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Weathering fronts

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ABSTRACT

A distinct boundary between unweathered and weathered rock that moves downward as weathering proceeds—the weathering front—is explicitly or implicitly part of landscape evolution concepts of etchplanation, triple planation, dynamic denudation, and weathering- and supply-limited landscapes. Weathering fronts also figure prominently in many models of soil, hillslope, and landscape evolution, and mass movements. Clear transitions from weathered to unweathered material, increasing alteration from underlying bedrock to the surface, and lateral continuity of weathering fronts are ideal or benchmark conditions. Weathered to unweathered transitions are often gradual, and weathering fronts may be geometrically complex. Some weathering profiles contain pockets of unweathered rock, and highly modified and unmodified parent material at similar depths in close proximity. They also reflect mass fluxes that are more varied than downward-percolating water and slope-parallel surface processes. Fluxes may also be upward, or lateral along lithological boundaries, structural features, and textural or weathering-related boundaries. Fluxes associated with roots, root channels, and faunal burrows may potentially occur in any direction. Just as pedology has broadened its traditional emphasis on top-down processes to incorporate various lateral fluxes, studies of weathering profiles are increasingly recognizing and incorporating multidirectional mass fluxes. Examples from karst systems may also be useful, where concepts of laterally continuous weathering fronts, rock-regolith boundaries, and water tables; and an assumption of dominantly diffuse downward percolation are generally inapplicable. We also question the idea of a single weathering front, and of a two-stage process of weathering rock to regolith, and transforming regolith to soil. In many cases there appears to be three stages involving conversion of bedrock to weathered rock, weathered rock to regolith, and regolith to soil.

1. Introduction

The weathering front is the interface between intact or unweathered bedrock and the weathered rock, saprolite, regolith, or soil above it. The term reflects the concept of weathering as a predominantly top-down process that originates at the ground surface and proceeds to penetrate deeper into the rock material below. The purpose of this study is to explore the complex nature of many weathering fronts and the resulting weathering profiles, and the implications for weathering profile, soil and landscape evolution. By highlighting some inconsistencies between real-world complexity and application of terminology and concepts by practitioners (geologists, pedologists, engineers) we also hope to improve the ability to describe and interpret weathered mantles. First, we discuss the traditional approaches to weathering fronts and discuss shortcomings of these in some situations. We then analyze the importance of weathering fronts in landscape and soil evolution models. Finally, we propose an expanded view of weathering fronts and weathering profile evolution.

The weathering front term seems to have originated from Mabbutt (1961). The origin of the weathering front concept is often attributed to Linton's (1955) work on tors, which referred to the front as a basal surface and articulated a notion of landform evolution initiated by chemical weathering in the subsurface. Physical weathering is also important, and in many cases closely interrelated with chemical weathering, as both a facilitator (see Section 2.1) of and a result of the latter (Royne et al., 2008; Reis and Brantley, 2019). However, the front concept is not necessarily applicable to situations where chemical alteration is absent. Ruxton and Berry (1959) also referred to a "basal surface of weathering" in their study of weathered granitic rocks. Earlier, a similar concept, the "basal horizon of atmospheric weathering" sitting atop an "unaltered geologic formation" was stated by Veatch (1925). While the boundary between unweathered and weathered

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material is indeed sometimes rather sharp, recognition that the weathering front is often irregular and discontinuous goes back at least to Jenny (1941), who wrote, “there is no sharp boundary between undecomposed rock, weathered rock, soil material, and soil.”

Weathering fronts may be perceived at a variety of spatial scales, from intergranular to landscapes, and at temporal scales from the rate of propagation of wetting fronts and chemical reaction fronts to long term landscape evolution. Here we are concerned primarily with the spatial scale at which they are observed in outcrops, soil pits, and core samples, and the temporal scales of pedogenesis and landform evolution.

A weathering front is often conceived as a more-or-less planar zone parallel to the surface that propagates downward into underlying bedrock. This has long been known to be a simplification. That weathering fronts may be gradual rather than sharp, geometrically irregular (locally variable in depth), and subject to spatial and temporal variability in propagation has been recognized for decades (e.g. Taylor and Eggleton, 2001). Likewise, it is long established that some weathering profiles contain core stones or other pockets of minimally weathered material (e.g., Ollier and Pain, 1996). Thus, to simply show that weathering fronts may be more complex than a single distinct feature separating weathered from unweathered material is something of a straw man argument. However, a more detailed consideration of weathering front concepts is warranted for several reasons.

First, the nature of weathering fronts is directly or indirectly relevant to several concepts and models of landscape and regolith evolution (Chen et al., 2014; Minasny et al., 2015; see Section 1.2). Second, the weathering front question is directly related to the measurement or estimation of regolith thickness, which has direct applications in hydrology, agriculture, forestry, mineral exploration, geochronology and seismic risk assessment (Wilford and Thomas, 2014). The complexity of weathering fronts is also relevant to the development of layering and stratigraphy, which is crucial in considerations of moisture and pollutant fluxes, carbon storage, and other applications (Lorz et al., 2011) and in palaeoecological and palaeoclimate reconstructions (e.g. August and Wojewoda, 2004). Also, weathered rock is increasingly recognized to have soil-like properties in some cases, and to support many of the same ecosystem functions as soil, including plant substrate, moisture supply, and nutrients; and faunal and microbial habitat (Graham et al., 1994; Stone and Comerford, 1994; Tate, 1995; Wald et al., 2013).

Third, reconsideration of weathering fronts is part of ongoing efforts to understand regoliths and the critical zone in terms of multidirectional moisture fluxes rather than dominantly top-down processes. This parallels recent developments in pedology (c.f., Paton et al., 1995; Phillips and Lorz, 2008; Lorz et al., 2011; Schaetzl and Thompson, 2015), hydropedology (e.g. Ma et al., 2017) and hydrology (e.g. Worthington et al., 2016). Recent models of critical zone evolution, for example, emphasize multidirectional water flows and other mass fluxes (Brantley et al., 2017; Lebedeva and Brantley, 2017; Riebe et al., 2017; Yu and Hunt, 2017; Van der Meij et al., 2018).

Weathering fronts may also be important in understanding the development of specific types of landforms, such as etchplains (Migon, 2004) and rock shore platforms (Thornton and Stephenson, 2006).

One problem in gathering archived information is the different standards and protocols from different communities that study weathering profiles, such as pedologists, geomorphologists, and engineers (Ehlen, 2005). Soil surveys and profile descriptions rarely consider depths below 1.5 to 2 m, though Wysocki et al. (2005) described opportunities to convey more subsolum information in surveys. By contrast, geotechnical data such as core and borehole records often record soil, regolith, and saprolite as simply “overburden,” with no distinction among them. Geologists have long addressed deeper material, but until relatively recently focused on rock rather than unconsolidated surficial layers, and core descriptions and well logs typically reflect this.

1.1. *Terminology*

Here bedrock is used to denote intact, negligibly weathered or unweathered rock. A bedrock section at the base of a weathering profile (as opposed to bedrock fragments above the weathering front) has > 90% intact rock. Following Ollier and Pain (1996) and Ehlen (2005), there may also exist slightly, moderately, or highly weathered rock. In slightly weathered rock the rock structure is preserved, microfractures exist, and there may be interlocked core stones, including some weathered material. It is potentially slightly calcified, and readily broken with a hammer. Moderately weathered rock also conserves rock structure, but has fissures and fractures, and rectangular core stones. Earth material (soil or sediment) is < 50%. It is potentially calcified, and iron or oxide staining may be present; and it can be broken by a kick. Rock structure is still visible in highly weathered rock, but core stones are rounded, and unconsolidated material comprises > 50% of the volume. There may exist strong iron or oxide staining, and it is potentially strongly calcified and can be broken by hand (Ollier and Pain, 1996; Ehlen, 2005). Many other criteria have also been used, including bulk density, mineral ratios, presence of weathering features in thin section, hardness, and others.

