle, 1939; Trimble, 2008) and even caught the attention of Charles Lyell on his travels across the United States in the 1840s (Ireland, 1939). Piedmont farming for cotton (*Gossypium hirsutum* L.), tobacco (*Nicotiana tabacum* L.), corn (*Zea mays* L.), wheat (*Triticum aestivum* L.), and domestic animals increased throughout the 19th century and peaked in the early 20th before rapidly collapsing in the 1920s and 1930s (Coughlan, Nelson, Lonneman, & Block, 2017; Richter & Markewitz, 2001). Massive volumes of soil eroded from hillslopes as a result of land use practices, erosive rainfall, erodible soils, and the sheer depth and volume of regolith that was potentially available for mobilization. Many soil A horizons were completely removed from upland fields; clay-enriched Bt horizons were exposed and eroded as well. Trimble (2008) estimated that agriculturally caused gullies accounted for about half of the Piedmont's soil erosion. Intermittent and ephemeral streams became deeply incised

as new stream channels were extended by gullies many tens of meters in length and many meters in depth (Ireland et al., 1939). The Southern Piedmont became one of the most agriculturally eroded regions in North America, and the land use history motivated the USDA Forest Service and National Science Foundation to establish, the Calhoun Experimental Forest in 1947 and the Calhoun Critical Zone Observatory in 2013 (Richter et al., 2014). Metz (1958), who led the first soil, forest, and hydrologic research team, wrote that the Calhoun landscape "represented the poorest of Piedmont conditions."

The land-use history of the Piedmont also caused massive sediment deposition on lower hillslopes and floodplains (Happ, 1945). Because alluvial soils occupy but about 7.5% of the region's total area (Kevin Godsey, NRCS, personal communication, 2018), Piedmont floodplains, as receiving areas, are today inundated by deep legacy sediments. Along Piedmont floodplains of streams of the second order and higher, pre-1750 floodplain soils are typically buried by 0.5 to 5 m of legacy sediments (Dearman & James, 2019; Donovan, Miller, Baker, & Gellis, 2015; Happ, 1945; James, 2013; Wade, Richter, Cherkinsky, Craft, & Heine, 2019).

The third Piedmont regolith is thus composed of historic legacy sediment and pre-1750s deposits as well (Figure 9). Here, 115 cm of legacy sediment was deposited during times of high sediment delivery when the landscape was actively farmed from about 1800 to 1930 (i.e., when sediment supply rates exceeded the stream's capacity to carry sediment) (Happ, 1945; James, 2013). The profile is located in the middle reaches of the ~3.5-km-long Holcombe's Branch in Sedalia, SC, a watershed farmed from as early as the late 1700s to the mid-1930s that was rapidly reforested as nearly all of the catchment was purchased for the Sumter National Forest by 1935. The soils, too, have rapidly developed O horizons under pine (*Pinus* spp.) and pine-hardwood stands and accumulated soil organic matter in surficial A horizons as well (Mobley et al., 2015, 2019; Richter & Markewitz, 2001; Richter, Markewitz, Trumbore, & Wells, 1999). In the Holcombe's Branch floodplains, the youthful soils are classified as Entisols, specifically Fluvents, and are mapped by the NRCS in a Cartecay-Toccoa series mapping unit, a series mapped on about 350,000 ha of the Piedmont (Cartecay: coarse-loamy, mixed, semiactive, nonacid, thermic Aquic Udifluvents; Toccoa: coarse-loamy, mixed, active, nonacid, thermic Typic Udifluvents).

