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# CORE CONCEPTS OF PALEOPEDOLOGY

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The current renaissance of scientific interest in paleosols has brought a variety of views and approaches to paleopedology. Two main approaches have emerged for the description and labelling of paleosols. Geosols are ancient land surfaces, consisting of laterally connected suites of paleosols used for stratigraphic subdivision of sedimentary deposits. Pedotypes are individual kinds of paleosols named after localities like geosols. Pedotypes are used for mapping and describing individual profiles, usually for the purpose of paleoenvironmental interpretation. Both pedotypes and geosols are field-based labels for which genetic or interpretive considerations are at a minimum. They can be interpreted using at least three distinct approaches. Taxonomic uniformitarianism is based on the assumption that a paleosol is formed in a similar environment to a surface soil of the same type. The factor function approach interprets specific aspects of paleoenvironments from measured features of paleosols by comparison with paleoenvironmentally related variation of that feature in surface soils. Finally, the process model approach seeks to recreate soil-forming processes mathematically with input from measurable features of paleosols. Each approach has limitations, such as the need for proxy features to classify paleosols in systems designed for surface soils, the attainment of similar appearance of a paleosol by different pathways and the mathematical uncertainty of model assumptions. The approaches of classification, experimentation and modelling are not unique to paleopedology, being widespread among other sciences. Fundamental to paleopedology, however, are the concepts of profiles and soilscapes of the past.

## INTRODUCTION

Interdisciplinary research is much in vogue these days as a host of new areas of study arise within the rifts between established disciplines. Paleopedology has long been one of these interdisciplinary fields. Although paleosols have been noted since the very beginnings of modern geology (Hutton, 1795; Playfair, 1802; Webster, 1826), the term paleopedology and much of its theoretical basis arose from soil science (Polynov, 1927). In its current renaissance, paleopedology has spread its net wide to include geological scientists such as Quaternary geologists, sedimentologists and geochemists, in addition to soil scientists such as micromorphologists and soil taxonomists (Catt, 1990; Retallack, 1990). Paleosols can be viewed as natural boundaries in complex stratigraphic sequences (Morrison, 1978), as guides to former atmospheric oxygenation (Holland, 1984), and as trace fossils of former ecosystems (Retallack, 1990), to name just a few current views of paleosols. With such diversity of background and aims comes a wide variety of approaches to paleosols.

There is much to celebrate in this diversity of approaches and ideas about paleosols, but also some difficulties. Soil scientists may find themselves concerned with simplifications of soil taxonomy for interpretation of paleosols by geologists (Dahms, 1993). On the other hand, geologists may be dismayed to find soil scientists incorporating climatic criteria in classifications of soils ostensibly based on observable soil features (Retallack, 1993). It will take some time for conflicting interests to be resolved as paleopedology develops its own general philosophical approach. Most scientific disciplines have such a world view, or paradigm in the sense of Kühn (1962). This essay is an attempt to identify that paradigm, by outlining approaches and ideas about paleosols that are already widely used.

## NON-GENETIC APPROACHES

The data of paleopedology are observations and measurements of paleosols in the field and specimens of them in the laboratory. Observations and measurements of any kind are bound to be influenced in some way by concepts. For example, determining whether a particular rock layer is a paleosol involves some elements of interpretation (Retallack, 1988, 1992a). This is not proving a difficult interpretative hurdle, because in recent years literally thousands of paleosols have been discovered in rocks of every geological age on Earth, and perhaps also on other planetary bodies (Retallack, 1990). Two systematic ways of naming and describing this growing volume of paleosols are now well established, the geosol approach to paleosol stratigraphy and the pedotype approach to paleoenvironmental interpretation of paleosols.

## GEOSOL APPROACH

Quaternary sediments may present difficulties for establishing a stratigraphic framework because of the lithologic similarity of different loess and till beds. Buried soils within sediments on the other hand are often distinctive in color, texture and other features, and can be invaluable guides to the stratigraphic subdivision of sediments. These paleosols can form catenary arrays as widespread as the ancient land surfaces they represent (Valentine and Dalrymple, 1976; Follmer, 1983).