A classification system for subsolum materials proposed by Juilleret et al. (2016) includes the categories of regolith (or regolite), saprolite, saprock, and bedrock. Regolith and regolite have > 50% rock structure by volume, and are considered by Juilleret et al. (2016) to be composed mainly of transported or deposited material. A saprolithic layer has similar properties, but is mainly weathered in place. They also define paralithic layers, which have > 50% rock structure but are more coherent than regolith or saprolite. Paralithic layers also show roots along rock partings (but not in the matrix), and/or visible fillings such as clays or other weathered materials. A lithic (bedrock) layer in Juilleret et al.'s (2016) scheme has > 90% rock structure, and no roots or visible evidence of weathering (other than discoloration or staining) along rock partings. In other sources (e.g., Ollier and Pain, 1996; Schaetzl and Thompson, 2015) regolith is defined more broadly as all unconsolidated material (including soil) above the weathering front, transported or weathered in situ. Soil is generally agreed to refer to the upper part of the weathering profile, modified sufficiently by physical, chemical, and biological processes so that structure of underlying bedrock or other parent material is no longer evident. However, note that “soil” is used loosely by some geoscientists—particularly in a modeling context—to refer to all unconsolidated material above bedrock (c.f. Minasny et al., 2015). Ehlen (2005) reviewed the different classifications for material above the weathering front used by engineers, soil scientists, and geoscientists. Figs. 1 and 2 (from Taylor, 2011) show weathering fronts in two idealized profiles, and some additional terminologies. Tandarich et al. (2002):(Table 2) present a summary of > 40 concepts and definitions for subsolum layers, and other classifications and definitions have also been proposed (e.g., Ebert, 2008; Alavi Nezhad Khalil Abad et al., 2014; Hall et al., 2015a, 2015b). Of course, all efforts at defining or classifying weathering zones suffer from the general problem of attempting to discretize what is often a continuum. Table 1 specifies the definitions used in this paper.

1.2. *Role of weathering fronts in conceptual models*

Traditional concepts of pedogenesis emphasize top-down processes, and conceptual models of weathering in geomorphology often implicitly and sometimes explicitly (e.g., Riebe et al., 2017) use a “conveyor belt” metaphor. As the weathering front and pedogenesis move downward, there is a transition upward from bedrock to slightly, moderately, and highly weathered rock (or saprolite), to soil substratum C horizons (soil layers that retain some parent material properties) to the solum or “true soil.” However, many analyses and simulation models are based on a two-stage sequence whereby weathering turns bedrock into regolith (or saprolite), and pedogenesis turns

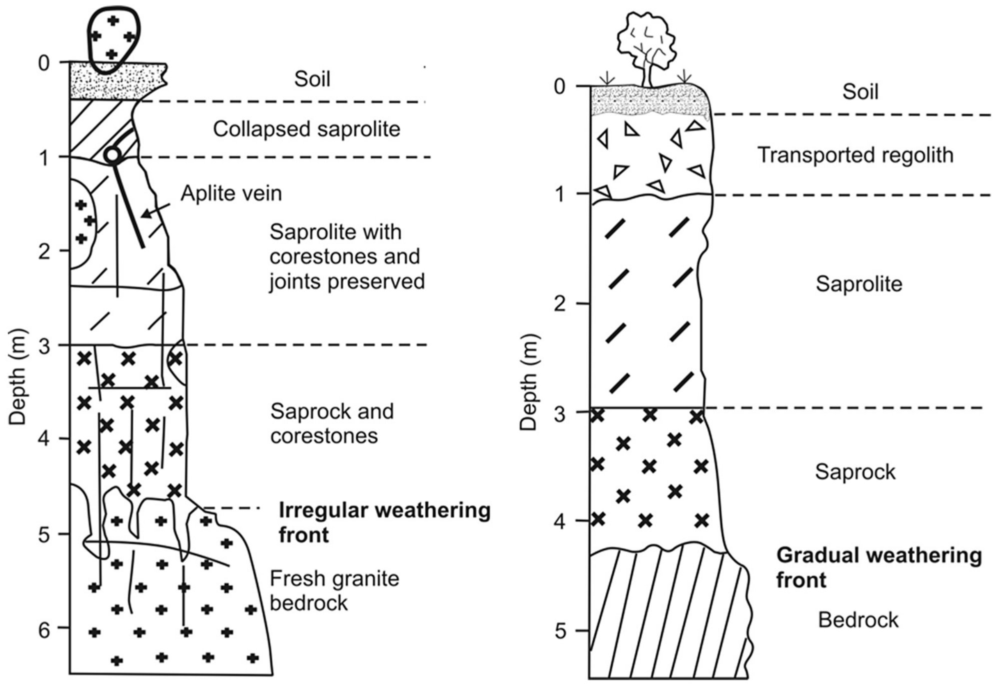

Fig. 1. Two idealized weathering profiles. (A) developed on granitic bedrock and (B) on deformed clastic sedimentary rocks. After Taylor (2011).

regolith into soil (e.g., Gabet and Mudd, 2010; Riebe et al., 2017). In our own previous work this has been explicit in some cases (Phillips, 2010, 2018) and implicit in others (Phillips et al., 2005).

Like most conceptual models of Earth surface processes, the conveyor belt is in many cases only a loose approximation. Conveyor-belt models do sometimes capture the essence of regolith and hillslope evolution, and work well in many applications (see references above). However, this conceptual framework is not always applicable, and is often incomplete. Variations in rock properties, dynamical instabilities, lateral processes, bioturbations and positive feedbacks in weathering and other pedogenetic processes work in many cases to create increasingly variable and heterogeneous (both vertically and

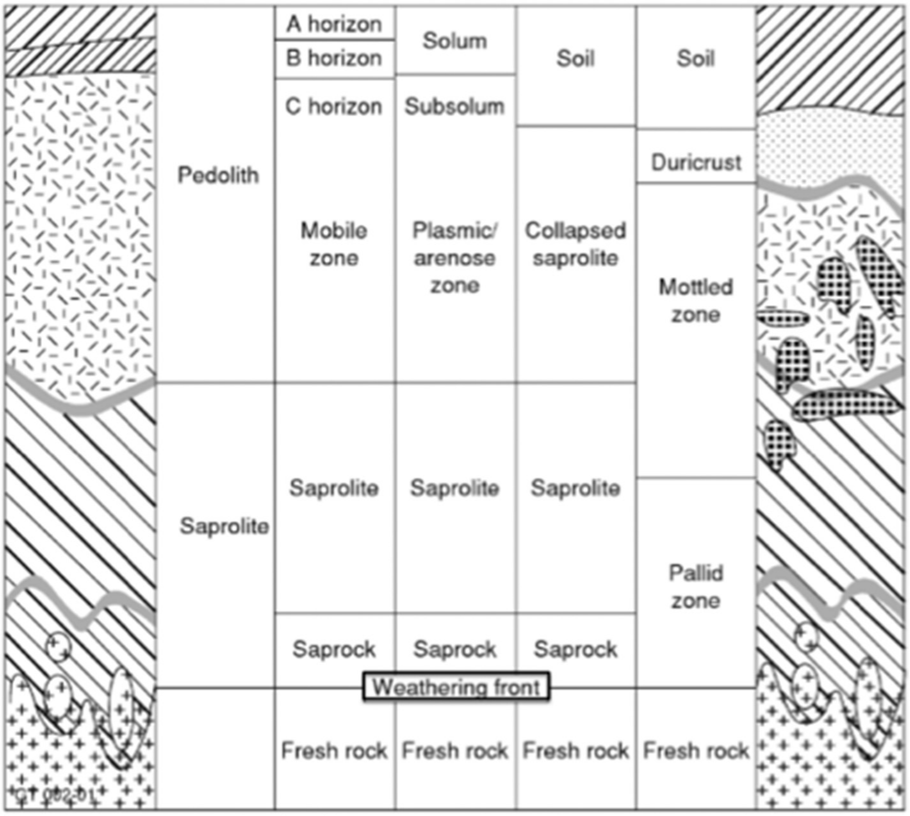

Fig. 2. Some terms used to define weathered zones in an in situ regolith profile (after Taylor, 2011). No vertical scale is intended.

