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Soil production and the soil geomorphology legacy of Grove Karl Gilbert

Daniel D. Richter[1], Martha-Cary Eppes[2], Jason C. Austin[1, 3], Allan R. Bacon[4], Sharon A. Billings[5], Zachary Brecheisen[1], Terry A. Ferguson[6], Daniel Markewitz[3], Julio Pachon[4], Paul A. Schroeder[3], Anna M. Wade[1]

[1] Duke University, Durham, NC 27708 USA
[2] University of North Carolina, Charlotte, NC 28223 USA
[3] University of Georgia, Athens, GA 30602 USA
[4] University of Florida, Gainesville, FL 32611 USA
[5] University of Kansas, Lawrence, KS 66047 USA
[6] Wofford College, Spartanburg, SC 29303 USA

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

USA's ancient Piedmont may have many soils formed within paleocolluvium

Abstract. Geomorphologists are quantifying rates of an important component of the bedrock's weathering in research that needs wide discussion among soil scientists. 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 greater understanding of our sciences’ history. We show how legacies of Grove Karl Gilbert extend across soil geomorphology and 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, of non-steady 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 a 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 understanding of soil, regoliths, and landscape evolution in all physiographic regions.

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Although the superficial layer of vegetable mould … 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)

INTRODUCTION

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 and 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 of 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 terminology and introduce methods and models with regard to soil and mobile-regolith production research. The potential for this research is demonstrated in a variety of recent and important publications (Dixon et al., 2009; Stockmann et al., 2014; Amundson et al., 2015; Yoo and Jelinski, 2016; Wang et al., 2018). We also write this paper to reinforce if not rekindle the soil geomorphology of Ruhe (1974) and many others (Holliday, 2006) who argue for integration of these two fundamental Earth sciences (Gerrard, 1981; Jungerius, 1985; Birkeland, 1984, 1990; McFadden and Knuepfer, 1990; Schaetzl and 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 steady state, and thus it also represents the physical lowering of bedrock by weathering. Soil production (9) is also known as mobile regolith production (9).

While pedologists have discussed soil production (9) (e.g., Minasny and McBratney, 2001; Yoo et al., 2006; Humphreys and Wilkinson, 2007; Dixon et al., 2009; Stockmann et al., 2014; Amundson et al., 2015; Schaetzl and Thompson, 2015; Yoo and Jelinski, 2016; Wang et al., 2018), soil production (9) research deserves much wider

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attention across the soil sciences for it is highly relevant to soil formation and soil evolution (7). Cosmogenic methods that estimate rates of soil production (9) have been most commonly employed on divergent, convex-up hillslopes, and 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 c. 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, and 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, 1965, 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 (1883) was studying chernozems across the steppes of Russia, 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: (a) examine recent approaches and rates of what geomorphologists call soil production (9) and consider how pedology can contribute to future soil production (9) research; (b) evaluate the scientific contributions of Gilbert (1877) to pedology and examine Gilbert-like ideas already in the mainstream of pedology in recent decades (Johnson 1985; Buol et al., 2011); and (c) 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).

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 non-linear 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 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 that rates of

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weathering are highest at intermediate soil (4) depths (Figure 1), in soils (4) that would 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 and 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 and Brantley, 2013; Riebe et al., 2017). In the 1990s, however Gilbert's proposal (Figure 1) was finally quantitatively tested, thanks to advances in cosmogenic nuclide analyses and geochronometry (Lal, 1991; Gosse and Phillips, 2001) and to geomorphologists' insights into the mechanics of soil (3) creep. Because cosmic radiation produces long-lived cosmogenic nuclides (CNs) in the atmosphere and in minerals, Earth scientists began to track accumulations of CNs to date and estimate rates of processes associated with bedrock exposures, glacial moraines, 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}H, ^{21}Ne) and others are radioactive with half-lives on the order of 10^3 to 10^7 years (^{10}Be, ^{14}C, ^{26}Al, ^{36}Cl, ^{41}Ca, and ^{129}I), timescales over which many soils, weathering profiles, and landscapes evolve. Some CNs are specifically 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. Production rates of TCNs decrease exponentially with depth belowground, specifically due to the density of soil or rock. While sample preparation and analytical instrumentation are specialized and costly, the techniques have remarkable accuracy and precision (Anderson and Anderson, 2010) and a literature is developing that points to many potential applications for pedology (Schaetzl and 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 steady state this is equivalent to the rate of bedrock lowering (Anderson and Anderson, 2010). Figure 2 (from Figure 10.3 in Anderson and 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 ($\dot{W}$), plus the mobile regolith transport inputs from upslope (Q_x) minus mobile regolith transport outputs downslope (Q_{x+dx}). An important aside is that the constant depth of mobile regolith (R) and spatially uniform weathering rates ($\dot{W}$) 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 constant depth-dependent mass of mobile regolith (3). Steady state requires that the net erosional loss from the surface due to the divergence of transport rate (mass in minus mass out) matches the mass of bedrock