Geosol is the formal term recommended for soil stratigraphic units in the most recent North American Stratigraphic Code (North American Commission on Stratigraphic Nomenclature, 1983). A geosol is not a soil or paleosol but rather a whole soilscape that can be recognized as a laterally extensive stratigraphic horizon (Morrison, 1978). Geosols are named from localities or areas, for example, the Sangamon Geosol (Follmer, 1983). Geomorphic surfaces also are named after localities, for example, the Bethel Surface of the Willamette Valley of Oregon (Parsons *et al.*, 1970). Geosols are in a sense fossil geomorphic surfaces.

The main contender among a variety of other terms for these ancient land surfaces (discussed by Catt, 1990) is the term pedoderm (of Brewer *et al.*, 1970) which has been endorsed by the International Union for Quaternary Research (Birkeland, 1984). Other ways of naming these features are less satisfactory. Names such as the pre-Pongola paleosols of Grandstaff *et al.* (1986), from their position unconformably below sediments of the Pongola Group, defeat the concept of soil stratigraphic units as independent markers. Terms such as Violet Horizons of the German Triassic (Ortlam, 1971) are usefully descriptive, but could be confused with other senses for the term horizon in stratigraphy and in soil science.

An early development in the formulation of the geosol concept was an attempt to interpret them as representing geologically brief soil-forming intervals. These times especially conducive to active soil formation were envisaged to punctuate longer periods of conditions too dry or cold for soil formation (Morrison, 1978). An opposite and equally extreme view is that soil formation proceeds at a constant rate unless interrupted by sedimentation or erosion. The true situation probably lies between these extremes, with rates of soil formation varying considerably with climatic conditions, degree of prior development and other factors (Birkeland, 1984). These are interpretive issues that should be independent of the non-genetic recognition and mapping of geosols as natural stratigraphic markers.

Other sources of difficulty are lateral overlap, subdivision and variation in character of geosols (Wright, 1992a). The Sangamon Geosol, for example, includes at least three distinctly different kinds of profiles within a buried catena (Follmer, 1983): grey clayey 'accretion gleys' (Udifluvents in terms of Soil Survey Staff, 1975), grey-over-red profiles (Ochraqualfs or Albaqualfs) and red clayey profiles (Hapludalfs or Hapludults). These lateral variations have been called soil facies (Morrison, 1978; Birkeland, 1984), but this is a poor choice of terms, because of widespread use of the term facies in sedimentology. The term pedofacies has been used in a similar sense to soil facies (McFadden and Knuepfer, 1990), but pedofacies as originally defined by Bown and Kraus (1987) is a different concept again: a kind of sedimentary facies consisting of one or usually more paleosols within a sedimentary sequence that is characterized more by pedogenic than sedimentary features. Pedofacies were designed as lateral subdivisions of alluvial sequences, and differ profoundly from soil facies (of Morrison, 1978) in their sedimentary component. Geosols and pedofacies have clear application in the solution of stratigraphic and sedimentological problems. Individual kinds of paleosols are recognized for different purposes such as paleoenvironmental reconstruction, and for this kind of study a pedotype approach is needed, with emphasis on pedons rather than soilscapes. Geosols, pedofacies and pedotypes can be distinct and yet complementary approaches to the study of sequences of paleosols (Fig. 1).

## *Pedotype Approach*

Many sedimentary sequences provide special challenges because of the sheer number of paleosols and their complex lateral interfingering within a variety of alluvial facies. In the Potwar Plateau near Khaur, Pakistan, a trench excavated for detailed study of paleosols contained 80 separate profiles of eight distinct kinds within 58 m of strata (Retallack, 1991b). This number of paleosols is typical for clayey sediments of the Siwalik Group, which has been estimated to be about 8 km thick (Harrison *et al.*, 1993) and so probably contains thousands of buried soils. There are too many paleosols for each to be named and characterized as geosols. In any case, each paleosol is not mappable laterally with any confidence, because many were locally eroded away by paleochannels or merge into other paleosols. One particularly prominent paleosol traced laterally for 30 km was cut by a paleomagnetic isochron (Behrensmeyer and Tauxe, 1982), and is thus demonstrably of different ages along the length of its exposure. For similar reasons it is difficult to apply the approach of pedofacies. These stratigraphically oriented approaches are not appropriate for