Table 1
Definitions used in this paper.

Soil: Highly modified (relative to parent material) upper portion of the regolith. Includes the solum (O, A, E, B horizons). Soil is typically strongly influenced by biota, and may include transported material as well as in situ weathered material.
Regolith: Weathering mantle plus any transported material that rests above it. Includes soil, saprolite, and highly-weathered rock.
Saprolite: Highly weathered rock in situ that retains original rock structure and fabric, with $< 50\%$ intact rock, and can be excavated by hand or trowel.
Weathered rock: Moderately (50–80% intact rock) and slightly weathered rock (–80-95% intact rock) below regolith and above bedrock.
Bedrock: Unweathered or barely-weathered rock with $> 90\%$ intact rock; no visible weathering other than discoloration.
Weathering front: Boundary between fresh and weathered rock, which may be a gradual and/or irregular transition zone rather than a sharp separation. We will use the following modifiers for more specific usages:
  Bedrock weathering front: boundary between fresh bedrock and the overlying weathering mantle at the base of a profile or section.
  Isolated weathering front: weathering fronts associated with core stones or unweathered remnants within a weathering profile.
  Regolith weathering front: boundary between moderately and/or slightly weathered rock and overlying saprolite or other regolith.
  Sedimentary weathering front: Boundary or transition between weathered and unweathered material in regoliths or weathering mantles formed in unconsolidated sedimentary parent material (see, e.g., Worthington et al., 2016, Fig. 4).

horizontally) weathering profiles over time. Critical processes operate in all directions (not just vertically), and moisture fluxes and biological activity follow preferential, self-reinforcing paths. Further, mass is added not just from weathering, but also from deposition and organic matter, and is removed not only by erosion, but also by harvesting, leaching, fire, and decomposition.

There sometimes exists a negative feedback (either in general, or after a relatively thin threshold thickness has developed) between soil and regolith thickness and weathering rates at the base of the regolith. This relationship, commonly referred to as the soil production function (Humphreys and Wilkinson, 2007) implies the presence of a distinct subsurface focus of conversion of rock to regolith. This is justifiable as a simplifying model assumption regardless of its applicability at a given site. A more nuanced understanding, however, would help explain the infrequency of the steady-state soil and regolith thickness (at the scales of interest here) implied by the production function (e.g., Phillips et al., 2005; Phillips, 2010; Tye et al., 2011; Zollinger et al., 2016; Yu and Hunt, 2017), and the occurrence of very deep weathering profiles with active weathering still occurring at the bedrock interface (e.g., Hill et al., 1995; Migon and Lidmar-Bergstrom, 2002; Carmo and Vasconcelos, 2004; Arias et al., 2016; Jiang et al., 2018). Weathering fronts may also be more directly related to surface topography. Tors and bornhardts are defined and described in terms of exposed weathering fronts (Linton, 1955; Twidale and Vidal Romani, 2004), and Kroonenberg and Melitz (1983), for instance, suggested that major topographic features—steps separating summit levels of different altitudes in Suriname—might be associated with "jumps" in the weathering front due to differential weathering rates of varying lithologies.

Models of landscape evolution are generally based on two key surfaces—the ground surface itself, where (in a landscape undergoing denudation) material is removed, and the weathering front, where potentially mobile material is produced. A variation on these conveyor-belt models is the two-stage or etchplanation concept, whereby chemical weathering or etching at the weathering front builds a regolith cover, followed by erosional stripping to expose the weathering front (Twidale, 2002 reviews the history and development of this idea). Note, however, that not all workers equate the etched surface with the weathering front (Beauvais et al., 2003; Migon, 2004; Ebert, 2008).

Aleva (1983, 1987), working in tropical landscapes with texture contrast soils, developed a triple planation conceptual model, with more emphasis on lateral subsurface processes, and recognizing an additional planation surface at a coarser-to-finer transition at the base of a biomantle or an A or E to B horizon boundary. This is dominated by lateral throughflow, whereby solutes leached from overlying layers can be removed. Johnson (1993) incorporated triple planation into his dynamic denudation model, referring to the ground surface, weathering front, and lateral throughflow levels, respectively, as the P1, P2, and P3 surfaces.

Where there is a sharp or thin transition zone from soil, regolith, saprolite or highly weathered rock to fresh bedrock, a double or triple planation surface concept is appropriate (depending on whether P3 is present). However, where a thick layer of (moderately or slightly) weathered rock exists, there exists an additional level. Two weathering fronts may be perceived in this case, at the weathered rock/bedrock interface, and at the boundary between highly- and moderately weathered rock (bedrock and regolith weathering fronts). This is supported by the fact that in geotechnical boreholes the top of bedrock or depth to bedrock typically corresponds to the moderately weathered rock level (Ehlen, 2005). One might also suspect the presence of multiple P3 sublevels, particularly where layered, tilted rock of varying permeability and weathering resistance exist.

A key theoretical concept in geomorphology is that of weathering- vs. transport-limited systems. While Carson and Kirkby (1972) did not originate this concept (they attribute it to Gilbert, 1877), their articulation has been the most influential, and is typically cited in literature on hillslope, regolith, and landscape evolution modeling. Denudation rates are ultimately limited either by the rate at which weathering produces transportable products, or by the rate at which transport processes can remove this debris. In the former, weathering-limited case, little regolith accumulates and the weathering front is shallow (or bedrock is exposed at the surface). If a system is transport limited regolith accumulates and the weathering front may be deep.

In the U.S. National Science Foundation Critical Zone program, the critical zone is defined as "Earth's permeable near-surface layer... from the tops of the trees to the bottom of the groundwater" (http://criticalzone.org/national/research/the-critical-zone-1national/). The critical zone (the term is in wide use outside the USA, with similar definitions) is not really a conceptual framework, but an integrated approach to the study of rock, regolith, soil, water, biota, and atmosphere interactions near Earth's surface. While the weathering front is a key component of the critical zone, the approach makes no a priori assumptions about its role or behavior. In general, critical zone studies that address the weathering front treat it as being influenced by complex interactions among geological controls, biogeochemical reactions, geomorphic and hydrological processes, organisms, and climate (c.f. Holbrook et al., 2014; Brantley et al., 2017; Riebe et al., 2017). A key component of some critical zone work is reactive transport modeling based on chemical weathering and solute transport. In this work the reaction front at least approximately corresponds to the weathering front (e.g., Brantley et al., 2013, 2017; Lebedeva and Brantley, 2017). However, reaction fronts are perceived at the time scale of geochemical kinetics, while weathering fronts as perceived by geomorphologists, pedologists, and stratigraphers are longer-lived features and may contain multiple reaction fronts at a given time.

The biomantle concept as developed by Johnson (1990, 1993, Johnson et al., 2005a) conceives of a surficial layer of soil and regolith actively influenced by faunalturbation, floralturbation, and other biomechanical and biochemical processes. In the case of shallow regoliths, bioturbation may directly influence the weathering front, resulting in regolith thickening and downward migration of the front (Johnson, 1985; Johnson et al., 2005b). However, the weathering front does not otherwise directly relate to biomantle formation, which (in thick regoliths) can occur entirely above the weathering front.

