Pergamon

Quaternary International, Vols 51/52, pp. 109–114, 1998.

1040–6182/98/$19.00

PII: S1040–6182(97)00037–2

SOIL TAXONOMY AND PALEOENVIRONMENTAL RECONSTRUCTION: A CRITICAL COMMENTARY

Dennis E. Dahms* and Vance T. Holliday†

* Department of Geography, University of Northern Iowa, Cedar Falls, IA 50614-0406, USA
† Department of Geography, 550 North Park Street, University of Wisconsin, Madison, WI 53706, USA

INTRODUCTION

An important focus of paleopedology is the reconstruction of past environments. In particular, considerable interest in ancient (mostly pre-Quaternary) soils has appeared since the last paleopedology symposium (Yaalon, 1971), with an emphasis on paleoenvironmental reconstruction (e.g. Retallack, 1990). A significant amount of current research uses soil-like features in the sedimentary record as stratigraphic marker zones, as evidence to infer past environmental conditions, and as a basis for paleo-geomorphic interpretations by applying the principles of soil geomorphology and pedology to paleosols. Some investigators view the classification of paleosols as an important step in their interpretation (Mack *et al.*, 1993; Retallack, 1993, 1994; Nettleton *et al.*, 1998). Classification of these ancient soils can serve several useful purposes: to order the profiles that have been described, to provide initial descriptive information, and as a convenient shorthand reference.

A more contentious issue is use of the U.S. soil taxonomy as a direct indicator of past environments (e.g. Fastovsky and McSweeney, 1987). Soil taxonomy was developed primarily for agricultural, mapping, and land use purposes and is based on a number of present soil-forming conditions and processes. The problem with using soil taxonomy for ancient lithified soils is that classification to even the great group level (even to order level in some cases, e.g. Aridisols) requires that the nature of the soil-forming paleoenvironments must be known first. The system is based entirely upon diagnostic terms that require knowledge of current, observable conditions of the soil and its local environment. However, ancient soils often do not preserve the information required to assign diagnostic terms used in soil taxonomy due to diagenetic overprints in the sedimentary rocks. If diagnostic terms cannot be assigned because these soil conditions cannot be determined, then further classification using the soil taxonomy is groundless. In this paper we argue that the system simply does not permit the classification to be used to infer past environments.

Some paleopedologists use terms and concepts taken directly or modified from soil taxonomy (Retallack, 1990; Lehman, 1989; Mack *et al.*, 1993). These applications of the soil taxonomy improve communication only when the assumptions used as the basis for the taxonomy also can be made for the ancient sedimentary record (Soil Survey Staff, 1975). Classification of paleosols has precisely the same utility as classification of sediments and sedimentary rocks. Clearly, there is demand for classification systems that can be applied to paleosols, including quaternary and pre-quaternary buried, relict, and lithified soils (e.g. Mack *et al.*, 1993; Nettleton *et al.*, 1998). By classifying these soils, however, we must ask the larger questions: (1) how useful is the U.S. soil taxonomy for classifying lithified soils, (2) can the U.S. soil taxonomy be used without access to past (diagnostic) soil conditions without violating the underlying principles on which it is based, and/or (3) more broadly, which system, if any, is best for application to such profiles?

INTERPRETIVE APPROACHES IN PALEOPEDOLOGY

A review of the literature shows that geoscientists working with pre-quaternary soils use paleopedology to construct ancient environments chiefly in two ways. In the first way, soil-like sequences found in the sedimentary record serve to identify the stratigraphic position of ancient land surfaces and to correlate facies changes within rock-stratigraphic units. Once identified, the paleogeography of stable land surfaces can be interpreted together with the facies changes of sediments that accumulated on and adjacent to them. Examples of such a use of paleosols is that of Bown and Kraus (1981, 1987), Kraus (1987), Sigleo and Reinhardt (1988), and Kraus and Aslan (1993). These studies use paleosols (including lateral variations) and sedimentologic characteristics to interpret the processes and paleogeography of ancient floodplain construction. Such work represents an extension of quaternary paleopedology to the pre-quaternary sedimentary rock record in those places where it is based on accepted soil-geomorphic principles that seek to explain the variability of modern surface soils over contrasting landscapes (Ruhe, 1956; Ruhe and Walker, 1968;

Daniels *et al.*, 1971; Conacher and Dalrymple, 1977; Valentine and Dalrymple, 1976; Jenny, 1980; Birkeland, 1984).

