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Origins and implications of soil layering

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ABSTRACT

Layering is common in soils, due to a variety of pedologic and geologic processes, and has important consequences for the interpretation of soils and landscapes. Layering can derive from original sedimentary layering; depositional upbuilding; episodic surface erosion, deposition, and stability; soil production by weathering; vertical or lateral translocation; bioturbation; and various combinations of these. Complex and polygenetic models incorporate both geogenic and pedogenic processes, and allow for physical and biological processes, as well as both vertical and horizontal movements. We review these conceptual frameworks and synthesize them into a vertical contrast model (VCM) for interpreting layered surficial materials. The VCM incorporates a variety of geologic and pedologic processes which may create, destroy, enhance, or obscure vertical contrasts. The model is illustrated via application to sites in the Ouachita Mountains, USA, and northwest Saxonian Lowlands, Germany. The examples illustrate the importance of a comprehensive pedogeomorphic interpretation of layering, since neither standard stratigraphic or top–down pedogenetic principles necessarily apply. The examples also show that the same process can, sometimes contemporaneously, both create and destroy vertical contrasts.

Contents

1. Introduction

1.1. Soil layering

Layering is widespread in soils, regoliths, and surficial sediments, and the subdivision of profiles, outcrops, and geological sections into

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vertically differentiated zones (vertical organization) is fundamental to geological, pedological, ecological and archaeological analyses. Layering in soils and other surface materials can have numerous and complex origins, involving geological, pedological, hydrological, and biological processes and various combinations thereof. Earth scientists of different backgrounds, training, and predispositions often bring to the study of layered materials different conceptual models. The purpose of this review is to identify the major conceptual models applied to the study of layering in soils, and to show how a synthetic approach incorporating elements of several of these can be useful in interpreting soil layering. While soils are indeed our primary focus, we use the term soil layering in this paper as a general term for layering in surficial or exposed material in general, be they soils *per se* or other regolith materials.

Ruellan's (1971) discussion of historical aspects of the study of soil horizonation and layering draws a contrast between "allochthonists" who attribute great importance to erosion and deposition in creating vertical zonations in soils, and "autochthonists" who attribute the majority of horizon differentiation to pedological processes. Ollier and Pain (1996) recognized this schism and commented "…the regolith is a kind of no man's land. It is generally conceived as the loose, weathered, ill-defined rubbish near the earth's surface that nobody wants to deal with […] to a soil scientist it may be the parent material for a soil but is itself of no further interest…" (Ollier and Pain, 1996: 1). The contrasting approaches of geomorphologists, geologists, soil scientists, and engineers to the study of weathered mantles is reviewed by Ehlen (2005), who advocated an approach borrowing elements from each.

While some of the disparities in the approach to the study of (layering in) weathered mantles and sediments are perhaps inevitable byproducts of different research goals, institutional and historical factors may also play a role. Tandarich et al. (1994) discussed the informal assignment of the solum as the domain of pedologists, while lower parts of the regolith were considered the domain of Quaternary geologists. The very concept of solum or "true soil," and the pronouncement of this as the domain of soil science by politically and institutionally influential figures in the USA, played a major role in this flawed division (Johnson, 1994). The arbitrary distinction between a pedological upper and geological lower zone resulted in, among other things, different terminologies for the same profiles and features, and a divergence in research paradigms. The historical development of soil and weathering profile concepts in the U.S. and Europe is outlined by Tandarich et al. (2002).

The importance of interpreting surficial layering is apparent in pedology, and in other earth science subfields such as sedimentology, stratigraphy, soil geomorphology, and paleopedology (see, e.g., Ruhe, 1956, 1974; Johnson, 1990; Wright, 1992; Pain and Ollier, 1996; Kraus, 1999; Retallack, 1999; Kemp, 2001; Schaetzl and Anderson, 2006). Such interpretations are also important in geoarchaeology, as they have a critical bearing on the interpretation of cultural materials contained within the layers (e.g. Harris, 1979; Johnson, 1990, 1993; Balek, 2002; Van Nest, 2002). Assumptions about the nature and origin of soil layers can also impact assessments of element dispersal and distributions in soils (Lorz and Phillips, 2006; Kacprzak and Derkowski, 2007).

The application of standard geological stratigraphic principles to regoliths and weathering profiles can lead to numerous errors, as those principles do not apply to regoliths. Ollier and Pain (1996; Pain and Ollier, 1996) provide numerous examples, as well as a proposed set of principles for regolith stratigraphy. The uncritical application of pedological conceptual models without consideration of geological processes can similarly lead to errors (e.g. Arnold, 1968), as Paton et al. (1995) discuss and illustrate.

1.2. Definitions

Following both pedological and geological convention, we use the term layer (see Table 1) to refer to any more-or-less tabular body of unconsolidated material or rock roughly parallel to the land surface or the surface on which it (is presumed to have) formed, and which is more or less distinctly limited above and below. In pedology, the term horizon is generally understood to refer to layers which are the product of, or are substantially modified by, pedogenic processes (soil layer). The U.S. Soil Survey Manual (Soil Survey Division Staff, 1993) specifies that horizons are "… distinguishable from adjacent layers by a distinctive set of properties produced by the soil-forming processes," while the term layer is used if the differentiation is inherited, or if no interpretation is made as to whether the differentiation is inherited or pedogenic. Standard geologic terminology defines soil and pedologic horizons in a manner consistent with pedologists, but note that a "geologic horizon" is defined as an "interface indicative of a particular position in a stratigraphic sequence," and is thus not necessarily related to pedologic horizon concepts (Jackson and Bates, 1997).

Geological discontinuities denote abrupt changes in rock properties. In pedology, a lithological discontinuity in soils is a significant change in particle size distribution or mineralogy presumed to indicate a difference in the material in which the horizons formed and/or a significant difference in age (Soil Survey Division Staff, 1993; see also FAO, 2006: 46). Lithological discontinuities in soils are discussed at length by Schaetzel (1998), who surveys the theory and detection of pedological discontinuities and applies the methods to drumlins.

Stratigraphic terminology includes a hierarchy of terms for geogenic layers assumed to be derived from depositional processes, with laminae being the thinnest recognizable units of original deposition. Several laminae may constitute a bed, while a number of beds may be included in a stratum (Jackson and Bates, 1997). However, terms such as stratum, bed, lamination, and layer are often used in

Table 1
Summary of definitions discussed in Section 1.2, along with any presumption of pedological (pedogenic), or geological (geogenic) origin stated or implied in the definition

Term	Definition	Presumed formation
Layer(ing)	More-or-less tabular body of rock or unconsolidated material roughly parallel to surface on which it presumably formed; distinctly limited above and below. Layering is the vertical organisation of a soil or regolith profile	None
(Soil) Horizon	*Layer* which is the product of, or substantially modified by, pedological processes	Pedogenic
Lithological discontinuity	Significant change in particle size characteristics or mineralogy that indicates a difference in parent materials or age	Geogenic
Beds	Sedimentary layer composed of several *laminae*	Geogenic
Cover beds	Surface depositional layer(s) distinctly younger than the underlying material	Geogenic
Stratum	Sedimentary layer composed of several *beds*; pl. strata	Sedimentary deposition
Stratigraphic unit	*Strata* recognized as a unit with respect to any of the many characters, properties, or attributes that rocks might possess; e.g., chrono-, bio-, or lithostratigraphic units	Predominantly geogenic
Soil-stratigraphic unit	Soils with physical features and stratigraphic relations that permit consistent recognition and mapping	Pedogenic
Pedostratigraphic unit	Buried, traceable three-dimensional body consisting of one or more differentiated soil horizons	Pedogenic
Geosol	Mappable ancient land surface	Pedogenic
Regolith	All unconsolidated material overlying bedrock	None
Soil	That portion of the regolith which differs significantly from the parent material, primarily due to pedological processes	Pedogenic

practice with imprecise and overlapping meanings. Stratigraphic units are strata “recognized as a unit with respect to any of the many characters, properties, or attributes that rocks might possess” (Jackson and Bates, 1997). Stratigraphic units may be defined for any purpose; and units defined on basis of one property (for example chrono- or lithostratigraphic units) may not necessarily correspond with others (for instance bio- and allostratigraphic units). Included are soil-stratigraphic units (soil with physical features and stratigraphic relations that permit consistent recognition and mapping) and pedostratigraphic units (Jackson and Bates, 1997). The latter are buried, traceable three-dimensional bodies consisting of one or more differentiated soil horizons. According to the North American Stratigraphic Code (North American Commission on Stratigraphic Nomenclature, 1983), the upper boundary of a pedostratigraphic unit is the top of the uppermost pedologic horizon formed by pedogenesis in a buried soil profile. The lower boundary of a pedostratigraphic unit is the lowest definite physical boundary of a pedologic horizon within a buried soil profile. The fundamental and only unit in pedostratigraphic classification is a geosol (mappable ancient land surface).