Along the Holcombe's Branch, legacy sediment profiles have A over C horizons that often overlie paleo-A horizons from the preagricultural past. We can generally conceive of the sequential deposits of legacy sediments as representing an inverted upland soil profile. In other words, since the lowest layers of the legacy sediment were the result of initial erosion, these layers have particles dominated mainly by former upland A horizons. As the sequence of deposition continued, particles derived from across the upland profiles,

including the C horizon saprolites. Overall, the legacy sediment A and C horizons are coarse-textured sandy loams along most of the 3.5-km length of floodplain soils along Holcombe's Branch. Although these floodplain soils (1) may periodically become saturated, especially during the winter season, their high hydraulic conductivities ( $>1 \text{ cm min}^{-1}$ ) allow them to drain relatively rapidly to the stream channel (Wade et al., 2019). Legacy sediment C horizons typically have  $>7.5\text{YR}$  hue and are largely devoid of redoximorphic features, which we attribute to the legacy sediment's coarse texture and effective aeration. Other than occasional lamellae, the profiles exhibit minor evidence of B horizon development.

Below the legacy sediments, however, one may often find recognizable Ab horizons of 10- to 20-cm thickness and occasionally Bb horizons with colors suggesting that the previous soil environments were subject to low redox potential prior to burial (Figure 9). Depth-dependent  $^{210}\text{Pb}$  dating,  $^{14}\text{C}$  dates of buried charcoal, and  $^{14}\text{C}$  dates of tree stumps buried by legacy sediments suggest that the majority of Holcombe's Branch legacy sediment was deposited 100 to 150 yr ago between 1870 and 1920 – similar to other legacy sediment deposits in the Southern Piedmont (Spell & Johnson, 2019) – and that they have been stable at this particular site (Figure 9) for a century or more (Wade et al., 2019). During the last century, we believe that the stream channel has widened and deepened such that overbank flooding today occurs infrequently, if ever, at this location in the middle reach of Holcombe's Branch.

These Fluvents are instructive for what they can inform us about soil and regolith polygenesis and soil and regolith evolution. Pedogenesis will continue into the future until the soils are mobilized by streamflow and swept downstream. The mineral particles in legacy sediment soils have been part of at least two previous soil profiles and regoliths (5, 6) in the past, one where they were initially weathered from bedrock; the other where they are residing today in a legacy sediment soil profile (6). Reconstructing the details of this polygenetic evolution requires new partnerships, not only among pedologists and geomorphologists, but among ecologists, biogeochemists, archeologists, and other critical zone scientists as well.

## 8 | CONCLUSIONS

Gilbert's (1877) Henry Mountains Report contains a number of insights related to his statement that "Over nearly the whole of earth's surface, there is a soil and wherever this exists we know that conditions are more favorable to weathering than to transportation." Even after over a century of scientific development of geomorphology and pedology, it is remarkable how well Gilbert understood not only geomorphological processes but, in an important sense, the soil geomorphological processes that we continue to study today. As our three Piedmont regoliths (5) demonstrate, soil and regolith evolve (7,

12) on interfluves, hillslopes, and floodplains driven by temporal variations in weathering and transport, including deposition rates of weathered material. Today, the rates of soil geomorphologic processes are governed not only by climate, biota, bedrock, geomorphology, and regolith, but increasingly by human activity. As an understanding of both weathering and transport is required to quantify the evolution of soils, regoliths, and landscapes (i.e., Earth's critical zones), it is clear that pedologists and geomorphologists should be working most closely on the important problems of the landscape in the Anthropocene.

We specifically conclude that since the 1990s, geomorphologists have begun to quantify the rates of weathering, geologic erosion, and what they call soil and mobile regolith production (9) by using cosmogenic nuclides with methods best applied on convex-up, steady-state settings. This important research needs far wider discussion among soil scientists and pedologists. Furthermore, future estimates of soil production on complex landscapes can benefit from a more integrated approach to pedology and geomorphology (i.e., soil geomorphology). The application of a Gilbert-inspired model of regolith evolution (12) in three contrasting soil and weathering profiles (6, 8) has demonstrated the utility of the soil geomorphology approach. This exercise leads us to conclude that soil geomorphologists can carefully reread the Piedmont's contemporary to ancient landscapes and their polygenetic soil and weathering profiles, thereby reconstructing a more comprehensive history of Piedmont soils forming in regoliths weathering in place and also soils forming in paleo-colluvial deposits and historic legacy sediments.

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