Late 19th and early 20th century theories of landscape evolution of Davis, Penck, Gilbert, and King acknowledged the role of weathering, but did not generally ascribe a key role to the weathering front, focusing instead on relationships between topography and surficial

Table 2

Role of weathering fronts in various conceptual frameworks. See text for further explanation.

Conceptual model or framework	Role of weathering front (WF)
Conveyor belt	WF moves downward as rock is converted to saprolite, etc. From WF to surface there is a gradient of increased alteration.
Soil production function	Weathering at WF is primary mechanism of soil[a] formation. Soil thickness is inversely related to weathering rate.[b] Often associated with a proposed steady-state soil thickness where soil production ≈ erosion.
Etchplanation	Chemical weathering of bedrock at etch surface[c] is primary means of denudation. Weathered mantle sometimes stripped by erosion to expose etch surface.
Multiple planation, dynamic denudation	Denudation occurs at multiple vertical levels, one of which is the WF.
Weathering vs. transport-limited systems	If weathering-limited, transformation of rock at WF is limiting factor in rate of denudation. Little regolith accumulates; WF is shallow. If transport limited, denudation is limited by sediment transport capacities. Regolith accumulates; WF may be deep.
Critical zone (CZ)[d]	WF is critical part of the CZ. No specific assumptions about WF role or behavior; WF is influenced by complex interactions among geological controls, geochemical reactions, biota, & geomorphic processes.
Reactive transport models	Geochemical reaction front may roughly correspond to WF, though WFs are considered to be more persistent features & may contain multiple WFs
Biomantle	In shallow weathering mantles, biochemical & biomechanical processes at the WF may thicken regolith. In deeper profiles, biomantle may exist above bedrock WF.
Early 20th century landscape evolution models (e.g., Davis, Gilbert, Penck, King)	No specific role or behavior of WF asserted or assumed. Weathering rate-WF depth feedbacks similar to soil production function generally assumed, but do not play a definitive role.
Mechanistic hillslope & landscape evolution models	Role of WF manifested via soil production function and/or weathering & transport-limited concepts.
Karst geomorphology[d]	WF generally conceived as a reactive surface; typically geometrically complex and irregular. Regolith-rock transition zone near ground surface treated and referred to as epikarst. WFs controlled largely by geological structures; lower limit controlled by hydrological base level.

[a] Soil is used in this context to refer to transportable regolith in general.

[b] In some cases there is a threshold thickness after which the inverse relationship holds.

[c] Etch surface is sometimes, but not always, equated to weathering front.

[d] This entry reflects prevailing concepts in a subdiscipline rather than a distinct conceptual framework.

processes. However, Davis (1892), Gilbert (1877, 1909), and Penck (1924) all described negative relationships between thickness of weathered mantles and bedrock weathering rates conceptually identical to the soil production function.

The weathering front as a more-or-less planar basal surface does not play a major role in karst geomorphology and hydrology, which recognizes and focuses on reactive surfaces and water-rock interactions along fissures, fractures, and conduits. The hydrological base level is generally considered a first-order control on landscape evolution. The boundary or transition zone between weathered rock and overlying soil or regolith is commonly referred to as epikarst rather than a weathering front, with the recognition that the weathered/unweathered rock interface is not restricted to epikarst (Klimchouk, 2004; Williams, 2008; Jones, 2013).

Table 2 shows a summary of the role of weathering fronts in these various conceptual frameworks.

2. Weathering front complexity

Several aspects of weathering front complexity are described below, with complexity implying deviations from benchmark conditions of: (1) a relatively sharp, abrupt transition from weathered to unweathered material; (2) a monotonic trend of increasing alteration from underlying bedrock to the surface; and (3) lateral continuity of layers and boundaries within the weathering profile. We focus here on bedrock weathering fronts in profiles developed mainly in situ as opposed to within deposited material. We are also concerned primarily with the scale of outcrops and soil pits, recognizing that observation of complexity may vary with scale.

Weathering is a dynamic, three-dimensional phenomenon. However, observation is usually restricted to profiles revealed in soil pit or trench walls, road cuts or quarries, natural outcrops, or from core samples. Thus we will speak here in terms of vertical (top-bottom; ground surface to bedrock) and lateral (as observed in an outcrop or exposure) variations.

2.1. Geometric irregularity

Even where a distinct weathered/unweathered boundary is evident, this interface is often quite irregular (this is often particularly evident in epikarst). The topography of the upper surface of the bedrock is often substantially more variable, with greater relief, than that of the overlying surface topography (Collins et al., 1989; Twidale, 1991; Gunnell and Louchet, 2000; Beauvais et al., 2003; Sucre et al., 2011). This is generally due to focused weathering along joints, fractures, etc., and other local zones of higher permeability to water and/or lower resistance to dissolution or other alterations. This is often characterized by positive feedbacks, whereby initial variations become enhanced over time (i.e. divergent weathering), with increasing variability of the weathering front or bedrock surface topography (Torrent and Nettleton, 1978; Nahon, 1991; Twidale, 1991, 1993; Taylor and Blum, 1995; Gunnell and Louchet, 2000; Phillips, 2001; Worthington et al., 2016). Chemical and volume-expanding weathering processes may also drive fracturing processes that generate new reactive surfaces in a self-reinforcing manner (Royne et al., 2008; Worthington et al., 2016; Brantley et al., 2017). In karst, dissolution widens fissures, eventually forming conduits. Increased moisture flow reinforces the dissolution process until weathering becomes reaction- rather than moisture-limited (Kaufman and Braun, 2001). Worthington et al. (2016) examined the role of weathering in enhancing permeability of limestone, basalt, granite, sandstone, and shale. Feedbacks result in self-organization of networks of flow paths in rock, originally guided by focused weathering in fractures. While the dynamics operate at different rates and intensities among the different lithologies, Worthington et al. (2016) found that weathering tends to enhance permeability of most bedrock aquifers.

The difficulties observing the fresh bedrock interface are highlighted by Rempe and Dietrich (2014), whose model shows the depth of the interface as a function of fluvial incision (local base level), and groundwater drainage of bedrock. At ridgetops, their model suggests that the ratio of surface topographic relief to bedrock surface relief is equal to the relative slopes of the ground surface and water table. Interactions among weathering reactions, subsurface water flow, and weathering profile and landscape evolution were further explored by

Harman and Cosans (2019). Their model identified conditions under which the geochemical weathering front is located so as to maintain steady state, and to keep pace with stream incision.

Subsurface bedrock topography or weathering front geometry that is more complex and variable than surface topography is often revealed by geophysical methods such as ground penetrating radar or electrical resistivity (e.g., Collins et al., 1989; Beauvais et al., 2003; Sucre et al., 2011; Arias et al., 2016). This geometric irregularity is often particularly pronounced in epikarst (e.g. Mueller et al., 2003; Klimchouk, 2004; Williams, 2008; Estrada-Medina et al., 2013; Jones, 2013). Note, however, that local variability over short distances and small areas may be overprinted on broader-scale regularity. For instance, Lidmar-Bergström (1995) shows local weathering front variability caused by etching on the Baltic Shield but at a broader scale the weathering front has a more regular pattern and forms joint valleys.

The dynamical instabilities and positive feedback domination of chemical weathering mean that divergent evolution, increasing the contrast between areas of concentrated weathering and relatively unweathered zones (thereby increasing geometric variability) of weathering fronts is likely to be the rule rather than the exception. Unlike the surface, where erosion of microtopographic highs and infilling of lows may smooth topography, weathering may be increasingly focused in the depressions of the bedrock surface, and infilling with overlying weathered material does not smooth the bedrock surface topography (c.f. Niskiewicz, 2000; Migon and Kacprzak, 2014).