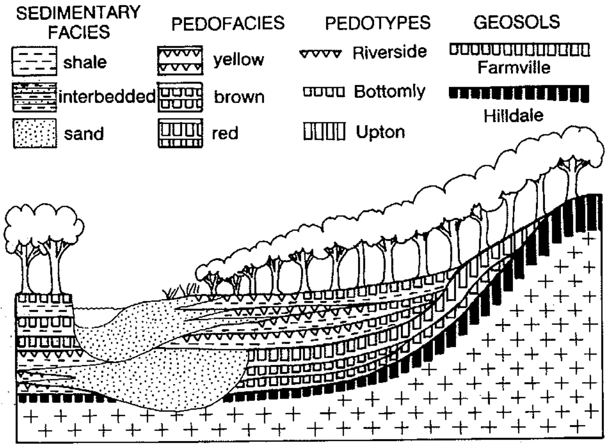

FIG. 1. The relationship between sedimentary facies, pedofacies, pedotypes and geosols, in an hypothetical landscape cross section.

description of isolated paleosols, for complexes of profiles whose lateral inter-relationship is unclear or for long sequences of paleosols studied in order to assess paleoenvironmental change through time.

An alternative and more flexible scheme for naming and characterizing paleosols can be envisaged analogous to the procedure of soil survey (Soil Survey Staff, 1951, 1962). Each distinctive kind of paleosol recognized in the field can be given a descriptive name. The names are preferably from localities where the paleosols are found, but so many such names are already employed for geological formations and modern geomorphic and soil mapping units, that it may be necessary to use other names. Names for paleosols should not be named from localities if those locality names already are used for geological formations or soil series. In Pakistan I employed common Urdu descriptive words. For example, Lal paleosols are red and have a clayey subsurface (Bt) horizon as well as scattered calcareous nodules (Bk), whereas Pila paleosols are similar although less clayey and brown with fine soil clod structure. Each pedotype should be based on at least one profile studied in detail, designated the type profile. The term 'type' can be used to specify this profile, and other profiles studied can be specified using textural terms such as 'clay loam' or other features such as 'nodular variant'. The type profile serves a similar function to the type specimen of a fossil species, and carries no implications for correlation like the type section of a stratigraphic unit. Profiles and the variation of features within them (so-called 'depth functions') are the main method for characterizing pedotypes, which are ancient equivalents of pedons.

One problem with these kinds of pedogenic units is what to call them. For many years, I have used the phrase 'paleosol series' for them (Retallack, 1977, 1983a, b, 1991b), but I now feel that this terminology should be abandoned for paleosols, and perhaps for soils as well (Retallack, 1994b). In soil science, soil series have unfortunate dual usage both as descriptive local mapping units for soil survey (Soil Survey Staff, 1951, 1962) and as the lowest rank in a highly interpretive system of soil classification (Soil Survey Staff, 1975). In geology, series are something else again, high ranking chronostratigraphic units also named after localities (North American Commission on Stratigraphic Nomenclature, 1982). To avoid confusion, I recommend that descriptive paleosol mapping units should instead be called pedotypes, meaning simply kinds of soils or paleosols, such as Lal, Pila and Pandu pedotypes (Retallack, 1994). Apart from the change of name, the Soil Survey Manual remains a useful guide to the mapping of both paleosols and soils.

A second problem is the possibility of thousands of new paleosol names added to scientific nomenclature already strained by continually adding names for different kinds of fossils, trace fossils, rock layers, formations and soils. An alternative would be informal schemes using common names such as red paleosols, acronyms such as paleosol A and alphanumeric schemes such as paleosol 3ABk. During formative years of the study of fossil pollen such informal schemes were widely used and subsequently disregarded (Traverse, 1988). It was only when palynology settled on formal Linnaean binomial Latin nomenclature that different investigators began to build a serviceable, consistent data base. Similarly for paleosols, names need to be concise and constructed along a pre-established set of rules (such as those of Soil Survey Staff, 1951, 1962 for soil series), including recognition of priority and adequately characterized type profiles.