The terms discussed above, and related terms, are summarized in Table 1. Because layers in surficial materials may be of purely geological origin, purely pedogenic origin, or various combinations, they may therefore constitute one or more of soil horizons, strata, stratigraphic units, or combinations thereof.

2. Origins of layering

2.1. Simple conceptual models

The simplest conceptual models of the formation or presence of layering in surficial materials can be lumped into six basic categories (Table 2). More complex conceptual models which incorporate multiple causes and processes are discussed later.

Original sedimentary layering attributes layering to the deposition of laminae, beds, and strata by depositional processes, and may apply to unconsolidated surficial sediments or to layering inherited from sedimentary rock. Explanations of soil layering based on this notion require the assumption that depositional layers have not been significantly modified or disrupted by pedological, geomorphological, or biological processes, or at least that any such modifications preserve the original sedimentary layering. *Depositional upbuilding* is conceptually similar, but assumes that one or more depositional layers are deposited on, or assimilated into a pre-existing soil or regolith. The idea of this concept is not restricted to alluvial landscapes, but is valid for regions having near surface movements such as hillslope runoff, mass movements solifluction, eolian inputs, etc (e.g. Gerrard, 1995:106, 2000:47; Daniels and Hammer, 1992:57). Examples are periglacial cover beds (e.g. Kleber, 1997), and hillslope sediments (e.g. Carey et al., 1976; Foss et al., 1978; Ciolkosz et al., 1979; Hoover and Ciolkosz, 1988; Graham et al., 1990; Kleber, 1999).

A longer time scale, or least more time-transgressive, framework is based on landscape and land surface evolution: *erosion, deposition, and surface stability*. In this view the vertical differentiation of the regolith is attributed to the successive episodes of depositional accumulation, erosional stripping, and relative steady-state surface stability under which soil and weathering profiles form. This approach is common in studies of landscape evolution in areas where weathering profiles are part of the geologic record (e.g., Migon and Lidmar-Bergstrom, 2002; Twidale and Vidal Romani, 2004). The most explicit statement of this view in a soil science context is Butler's (1959, 1982) K-cycle concept, in which periods of surface stability and soil formation are seen as alternating with upbuilding and erosional stripping episodes. Very similar is the idea that geogenic layering is a consequence of the alternation of periods of geomorphodynamic activity (and geomorphodynamic stability, the latter indicated by soil formation (Rohdenburg, 1989: 120 f.; Schlichting, 1993: 103; Gerrard, 1995: 16). Erosion and accumulation form new landsurfaces (erosional or depositional surface) and as a consequence new parent material. This simplified notion can be broadened by the consideration that (1) parent materials may include incorporated pedorelicts or paleosols; and (2) erosion may bring old soils to the surface (Felix-Henningsen and Bleich, 1996: 1; Mailänder and Veit, 2001: 268).

Table 2
Simplest conceptual models of layering in soils. See text for explanation

1. Original sedimentary layering
Stratified sediment
Inherited from layered sedimentary rocks
2. Depositional upbuilding
3. Episodic erosion, deposition, and surface stability
4. Soil production function
5. Translocation by water and gravity
Vertical: top–down
Vertical: bottom–up
Lateral
6. Bioturbation and biomantle formation

Another landscape evolution-based concept is what has come to be called the *soil production function* (SPF; see review by Humphreys and Wilkinson, 2007). This is based on a notion, going back at least to the late 19th century, that soil or regolith thickness is a function of the balance between production of debris by weathering at the bedrock weathering front and surface erosional removals. The SPF also involves feedbacks between regolith thickness and weathering. The SPF notion implies at least four layers or boundaries in the vertical dimension—a surface layer subject to potential removal, a subsurface layer of weathered debris, the weathering front, and the underlying unweathered material.

Translocation by water and/or gravity is the core of traditional pedological models of horizonation. The depletion of materials from some zones and their accumulation in others is presumed the dominant process of vertical differentiation, and is in fact implicit in the definition of A, E, and B horizons in many standard soil science texts and taxonomies (A–B–C-model; Tandarich et al., 2002: 340). Discussions of the origins and impacts of these concepts in pedology are given by Johnson (1994) and Tandarich et al. (2002). While the emphasis has been overwhelmingly on downward vertical movements, pedological literature and theory has also identified and allowed for lateral (throughflow) and upward translocation as well (e.g., Daniels and Hammer, 1992; Paton et al., 1995; Schaetzl and Anderson, 2006).

The mixing and churning of upper soil levels by flora and fauna is the basis of *bioturbation/biomantle* concepts (see, e.g. Johnson, 1990; Paton et al., 1995; Van Nest, 2002). At minimum, this would result in an upper biomantle layer and a lower minimally-bioturbated layer, though more complicated vertical differentiation is also possible.

None of these simplified conceptual models claims or presupposes that no other causes for layering in soils exist, but they have tended to dominate certain debates and lines of inquiry. Studies of soil genesis and morphology, for example, were long dominated by the top–down translocation model (see, e.g., Johnson, 1993; Paton et al., 1995; Johnson, 2002; Schaetzl and Anderson, 2006). Debates on the origins of subsurface stone lines and stone zones have typically been framed in terms of buried erosional lag surfaces *versus* bioturbational accumulation of rock fragments at the base of a biomantle (Johnson and Balek, 1991; Johnson, 2000). Archaeological stratigraphy has traditionally relied on notions of original depositional layering (Harris, 1979).

2.2. Complex and polygenetic models

Some geologists and soil scientists realized early on that in many situations layers and horizons were not necessarily attributable to any single dominant cause. Milne (1935, 1936; see also Robinson, 1936) combined consideration of surface-parallel geomorphic and hydrologic processes with dominantly top–down pedologic processes to originate the catena concept. Catenas (from the Latin term for chain) are genetically related topographic sequences of soils with pedological processes and surficial fluxes explicitly linked. While soil scientists long acknowledged the catena concept, catenary relationships were typically treated as toposequences whereby topographic settings influenced the nature of top–down pedologic horizonation. Subsequent elaborations which explicitly incorporate lateral as well as vertical translocations and a combination of geologic, hydrologic and pedologic processes include the nine unit land surface model of Dalrymple et al. (1968) and Conacher and Dalrymple (1977), Huggett's (1975) soil landscape system model, and the archetypal mass flux catenas outlined by Sommer and Schlichting (1997).

The work of geologist Robert Ruhe is credited with ushering in an era of the study of the coevolution of soils and landforms. Ruhe (e.g., 1956, 1974), among other things, insisted that catenary relationships depended on geomorphic as well as pedologic fluxes, and were not limited to topographic effects on soil-forming factors. An extensive review of soil geomorphology theories and methods, with numerous examples, is given by Schaetzl and Anderson (2006).