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physically introduced into mobile soil (3) from below ($\dot{W}$), 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 McKean et al. (1993), Dietrich et al. (1995), Heimsath et al. (1997), and Small et al. (1999). McKean et al. (1993) estimated the rate of soil (3) creep on convex-up hillslopes in California using a mass-balance model that incorporated concentrations and inventories of depth-dependent, meteoric ^{10}Be. The study estimated the average rate of soil production (9) to be about 260 m My^{-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}Be rather than meteoric, as the production rates of *in situ* ^{10}Be are far better constrained than meteoric ^{10}Be). Following McKean et al. (1993), Dietrich et al. (1995) 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 using the assumption of 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., Heimsath et al., 1997, 1999, 2000, 2005; Small et al., 1999; Riebe et al., 2001; Anderson, 2002; Wilkinson and Humphreys, 2005; Yoo et al., 2006; Dixon, et.al., 2009; Gabet and Mudd, 2009; Roering et al., 2010; Anderson and Anderson, 2010; Decker et al. 2011; Riggins et al., 2011; Lebedeva and Brantley, 2013; West et al., 2013; Larsen et al., 2014; Amundson et al., 2015; Yoo and Jelinski, 2016; Riebe et al., 2017; Wang et al., 2018). Many of these studies examine the shape of the soil production function (10), and 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}Be and ^{26}Al in bedrock sampled immediately below mobile soil (3). With the assumption of steady state, the ^{10}Be and ^{26}Al data supported an exponential decline in rate of soil production (9) with increasing hillslope soil (3) thickness much like in the previously described Dietrich et al. (1995). In contrast, Small et al. (1999) used TCN ^{10}Be and ^{26}Al analyses high in the Wind River Mountains of Wyoming to examine the importance of frost weathering and concluded that mobile regolith at about 90 cm depths 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 begin to quantify rates of bedrock weathering and thus natural soil formation (7), rates that heretofore have been very poorly resolved, this research is

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not only fundamental to 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 controller of bedrock weathering, suggest many opportunities for pedologists to help expand this research with investigations of the weathering processes themselves as they respond to depth. Indeed, these opportunities are already being explored (Persico et al., 2011; McFadden, 2013; Anderson et al., 2013; Amundson et al., 2015; Yoo and Jelinski, 2016; Wang et al., 2018).

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 and 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 and Anderson, 2010; Schaetzl and Thompson, 2015). Mobile regoliths are mixtures of mineral particles and organic matter that range in size from colloids to boulders and that 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. While regolith moves and rests, it weathers chemically, biologically, and physically, all 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 et al., 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 depth-dependent rates of soil production is a 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 are increasingly focused on how regolith *processes* interact and control weathering and transport, i.e., 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). The authors demonstrate via models 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 meters elevation in the Southern Sierras, and estimated that chemical weathering rates within saprolite averaged 75% of the rates of soil production (54 *vs* 74 Mg $km^{-2}y^{-1}$). Pedologists can help quantify process rates of pedoturbation and soil creep, shear strengths and stresses, and extend estimates of

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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 and was part of an argument made by Ahnert (1998) to suggest that while mechanical weathering may exponentially decline 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 non-linear 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 et al. (1993) in hyper-arid landscapes where salt-shattering peaked in the regolith at 20-cm depth.

Soil production research marks a fundamental achievement for geomorphology. The approach however estimates a component of weathering and is to date mainly applicable to a portion of the Earth's surface – to mobile soils (3) found on divergent convex-up hillslopes that can be taken to be in steady state. To extend soil production research, pedologists can formally describe soil and weathering profiles (6, 8) and greatly enrich soil production inquiries of environmental reconstruction (Eppes and McFadden, 2008; Richter and Yaalon, 2012; McFadden, 2013). 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., Wilkinson and Humphreys, 2005; Heimsath et al., 2009; Yoo et al., 2011; Amundson et al., 2015; Wang et al., 2018). For example, all 12 soil orders in the USA's *Soil Taxonomy* 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 approximately 70,000 years. In a second example, Persico et al. (2011) in the Sandia Mountains of New Mexico described and interpreted hillslope soil and weathering profiles (6, 8) derived from aplite and granite. Significantly, soil profiles (6) from aplite though not from granite developed 1 to 2-m thick argillic B horizons that stabilized hillslopes contributed to preventing “attainment of a steady state balance between soil production and downslope transport” (Persico et al., 2011).