## INTERPRETIVE APPROACHES

Named geosols or pedotypes are merely labelled objects established for ancient land surfaces and profiles, respectively. Interpretation of these objects in terms of environments of the past requires a different set of approaches. The best known among these are classification, experimentation and modelling. Each has its own strengths and weaknesses and each has its defenders and detractors. My preference is to attempt all three approaches as checks on one another (Retallack, 1983a, b, 1991b, 1994b).

### *Taxonomic Uniformitarianism*

One approach that has proven useful in paleoenvironmental interpretation of paleosols is similar to that widely known among paleontologists as taxonomic uniformitarianism (Dodd and Stanton, 1990). If, for example, fossil bones are identified as those of a large fossil alligator or a fossil snail is identified as that of a large Humboldtianid, then assuming that the fossil creatures had ecological tolerances similar to their living relatives, a warm, moist, frost-free paleoclimate is indicated (Evanoff *et al.*, 1992; Hutchison, 1992). Similarly, identification of a paleosol within a modern soil taxonomy may be taken to imply past conditions similar to those enjoyed by such soils today.

There are also practical reasons for attempting to classify paleosols in soil taxonomies. Classification is a way of navigating the enormous published literature on soils to find comparable profile descriptions. The classifications of the U.S. Soil Conservation Service (Soil Survey Staff, 1975), UNESCO (FAO, 1971–1981) and the Australian CSIRO (Stace *et al.*, 1968) are supported by vast banks of soil profile descriptions, often with chemical and petrographic data. The taxonomic approach is strengthened by comparing suites of paleosols to soil mapping units in local soil surveys or regional soil maps such as those of FAO (1971–1981). Groups of associated paleosols commonly show a greater array of features for comparison with modern soilscapes than apparent from single paleosol profiles.

Unfortunately, the differentiating criteria of most soil classifications are not directly applicable to buried soils, and new criteria for delimitation of paleosols are needed. Bulk chemical, mineralogical and micromorphological criteria are especially promising, because they often differentiate effectively between surface soils (Fig. 2) and have been increasingly reported from paleosols (Retallack, 1983b, 1991b, 1994b). For example, among molecular weathering ratios based on chemical analyses of 126 North American soils reported by Marbut (1935), a value greater than 2 for the ratio of alumina/bases distinguishes Ultisols from Alfisols in most cases (Retallack, *unpublished results*). Another study (Retallack, 1994a), on the relationship between depth to calcic horizons and mean annual rainfall, confirmed that an uncompacted depth of 1 m or less to the calcic horizon is a useful criterion for defining Aridisols (Fig. 3). Even though the organic matter of Mollisols is seldom preserved at anywhere near original levels in paleosols, granular ped structure and fine root networks are often preserved as evidence of a mollic epipedon (Retallack, 1991b). Fossil root traces are especially useful for recognizing paleosols of minimal