Where plant roots encounter bedrock they promote both chemical and biomechanical weathering, and may locally thicken the regolith. In forests where soil or regolith depth is less than tree rooting depth, this may result in increasing local spatial variability in depth to bedrock, as trees may preferentially reoccupy the same patches (Phillips and Marion, 2004; Phillips, 2008; Shouse and Phillips, 2016; Pawlik and Kasprzak, 2018; Pawlik and Samonil, 2018). However, due to continued weathering and gradual overall regolith thickening in some cases, the overall thickness may exceed typical rooting depths, with eventual convergence of thicknesses (Pawlik and Kasprzak, 2018; Pawlik and Samonil, 2018; Phillips, 2018). However, it is also plausible that where bedrock joints have been widened by root effects, positive feedbacks may continue to focus weathering even when the bedrock interface is no longer in the root zone. This, while in some cases tree roots lead to weathering front complexity, the extent to which this applies to the regolith vs. the bedrock weathering front, and the long term persistence of these effects, are unclear.

2.2. *Gradual transitions*

In a weathering profile formed mainly from weathering of underlying rock, there is often not a sharp demarcation between weathered and unweathered material. Independently of any geometric complexity as described above, there may be a gradual transition from soil to subsoil regolith to weathered rock to unweathered rock. For example, Holbrook et al. (2019) found a gradational transition from saprolite to weathered rock over a depth of 11 to 18 m.

These transitions may or may not correspond with boundaries or transitions in biotic features. In their review of the pedologic nature of weathered rock, Graham et al. (1994) reported occurrences of roots and organic matter in weathered rock, to depths of 9 m. Fan et al.'s (2017) global synthesis reported even deeper roots. Graham et al. (1994) also summarized occurrences of illuvial clay in weathered rock, as much as 2.4 m into the rock and nearly 4 m below the surface.

Weathering sometimes produces corestones of intact bedrock within a weathered matrix, often via spheroidal weathering processes (Linton, 1955; Ollier and Pain, 1996; Migon and Lidmar-Bergstrom, 2001, 2002; Migon and Thomas, 2002; Twidale and Vidal Romani, 2004). Highly weathered material may form within, or pedogenic material may be transported to, widened joints and fractures in weathered rock. Thus it is often possible to have highly altered and essentially unweathered parent material immediately adjacent to each other in a profile. The unweathered zones or stones can be considered to have their own isolated weathering fronts.

A theoretical model by Lebedeva and Brantley (2017) focused on the role of joints and fractures in bedrock weathering. They used a simulation distinguishing between non-fractured rock and fractures filled with more porous or highly weathered material. Not surprisingly, the advance of the weathering front (considered to be chiefly top-down, though horizontal advection is included in the model) is more rapid in fractured material and is inversely related to fracture spacing. Consistent with geomorphic principles, if the hillslope system is transport limited, bedrock blocks weather completely as the weathering zone advances. If the slope is weathering-limited, however, the model of Lebedeva and Brantley (2017) shows exposure of blocks of various size at the ground surface. Conceptually, these ideas were pioneered by Linton (1955).

Some geoscientists may consider situations where only gradual transitions from weathered to unweathered rock exist to lack a weathering front. However, we consider this largely a matter of semantics, as long as there is indeed a clear transition, be it sharp and abrupt or gradual and diffuse.

Bazilevskaya et al. (2013) showed that regolith and weathering front thickness may be thicker or thinner due to variations in deep oxidation reactions and their effects on fluid flow. They compared diabase vs. granite of similar initial porosities in similar landscape positions. Despite the fact that the dominant feldspar minerals in the diabase less weathering resistant than the dominant granite minerals they found much deeper weathering in granite. They attributed this to connectivity of micron-sized pores, microfractures formed around oxidizing biotite in the granite, and lower iron content in the felsic rock, allowing pervasive advection and deep oxidation in the granite (Bazilevskaya et al., 2013).

2.3. *Lateral variations*

At a slightly broader scale, weathering profiles may exhibit pronounced lateral variations independent of irregular weathering fronts and unclear vertical transitions. For example, granitic weathering profiles exposed by tunnel construction in northwest Spain show extensive vertical and horizontal variation in the patterns and depths of unweathered granite, saprock (partially weathered granite), granitic saprolite, and roof pendants (country rocks metamorphosized by the surrounding igneous intrusion) (Arias et al., 2016).

The causes for this are sometimes obvious, as in the case of lateral or along-strike geological boundaries or contacts, or cases of strongly tilted sedimentary rock layers, where initially horizontal layering becomes more vertically oriented (Fig. 3). In other cases lithologically similar bedrock of the same formation may exhibit strong variations in structure, such as the degree of jointing or fracturing (Fig. 4). Preservation of very large corestones can also occur (Fig. 5). Riebe et al. (2017) proposed that microclimate and aspect control variations in subsurface rock damage, which could account for some landscape-scale lateral variations. This further implies the possibility of climate-driven changes in weathering profile morphology over time scales commensurate with climate change.

Pedological processes such as podsolization, generally thought of as mainly vertical phenomena, may also operate laterally, contributing to lateral variation in weathering features (Sommer et al., 2000, 2001).

2.4. *Multiple weathering fronts?*

While many geologists may readily recognize multiple weathering fronts in layered or heterogeneous parent materials, and geochemists routinely consider multiple reaction fronts, many conceptual frameworks and simulation models in pedology and geomorphology implicitly or explicitly assume a single, or at least a single dominant

Fig. 3. Ouachita Mountains, Arkansas, U.S.A. Near-vertical tilting of sedimentary rocks shows shales on the left of the lower outcrop, horizontally adjacent to sandstones.

Fig. 4. Sumava Mountains, Czech Republic. Massive granite adjacent to highly fractured granite of the same formation.

weathering front. In some cases there may be uncertainty over what constitutes the weathering front, or whether there may be multiple fronts independently of any isolated weathering fronts associated with corestones. In Fig. 6, for example, one might be tempted to define the weathering front along the boundary shown. However, the material below the line is moderately weathered, and fresh bedrock is considerably deeper. Moderately weathered rock often has sufficient strength to support structures, and depth to bedrock reported in geotechnical drillings, soundings and boreholes often corresponds with moderately weathered rock rather than the interface with fresh, unweathered rock. Thus many profiles could be considered to have both a bedrock and a regolith weathering front (see Table 1).

In sedimentary and some volcanic rocks, there may exist alternating

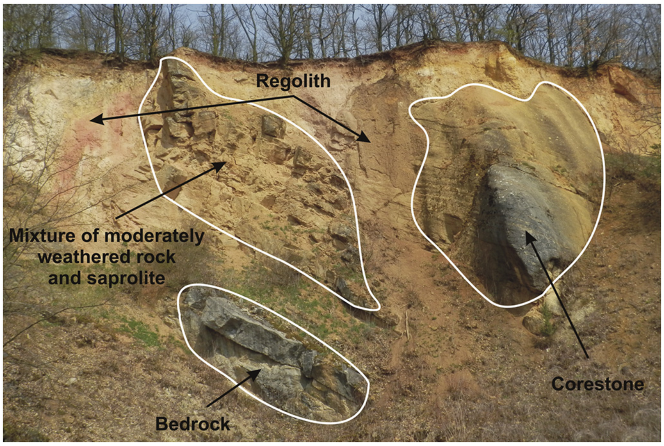

Fig. 5. Large corestone and unweathered remnants in limestone, Bohemian Karst, Czech Republic.

Fig. 6. Is the weathering front at the approximate boundary shown, atop saprolite? Or deeper, at the contact with unweathered rock (Flinders Ranges, South Australia).