REGOLITH EVOLUTION

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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 intrenched 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.” While Butler (1958) maintained that time would always remain as a major soil-forming factor, it has only been in recent decades when a new generation of pedological research embraces that nearly all soils (1) have polygenetic histories to their formation (Chadwick et al., 1995; Buol et al., 2011; Richter and Yaalon, 2012; Schaetzl and 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 <0.1 to >1000 ky.

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, on approximately 20, 40, and 100 ky (Shepard et al., 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, organo-mineral complexes, secondary minerals, structural aggregates, clay films, soil’s surface areas, soil pans, and pore networks. Soils and regoliths (1, 5) are intrinsically unsteady systems that are fundamentally contingent upon their pedogenic history. Soils are thus polygenetic paleosols with physical, chemical, and biological features that form, persist, and eventually are erased (Yaalon, 1983; Chadwick et al., 1995; Buol et al., 2011; Richter and Yaalon, 2012). The exceptional soil and regolith (1, 5) is monogenetic, 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 while bedrock 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 non-steady state, the lack of endpoint, and evolutionary change (Johnson and Watson-Stegner, 1987).

We modify Crozier's (1986) transport equation of rate change in regolith depth (*dReg/dt*) to represent regolith evolution (12), which includes both regolith production, *Vw* (11), removals via transport, +*Vt*, and inputs via transport, -*Vt*:

$$\frac{dReg}{dt} = a\,Vw - (\pm Vt) \qquad (1)$$

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where *Reg* is thickness of the entire regolith (5), the entire weathering profile (8),

Vw is 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

$\pm$ *Vt* is a rate of transportation-related removal (+*Vt*) or deposition (-*Vt*).

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 upslope. 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), using three contrasting soils and regoliths (1, 5) in the Calhoun Critical Zone Observatory of the Southern Piedmont.

GILBERT'S WEATHERING AND TRANSPORTATION

At precisely the time that Hilgard (1860), Darwin (1882), and Dokuchaev (1883) 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 or what we call today landscape evolution, as the overcoming of the forces of cohesion by agents that weather indurated rock and that transport weathered products by 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 (Stegner, 1954; Pyne, 1980). 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 had 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%.

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Gilbert used the word soil (4) differently than soil is used today (Table 1), for example, 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 as regolith (Nikiforoff, 1959; Carson and Kirkby, 1972; Richter and 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) say "is weathered to any degree," and is taken from ῥῆγος *(rhegos)* in Greek meaning rug or blanket and λιθος *(lithos)*, 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 are by both dissolution and suspension. Net erosion (a part of *Vt* in Equation 1 and Figure 3) means more is lost by transport than is gained, hence is a positive gradient in physical transport. Also important is that Gilbert 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.

Jahn (1968) in "Denudational Balance of Slopes" (first published in Polish in 1954) made use of both Gilbert's Henry Mountains report and Gilbert's paper on hilltop convexity (1909) 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, Carson and Kirkby (1972) in *Hillslope Form and Process* illustrated Gilbert's proposed relationship between soil (4) depth and 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 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 and Wilkinson 2007). The latter delay is due to most soil scientists being focused on soil profiles (6), soil profile classification, and agronomy (Paton et al., 1995; Tandarich et al., 2002; Johnson et al., 2005; Humphreys and Wilkinson, 2007). Despite this history, considering how well Gilbert (1877, 1909) articulated the processes and feedbacks 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 Hilgard (1860), Darwin (1882), and Dokuchaev (1883).

GILBERT-LIKE IDEAS IN PEDOLOGY

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Although Gilbert is not well known to most pedologists (Humphreys and 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 and Buol 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 (7, 12).

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, 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, in bioturbation, and in 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), Buol et al. (2011) in several editions of *Soil Genesis and Classification* 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, i.e., downward without geologic uplift due to 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 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 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). In 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 and 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 due to variations in bedrock evolves from a transport-limited A-Bt-C horizon to a shallow, weathering-limited Entisol

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with an A-C profile. According to Carson and Kirkby (1972), Gilbert (1877) was the first to describe weathering- and transport-limited landscapes, endmembers fundamental to our understanding of soil, hillslope, and regolith development.

While Johnson and Buol and 100 years 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 to the ideas of Gilbert (1877) reinforces our support for Gilbert being much more widely read and recognized in the science of pedology.