Studies of paleosols (particularly in alluvial environments) and loess-paleosol sequences drew attention to the fact that deposition and pedogenesis often do not occur in discrete episodes, and frequently do occur simultaneously or contemporaneously. This resulted in the development of an explicitly “pedosedimentary” approach, originally to recognize that pedogenesis could occur simultaneously with deposition of loess or other deposits. The approach later developed along more complex lines including also erosion, reworking, and welding of paleosols. The pedosedimentary approach is well-exemplified in recent years by the work of R. Kemp and colleagues (e.g., Kemp, 2001; Kemp et al., 2004, 2006). McDonald and Busacca (1990) also engaged this theme, depicting soil formation on an aggrading surface as a competition between sedimentologic and pedologic processes. They also highlighted the knock-on effects, whereby properties of a pre-existing buried soil may have important impacts on subsequent soil development. Kraus (1999) reviewed the study of alluvial paleosols in the context of the interplay of deposition, erosion, and pedogenesis, and Krasilnikov et al. (2005) is one illustration of interpreting the coevolution of topography and soils in terms of the interplay of pedogenic and geogenic processes. Pedosedimentary methodologies have been most common in paleopedology and soil geomorphology, but Kühn et al. (2006) is an example application in soil science. The distribution and genesis of a particular taxon (Albeluvisols) in Germany was explained via a model which chronologically connects sedimentation, geomorphic (periglacial) processes, vegetation development, and soil-forming processes (Kühn et al., 2006). A contemporary example of applications of a coupled sedimentary–geomorphic–pedologic model to explicitly interpret soil layering is Lorz (2008).

While pedosedimentary analyses can be seen as partly arising from dissatisfaction with static stratigraphic approaches, they have also arisen due to recognition of inadequacies of top–down pedological approaches. This is the case, for instance, with Jacobs and Mason (2007), who found a pedosedimentary approach to be necessary in their study of soils influenced by dust deposition, and thus affected by upbuilding rather than developing from a stable ground surface. This work is noteworthy in the context of this review in showing explicitly how incorporation of depositional upbuilding along with top–down translocation results in a fundamentally different intepretation of certain horizons than one based solely on the traditional pedological model. In Europe, extensive research on relict periglacial cover beds triggered criticism of the A–B–C-model (see Kleber, 1997 for an overview); particularly with respect to the intensity of Holocene soil formation (brunification and lessivage).

While not explicitly addressing soil layering, Johnson's (1985) soil thickness model in essence expanded SPF-type approaches by recognizing that a variety of upbuilding, removal, volume expansion/contraction, and deepening processes in addition to erosion and weathering could influence soil thickness. The soil thickness model was subsequently expanded and refined by Johnson et al. (2005) and Phillips et al. (2005b). The early version (Johnson, 1985) led to a view that other soil properties—including horizonation—are dynamic and may behave regressively or progressively over time. This in turn inspired the evolution model of pedogenesis (Johnson and Watson-Stegner, 1987), based on the possibility of both progressive (e.g., horizonation) and regressive (e.g., haploidization) pedogenetic pathways. Further, Johnson and Watson-Stegner (1987) explicitly included pedological, biological, geomorphological, hydrological, and sedimentological processes in both types of pathway. The evolution model implicitly incorporates depositional upbuilding, erosion/deposition, translocation in all directions, and bioturbation as possible mechanisms, alone or in combination, for producing (or destroying) soil horizonation. Subsequently, the model of Brimhall et al. (1991) explicitly treated soil differentiation by coupled chemical, mechanical, and biological transport processes. The vertical variation of soil properties in this model depends on subsurface stresses and the balance between mass removal and accumulation.

The most comprehensive framework yet applied is Johnson's (1993, 2002) dynamic denudation theory, which accomodates all the mechanisms discussed heretofore, except perhaps purely inherited stratification. Though dynamic denudation is a general soil-landscape evolution model, an important impetus in its development was to explain the different nature of characteristic layering in tropical and midlatitude soils. Phillips (2004) used a dynamic denudation-type model for the specific problem of vertical texture contrasts in soils, and later applied it to coastal plain soils where a combination of downward vertical translocation and bioturbation, acting on stratified sediments, are the key processes in creating texture-contrast layering (Phillips, 2007).

The choice or acceptance of a particular theoretical model of soil layering is not trivial. Application of different conceptual frameworks to the same sites can result in different interpretations, as illustrated by the study of Jacobs and Mason (2007). Further, even within a relatively restricted geographical area, multiple mechanisms may be operating. Phillips (2001), for example, showed that at least five different general explanations for the formation of texture-contrast layering could be shown to apply in a single county in east Texas. Another example, from southeastern Brazil, shows that soil morphology and pedosedimentary layering is influenced by historical legacies of erosion, desposition, and stability (themselves driven by tectonics and climate); surface erosion; weathering; biological activity; and upward and downward vertical and lateral translocation (Muggler and Buurman, 2000).

This points to the benefits of a conceptual model similar to dynamic denudation, in accommodating numerous possible processes and controls operating at the top, within, and at the base of, the regolith. Because it is based on broad categories of process bundles, and explicitly addresses the localized mass balances we believe are important to layering, the model below is an adaptation of Simonson's (1959, 1978) process model.

2.3. Vertical contrast model

A conceptual model of soils developed by Simonson (1959, 1978) holds that soils are a function of additions and removals of mass and energy, and of translocations and transformations to, within, and from soil profiles. Simonson's model also recognizes soils as representing both inherited and pedogenically acquired characteristics (and combinations thereof). Simonson's (1959, 1978) framework is often used as a pedagogic device in soil science, and implicitly underpins many soil and regolith studies, but is rarely explicitly employed as an interpretive device. Schaetzl and Anderson (2006: 321) consider the

Fig. 1. A layered soil profile in Beauregard Parish, Louisiana, USA. The vertical differentiation is due to post-depositional processes acting on more-or-less homogeneous, unstratified coastal plain parent material. Soil morphology shows evidence of vertical translocation and bioturbation, with possible erosional winnowing at the surface. The sharp color contrasts evident in the field are not as apparent on the black-and-white photograph. Horizons are designated according to standard U.S. Department of Agriculture methods and nomenclature (Soil Survey Division Staff, 1993). Thickness of the section shown is about 1.5 m.

model to be part of a broader class of mass balance models, which views the nature of soils (and soil layers) as the outcome of the balance and character of simultaneously operating additions, removals, transformations, and translocations. Here we adapt Simonson's approach to examine processes of addition, removal, transformation, and translocation to either enhance or reduce vertical contrasts (or lack thereof) inherited from parent materials.

Recognizing that soils may have multiple parent materials, the geological materials underlying the soil are referred to as underlying geological material. Taking t_o as the time of deposition or exposure of the underlying material, and t_n as the present, the age of the regolith is given by $t_n - t_o$. Layering can occur in three general ways.

First, stratification may be present at t_o, for example in stratified alluvium or layered sedimentary rocks. This layering may persist as weathering proceeds and other geomorphological and pedological processes occur and may be either enhanced or obscured by the latter. Second, layering can occur as a consequence of relatively abrupt, episodic formation some time after t_o, say t_i, $t_o < t_i < t_n$. For instance, a flood, landslide, or wind storm may deposit a lithologically distinct layer on an existing surface, thereby generating at least two layers—more if the deposited material is itself stratified. This type of layering is more likely to be associated with surficial processes, but episodic layer formation could be associated with subsurface processes as well, triggered by, for example, abrupt changes in water table, or by major leaching or throughflow events. Third, layering can be developed by gradual (though probably variable in rate) processes operating over some time period $t_i - t_j$, $0 < j < i < n$,. Vertical horizonation by eluviation–illuviation, or by formation of a surface biomantle, are examples. A distinction between active ($t_i = t_n$) and relic ($t < t_n$) may be made. Again, the processes may be primarily surficial or subsurficial. Further, they may be primarily vertical (top–down or bottom–up) or horizontal (for example slope erosion/deposition, or throughflow).