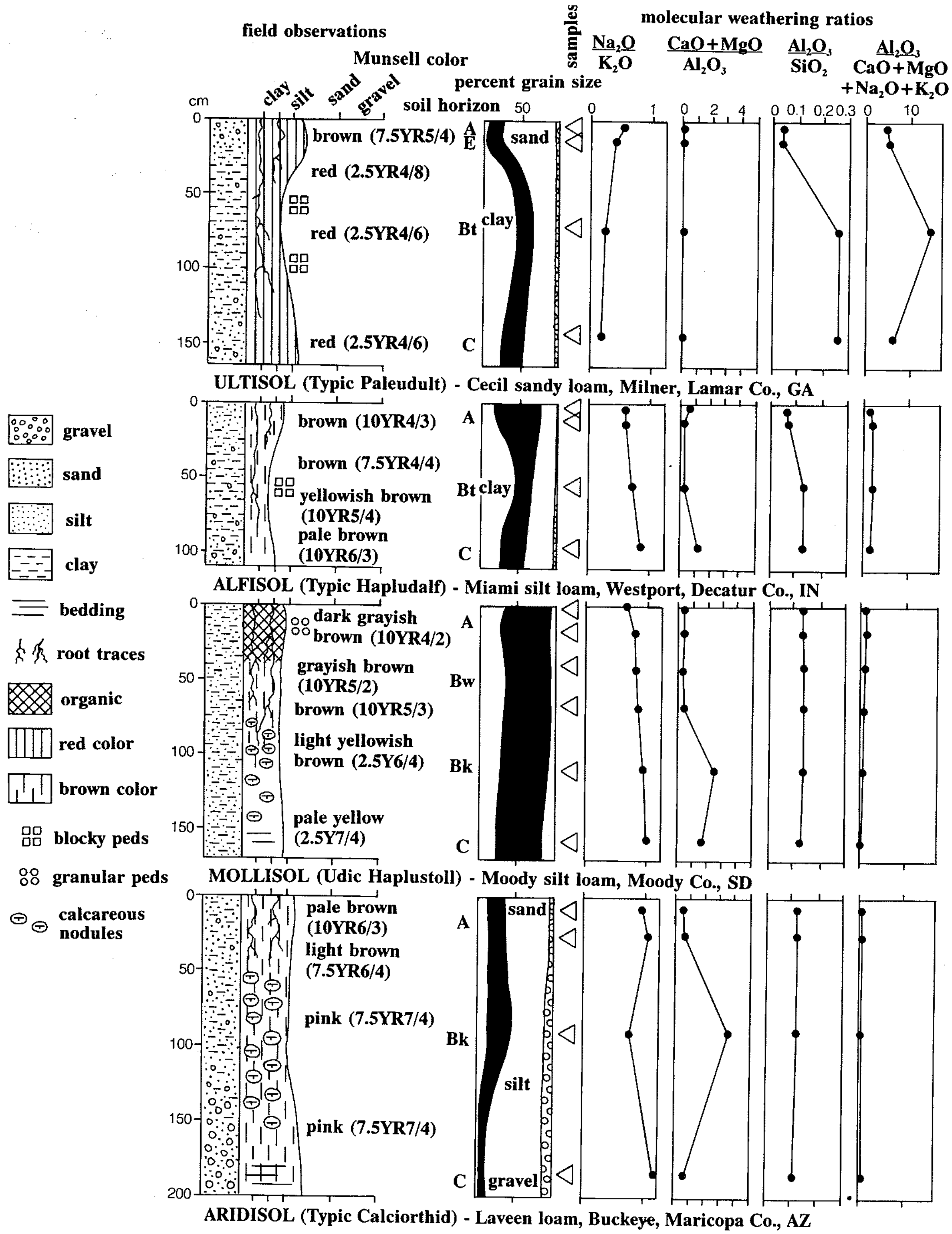

FIG. 2. Differences in grain size distribution and molecular weathering ratios of bulk chemical composition for four typical profiles of surface soils (data from Marbut, 1935; Davis, 1972; Hartman, 1977; Shiveley, 1983; Kunze, 1989). Such petrographic and chemical measures can also be obtained from paleosols (Retallack, 1990, 1991).

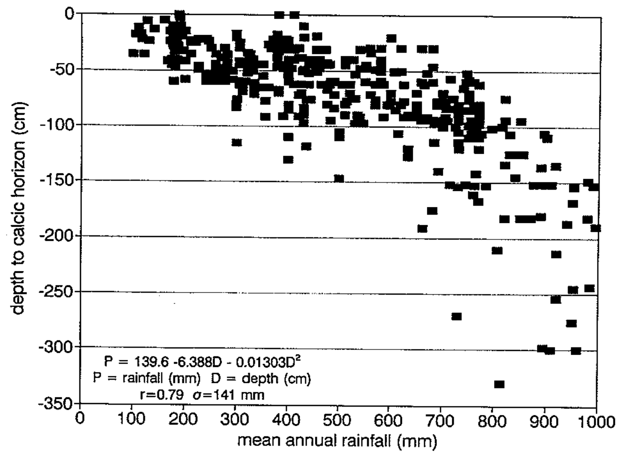

FIG. 3. The relationship between mean annual rainfall and depth of the calcic horizon in 317 surface soils from all continents including Antarctica, Greenland, Australia and New Zealand (from Retallack, 1994a).

profile development (Entisols) in the rock record (Retallack, 1988, 1992; Berry and Staub, 1993). More could be done with modern soils to find and quantify features that are robust enough to withstand burial alteration and that are useful for classification of soils. Although perhaps premature, a simplified set of criteria designed as proxies for orders of the U.S. soil taxonomy can already be envisaged (Fig. 4).