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 Vt, (Figure 3, Equation 1):

a) a residual regolith with an Ultisol soil (34.606890N, -81.723795W) that is directly inherited from underlying granitic gneiss with the regolith (5) derived from $V_w >> |-Vt|$ (i.e., regolith largely from weathering rather than deposition),

b) a mixed regolith with an Ultisol soil (34.808312N, -81.898182W) that is formed within a thick paleo-colluvium with a regolith (5) derived from both V_w and $-Vt$ (i.e, a regolith from weathering and deposition), and

c) a alluvial depositional regolith with an Entisol soil (34.618992N, -81.690902W) formed within historic legacy sediments with a regolith (5) derived from $|-Vt| >> V_w$.

a) Residual regolith from $V_w >> Vt$

In the Southern Piedmont, broad, low-curvature, and ancient interfluves (Brecheisen, 2018) have regolith (5) that is weathered to 10s of meters in depth (Pavich, 1989; Bacon et al., 2012; Holbrook et al., 2019). 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). While rates of weathering and transportation are today very low (Richter and Markewitz, 2001), weathering over time has outpaced transport losses and accumulated regolith about 38 m in depth (Holbrook et al., 2019), a regolith that totals nearly 70 Mg m^{-2} in mass (Figure 7). The profile has an advanced weathering state with near complete dissolution of plagioclase to ~12-m depth, and with the deepest evidence of weathering at about 38-m (Holbrook et al., 2019). Using a slogan adapted from Dokuchaev and Targulian (Richter and 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) classifies as a residual Cataula series (Lance Brewington, USDA-NRCS personal communication), a soil formed directly from underlying bedrock. The Cataula is in the taxonomic class of the fine, kaolinitic, thermic Oxyaquic

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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/, accessed 5 July 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 (Daniels et al., 1999; Buol et al., 2011). At the same time, pedoturbation and eluviation-illuviation have thoroughly mixed particles that make up A, E, and Bt horizons, and even on these broad, low curvature, low slope landforms, we suspect that mineral particles of the *solum* (0 to 3-m) are somewhat displaced from the C-horizon saprolite immediately below. It remains for future soil geomorphologists to estimate 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 (Richter and Markewitz, 1995, 2001; Bacon et al., 2012; St. Clair et al., 2015; Holbrook et al., 2019). For example, inventories of meteoric ^{10}Be within this weathering profile (2 x10^{12} atoms cm^{-2} (Bacon et al., 2012)) help demonstrate its very great age, >2 to 3 million years. In the >10s of hectares that surround the 65-m deep bore hole, many dozens of boreholes have been hand-augered 5 to 8.5 m in depth (Richter and Markewitz, 1995; Brecheisen, 2018); biological, chemical, and physical properties have been analyzed from the solid samples from most of these boreholes (Richter and Markewitz, 1995, 2001; Callaham et al., 2006; Bacon et al., 2012; Richter et al., 2014; St. Clair et al., 2015; Richter and Billings, 2015; Austin et al., 2018; Billings et al., 2018; 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 from <10% to 100%, and plagioclase from nearly 0% to about 20% of the bulk mineral mass. Between 18 and 38 m the bedrock is physically fractured and geochemically most weathered within fractures. 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 (Ca^{2+}, Mg^{2+}, plus K^{+}) in soil waters that average <40 umol$_c$ L^{-1} down through 6 m depth in Bt and upper C soil horizons (Markewitz et al., 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-meters

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(Markewitz et al., 1998; Richter and 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 meters 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 on-going weathering reactions today. This regolith is in an advanced state of weathering (Richter and 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 $V_w >> Vt$ (Equation 1).

b) Mixed regolith from both V_w and -Vt

Like the residual Cataula soil and regolith (1, 5) illustrated in Figures 6 and 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 than 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 $|-Vt|$ and Vw). 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 the fine, kaolinitic, thermic Typic Kanhapludults and is one of the most extensive soil series on the Southern Piedmont, covering about 2.5 million hectares (www.websoilsurvey.nrcs.usda.gov/, accessed July 5, 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 |-*Vt*| and *Vw*) was first exposed in the 1930s by a massive agricultural gully that grew to be nearly 10 meters deep at the gully head (Cain, 1944). By 2018, the gully was <6 meters deep, due to regolith sloughing and detritus that includes a complete wood-frame house with contents that was pushed into the gully in the 1970s or early 1980s. However, within 20 meters 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 paleocolluvium is itself mixed but is also stratified with a 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 paleocolluvium and its contemporary soil horizons suggest that the colluvium is composed of material that was pre-weathered 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) a 2-meter thick organic-enriched sandy deposit (Figure 8). This layer contains ^{14}C-dead soil organic matter, charcoal, tree trunks up to 30-cm diameter, and plant macro-fossils including acorns and hickory nuts (Eargle, 1946). The organic-enriched layer that resides at ~6 to ~8-m depth also contains abundant

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Abies and *Picea* pollen (Cain, 1944; Deb Willard, US Geological Survey, personal communication). 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 4-m depth were measured for their optical and infrared stimulated luminescence (OSL and IRSL) and estimated to have been buried for ~109,000 years BP (Michelle Nelson, personal communication, Utah State University Luminescence Laboratory). Overall, this second profile's stratigraphy, sedimentology, and pedology indicate a regolith system far from steady state. We attribute 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 weathered, plagioclase-free regolith (5), perhaps not unlike that of the upper 10 to 12-m of the residual regolith with Cataula series soil illustrated in Figures 6 and 7.