Vertical discontinuities associated with layering may thus be present at t_o, formed more-or-less suddenly at t_i, or formed more gradually over a longer time interval. The layering processes may be sequential, contemporaneous, or cyclical. They may be mutually reinforcing, or antagonistic. Both geomorphic and pedologic processes may work to reduce or erase discontinuities or to sharpen them. Examples of various combinations of these phenomena are shown in Figs. 1–2. More formally,

$$C(t_i) = C(t_o) + (A_{a+} - A_{a-}) + (A_{b+} - A_{b-}) + (R_{a+} - R_{a-}) + (R_{b+} - R_{b-}). \quad (1)$$

C represents the vertical contrast at a given time (t_i) and at time zero (t_o) between any two upper (a) and lower (b) zones. The term A represents additions (depositions, accretions, accumulations) and R indicates removals (losses, erosion, leaching) from the upper (a) and lower (b) zones. The plus and minus signs (+, −) indicate additions or losses which would tend to, respectively, increase or decrease the degree of contrast.

For example, the deposition of a lithologically contrasting surface layer would increase C at the original soil surface via the term A_{a+}, while erosional removal of a lithologically contrasting layer would reduce C at the base of the removed layer through the term R_{a-}. Vertical translocation which removes material from surficial zones and deposits it in a subsurface horizon would increase C across the boundary via R_{a+} and A_{b+}. Soil mixing with the net effect of reducing vertical contrasts would tend to reduce C at any point via A_{a-}, A_{b-}, R_{a-}, R_{b-}. These are simple examples to illustrate Eq. (1); there are innumerable possibilities.

In dynamic form,

$$\partial C / \partial t = \sum^{m} (\partial X_m / \partial t) \quad (2)$$

where the X_m represent the various A and R terms of Eq. (1).

The vertical contrast model (VCM) is synthetic, in the sense that it is based on the general conceptual framework of Simonson (1959,

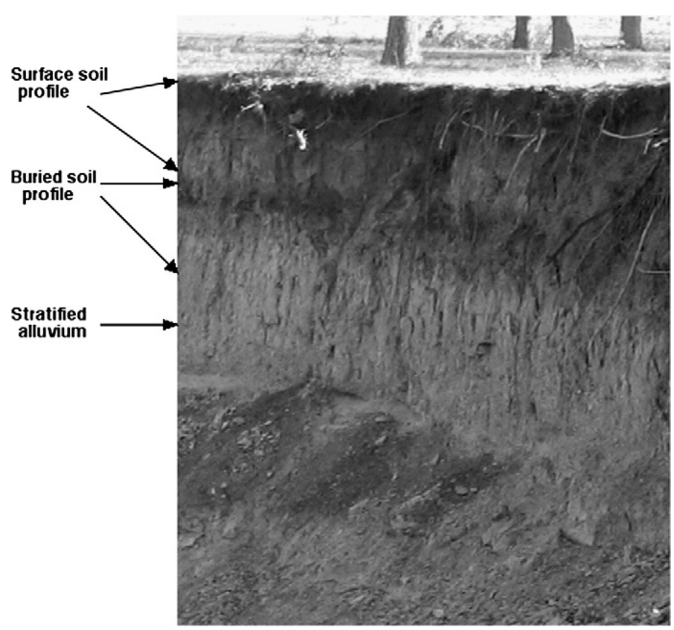

Fig. 2. Alluvial soils and sediments Brazos County, Texas, USA. Some stratified alluvium is present at the base, but sedimentary stratification has been destroyed in the overlying buried soil profile, in which apparently pedogenic layering is evident. Burial of this soil created an additional depositional layer, which is currently being vertically differentiated. Section shown is about 4 m thick.

1978) and the dynamic denudation and soil thickness models of Johnson (1985, 1993, 2002; Johnson et al., 2005), which themselves incorporate several earlier conceptual models in geomorphology, pedology, and hydrology. Further, the VCM accommodates all the mechanisms discussed in Section 2.1 and listed in Table 2. The applications and implications of the synthetic VCM are best shown with respect to specific cases. Thus, rather than a broad review, we have opted for a more restricted illustration. This is based on our own work, but in the spirit of a review, we applied the VCM *post hoc* to interpret the results of work already completed. Thus, in the sections below, we apply the model to several contrasting geological, pedological, and geoarchaeological problems in two distinct settings to illustrate some of the general principles discussed above.

3. Ouachita Mountains, Arkansas, USA

Several studies of soil and regolith have been carried out on sideslopes of the Ouachita Mountains of the Ouachita National Forest, Arkansas (Fig. 3). Conducted in the context of broader investigations of relationships between soil, forest vegetation, and geomorphic processes, these soil geomorphology studies have focussed on regolith development and landscape evolution, soil spatial variability, and biomechanical effects of trees on soil (Phillips and Marion, 2004, 2005; Adams, 2005; Phillips et al., 2005a,b; Phillips and Marion, 2006).

Details of these study designs and methods, and full descriptions of the geology, geomorphology, soil geography, climate, vegetation, and land use are given in the references above. The soils are predominantly Hapludults. The interpretations in this review are based on this body of work, which in turn is based chiefly on 16 study plots on sideslopes, slightly less than 0.13 ha in area each. A minimum of three full-size soil pits per plot plus eight additional pits in the study region (59 total) and 10 pairs of "posthole" pits per plot (320 total) were described using standard methods (Soil Survey Division Staff, 1993). Topography and vegetation were also mapped in detail, tree uprooting and stump hole disturbances were inventoried, and a number of specific soil properties were measured.

Almost all the sample pits display a vertical contrast of at least three textural classes between the surface (A) and subsurface (B) horizon(s). Texture of A horizons is typically loam or sandy loam, but ranges from sandy clay loam to loamy sand. B horizons are typically clay loam or silty clay loam, ranging from sandy clay loam to clay. In some pedons E horizons were recognized. B horizons were designated Bt in most cases due to high concentrations of silicate clays. Multiple B horizons in the same pedon generally did not differ in