A second way pre-quaternary paleosols are used by geoscientists is described by Retallack: '(This) approach to interpreting paleosols is to identify them within a soil classification and compare them to modern soils ... ' (Retallack *et al.*, 1990, p. 1325; see also Retallack, 1993). Retallack refers to this approach as 'taxonomic uniformitarianism' (1994, pp. 51–53; and this volume). This approach involves describing the profiles and applying diagnostic terms to classify ancient soils, using the nomenclature and classification system of the U.S. soil taxonomy. Ancient environments and processes that influenced the ancient soils then are inferred from the classification.

Retallack likens soil taxonomy to biological taxonomy in the sense that 'identification of a paleosol within a modern soil taxonomy may be taken to imply past conditions similar to those enjoyed by such soils today' (1994, p. 51). The problem with taxonomic uniformitarianism is well stated in a recent critique by Fastovsky (1991, p. 182):

'The idea that analogies can be drawn between soil classifications and biological classifications is misleading. Biological classifications are developed for their abilities to reflect genetic relationships among organisms. The assumption underlying this is that there exists one true phylogeny, the reflection of which is sought in the classification. Biological classifications are hierarchical because the character distributions in nature that they reflect are likewise hierarchical. Established soil taxa, however, have no single, inferred historical and genetic connection, such as is presumed to exist among organisms. Indeed, soil classifications have been developed for multiple purposes and impose an arbitrary typological system upon natural continua of overlapping processes. Because of this, soil taxonomies do not have the predictive power inherent in biological classifications'.

Relatively few specific soil features or types of surface or buried soils are related to unique or easily identified environments of formation. Most soil taxonomic terms are influenced by all of the soil-forming factors, not just climate and organisms (which are of most interest in paleopedology). *Argillic* horizons, for example, occur throughout North America, from coast to coast and from Mexico to Canada. Specific soil orders with argillic horizons range in environmental setting from *aridisols* to *ultisols*. Clay illuviation can be due to lessivage in response to moist forested environments (and under a wide array of tree species and under a wide variety of climates) or the translocation of clay-rich dust in response to irregular precipitation grasslands and deserts. Additionally, we often encounter incomplete, polygenetic or 'cumulate' soils (e.g. see Marriott and Wright, 1993) whose features are difficult to associate with a definite soil-forming environment because the soils have gone through two (or more) different phases of pedogenesis under different conditions.

DISCUSSION

Problems of Post-burial Alteration

The problem with applying diagnostic horizon terms to both modern and ancient soils is that post-burial diagenetic processes confuse an interpretation based on modern pedogenesis. In order to identify diagnostic surface horizons in an ancient soil one has to be certain that the properties were formed at the land surface and are not the result of post-burial diagenesis. We offer that this is the case only in a few instances to date.

Recent work by Patterson and others (1988, 1990) in Eocene floodplain settings of Wyoming suggests that differences in lithology can create diagenetic pathways that mimic soil horizonation. Walker and others (1978) show that pellicular clay coatings that mimic argillans can form through infiltration below the zone of soil formation. Even a few thousand years of burial is enough to deplete much of the original organic carbon from the A-horizons of many late Pleistocene–Holocene soils (Dahms, 1994; Holliday, 1988). Thus, a number of processes can either mimic, block, or otherwise interfere with our ability to see through the 'veil of diagenesis' (Patterson *et al.*, 1990, p. 845) to past environmental conditions (also see Blodgett, 1988; Nesbitt and Young, 1989; Patterson, 1991).

To classify ancient soils according to the orders, suborders, or great groups of soil taxonomy is to risk compounding the interpretive error. The problem may be the greatest when interpreting soils influenced by aquic moisture regimes. For example, the designation *aquept* requires detailed information about how long a soil remains saturated during the year, information that is simply not available for ancient soils. Furthermore, calling an ancient soil an *aquept* (Retallack, 1990, Fig. 4.11, p. 85) implies that present oxidation–reduction states resemble those of the past. But, analysis of modern mineral oxidation states and redox calculations cannot proxy for ancient conditions even if we could reconstruct diagenetic pathways more directly. In the case of buried soils in floodplain environments, it should be very hard to tell pre-burial aquic conditions from aquic conditions produced by diagenesis. Redoximorphic features often will change over time as pH and local hydrologic conditions vary (Vepraskas, 1992), so that one must account for the transience of Eh-pH conditions when assigning taxonomic terms that by definition signify the presence of differing redox conditions. We question the validity of environmental interpretations that infer such transient conditions without verification.