There is precedent for such an approach in paleontology, where proxy indicators are used to identify fossils. For example, the paleontological definition of mammals on the continuum of bones representing the evolution of reptiles to mammals is taken at the point when the dentary becomes the only bone of the lower jaw, or mandible. A zoological definition of mammals in contrast would be based on their hair, suckling or warm blood. However, a variety of lines of evidence now indicate that many dinosaurs had hair or feathers

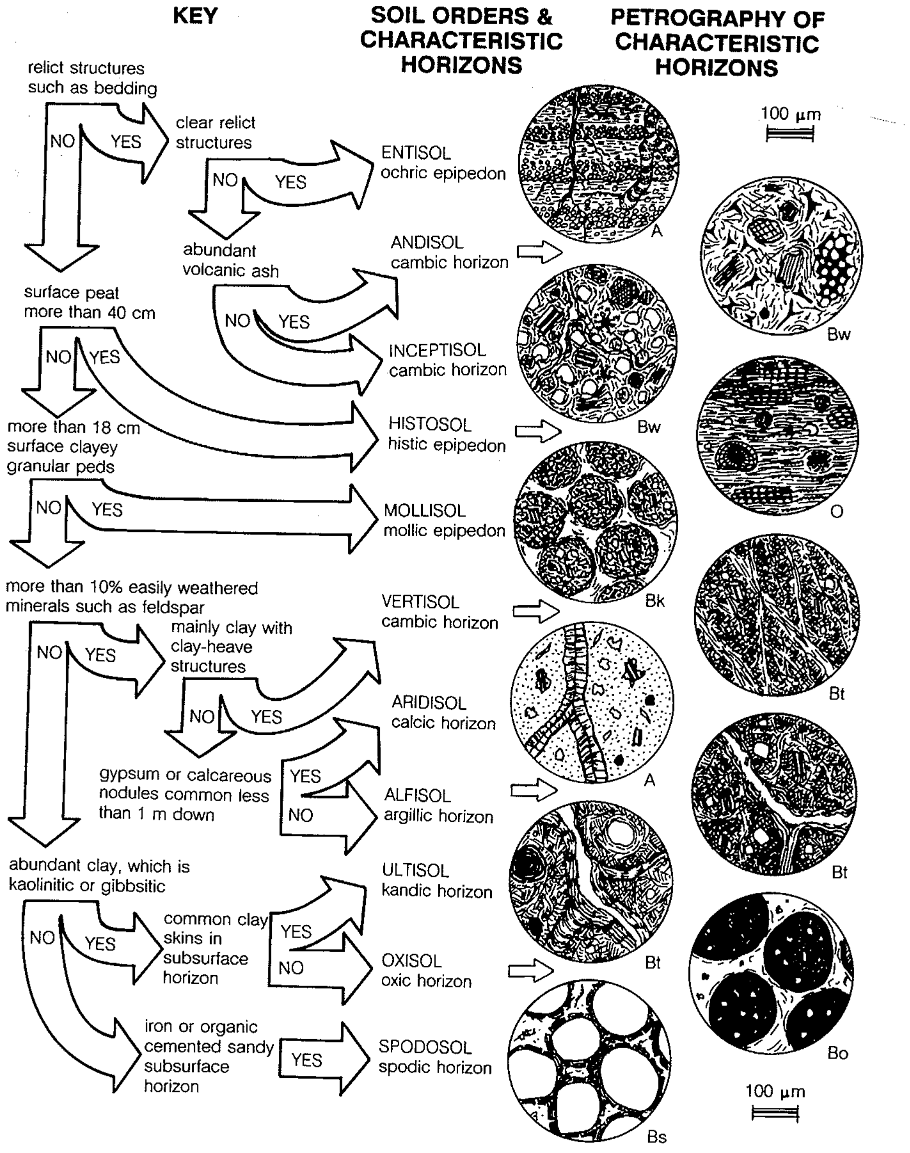

FIG. 4. A simplified key to orders of the U.S. soil taxonomy for use with paleosols, with emphasis on petrographic and bulk chemical criteria (data from Retallack, 1988, 1990, 1991, 1993). Each order has a characteristic appearance in petrographic thin section (after Douglas and Thompson, 1985).

and were warm blooded (Benton, 1990). This example is instructive because zoologists have reassessed their concepts of mammals and reptiles from the perspective of extinct groups of animals, including dinosaurs. This would not have been achieved if classification of the fossils had been eschewed or if alternative non-biologically oriented classifications had been proposed.