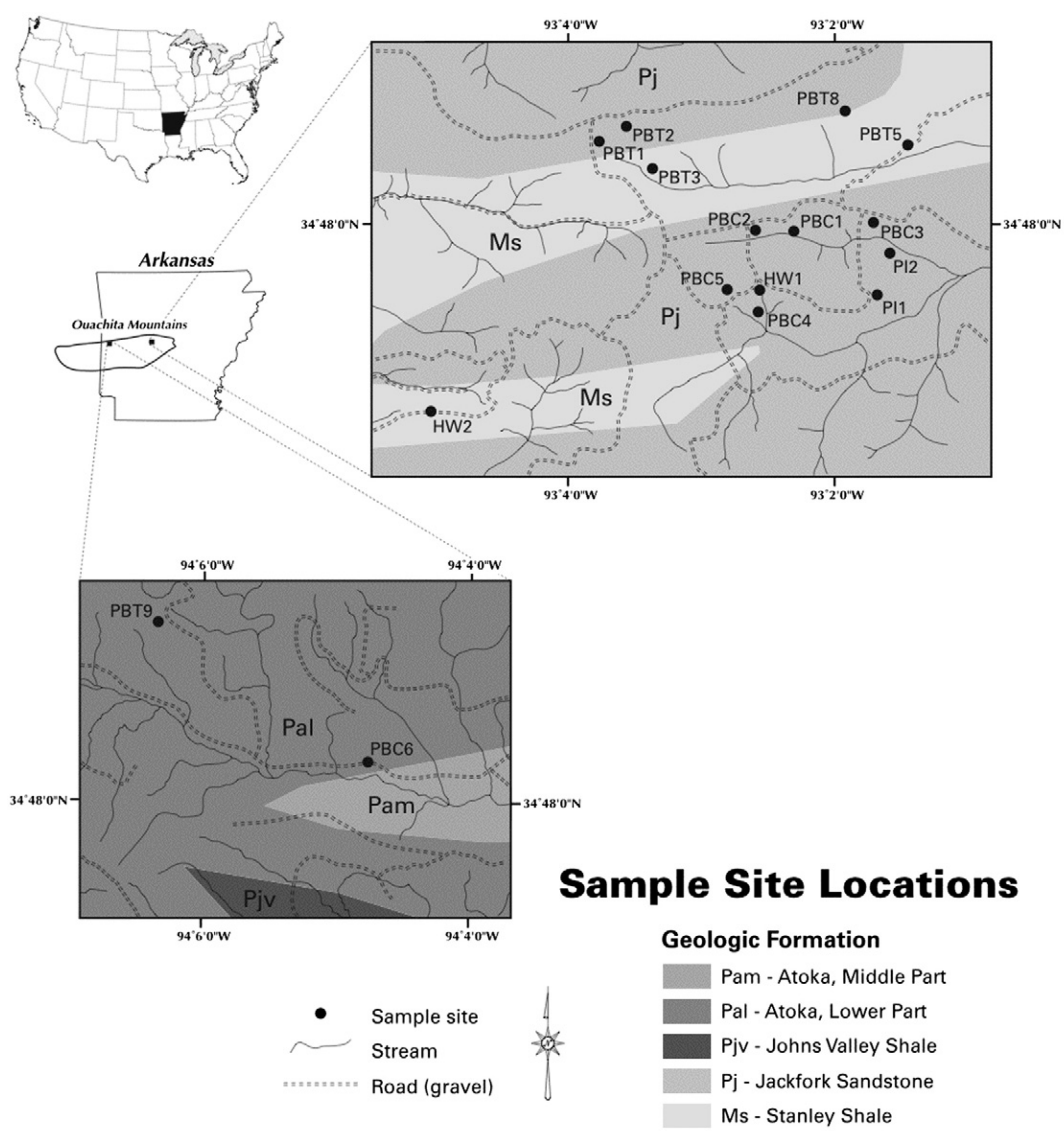

Fig. 3. Ouachita Mountains, Arkansas, study sites. The study plot labels refer to a study design described in detail elsewhere (Phillips and Marion, 2004).

texture, but rather in color, rock fragment content, clay films, and root and pore densities. C horizons were typically the same texture as B, but lacking in structure and clay films, and containing fragments or pockets of weathered or unweathered bedrock. Cr horizons generally occurred in shale, and were recognized on the basis of at least 50% black (unweathered) rock. R horizons were mainly found in sandstone, and were identified based on inability to penetrate with excavation tools or augers. Horizon designations are used here in a purely descriptive sense (c.f. Johnson, 1994).

3.1. Geomorphological Interpretation of layering

Eq. (1) was applied to the general interpretation of these soils with respect to the coevolution of topography and regolith, with results given in Table 3. The terms on the right of Eq. (1) were considered with respect to the layering reflected in the A (and occasionally E) horizon boundary with the uppermost B horizon, the contrast of the lowermost B with C horizons, and the boundary between C horizons and weathered (Cr) or intact (R) bedrock.

Surface additions are mainly in form of sandstone fragments weathered from the resistant ridgetops and transported downslope. This results in a surface cover of rock fragments, working of fragments into the soil by bioturbation, and sandstone weathering to coarsen surface layers (Phillips et al., 2005a). This tends to increase A/B texture contrasts and rock fragment concentration contrasts in both the upper and lowermost regolith, but may decrease B/C contrast. Clay illuviation, indicated by clay films in many B horizons, and by eluvial bodies in some pedons, contributes to A/B contrasts.

Weathering processes within the regolith and at the bedrock weathering front introduces rock fragments, increasing B/C contrast. Weathering blurs the C/Cr contrast. Solutional removal from the B horizon (inferred from bulk density) tends to increase contrast with the C, and likewise from C to Cr. Surficial erosion may serve to enhance textural differences between A and B via preferential removal (winnowing) of fines, but local erosional removal of coarse surficial horizons may decrease the contrast. Tree uprooting also is an important process in the study area. The mining of rock fragments from the subsoil by uprooting tends to increase A/B contrast in rock fragments, but the general soil mixing regime is proisotropic (Phillips et al., 2005a).

Any initial textural contrasts inherited from the sandstone and shale parent material cannot be confidently reconstructed in such highly weathered and bioturbated material. But systematic differences do exist at a broad scale in layering characteristics of soils underlain by sandstone vs. shale. While inherited contrasts are not a general explanation for vertical contrasts in the study area, local lithological variations (for instance local layers or lenses of sandstone, or transported boulders), are important sources of local variability (Adams, 2005; Phillips and Marion, 2005).

These results and interpretations are applied below to three specific problems or issues in soil, stratigraphic, and landscape interpretations: effects of tree uprooting, the rate at which layering or horizonation is developed, and geoarchaeological interpretations.

3.2. Effects of tree uprooting on layering

Tree uprooting (treethrow) is an important pedologic and geomorphic process in many forested environments, and the Ouachita study sites are no exception. Uprooting and other biomechanical effects of trees are critical with respect to local variability in soil morphology (including soil thickness and horizonation), rock fragment distributions, and regolith evolution (Phillips and Marion, 2005; Phillips et al., 2005a,b; Phillips and Marion, 2006).

Based on the contemporary density and frequency of uprooting, and estimating disturbance area from root wads, Phillips and Marion (2006) estimated that uprooting influences an area equal to 100% of the forest floor about every 11 Ka (assuming a 100 year forest turnover time). Typical thickness of root wads is about the same as soil thickness above bedrock, implying complete turnover of the regolith cover (Phillips and Marion, 2006).

In the short term, uprooting and subsequent log decay and root wad deposition often disrupts layering and horizonation (Fig. 4). However, uprooting systematically mines rock fragments from the subsoil and enriches rock fragment content of the surface and surficial soil horizons, producing a characteristic surface or near-surface layering (Phillips et al., 2005a; Table 3). Further, deposition of material in uprooting pits (and decayed stump holes) helps create and enhance vertical contrasts in the lower regolith (Phillips and Marion, 2004, 2006; Table 3).

This example illustrates that the same process can contemporaneously both create and enhance, or destroy and diminish, layering and vertical contrasts. This finding is consistent with those of Johnson and Watson-Stegner (1987), that the same bioturbation processes may be either proisotropic or proanisotropic.