Use of Soil Taxonomy to Classify Paleosols

Judged by the number of current efforts at classification in North America (e.g. Retallack, 1990; Mack *et al.*, 1993; Nettleton *et al.*, 1998), a taxonomic scheme for both unconsolidated and lithified buried soils can be useful in paleopedology. The concepts underlying the diagnostic horizons used in soil taxonomy are certainly applicable to paleopedology. It is not necessarily wrong to apply modern terminology to old soils as taxonomic terms can be useful for descriptions. Sedimentologists often apply the same terms to old and modern sediments. Likewise, we do not object to applying diagnostic terms from soil taxonomy to purported ancient soils. For example, *argillic* is a perfectly reasonable term to use if the point is that there is a significant amount of illuvial clay. The problems arise with interpretations of illuvial processes.

We consider the approach of using classification to infer former environment as exemplified by Retallack's voluminous body of work to be misleading for a number of reasons. Soil Taxonomy is meant to be strictly descriptive. It is intended for use with surface profiles and so requires soils to be classified according to their present (and strictly observable or measurable) physical and chemical properties. Soil taxonomy was created mainly for practical applications, e.g. rationalization of land management, crop suitability, and soil conservation (Soil Survey Staff, 1975; Brasfield, 1984; Smith, 1986). These purposes required a system of soil classification based on simple, well-defined soil characters, many of which can be recognized easily in the field. Consequently, only general, broad characters are considered. For soil taxonomy, only the percentage increase in clay content is needed for designating the argillic horizon. On the other hand, scientific pedology (to which paleopedology belongs) requires a collection of all data on particle translocation within the profile to infer the processes of soil formation. Soil taxonomy also is based on a key. If one does not follow the key rigorously, major taxonomic mistakes may occur. It is often impossible to follow this key when using ancient soils, as data required for the nomenclature (e.g., temperature and moisture regimes) occur at a very high taxonomic level (e.g., *aridisols*). Temperature and moisture regimes are, in a sense, attached to other soil characteristics for soil taxonomy. These regimes can only be inferred for paleosols.

The developers of soil taxonomy state that the objective of the system is 'to have ... classes that permit us to understand ... the relationships between soils and also between soils and the factors responsible for their character' (Soil Survey Staff, 1975, p. 7). Though they may have wished that the system ultimately to be used to infer soil-forming conditions and how soils are linked to environmental factors, soil taxonomy was designed first and foremost for soil survey, mapping, and land use. The taxonomy, above all, is based on soil properties, not inferences regarding genesis. The focus on properties comes through repeatedly in soil taxonomy and in the more recent keys to soil taxonomy as well as in discussions of the system (e.g., Grossman *et al.*, 1984, especially the paper by Bartelli, 1984). Guy Smith, the 'father' of the system was explicit on this point: 'The philosophy of soil taxonomy is that a soil should be classified according to its own properties, and not by those that are presumed to have existed at some time in the past' (Smith, 1986, p. 17). Interpretations of genetic specifics were avoided as much as possible.

Several examples help to illustrate our points. A-horizon properties often are transient following burial. Characteristics such as organic matter content and pH can be altered by burial after a few thousand or even a few hundred years (e.g. Holliday, 1988). In soil taxonomy surface horizons are designated *mollic*, *umbric*, or *ochric*, and are differentiated on the basis of organic carbon content, base saturation, thickness, and color (Soil Survey Staff, 1975) that can be directly observed or measured. Use of these diagnostic terms for ancient lithified soils (e.g. Retallack, 1993, Fig. 1) is misleading if the characteristics used to define them were permanently altered after burial and, thus, are unrecoverable.