From this perspective, classifications designed specifically for paleosols (for example, by Mack *et al.*, 1993) may simplify communication between paleosol workers, but do not lead to comparative data on soils useful for interpretation. There is a vast store of experience with soils encapsulated in soil classifications. Soil scientists have shown commendable flexibility in allowing soil taxonomy to be modified and grow (Soil Survey Staff, 1990). Now is the time to meld the unique perspective of geological sciences with the established experience of soil sciences for the benefit of both disciplines.

It can be argued that paleosols should not be identified in classifications of surface soils, which were not designed for this kind of use (Fastovsky and McSweeney, 1989; Dahms, 1993). However, classification of paleosols should be a better guide to paleoenvironments than biological classification of fossils, because soil taxonomy is based primarily on environmentally significant features. Organisms, on the other hand, are classified by a mixture of characteristics, including adaptations to environment as well as traits reflecting evolutionary ancestry. Although soil classifications were designed in part for agricultural and other human uses, they have fundamental underpinnings in genetic concepts from the accumulated experience of several generations of scientists. My use of a variety of soil classifications has impressed upon me their similarity in stressing such features as degree of development and the importance of such materials as peat, carbonate and clay (Retallack, 1990). They organize data in a way that is useful for trying to understand a paleosol.

There is also concern that use of soil classifications for paleosols will cause confusion whether a soil or paleosol is being discussed (Dahms, 1993), so that separate classifications with entirely new names are needed for paleosols (Nettleton and others, 1993). As already argued in the discussion of the classification of Mack *et al.* (1993), such new classifications do not lead to useful comparative data or inferences, and so lack a wider purpose. Some investigators have used the prefix 'paleo-' to indicate a paleosol identification, as in 'paleovertisols' (of Cotter *et al.*, 1989). This is confusing because the same prefix is also a part of soil taxonomy (Soil Survey Staff, 1990) for strongly developed soils, which are not necessarily the same thing as buried soils or paleosols. If a distinguishing mark is needed, it is best to use a dagger mark to indicate a paleosol, as in Paleudalf†. This kind of marking has been used in paleontology to distinguish extinct from extant species, and is in general use to indicate deceased people. Such markings are not widely used because the meaning is usually clear from context, and this will probably prove so for paleopedology as well.

The main problem with taxonomic study of paleosols is not these philosophical and nomenclatural issues but the practical result that the paleoenvironmental implications of taxonomic study are imprecise and difficult to quantify. Even units deep within the taxonomic hierarchy of soil classification or of landscape assemblages of soils commonly have wide environmental range. If the classification is followed out to find specific surface soils analogous with a paleosol, they are seldom identical in all respects (Retallack, 1991b). Each soil and landscape has endured an individual history.

### *Factor Function Approach*

There is now an enormous literature on the mathematical relationship between soil features and environmental conditions (Birkeland 1984). For paleoenvironmental interpretation of paleosols one must invert the logic of these natural experiments in soil formation in a manner common to geological sciences: deducing paleoenvironments from observed paleosol features, rather than deducing variation in soil features with observed environmental differences.

One of the most impressive quantifications of factors in soil formation in Jenny's (1941) book and an earlier paper (Jenny and Leonard, 1935) was a scatter plot of the depth to the zone of calcareous nodules in soils versus mean annual rainfall. Several subsequent studies have refined this work (Ruhe, 1984) and extended it to other parts of the world (Arkley, 1963; Dan and Yaalon, 1982; de Wit, 1978; Sehgal and others, 1968). This consistency stimulated me to compile as many data as could be found in the literature on depth to the calcic horizon of soils whose mean annual precipitation is also known (Fig. 3).