3.3. Rate of layering

Erosion–deposition events which can influence layering may occur rapidly and sporadically. Pedogenic layering processes may occur gradually. And in addition to uprooting, Ouachita soils are subject to other significant biomechanical effects of trees, such as displacement of mass by tree growth, and the infilling of pits formed by stump rot or burning (Phillips and Marion, 2006). Again assuming a 100-year forest turnover time and extrapolating contemporary rates, Phillips and Marion (2006) estimate that an area equivalent to 100% of the forest surface would be affected in less than 3.7 Ka by the combination of physical displacement, uprooting, and stump hole infill. While clear soil

Table 3
Interpretation of additions and removals which might enhance (+) or reduce (−) vertical contrasts between surface and subsoil layers (A/B), lower solum and sub-solum lower regolith (B/C), and lower regolith and underlying rock (C/[Cr, R]). Surface and subsurface, respectively, refers to material gains or losses from above or at the top of, versus below or at the bottom of, the transition. Interpretations apply to the Ouachita field sites

	A/B	B/C	C/Cr,R
Surface additions, +	Deposition and weathering of colluvial sandstone fragments	Illuviation of translocated clay	Deposition of soil and rock fragments in stump holes and tree throw pits
Surface additions, −	None	None	None
Subsurface additions, +	Rock fragment deposition in stump holes and tree throw pits	Introduction of rock fragments from the weathering front	None
Subsurface additions, −	None	Rock fragment deposition in stump holes and tree throw pits	None
Surface removals, +	Winnowing of fines	Solutional removal	Solutional removal
Surface removals, −	Erosion of coarser surficial layer	None	None
Subsurface removals, +	Mining of rock fragments by tree uprooting	None	None
Subsurface removals, −	Soil mixing by tree uprooting	None	Weathering

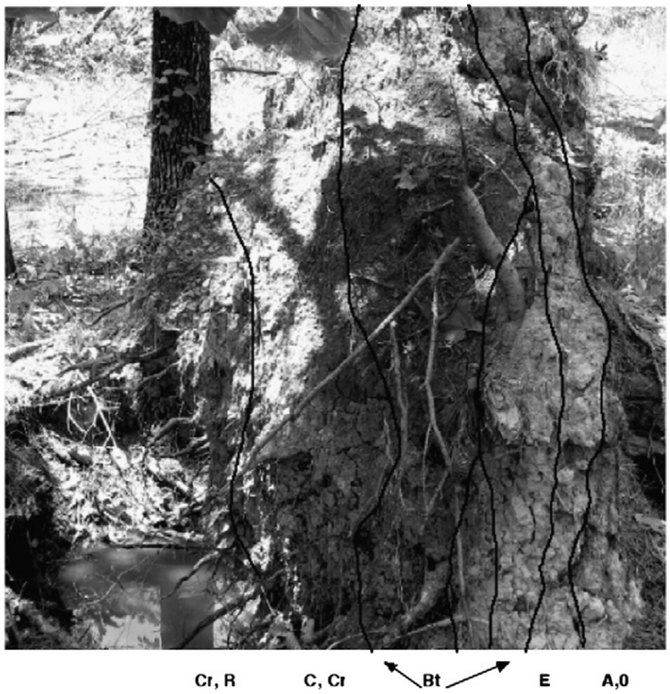

Fig. 4. Uprooted tree in the Ouachita Mountains, Arkansas. shows the uprooting disruption of layering created by a combination of *in situ* weathering, vertical translocation of clays, bioturbation, surface winnowing, and surface deposition (Adams, 2005; Phillips et al., 2005a).

stratigraphic signatures of faunal turbation were not apparent, burrowing and tunneling insects, mammals, and reptiles are common in the study area and can be presumed to add to the rate of bioturbation.

Despite this bioturbation, clear evidence of disrupted layering or unlayered material is absent except in recently-disturbed patches. All sample pits exhibited some layering, and nearly all showed significant vertical textural contrasts. This suggests that pedogenic processes which produce or enhance layering occur relatively rapidly; presumably in time frames comparable to those required for the decay or oxidation–combustion of stumps or uprooted trees, and infilling of holes or pits. The rates of these processes are not well known, but are on the order of decades for infrequently burned sites, and likely faster for regularly burned stands.

The ubiquity of layering points to processes which are also ubiquitous (as opposed to localized erosion/deposition). This in turn suggests eluviation–illuviation processes (see Table 3). Sandy podzolized soils in humid climates can develop full podzol profiles in several hundreds of years (Schaetzl and Anderson, 2006), and color-contrast layering in sandy dune soils may occur in less than a decade (Phillips, 2007). Where contrasting materials that are vertically transportable by water are readily available, as in bioturbated Ouachita soils, these processes may restore disturbed texture- and color-contrast layering at a rate limited only by the frequency and magnitude of infiltration and percolation (c.f. Phillips, 2004, 2007).

The implication is that where environments favor proanisotropic pedogenic layering, disturbed layering is likely to be rapidly countermanded and layering restored. In such situations, then, well-developed vertical contrasts or horizonation does not necessarily imply a lack of disturbance, or long periods of stability.

Stump holes or uprooting pits may be infilled with mass wasted surficial material, by slumping of the surrounding soil material, or combinations thereof (Phillips and Marion, 2006). The relative importance of these is poorly understood but bears further investigation. A predomination of slumping of surrounding soil over external infill could be an important process in rapid recovery of pedogenic layering.

3.4. Archaeological materials

The burial of archeological materials, and the extent to which buried archaeological material can be assumed to be in stratigraphic sequence, is a classic and chronic problem in geoarchaeology and archaeological pedology (c.f. Harris, 1979; Johnson, 1990; Leigh, 1998; Balek, 2002; Peacock and Fant, 2002). Archaeological interpretations are greatly simplified if layering is predominantly sedimentary (geological) and principles of superposition apply, and if pedogenic layering processes do not result in the translocation of achaeological materials (which might be rare).

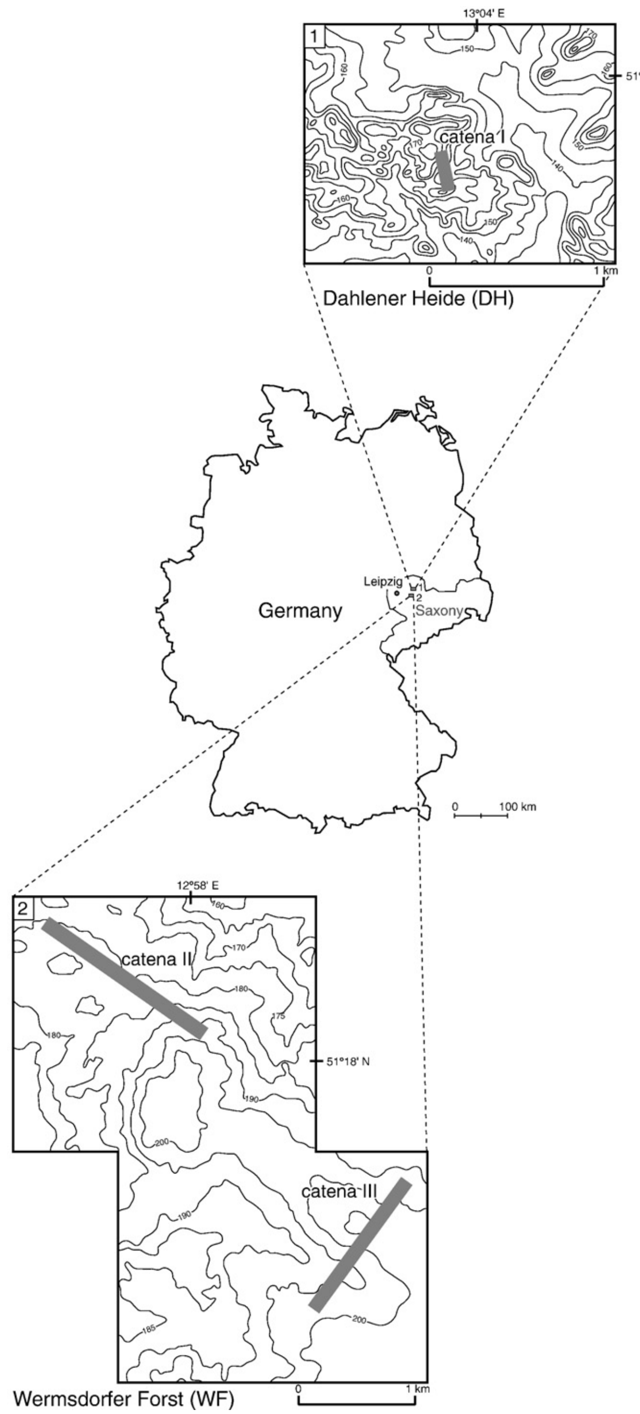

Fig. 5. Northwest Saxonion Lowlands, Germany, study sites The study plot labels refer to a study design described in detail elsewhere (Lorz, 2008).