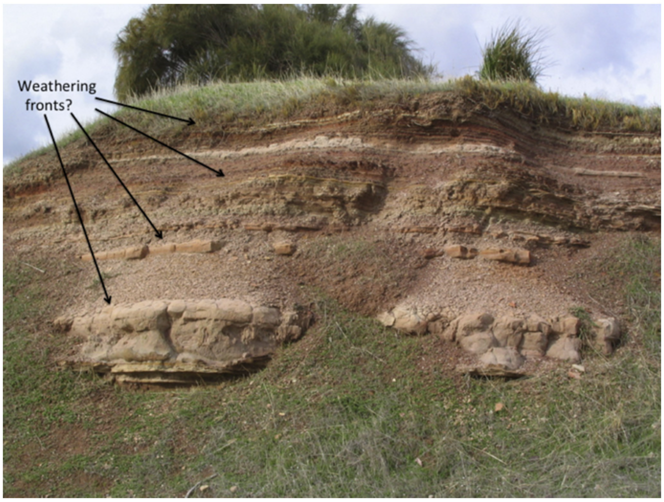

Fig. 7. Multiple interfaces between weathered weaker layers and relatively unweathered resistant layers in layered sedimentary rocks. Do these constitute multiple weathering fronts? (Adelaide area, South Australia).

layers of variable resistance. Thus there may be several interfaces between weathered weaker layers and relatively unweathered resistant layers (Fig. 7).

Twidale and Vidal Romani (2004) pointed out that the perimeter of a corestone is a weathering front, and thus nested within a saprolite or regolith that may have multiple fronts, both around corestones and basally. This broader conception of weathering fronts as features that may occur within, in addition to at the base of, weathering profiles is consistent with Ollier and Pain (1996: 10-13), and is implied by Linton (1955). These are the isolated weathering fronts we referred to above.

More fundamentally, as mentioned above, many analyses, conceptual frameworks, and simulation models imply a two-stage sequence whereby weathering turns bedrock into regolith or saprolite, and pedogenesis turns regolith into soil, or even a one-step sequence where immobile rock is transformed to potentially mobile regolith (e.g., Phillips, 1993). These concepts indicate direct conversion from bedrock to regolith at the weathering front. However, in many cases there exists at least one intermediate stage between rock and regolith. This is certainly indicated in profiles where significant thicknesses of slightly and moderately weathered rock exist. Thus in many cases weathering converts fresh to weathered rock, and then weathered rock to saprolite or regolith. The 10 to 35 m thick granitic weathering zone examined by Holbrook et al. (2014), for instance, is comprised of approximately equal thicknesses of saprolite and moderately weathered rock above unweathered bedrock–though their conceptual model is based on a two stage rock-to-regolith, regolith-to-soil (or mobile regolith) sequence. A 65 m borehole analyzed by Holbrook et al. (2019) showed a 38 m thick regolith, with weathering of biotite and placioglase occurring 20 m below the base of the saprolite. The transition from saprolite to weathered rock was gradational, over a depth of 11 to 18 m.

Tree uprooting may produce local inverse stratigraphy of soil and regolith (Schaetzl, 1986). While this might complicate weathering profile interpretations and directly affect the regolith weathering front, it should influence the bedrock front only where the root system penetrates bedrock.

2.5. Vertical variations above the bedrock weathering front

Bedrock-to-surface deviations from the expected pattern of increasing degree of weathering may occur due to several general factors. These include variations in rock resistance, which may be either reduced or enhanced by weathering and pedogenesis over time. Weathering may also be associated with lateral, subvertical, or upward hydrological fluxes rather than (or in addition to) downward-percolating water. These are often controlled or influenced by structural (e.g., joints, bedding planes) or lithological variations in the rock, but also by biogenic pathways such as roots, root traces, and faunal burrows or tunnels.

In addition, in many settings surface processes of erosion and deposition influence stratigraphic relationships. For instance, a buried recent soil or paleosol may result in less-weathered overlying more-weathered material. An “inverted” weathering profile where the degree of weathering increases rather than decreases with depth was studied by Little and Lee (2006). The profile, on volcanic substrate in Tanzania, was found to be due either to burial of a paleosol by subsequent tephra deposition, or due to subsurface weathering associated with groundwater flow. Little and Lee (2006) also identified two other scenarios that could explain inverted profiles—re-precipitation of solutes followed by erosion, and aeolian deposition, though these were ruled out at their study site.

Hall et al. (2015a) reported that in northern Finland an abrupt basal surface of weathering is common on granite and gabbro but weathered zones occur tens of metres below fresh rock bands in the heterogeneous rock of the Central Lapland Greenstone Belt. Though their study focused on climate effects, Goodfellow et al. (2014) found that subsurface hydrological flow paths and permeability variations influence the depth and vertical variability of weathering along a basaltic climosequence in Hawai'i. They also present several weathering profiles showing harder overlying softer saprolite. Vertical ordering of more or less intensely weathered material reflects initial variations in permeability more than systematic changes from surface to bedrock (Goodfellow et al., 2014).

The thickness of a weathering profile may be limited only by the geomorphic base level (Linton, 1955; Ford and Williams, 2007; Goodfellow et al., 2014; Rempe and Dietrich, 2014; Harman and Cosans, 2019). Deep weathering profiles of several tens of meters are not uncommon, and some profiles reach hundreds of meters deep (e.g., Stone and Comerford, 1994; Hill et al., 1995; Ollier and Pain, 1996; Retallack, 2001, Migon and Lidmar-Bergstrom, 2001, 2002; Carmo and Vasconcelos, 2004; Olesen et al., 2013). Such deep weathering is bound to transgress materials of variable composition and hydrological properties, which could complicate or obscure surface-to-bedrock variations.

Some areas may exhibit complex vertical (and horizontal) variation in the degree of weathering associated with a combination of lithological variability, preferential flow and weathering phenomena (with likely self-reinforcement), and overprinting by multiple episodes of changes in climate and base level. Bosák (1995) describes this type of situation in the Bohemian massif, Czech Republic.

2.6. Complicating factors—rock fragments, edge effects, and depths

A complicating factor in interpreting weathering profiles—particularly when based on point samples such as cores, augering, or probing—is the presence of rock fragments. Often called “floaters” by field scientists, these can be mistaken for a bedrock interface when encountered by auger or probe. In some cases these floaters may be corestones—unweathered remnants of underlying bedrock in their approximate original position. However, there are other potential sources for such stones.

Many rock fragments are derived from underlying bedrock, but they may also be transported onto the surface, either by mass wasting from upslope, deposition by large floods in stream valleys, or transported by humans (see, e.g., https://www.obec-kounov.cz/kounovske-rady/). The latter may be obvious in the case of building construction, but material used for, e.g., fire rings, may not be evident if some scattering or displacement has occurred. These surface fragments may become buried by surface deposition, organic matter, and gravitational settling. Transported rock fragments may also be deposited in stump holes or tree uprooting pits and subsequently buried (Phillips et al., 2005; Pawlik, 2013; Pawlik et al., 2016). Faunalturbation often results in undermining of rocks and their gradual settling (Johnson, 1989, 1990, 2002).

Rock fragments may also be transported upward, so that material derived from underlying rock may not be in its original position. Cryoturbation and argilliturbation are capable of doing this, and tree uprooting often brings rock fragments—including from the bedrock interface—to the surface (Johnson et al., 1987; Phillips et al., 2017). Limited upslope movement is even possible, associated with uphill-oriented tree uprooting (Šamonil et al., 2016).

Direct observation and sampling of weathering profiles over a lateral extent greater than a core sample are necessarily dependent on outcrops such as road cuts, quarries, trenches, pits, and construction sites. One problem with such sites is edge effects—features or processes unique to or concentrated at boundaries or transition zones, including exposures and outcrops of various kinds (Phillips, 1999). For example, groundwater discharge on valley side slopes in certain settings results in the formation of ferricretes confined to the edge environment, but which have been mistaken as representing laterally continuous strata or weathered layers (Pain and Ollier, 1992; Phillips et al., 1997; Bourman and Ollier, 2002). Weatherable shales exposed at outcrops can be significantly altered in decades or less relative to unexposed material (e.g., Tuttle and Breit, 2009), thus giving a misleading impression of weathering stratigraphy.