Retallack (1988, p. 9; 1990, p. 369) presents granular structure as essentially diagnostic of *mollic* epipedons and *mollisols*. Granular structure, however, is not unique to *mollic* epipedons nor to A-horizons (Buol *et al.*, 1989). Retallack (1983b, pp. 39, 43), for example, describes granular structure in C-horizons of paleosols in the South Dakota Badlands. Moreover, *mollisols* are classically the soils of grasslands, but because of the way soil taxonomy is designed, they are not exclusive to grassland soils. In the same sense, *mollic* epipedons are permitted in the classification of *inceptisols*, *alfisols*, *ultisols*, and *vertisols*. 'The objective of including soils formed under grass vegetation in the *mollisol* order does not hold true in all cases nor do the *mollisols* include only soils found under grass' (Bartelli, 1984, p. 10). All that is required for the *mollic* epipedon to form is high organic matter production and retention in a high base status setting. To identify granular structure and use this as a direct indicator of some form of mollisol requires considerable interpretive leaps.

The application of diagnostic subsurface horizon terms of ancient soils can lead to similar misinterpretations. Diagnostic subsurface horizons also are described from presently observable or measurable soil properties, not what these properties might have been in the past. We may have to make some subjective interpretation of the presence or absence of clay illuviation to identify a Bt or an *argillic* horizon, but an understanding of the specific processes and conditions responsible for illuviation are expressly not required. The designation *argillic* denotes that clay has been translocated (Soil Survey Staff, 1975; Brasfield, 1984). It is based on supporting evidence from grain-size data and from thin sections. Thus, to call a subsurface horizon *argillic* is to say that it exhibits specific properties that require translocation of clays (usually *fine* clays), usually, from the A- or E-horizons (Brasfield, 1984). Often buried quaternary soils have had their A-horizons stripped during erosion associated with burial processes. No evidence of an A-horizon's presence exists, once burial has occurred, except an erosional unconformity. A-horizons also may be destroyed after burial during a period of diagenesis and loss of organic matter. This problem is often seen in buried soils in Quaternary loss units. In this case, materials of the A-horizon may still be present, but without organic matter it is difficult to call this buried horizon an 'A'. It is possible, however, to detect *argillic* horizons in modern eroded soils by comparing clay content in B with that in C, from the presence of oriented clay films or from papules.

Bt and *argillic* horizons as well as Bs horizons frequently are identified in the paleosol literature on the basis of having high clay content or being iron-rich (Retallack, 1990, pp. 110–111, 402). Such clayey zones then are used to infer the presence of *alfisols* and to reconstruct forest vegetation (Retallack, 1986, pp. 25, 37). 'Soils of young land surfaces ... support early successional vegetation and have only an organic (A) horizon over mildly weathered parent material (C-horizon) ... A full sequence of horizons (A–Bt or Bs–C) is formed under mature woody vegetation' (Retallack, 1988, p. 8). We question the necessary association of vegetation successional maturity with soil horizonation. For example, is it not possible to have an A–C or A–Bw–C with mature woody vegetation as well? In the same sense, Lehman (1989) discusses the presence of *argillic*, *cambic*, *spodic*, and *petrocalcic* horizons and their origin in upper cretaceous paleosols under woodlands in Trans-Pecos Texas. Lehman assigns diagnostic horizons simply from the presence of clay-, iron-oxide-, and carbonate-enriched zones, and compares the paleosols to modern *alfisols*. As Patterson *et al.* (1990) point out, Lehman's interpretations do not account for the effects of diagenetic alterations on the floodplain strata. Generalizations such as these grossly oversimplify and even distort the complex relationship between soils, landscapes, vegetation, and time. There are neither indications that the clay is necessarily illuvial, nor data to show that the sesquioxides and carbonates are pedogenic. These interpretive leaps are misleading. In any case, an *argillic* horizon is not necessarily 'clayey' because it may also be silty, sandy, or even gravelly. And as noted above, soils with *argillic* horizons are found in an extremely wide variety of environments that include forests, grasslands, and deserts.