In the 1930s, the Soil Conservation Service (SCS) systematically studied soil erosion and gullying across the Southern Piedmont in efforts that included the Civilian Conservation Corps (Eargle, 1946); Hans Albert Einstein, the son of Albert (Ettema and Mutel, 2014); and Carl O. Sauer (2009), efforts that led to new ideas and data about the Southern Piedmont paleocolluvium and its important relations to Piedmont soils and geomorphic surfaces (Sharpe, 1938; Eargle, 1940, 1946, 1977). 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 (Sharpe, 1938; Cain, 1944; Eargle, 1940, 1946, 1977). 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 largely a region largely characterized by deep residual regoliths with soils directly inherited from the underlying bedrock (Coffey and Hearn, 1901; Pavich, 1989; Daniels et al., 1999; Richter and Markewitz, 2001; Buol et al. 2011). While Eargle (1940) and Sharpe (1938) were well aware of this conflict, except for a paper by Eargle (1940) in *Science* magazine, the SCS studies was not widely circulated. World War II quickly and completely terminated the SCS research on the region's paleocolluvium and very little of these spectacular data are circulating today (Terry Ferguson, personal communication). 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 and 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 re-construct 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

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and mobile regolith far from steady state, a biogeochemical system derived from materials derived from both V_w and $-Vt$ (Equation 1).

c) Depositional regolith from $|-Vt| >> V_w$

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. These profiles composed of 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, processes of great interest to Gilbert (1917) and one about which he made seminal contributions (James et al., 2017).

By the late-1700s, farming began accelerating soil erosion in the Southern Piedmont (Ireland et al., 1939; Happ, 1945; 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, tobacco, corn, wheat, and domestic animals increased throughout the 19th century and peaked in the early 20th, before rapidly collapsing in the 1920s and 1930s (Richter and Markewitz, 2001; Coughlan et al., 2017). Massive volumes of soil eroded from hillslopes due to 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 and clay-enriched Bt horizons were exposed and eroded as well. Trimble (2008) estimated that farming-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 10s 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 America, and the land use history motivated the USDA Forest Service and National Science Foundation to establish in 1947, the Calhoun Experimental Forest, and the Calhoun Critical Zone Observatory in 2013 (Richter et al., 2014). Metz (1958) who led the first soil, forest, and hydrologic research 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), Piedmont floodplains as receiving areas are today inundated by deep legacy sediments. Along Piedmont floodplains of streams 2nd order and higher, pre-1750 floodplain soils are typically buried by 0.5 to 5 m of legacy sediments (Happ, 1945; James, 2013; Donovan et al., 2015; Dearman and James, 2019; Wade et al., submitted).

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

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~3.5 km long Holcombe's Branch in Sedalia, SC, a watershed farmed from as early as the late 1700s to the mid-1930s, which was rapidly reforested as nearly all of the catchment was purchased for the Sumter National Forest by 1935. Soils too have rapidly developed O horizons under pine and pine-hardwood stands and accumulated soil organic matter in surficial A horizons as well (Richter et al., 1999; Richter and Markewitz, 2001; Mobley et al., 2015, 2019). In the Holcombe Branch floodplains, the youthful soils classify as Entisols, specifically Fluvents, and are mapped by the NRCS in a Cartecay-Toccoa series mapping unit, series mapped on about 350,000 hectares of the Piedmont.

Along the Holcombe's Branch, legacy sediment profiles have A over C horizons that often overlie paleo-A horizons from the pre-farming past. We can generally conceive of the sequential deposits of legacy sediments to represent 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 derive 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 (Ksat of >1-cm min^{-1}) allow them to drain relatively rapidly to the stream channel (Wade et al., submitted). Legacy sediment C horizons typically have >7.5YR hue and are largely devoid of redoximorphic features, which we attribute to the legacy sediment's coarse textures and effective aeration. Other than occasional *lamellae*, the profiles exhibit minor evidence of B horizon development.

Below legacy sediments however, one may often find recognizable Ab horizons of 10 to 20-cm thickness and occasionally Bb horizons with colors that suggest that previous soil environments were subject to low redox potential prior to burial (Figure 9). Depth-dependent ^{210}Pb dating, ^{14}C dates of buried charcoal, and ^{14}C of tree stumps buried by legacy sediments suggest that the majority of Holcombe's Branch legacy sediment was deposited 100 to 150 years ago between 1870 and 1920 – similar to other legacy sediment deposits in the Southern Piedmont (Spell and Johnson, 2019) – and that they have been stable at this particular site (Figure 9) for a century or more (Wade et al., submitted). 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 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, and 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

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geomorphologists, but among ecologists, biogeochemists, archeologists, and other critical zone scientists as well.