A straightforward complication in the study of weathering fronts in many cases is the presence of thick regolith and weathered rock layers. This is particular common in the tropics and subtropics, but sometimes occurs in higher-latitude settings as well. Weathering profiles tens of meters thick are not uncommon, and a few may reach hundreds of meters (e.g., Stone and Comerford, 1994; Hill et al., 1995; Ollier and Pain, 1996; Retallack, 2001; Migon and Lidmar-Bergstrom, 2001, 2002; Carmo and Vasconcelos, 2004; Olesen et al., 2013). Excavation in such cases poses obvious logistical and expense problems, but geophysical exploration methods such as seismic profiling, electrical resistance tomography, and ground penetrating radar have potential to facilitate analysis of deep weathering fronts (Anbazhagan and Sitharam, 2009; Sucre et al., 2011; Coulouma et al., 2012; Bernatek-Jakiel and Kondracka, 2016; Kasprzak, 2017; Pawlik and Kasprzak, 2018).

3. Multidirectional mass flux

The phenomena above indicate, to varying extents, mass fluxes within a weathering profile other than predominantly top-down, and operating at levels other than the ground surface and bedrock interface. Given the input of precipitation at the surface and the force of gravity, an emphasis on predominantly top-down moisture flux—and related phenomena such as propagation of wetting and geochemical reaction fronts and vertical translocation—is justified. However, this view is incomplete, as weathering profiles are influenced by mass fluxes in multiple directions (here we focus on water movement).

The direction of surface runoff, and throughflow when soil is saturated, is dictated by surface topographic gradients. Hydrologic fluxes also encounter low-permeability or impermeable barriers, or high-conductivity corridors (joints, bedding planes, macropores, porous layers, etc.) that direct flows laterally or sub-horizontally. In addition, chemical reactions between subsurface water and the surrounding material drive fracturing and other permeability changes, which further influences water movements (Worthington et al., 2016; Brantley et al., 2017). Riebe et al. (2017) hypothesize that drainage of chemically-equilibrated groundwater initiates (or rejuvenates) weathering at the weathering front. This phenomenon is not restricted to top-down ground water drainage.

Upward water movement occurs due to water table rise, matric suction in the capillary zone, and water vapor via evapotranspiration. Hydrothermal processes may drive upward water movements, and needle ice and other frozen forms may also propagate upwards. Roots may take many different pathways through soils and weathering profiles. Suction from plant water use results in a net upward/inward (soil to plant) transport, while flow along roots and root channels leads to net downward-outward transport (Fig. 8). Plants in general and trees in particular may result in hydraulic fluxes or redistributions within the regolith in virtually any direction (Nadezhda et al., 2010). Faunal tunnels and burrows lead to net downward gravity-driven moisture fluxes, but burrowing organisms also transport weathered material upward. Figs. 9, 10 illustrate these multidirectional flux pathways. Fig. 11 shows some different flux pathways, and at least eight different weathering zones. Fig. 12 contrasts the traditional focus on top-down pedogenesis and weathering and surface erosion/deposition and the recognition of multidirectional fluxes (focusing on water) described above.

Taking into account the multiple directions of moisture movements, chemical weathering, and solute fluxes, Brantley et al. (2017) reframed the "conveyor belt" concept of rock-to-regolith-to-soil into evolution of a complex "permeability architecture" in the weathered mantle.

4. Weathering profile evolution

At a given vertical section, total thickness of the weathering profile (T_{wp}) is the sum of thicknesses of the solum (T_s), non-soil regolith (T_r; C horizons, saprolite, highly-weathered rock) and weathered rock (T_w):

Fig. 8. Tree roots occupying joints and bedding planes in limestone, central Kentucky, USA. Arrows illustrate multidirectional fluxes by plant water use, and by flow along roots.

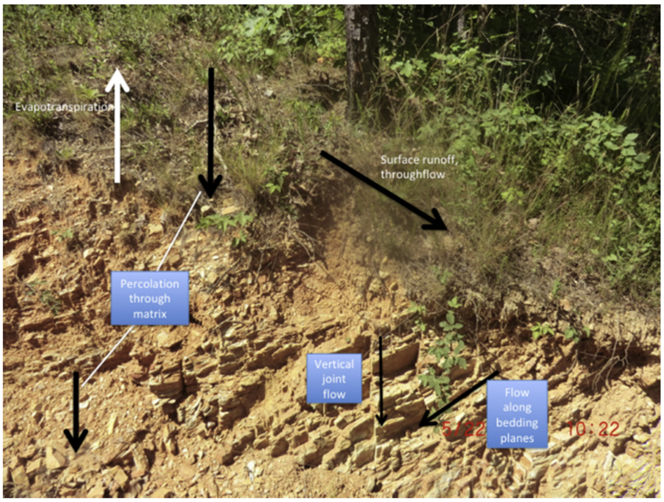

Fig. 9. Weathering profile in sandstone and shale in the Ouachita Mountains, Arkansas, USA showing several different water flux pathways.

$$T_{wp} = T_s + T_r + T_w$$

W1 is the conversion by weathering of fresh bedrock to weathered rock, and W2 the transformation of weathered rock to saprock, saprolite, or non-soil regolith. P is the formation of soil or solum material from saprolite, etc. The amount of transformation over the evolution of the profile is ΔW1, ΔW2, ΔP, and includes volume expansion or contraction and mass additions as well as weathering and mass losses (see Johnson, 1985; Johnson et al., 2005b; Phillips, 2010). For simplicity, we treat here in situ weathering profiles with negligible surface erosion or deposition, though in reality weathering and erosion or deposition often occur concurrently.

Fig. 10. Weathering profile in interlayered sandstone and shale at a minor fault contact, Big Walker Mountain, Virginia, USA. In addition to upward and downward moisture fluxes and root-related fluxes, at least three different joint or bedding-plane guided flux directions are evident.

Fig. 11. Weathering profile showing several different moisture flux paths (arrows) and distinctly different weathered zones (dashed lines). Area of exposure is about 2 m wide (Big Walker Mountain, Virginia, USA).

Where solum or regolith sits directly atop bedrock, $T_w \approx 0$, suggesting that W2 leads to very rapid transformation to soil or regolith, or that $dW1/dt \approx 0$ (at a non-eroding site this is consistent with the steady-state thickness concept). If a significant thickness of weathered rock exists ($T_w > 0$), a three-stage process is suggested (rock to weathered rock, weathered rock to regolith, regolith to soil). These stages typically occur concurrently at different points in the weathering profile. Some models now explicitly include a separate weathered rock layer between bedrock and regolith (e.g., Rempe and Dietrich, 2014).

Various case studies show that moderately and slightly weathered rock layers may be extensive in some cases, or minimal in others. For instance, Jiang et al. (2018) examined a 15 m thick tropical basalt weathering profile in south China. Elemental concentrations indicate that most hydrolysis and gibbsite formation occurs at the soil-saprolite interface. Precipitation and other mineral enrichments were indicated within the ~13 m thick saprolite. The layer they describe as "semi-weathered" between fresh basalt and saprolite corresponds to T_w, and is only about 15 cm thick. Jiang et al. (2018) interpret this as indicating rapid alteration of plagioclase and pyroxene in the tropical climate. They also found enrichment of transitional metals along the rock-regolith interface. This study suggests that even when the weathered rock layer is thin and the non-soil regolith thick, the bedrock weathering front may be quite active.