Reider (1982, 1987, 1990) classified buried soils at archeological sites in Colorado and Wyoming and then used the classifications to make paleoenvironmental interpretations. For example, a buried soil at the Horner site, Wyoming, was classified as a *calciaquoll* (Reider, 1987, pp. 352–353). Because *calciaquolls*, in particular, and *aquolls* in general are now common in eastern North Dakota, northern South Dakota, and western Minnesota, Reider (1987, p. 355) proposes that the environment at Horner 7000 yr. BP was therefore similar to the present environment of the eastern Dakotas and Minnesota. Two problems exist with this interpretation. First, the entire section with the buried soil has secondary carbonate, however (used as a criteria to assign the *aquoll* to the calci-Great Group), raising the possibility that the carbonate in the buried soil is a post-burial phenomena. Second, *aquolls* require only poor drainage with high production of organic matter, conditions that can occur in a wide variety of settings as long as the water table is high. The point here is that paleoenvironmental re-construction is problematic in aquic soils. Paleoenvironmental interpretations apparently are easier to deal with in well-drained soils.

We consider work such as that of Kraus (1987; Kraus and Bown, 1988; Kraus and Aslan, 1993) on the alluvial paleosols in northwestern Wyoming to be a more effective use of paleosols to illuminate past environments. The lateral and vertical relations of ancient soil-like features were studied to identify what is termed *pedofacies* in various eocene fluvial environments. This work used concepts of soil development at different positions in the ancient fluvial environment to indicate the position of hydrocarbon traps. Kraus also used the concept of pedogenic maturity to interpret relative sediment accumulation rates in ancient floodplain environments. For example, more weakly developed (immature) soils were found where sedimentation rates were rapid near channel margins and crevasse splays; mature (strongly developed) soils were found most often at distal floodplain locations where sediment accumulates more slowly. Categories of maturity were then used to interpret the local and regional alluvial subenvironments. Through this approach sedimentologic and stratigraphic observations can be directly traced to landscape processes of the past and used to infer geomorphic processes that affected the surfaces on which ancient soils developed. In this work, no environmental conditions are inferred from the classification, as it is used only as a reference for ordering the data.

Fastovsky and McSweeney (1987) also use the concept of pedogenic maturity to interpret a suite of paleosols developed in cretaceous–paleogene fluvial deposits in eastern Montana and western North Dakota. They infer a uniformity of soil processes across this fluvial landscape by using pedogenic features such as root traces and micromorphologic features to conclude that immature soil profiles developed predominantly in response to gleization and podzolization processes in an unstable fluvial setting. Fastovsky and McSweeney use mostly the same methods as do Retallack and Lehman to infer the presence of soil profiles in the rock record. The difference is that, unlike Retallack and Lehman, their work does not rely on typological designations to infer environmental conditions. Fastovsky and McSweeney avoid 'typological designations based upon modern classifications ... because of (a) the incompleteness of the database, (b) the interpretive limitations of such an approach, and (c) the design and intent of modern soil classifications' (Fastovsky and McSweeney, 1987, p. 66). They also note (pp. 66–67) that the use of modern classifications limits our ability to recognize ancient soil types that have no modern counterparts, so that as 'Retallack has noted (1981, p. 73) Fossil soils should not be strained to fit into classifications of modern soils, as some kinds of soils once formed on the earth are now extinct'. Whether soils once existed that have no modern counterparts or did not, the design of soil taxonomy has been simply to order those soils that exist on the present landscape; it is not constructed to translate ancient environmental conditions to geoscientists of the 20th and 21st centuries.

CONCLUSIONS

Classifying buried or lithified soils has the same utility as classifying sediments and sedimentary rocks, and there is demand for classification systems that can be applied to ancient soils (e.g. Retallack, 1990; Mack *et al.*, 1993; Nettleton *et al.*, 1998). We think the Mack system is a step in the right direction, though we disagree with taking terms for some of the soil orders directly from soil taxonomy. We think the use of similar terms for buried, lithified, and modern soils will cause confusion between those familiar with traditional soil classification (pedologists and quaternary geoscientists) and those using the Mack system (pre-quaternary geoscientists). Workers almost certainly will use the same terms in different ways, but may not realize this. Use of the same terms for differing situations may impede the kind of communication that soil classification was developed to promote among various groups of scientists (Cline, 1961). Mack *et al.*'s classification certainly is worthy of being applied in order to test its suitability to various burial and diagenetic situations, as well as the utility of its nomenclature. The utility of any classification system ultimately is determined by the people who use it.

Many modern soil features simply do not survive into the rock record and cannot be direct analogues to ancient soils (Yaalon, 1971). Even persistent soil properties are modified by diagenesis following burial (Mack *et al.*, 1993; Retallack, 1981, 1990). Nevertheless, many studies continue to apply to ancient soils diagnostic terms from soil taxonomy that require prior knowledge of soil conditions or transient weathering processes for their use.