The example used here is from the Albert Pike archeological site. This site is in the Ouachita Mountains and Ouachita National Forest, but not within the study sites described above. Archaeological excavations were conducted by U.S.D.A. Forest Service archaeologists, and three soil pits were described by Ouachita National Forest soil scientist Ken Luckow (a coauthor of Phillips et al., 2005a,b). The three pits have layering generally typical of the soils in the region.

A non-forest service archaeological consultant interpreted the site as a stratigraphic sequence dominated by deposition, based on changes in organic matter content with depth, and a general decrease with depth of the proportion of oxidizable carbon (and concomitant increase in the proportion of more resistant forms of organic carbon) (personal correspondence, K. Luckow and M. Etchison, forest archaeologist, 17 December 2001 and 7 January 2002). However, the layering at the site is consistent with dominantly pedogenic processes rather than deposition. All three pits have coarser-over-finer vertical texture contrasts, which does not disprove deposition, but is more consistent with a variety of pedogenic processes, both in general (Phillips, 2004), and in the Ouachitas (Adams, 2005; Table 3). All the subsoils (Bt horizons) have clay films, indicating translocation of clay, and one of the pits also has an eluvial horizon. The texture and mineralogy of the B horizons is consistent with formation primarily via weathering of the underlying shale bedrock, and the presence of shale rock fragments derived from the underlying shale in the lower regolith is further evidence of this origin.

In two of the three pits the soil organic matter (SOM) attenuates with depth, from 2.1 to 3.8% in the surface horizon to 0.5 to 0.7% in the lower soil. In one case SOM content increases to 2.8% in the subsoil, which was originally interpreted as a buried A horizon. However, in this pit the increase corresponds with a strong textural and rock fragment contrast which results in a pronounced lateral turning of tree roots, with the local root concentration accounting for the higher SOM. The systematic changes in the proportion of oxidizable vs. more resistant soil carbon would be expected in any forest soil, where fresh litter is primarily at the surface and the older, more highly decomposed material has a greater probability of being translocated downward.

Application of the conceptual model to these sites indicates that the layering is primarily due to pedogenic processes acting on a regolith formed primarily from *in situ* weathering of the underlying bedrock. While depositional additions (as well as erosional removals) likely occur(red) at this site, the observed layers are not derived from sedimentary layering. Archaeological artifacts are distributed throughout all three profiles. Given that the level of bioturbation is high in the region, the evidence that the soil layering is not depositional, and that rock fragment distributions in two of the three pits are consistent with tree uprooting (Phillips et al., 2005a), the soil and artifact layering cannot be assumed to represent a simple chronostratigraphic sequence. The layering likely represents burial and mixing via bioturbation.

4. Northwest Saxonian Lowlands, Germany

This example is based on 16 soil pits and about 150 auger holes located in two research areas—north Dahlener Heide (DH) and south Wermsdorfer Forst (WF), about 15 km apart in northwestern Saxony, Germany (Fig. 5). The soil pits are arranged in four catenas. Auger holes with depths of 1 m were used to sample areas between the soil pits. The methods and data underpinning the discussion below are described in detail by Lorz (2008; Lorz and Phillips, 2006).

4.1. Geomorphic setting

The NW Saxonian Lowlands are characterized by sediments and relief formed during at least two glaciations, the Elster and Saale, middle Pleistocene, and one periglacial period, Weichsel, upper Pleistocene. The underlying material consists mainly of lodgement tills. In the northern area (DH), a terminal moraine complex from the Elsterian period provides a highly diverse substrate comprising glaciofluvial sands and gravels. The topography is highly variable and is related to the variable erosional resistance of the glacial sediments. Ridges with steep slopes frame small, unchannelled flat-bottom valleys. The vegetation is dominated by managed forests consisting of pine on the ridges and mixed stands of oak, pine and beech in the valleys. In the WF area the substrate consists of tills, sometimes calcareous, rhyolitic saprolite, and rhyolite outcrops. The latter are detectable as small hilltops embedded in a landscape otherwise characterized by a smooth to flat terrain.

The parent material and relief of both study areas has been substantially influenced by periglacial processes. The most important processes during the last periglacial period (Weichselian) were the deposition of eolian sands and silts (sandy loess), and to some extent their mixing by solifluction and cryoturbation. The result is the formation of shallow cover beds of varying age and thickness. The youngest cover bed is thought to have formed during the late glacial period of the Weichselian. Due to eolian sorting, texture changes systematically with distance from the source area along the N–S-transect.

All soil profiles display stratification, particularly in the form of texture contrasts. In area DH (Fig. 6) the cover bed compromising the A, B, and E-horizon (again, horizon designations are used in a descriptive rather than genetic context) has a sand content of 45 to

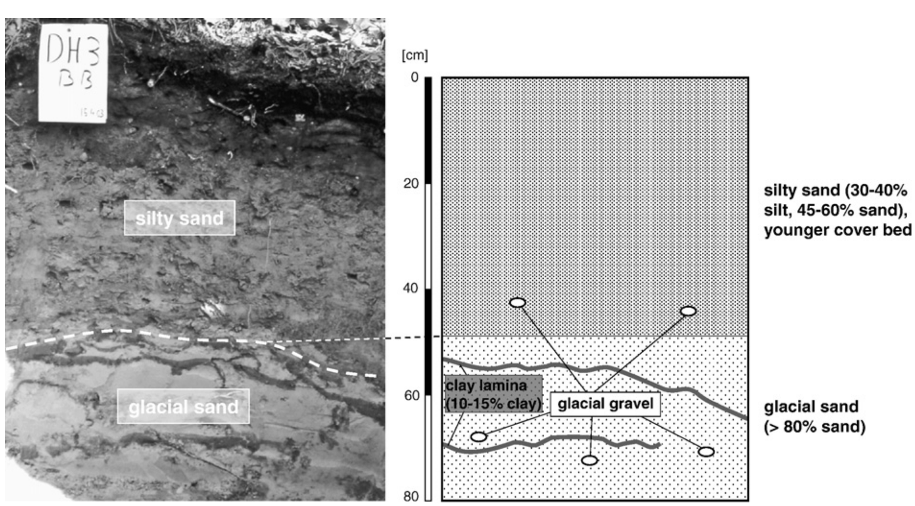

Fig. 6. Soil profile with sandy–silty mantle covering glacial sands in the Dahlener Heide. The upper cover bed is assumed to be of eolian origin with relic cryoturbation features (late Pleistocene) and subsequent Holocene pedogenesis. The clay bands in the subsoil may be older soil formations or of geologic origin.