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 with 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, 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:

1. Since the 1990s, geomorphologists have begun to quantify 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.
2. Future estimates of soil production on complex landscapes can benefit from a more integrated approach to pedology and geomorphology, i.e., soil geomorphology.
3. Application of a Gilbert-inspired model of regolith evolution (12) in three contrasting soil and weathering profiles (6, 8) demonstrates the utility of the soil geomorphology approach. This exercise leads us to conclude that soil geomorphologists can carefully re-read 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, but also soils forming in paleo-colluvial deposits and historic legacy sediments.

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Table 1. Historic and contemporary usages of soil (1 to 4), regolith and soil and weathering profiles (5, 6, 8), soil formation and evolution (7), and soil- and mobile-regolith-production and the soil production function (9 to 11), and regolith production and evolution (11, 12) in the literature of pedologists, ecologists, engineers, and geologists.

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, eg., O, A, E, B, and C horizons, which together 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* or in place (McKean et al., 1993; Dietrich et al., 1995; Heimsath et al., 1997; Anderson and Anderson, 2010). Also known as hillslope colluvium, soil creep, and hillslope sediment (Daniels and Hammer 1992). Relict rock structure is absent in this soil (3) due to movement and mixing often by biota, even though the materials are derived from underlying weathering bedrock or sediment.
(4) Soil, as in Gilbert's (1877) soil	Regolith (5), in the context and following Gilbert (1877) and Merrill (1897). This usage of soil (4) is also found throughout the 20th century, for example 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) to be 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 and Anderson, 2010). Derived from ῥῆγος *(rhegos)*, Greek for rug or blanket and λιθος *(lithos)*, stone, and including 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 biogeochemically and physically-fractured weathered geologic substratum. The *solum*, sometimes called "true soil", refers to the upper soil profile from A through the B horizons. The soil profile includes the O through 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 (Jenny, 1941; Buol et al., 2011; Richter and Yaalon 2012). Johnson and Watson-Stegner (1987) emphasize the polygenetic evolution of soil (1) and that processes operate that progressively and regressively alter 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 pre-conditioning of protolith (St. Clair et al., 2015). Also called the belowground critical zone.

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(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 (McKean et al., 1992; Dietrich et al., 1995; Heimsath et al., 1997; Anderson and Anderson, 2010). The generation of mobile material by the detachment of non-mobile saprolite, or weathered or fresh bedrock, through lateral translation and mixing. See Anderson and Anderson (2010) who use the phrase “mobile regolith production” rather than “soil production” to diminish potential confusion with definitions of soil (1, 3).
(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). SPF may hypothetically be humped (meaning the rates reach a maximum at some finite soil depth) and can be estimated with cosmogenic nuclides analyses (Heimsath et al., 1997). The SPF is a function of rock type, climate, and biota, geomorphology, and time, which together govern detachment rate of non-mobile 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 is Gilbert-inspired and the regolith production function is hypothetically non-linear as proposed by Gilbert (1877), Carson and Kirkby (1972), and Ahnert (1998). Ahnert (1998) modeled the non-linear function and suggested that while physical weathering rates might exponentially decline with depth of regolith, 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 weathering products’ additions and removals. Regolith evolution ebbs and flows and is characterized by dynamic equilibria and polygenesis.

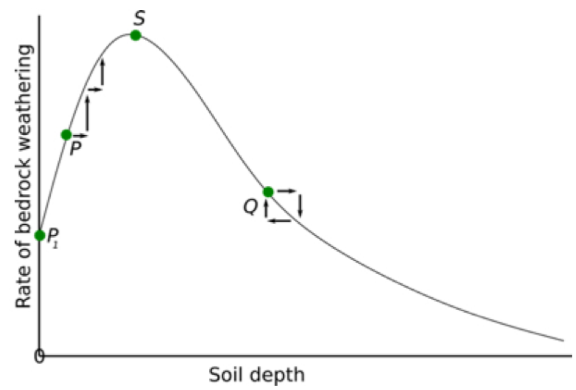

Figure 1. Variation in the rate of bedrock weathering with soil (4) depth, based on Gilbert's (1877) proposal of a non-linear (humped) relationship of weathering advance and soil (4) depth and illustrated by Carson and Kirkby (1972). Soil (4) as used by Gilbert (1877) and Carson and Kirkby (1972) is 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 maximum due to intensity of rooting and geochemical and geophysical weathering.