The application of soil taxonomy to ancient soils in the absence of information concerning diagenetic changes in their physical and chemical characteristics is an incorrect use of the principles underlying the soil taxonomy and paleopedology. Ancient soil characteristics often are not (or cannot be) traced through intervening diagenetic overprints. Fastovsky (1991) observed that ancient soils can tell us something of past climates, 'but exactly *what* is not always clear' because many ancient soils are the result of non-unique pathways and only one of several possibilities can be correct. It follows that diagnostic horizon nomenclature cannot be applied to ancient soils without direct evidence of soil forming conditions. To use taxonomic classes and later infer soil-forming conditions from the classes is to misuse the system of soil taxonomy and ignore the intervening diagenetic processes that link ancient soils to the rock units in which we find them today.

Soil taxonomy actually is an end product of environmental reconstruction. After having studied the physical and chemical characteristics of a buried soil, separated diagenetic from original pedogenic process imprints, and formulated an idea of how the soil formed, one may offer an environmental interpretation concerning soil temperature and precipitation regimes, and possibly even vegetation. For example, one might infer that a certain soil was some kind of *aquept*. The point is this: we can try to classify buried and or lithified soils; but a proper classification according to soil taxonomy requires environmental interpretation first. We cannot classify paleosols in order to interpret them. Classification can be a starting point for interpretation by providing a descriptive focus, and some components of the soil taxonomy can serve such a purpose; but clearly the environmental interpretations cannot be based on the classification.

ACKNOWLEDGMENTS

We thank Leon Follmer and Don Johnson for organizing the Paleopedology symposium. Leon was especially encouraging in the preparation of this paper. We also thank the 35 reviewers who provided commentary on this paper (out of the 86 who received it!). In particular, the comments and suggestions made by Mary Kraus, Greg Retallack, and P.W. Birkeland were crucial to the final form of the manuscript.

REFERENCES

Bartelli, L.J. (1984). Soil Taxonomy: Its evolution, status, and future. *In*: Grossman, R.B., Rust, R.H. and Eswaran, H. (eds), *Soil Taxonomy: Achievements and Challenges*, Vol. 14, pp. 7–13. *SSSA Special Publication.*

Birkeland, P.W. (1984). *Solids and Geomorphology*. Oxford University Press, New York.

Blodgett, R.H. (1988). Calcareous paleosols in the triassic dolores formation, southwestern Colorado. *In*: Reinhardt, J. and Sigleo, W. (eds), *Paleosols and Weathering Through Geologic Time: Principles and Applications*, pp. 103–122. *GSA Special Paper*, **216**, Geological Society of America, Boulder, CO.

Bown, T.M. and Kraus, M.J. (1981). Lower eocene alluvial paleosols (Willwood formation, northeast Wyoming) and their significance for paleoecology, paleoclimatology, and basin analysis. *Paleogeography, Paleoclimatology, Paleoecology*, **34**, 1–30.

Bown, T.M. and Kraus, M.J. (1987). Integration of channel and floodplain suites, I. Developmental sequence and lateral relations of alluvial paleosols. *Journal of Sedimentary Petrology*, **57**, 587–601.

Brasfield, J.F. (ed.) (1984). Guy D. Smith discusses soil taxonomy. Reprinted from *Soil Survey Horizons*, by the Soil Science Society of America, Madison, Wisconsin.

Buol, S.W., Hole, F.D. and McCracken, R.J. (1989). *Soil Genesis and Classification* (3rd ed.). Iowa State University Press, IA.

Cline, M.G. (1961). The changing model of soil. *Soil Science Society of America Proceedings*, **25**, 442–446.

Conacher, A.J. and Dalrymple, J.B. (1977). The nine unit landsurface model: an approach to pedogeomorphic research. *Geoderma*, **18**, 1–154.

Dahms, D.E. (1994). Mid-holocene erosion of soil catenas on moraines near the type pinedale till, wind river range, Wyoming. *Quaternary Research*, **42**, 41–48.

Daniels, R.B., Gamble, E.E. and Cady, J.G. (1971). The relation between geomorphology and soil morphology and genesis. *Advances in Agronomy*, **23**, 51–88.