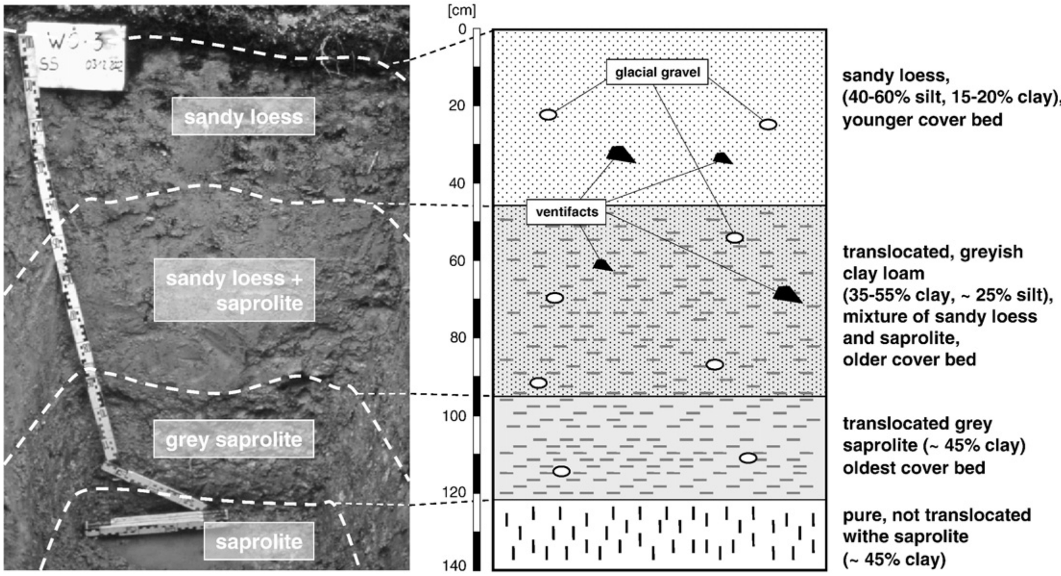

Fig. 7. Soil profile with silt mixed and transported material, and *in situ* saprolite in the Wermsdorfer Forst. The upper cover bed is of high silt content (sandy loess). The base of the soil profile is saprolite derived from rhyolite. The mixed glacial gravels in the soliflucted saprolite demonstrate its movement. The intermediate cover bed is a mixture of residual material and sandy loess.

60%, with 30 to 40% silt (loam or sandy loam), while the lower layers are sand (sand > 80%). Below the solum clayey laminae (2–10 cm thick, clay 10–15%) in the glacial sands are associated with small scale texture contrasts. In area WF (Fig. 7) the silt content of the cover beds (sandy loess) is higher, about 40–60%, forming a sharp contrast to the underlying material (sandy loess and saprolite with 35–55% clay; or saprolite with 45% clay).

Soil formation depends strongly on geomorphology and regolith accumulation. In area DH loamy sands were deposited in a flat valley bottom, and soils are weakly developed luvisols to cambisols. On the valley side ridges no loamy cover beds were observed; instead glaciofluvial sands and gravels are the parent material for podzols. Area WF is part of a region subjected to studies on waterlogged soils since the 1920s. Upper soil waterlogging occurs due to the texture contrast between topsoil and subsoil, which often reflects significant bulk density contrasts. The resulting soils, depending on the topographic setting, are planosols or stagnic luvisols in plains and flat hillslopes. Soils without hydromorphic features are found only on well drained hilltops (rhyolite outcrops). These are usually Cambisols, with incipient podzolization of topsoil.

4.2. Layering and vertical texture contrasts

Deposition of cover beds during periglacial periods is the most important process for producing layering and vertical texture contrasts. The younger cover bed formed due to the input of well sorted eolian material, presumably during the late glacial of the Weichsel period. The sorting results in a high degree of contrast with the underlying, unsorted, till. Gelifluction and cryoturbation contributed to the formation of an older cover bed, resulting in a mixed surficial layer with eolian input material. As a result a transitional zone was formed having some properties of both the upper and lower layer. Where underlain by sandy tills rather than saprolite, sand contents are higher and silt contents decrease with depth in the older cover bed. Where eolian sands are deposited on existing sands, the contrast is reduced (Table 4).

Other processes contributing to the vertical contrasts are minor. Clay eluviation and illuviation would enhance existing texture contrasts, because most of underlying material already possesses higher clay contents. However, clay translocation does not appear to be sufficient to cause a distinct texture contrast, because: (1) The differences in clay content are only around 2–5%; (2) the soils are in general too acidic (pH [H_2O] < 5) to allow lessivage and (3) only weakly developed clay films were observed (Table 4). Vertical leaching and solutional translocation also do not apparently contribute substantially to the contrasts. However, the extent to which lateral flows transport only dissolved vs. solid material is not known (Table 4). Forestry practices do not appear to have contributed in any recognizable way to texture contrasts.

Upward movement of rock fragments can reduce the vertical contrast. Two general processes could cause this movement: up-freezing of stones due to frequent freeze–thaw cycles, and tree uprooting. These processes may disrupt stone lines often found at the

Table 4
Interpretation of additions and removals at the Saxony field sites which might enhance (+) or reduce (−) vertical contrasts between surface and subsoil layers (A/B), lower solum and sub-solum lower regolith (B/C), and lower regolith and underlying rock (C/Cr, R). Surface and subsurface, respectively, refers to material gains or losses from above or at the top of, versus below or at the bottom of, the transition

	A/B, E	E, B/C	C/Cr, R
Surface additions, +	None	Eolian input	Eolian input; cryoturbation; solifluction
Surface additions, −	None	(Eolian input)	None
Subsurface additions, +	None	Clay illuviation	Clay illuviation
Subsurface additions, −	Up-moving of rock fragments	Up-moving of rock fragments; lateral accumulation of $CaCO_3$	Lateral accumulation of $CaCO_3$
Surface removals, +	None	None	None
Surface removals, −	None	None	None
Subsurface removals, +	None	Clay eluviation (lateral depletion of $CaCO_3$)	None
Subsurface removals, −	None	None	None

lithological discontinuity between upper cover beds (silty sands to sandy loess) and the underlying material. By deconcentrating rock fragments in the stone line and moving them upward, differences in rock fragment content between the upper and lower layer are reduced, in contrast to the effects seen in the Ouachitas (c.f. Tables 3, 4).

5. Discussion and conclusions

A number of conceptual models of layering in soils, sediments, and weathering profiles have emerged from geology, sedimentology, geomorphology, and pedology. Vertical contrasts in soils cannot be ascribed to any particular dominant process or set of processes. Rather, any of a number of geological and pedological processes (or a combination thereof) may be responsible for producing and enhancing (or destroying or blurring) contrasts. Layering in soils is characterized by polygenesis and multiple causality. Conceptual frameworks and interpretive tools such as the vertical contrast model outlined here are available which incorporate both geogenic and pedogenic processes and the potential roles of inheritance and sharpening or blurring of vertical contrasts. Deployment of such models can help avoid misinterpretations of layering, and facilitate recognition of potential processes and controls which would not necessarily be identified using traditional monogenetic stratigraphic or pedological perspectives.

In the Arkansas case study, surficial mass wasting, erosion, and deposition play a role in layering, as do bioturbation (predominantly floralturbation), weathering, solutional removal, and translocation by water. Variations in the underlying rock are significant, but layering in the soil is not inherited from sedimentary stratification. Static controls such as geological inheritance play a role along with active physical, chemical, and biological processes. Vertical movements, including translocation by water and biomechanical effects of trees, are important alongside horizontal movements such as mass wasting and surface/subsurface runoff. In the Saxony example, episodic geomorphic events play a greater role in the development of layering. These examples also illustrate both the enhancement and the reduction of depositional layering by predominantly pedogenic processes.

The processes resulting in layering in the Ouachita soils reflect a regolith actively evolving at three general levels—the ground surface, the bedrock weathering front, and within the soil, particularly along strongly contrasting boundaries. This conforms to the dynamic denudation model described by Johnson (1993). Regolith thickness varies locally, and its dynamics are much richer than the simplistic formation-by-weathering, removal-by-erosion conceptual framework included in numerical models of landscape evolution (Phillips et al., 2005b). Because profile stratigraphy and horizonation are strongly influenced by biomechanical effects of trees significant changes may occur, at least locally, at time scales commensurate with forest vegetation changes—e.g., decades to centuries.

The Saxony Lowland soils also exhibit processes that enhance and reduce layering at various depths. Here, however, geomorphic changes such as silty eolian deposition and periglacial sorting processes, play a greater role in producing the observed soil stratigraphy.

This review and synthesis illustrates the importance of evaluating apparent time–depth sequences in light of the overall pedogeomorphic interpretation of layering to determine whether basic principles of superposition apply. In soils and weathering profiles, simple stratigraphic principles rarely hold, and traditional top–down pedogenic models are typically incomplete.

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