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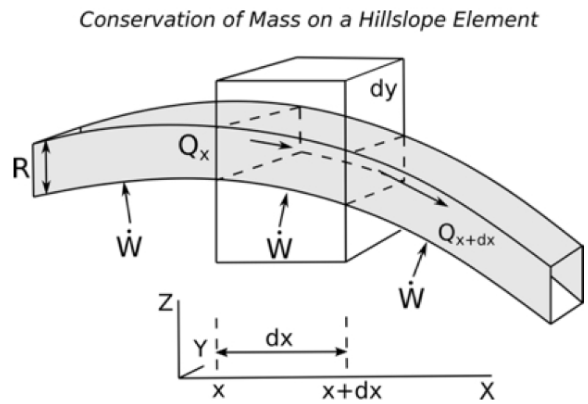

Figure 2. Conceptual hillslope model of Anderson and Anderson (2010) illustrating conservation of mass of a hillslope element, dx by dy, and that is related to hillslope models of Heimseth (1997), Dietrich et al. (1995), and Gilbert (1909). Spatially uniform weathering, $\dot{W}$, supplies new regolith 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 lateral transport of mobile regolith, Qx, that increases linearly with distance, x, from the hillcrest, Qx+dx.

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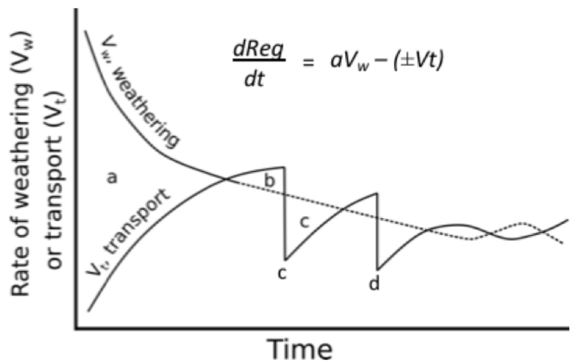

Figure 3. Regolith evolution as a modified presentation of Crozier's (1986) "waste production", as in regolith production (12), illustrating temporal changes in accumulated regolith (5) depth as a result of contrasting rates of weathering and transportation. Illustrated is (a) the gradual buildup of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

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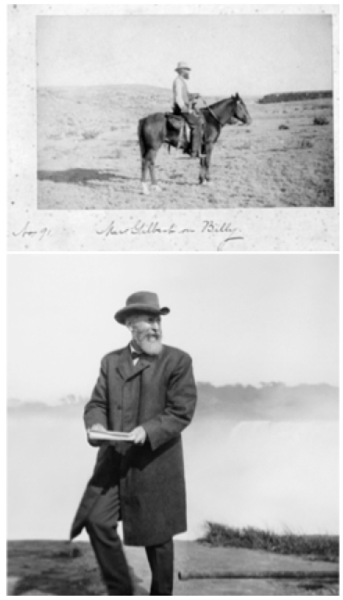

Figure 4. “Mr. Gilbert on Billy” and at Niagara Falls. Many summers in the 1870s, Gilbert worked with the Wheeler and Powell geological surveys. John Wesley Powell, Charles Dutton, Gilbert and others would return East in winter, to share and develop their findings and ideas, and to write reports (Stegner,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

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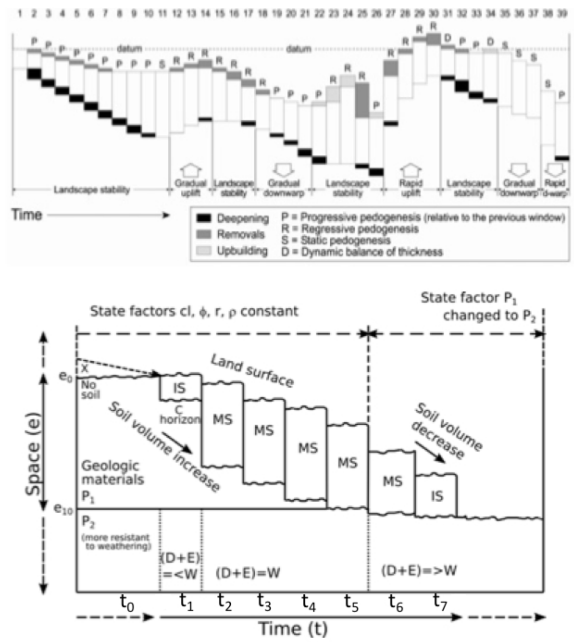

Figure 5. Pedological models of soil formation (7) and reg¬¬olith production (12) used by (a) Johnson (1985) and (b) Buol et al. (2011), conceptual models that parallel Gilbert's (1877) ideas that soils (4) are net products of weathering gains exceeding transportation losses. In (b), Buol et al. (2011) 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, W is weathering gain.