Fastovsky, D.E. (1991). Review of Retallack's soils of the past: an introduction to paleopedology. *Sedimentology*, **38**, 181–184.

Fastovsky, D.E. and McSweeney, K. (1987). Paleosols spanning the Cretaceous–Paleocene transition, eastern Montana and western North Dakota. *Geological Society of America Bulletin*, **99**, 66–77.

Feakes, C.R. and Retallack, G.J. (1988). Recognition and chemical characterization of fossil soils developed on alluvium: a late ordovician example. *In*: Reinhardt, J. and Sigleo, W. (eds), *Paleosols and Weathering Through Geologic Time: Principles and Applications*, pp. 35–48. *GSA Spec. Paper #216*, Geological Society of America, Boulder, CO.

Grossman, R.B., Rust, R.H. and Eswaran, H. (eds) (1984). *Soil Taxonomy: Achievements and Challenges*, SSSA Special Publication 14, Madison, WI.

Holliday, V.T. (1988). Genesis of a late-holocene soil chronosequence at the lubbock lake archeological site, Texas. *Annals of the Association of American Geographers*, **78**, 594–610.

James, W.C., Mack, G.H. and Monger, H.C. (1993). Classification of paleosols: reply. *Geological Society of America Bulletin*, **105**, 1637.

Jenny, H. (1980). *The Soil Resource*. Springer, New York.

Kraus, M.J. (1987). Integration of channel and floodplain suites, II. Vertical relations of alluvial paleosols. *Journal of Sedimentary Petrology*, **57**, 602–612.

Kraus, M.J. and Aslan, A. (1993). Eocene hydromorphic paleosols: significance for interpreting ancient floodplain processes. *Journal of Sedimentary Petrology*, **63**, 453–463.

Kraus, M.J. and Bown, T.M. (1988). Pedofacies analysis: a new approach to reconstructing ancient fluvial sequences. *In*: Reinhardt, J. and Sigleo, W. (eds), *Paleosols and Weathering Through Geologic Time: Principles and Applications*, pp. 143–152. *GSA Spec. Paper # 216*, Geological Society of America, Boulder, CO.

Lehman, T.M. (1989). Upper cretaceous (maastrichtian paleosols in trans-pecos), Texas. *Geological Society of America Bulletin*, **101**, 188–203.

Mack, G.H., James, W.C. and Monger, H.C. (1993). Classification of paleosols. *Geological Society of America Bulletin*, **105**, 129–136.

Marriott, S.B. and Wright, V.P. (1993). Paleosols as indicators of geomorphic stability in two old red sandstone alluvial suites. *Journal of the Geological Society of London*, **150**, 1109–1120.

Nesbitt, H.W. and Young, G.M. (1989). Formation and diagenesis of weathering profiles. *The Journal of Geology*, **97**, 129–147.

Nettleton, W.D., Brasher, B.R., Benham, E.C. and Ahrens, R.J. (1998). A classification system for buried paleosols. *Quaternary International*, **51/52**, 177–185.

North American Commission of Stratigraphic Nomenclature (1982). North American stratigraphic code. *Bulletin of the American Association of Petroleum Geologists*, **67**, 841–875.

Patterson, P.E. (1991). Differentiation between the effects of diagenesis and pedogenesis in the origin of color banding in the Wind River Formation (lower Eocene), Wind River basin, Wyoming. Unpublished Ph.D. dissertation, University of Colorado, Boulder, University Microfilms #DA9032864.

Patterson, P.E., Birkeland, P.W. and Larson, E.E. (1990). Upper cretaceous paleosols in trans-pecos Texas: discussion. *Geological Society of America Bulletin*, **102**, 844–846.

Patterson, P.E., Larson, E.E. and Walker, T.R. (1988). Effect of the depositional environment on the diagenetic control of color banding in lower Eocene strata of central and southern Wyoming. *Geological Society of America Abstracts with Programs*, **20**, A317.

Reider, R.G. (1982). Soil development and paleoenvironments. In: Frison, G.C. and Stanford, D.J. (eds), *The Agate Basin Site*, pp. 331–344. Academic Press, San Diego.