How common are T_w thicknesses greater than, say, 15 or 20 cm? A preliminary examination of soil profile descriptions and geotechnical borehole data for two geologically distinct areas of Kentucky (limestone karst landscape, and dissected sandstone-shale terrain) showed evidence that this is not uncommon. However, the exercise also demonstrated difficulties in addressing this problem based on readily available data. Many soil profiles, even when those developed in deposited material were excluded, did not extend to bedrock, and some cases even to a C or Cr horizon. Where an R (bedrock) horizon was recorded, there was no way of determining whether this may have been unweathered, slightly-, or moderately-weathered rock. Borehole data sometimes showed a weathered rock layer, but procedures for describing core or borehole properties are less standardized than for soil profile descriptions. Further, as Ehlen (2005) noted, the top of solid bedrock in such data often corresponds with moderately weathered rather than unweathered or slightly weathered rock. Additionally, the typical lumping of overlying material as "overburden" makes interpretation of profiles difficult.

Ground penetrating radar can typically identify the boundary between highly and moderately weathered rock, at least roughly corresponding to the regolith weathering front (Collins et al., 1989; Sucre et al., 2011). Electrical resistance tomography and seismic methods can identify deeper boundaries with intact bedrock (Beauvais et al., 2003, 2007; Anbazhagan and Sitharam, 2009; Olesen et al., 2013). Thus, using these techniques in tandem may allow better investigation of relative thicknesses of T_s, T_r, T_w (Coulouma et al., 2012; Bernatek-Jakiel and Kondracka, 2016; Kasprzak, 2017). This in turn could provide key indications of the relative rates of rock weathering and pedogenesis, and interactions among soil and regolith thickness and depth of the bedrock and regolith weathering fronts.

5. Discussion and conclusions

The concept of a clear boundary between unweathered and weathered rock, that moves generally downward as weathering proceeds—the weathering front—has been, and continues to be useful. Weathering fronts are explicitly or implicitly part of landscape evolution concepts of etchplanation, triple planation, dynamic denudation, and weathering- and supply-limited landscapes. Weathering fronts also figure prominently in many models of soil, hillslope, and landscape evolution, and in regolith mapping.

Notions of relatively clear transitions from weathered to unweathered material, monotonic trends of increasing alteration from underlying bedrock to the surface and lateral continuity of weathering fronts have long been recognized as ideal or benchmark conditions that are not always strictly applicable. Transitions from weathered to unweathered material are often gradual and indistinct, and weathering fronts may be geometrically irregular and complex. Some weathering profiles contain pockets of minimally weathered or fresh rock within highly weathered material, and highly modified and unmodified parent material at similar depths in close lateral proximity. Exceptions to the bedrock-to-surface gradient of increasing alteration also exist. This points to a need for more detailed study of weathered mantles, and more case studies in heterogeneous landscapes. This should involve continued use of excavations, core samples, and outcrops, supplemented with geophysical measurements. We also recommend more detailed and standardized characterization of weathered zones and "overburden" in geotechnical data collection, as well as increased attention to subsolum properties in soil surveys.

Some of the deviations from the idealizations above are due to both inherited and acquired environmental variability that is inevitable and unavoidable in geomorphology and pedology. However, they also represent the fact that mass fluxes driving, resulting from, or influencing chemical weathering are more varied than downward-percolating water and slope-parallel surface processes. Key fluxes may also be

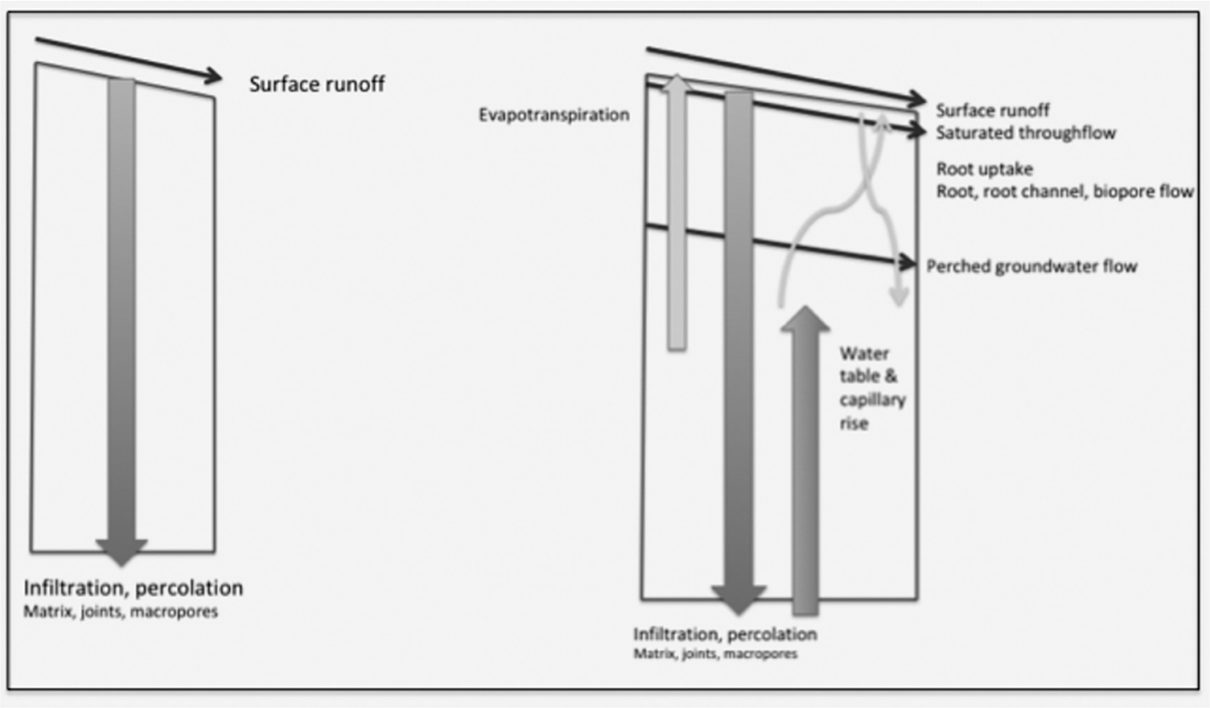

Fig. 12. Contrast between traditional concepts focusing on downslope surface processes and top-down moisture movement (left) and multidirectional mass fluxes (right) as described above.

upward, along lithological boundaries or structural features, and along textural contrast or weathering-related boundaries. Fluxes associated with roots, root channels, and faunal burrows may potentially occur in any direction. Increased attention should be given to collecting data on rooting depths and abilities of tree roots to penetrate different rock types. Just as pedology has recently broadened its traditional emphasis on top-down processes to incorporate various lateral fluxes, studies of weathering profiles are increasingly recognizing and incorporating multidirectional mass fluxes. In this regard, examples and guidance may be usefully gained not only from pedology, but also from karst geomorphology and hydrology, where concepts of laterally continuous weathering fronts, rock-regolith boundaries, and water tables; and an assumption of dominantly diffuse downward percolation are generally inapplicable.

This review also reveals reasons to question the idea of a single weathering front, and of a two-stage process of weathering rock to regolith, and transforming regolith to soil. In many cases there appears to be a three-stage process involving conversion of bedrock to weathered rock, weathered rock to regolith, and regolith to soil. The existence of thick layers of weathered rock between fresh bedrock and highly weathered rock or regolith supports the concept of multiple stages and planation surfaces. While there is no substitute for detailed direct examination and sampling of weathering profiles, geophysical methods that allow measurement of the relative thicknesses of soil, non-soil regolith, and weathered rock (and the depths of the regolith and bedrock weathering fronts) have the potential to provide important insights into the questions raised in this review. This will be explored in future work.

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