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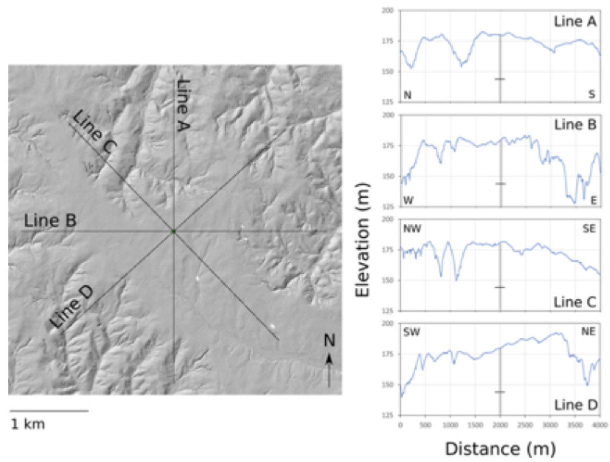

Figure 6. A LiDAR slope map of the Calhoun Critical Zone Observatory, near Cross Keys and Sedalia, SC. Here we show the broad, low curvature, nearly level interfluve and the location of the residual regolith and the 65-m deep corehole in the On the right, 4000-m long elevational transects are illustrated with the vertical corehole shown as a vertical line with a horizontal cross-hatch 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 seriously so. Nearly every channel in the LiDAR image is deeply incised or gullied due to historic agriculture.

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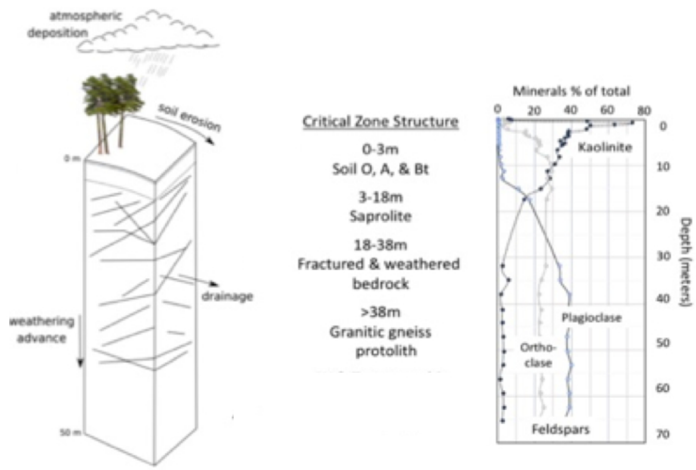

Figure 7. Diagram of a residual regolith (5) and its soil (1) with materials derived mainly from weathering in place (Vw in Equation 1). The residual, transport-limited Ultisol soil and weathering profile (6, 8) are forming directly from underlying bedrock. The figure at left is a conceptual model of the weathering profile, illustrating weathering advance and transport losses, and thereby 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).

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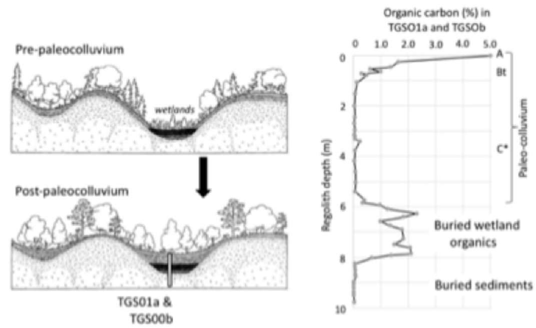

Figure 8. Diagram of a mixed regolith (5) and soils (1) derived from both Vw and -Vt in Equation 1 (from weathering gains and colluvial deposition). On the left is Eargle's (1946, 1977) concept of the Piedmont landscape's development during the late Pleistocene near Greer, SC. Two stages of landscape development are illustrated on the left, a deeply weathered landscape with wetland peats, residual weathering profiles (8), and cool temperature vegetation. In 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 carbon 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*.

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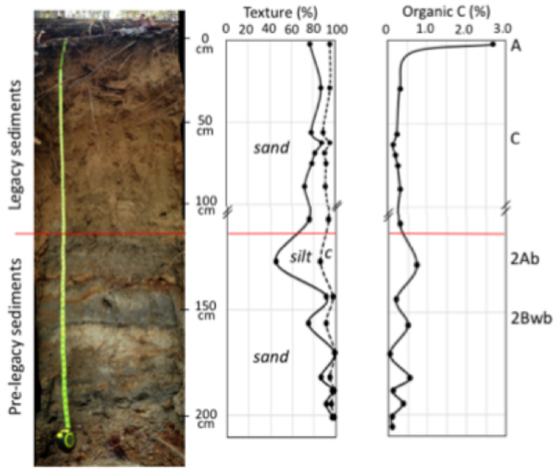

Figure 9. Diagram of a sedimentary regolith (5) and its soils (1) with materials almost entirely from transport (-Vt in Equation 1). On the left is a photograph of profile XHBr-6", with over a meter of coarse-textured legacy sediments that are low in organic carbon, well oxidized. The profile has a buried Ab horizon at about 117 cm depth 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 carbon, which except for the redeveloping A horizon is <1% with notable variability in the buried pre-legacy sediment.

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