Reider, R.G. (1987). Soil formation and paleoenvironmental interpretation at the Horner site, Park County, Wyoming. *In*: Frison, G.C. and Todd, L.C. (eds), *The Horner Site: The Type Site of the Cody Cultural Complex*, pp. 347–360. Academic Press, Orlando, FL.

Reider, R. G. (1990). Late Pleistocene and Holocene pedogenic and environmental trends at archaeological sites in plains and mountain areas of Colorado and Wyoming. *In*: Lasca, N. and Donahue, J. (eds), *Archaeological Geology of North America*, Vol. 4. pp. 335–360. Geological Society of America, Centennial Special.

Retallack, G.J. (1981). Fossil soils: Indicators of ancient terrestrial environments. *In*: Niklas, K.J. (ed.), *Paleobotany, Paleoecology, and Evolution*, Vol. I, pp. 55–102. Praeger, New York.

Retallack, G.J. (1983a) A paleopedological approach to the interpretation of terrestrial sedimentary rocks: the mid-tertiary fossil soils of Badlands National Park, South Dakota. *Geological Society of America Bulletin*, **94**, 823–840.

Retallack, G.J. (1983b). Late eocene and oligocene paleosols from Badlands National Park, South Dakota. *Geological Society of America, Special Paper*, **193**, Boulder, Colorado.

Retallack, G.J. (1986). The fossil record of soils. *In*: Wright, V.P. (ed.), *Paleosols: their recognition and interpretation*, pp. 1–57. Princeton University Press, Princeton, NJ.

Retallack, G.J. (1988). Field recognition of paleosols. *In*: Reinhardt, J. and Sigleo, W. (eds), *Paleosols and Weathering through Geologic time: Principles and Applications*, pp. 1–20. GSA *Special Paper* **216**.

Retallack, G.J. (1990). *Soils of The Past*, 520 p Unwin-Hyman, Boston.

Retallack, G.J. (1993). Classification of paleosols: discussion. *Geological Society of America Bulletin*, **105**, 1635–1636.

Retallack, G.J. (1994). The environmental factor approach to the interpretation of paleosols. *In*: Amundson, R., Harden, J. and Singer, M. (eds), Factors of Soil Formation: A Fiftieth Anniversary Retrospective, pp. 31–64. Soil Science Society of America, *Special Publication* **33**.

Retallack, G.J., Dugas, D.P. and Bestland, E.A. (1990). Fossil soils and grasses of a middle Miocene east African grassland. *Science*, **247**, 1325–1328.

Ruhe, R.V. (1956). Geomorphic surfaces and the nature of soils. *Soil Science*, **82**, 441–455.

Ruhe, R.V. and Walker, P.H. (1968). Hillslope models and soil formation. I. Open system. *Transactions, 9th International Congress of Soil Science*, **4**, 551–560.

Sigleo, W. and Reinhardt, J. (1988). Paleosols from some Cretaceous environments in the southeastern United States. *In*: Reinhardt, J. and Sigleo, W. (eds), *Paleosols and Weathering Through Geologic Time*: Principles and Applications, pp. 123–142. *GSA Spec. Paper* **216**, Geological Society of America, Boulder, CO.

Smith, G.D. (1986). The Guy Smith interviews. Soil management support services (USDA). *Technical Monograph*, **11**.

Soil Survey Staff (1975). *Soil Taxonomy: U.S. Department of Agriculture Handbook*, Vol. 436.

Soil Survey Staff (1992). *Keys to Soil Taxonomy*. SMSS Technical Monograph, **19**. Pocahontas Press, Blacksburg, VA.

Valentine, K.W.G. and Dalrymple, J.B. (1976). Quaternary buried paleosols: a critical review. *Quaternary Research*, **6**, 209–222.

Vepraskas, M.J. (1992). Redoximorphic features for identifying aquic conditions. *Technical Bulletin*, **301**. North Carolina Agricultural Research Service, North Carolina State University.

Walker, T.R., Waugh, B. and Crone, A.J. (1978). Diagenesis in first-cycle desert alluvium of Cenozoic age, southwestern United States and northwestern Mexico. *Geological Society of America Bulletin*, **89**, 19–32.

Yaalon, D.H. (1971). Soil-forming processes in time and space. *In*: Yaalon, D.H. (ed.), *Paleopedology*, pp. 29–39. Israel University Press, Jerusalem.