A few ground rules were used for selection of soils for this database. All are late Pleistocene and Holocene soils on unconsolidated sediments other than clay or limestone, and occur in low lying or rolling terrain of free drainage. Although soil horizons above the calcic horizon may be weakly calcareous because they are partly leached of carbonate, this measure of the depth to the horizon of carbonate accumulation is not the same as the depth of leaching of a calcareous parent material, which apparently reflects time for formation rather than climatic conditions (Birkeland, 1984). Carbonate 'veins' or 'cement' were not accepted as a calcic horizon, because these could be of groundwater origin, rather than pedogenic origin (Carlisle, 1983; Wright and Tucker, 1991). Solid carbonate layers ('K horizons' of U.S. or 'tosca' of Argentina) also were not included because they indicate soils of great antiquity and more complex history (Gile *et al.*, 1966; Pazos, 1990). No soils with stone lines or other indications of redeposition in alluvial parent materials were included (Courty and Féderoff, 1985). Also excluded were soils of hills and steep slopes, soils on bedrock, limestone, beach rock, obvious local sand dunes or clay.

The relationship between depth to calcic horizon ($D$) and mean annual precipitation ($P$) is not linear, but best fitted by the curve $D = -40.49 - 0.0852P - 0.0002455P^2$, which has a correlation coefficient ($r$) of 0.78 and a standard error ($s$) about the curve of $\pm 33$ cm. Application of an $F$-test to an analysis of variance (following methods of Davis, 1973) shows that this fit is highly significant at the 1% level, and is at least an equally significant advance over the fit provided by linear regression. The fitting of higher-order polynomial curves gave insignificantly improved fit. From the perspective of interpreting paleosols, the relationship of rainfall to depth of carbonate is needed, not the relationship of depth of carbonate to rainfall. Regression of this relationship for the new compilation yields the equation $P = 139.6 - 6.388D - 0.01303D^2$, with a correlation coefficient ($r$) of 0.79 and a standard error ($s$) of $\pm 141$ mm (Retallack, 1993). This level of resolution may not be helpful for studies of late Quaternary paleosols, but can be valuable for paleoclimatic interpretation of paleosols in ancient sedimentary rocks.

An obvious problem with trying to apply the factor function approach to the interpretation of paleosols is alteration of soils during burial (Retallack, 1991a; Wright, 1992b). Many paleosols are disfigured by three widespread alterations that occur very early during burial: decomposition of soil organic matter (Stevenson, 1969), formation of drab-colored gleyed haloes around remnant organic matter (de Villiers, 1965; Allen, 1986b) and dehydration reddening of ferric hydroxides (Simonson, 1941; Ruhe, 1969). These alterations may transform a grey/brown soil to a gaudy green/red mottled paleosol with minimal amounts of organic matter (Retallack, 1991a). As a consequence, such soil features as degree of reddening and amounts of organic matter and soil nitrogen cannot easily be used to interpret the paleoenvironment of paleosols, even though they correlate well with climatic variables in surface soils (Jenny, 1941; Birkeland, 1984).

A second problem is equifinality, or the attainment of a similar appearance by different developmental pathways. The degree of clayeyness of soils and their depth of weathering also are favorites for the development of climofunctions from modern soils (Birkeland, 1984, 1990), and these are variables that can be measured in paleosols. However, their application to paleosols may be defeated by the unknown contributions of temperature, rainfall and time for formation, all of which conspire to create clayey and deeply weathered soils. In some cases these contributing variables may leave other evidence in a paleosol that enables them to be teased apart, but for equifinal features of paleosols we may have to forego interpretation. However, there are at least a few relationships highly correlated and robust enough to avoid the equifinality problem (Fig. 3). These should be singled out for further investigation and refinement.

The factor function approach can be used to relate pedotypes to ancient landscapes. Topographic position is one of the five state factors (Jenny, 1941). Many profiles have nodules, root traces and other features that indicate position with respect to water table or other geomorphic elements. Paleosols commonly are found within sedimentary sequences, in which channel, floodplain and other facies of known geomorphic type form parent materials to the paleosols (Retallack, 1983b, 1991b). From such regularities of facies models even a sequence of paleosols and sedimentary facies in a single section can be used to reconstruct ancient landscapes using Walther's Facies rule (Retallack, 1983a). In those few cases where geosols can be mapped or an ancient land surface is preserved beneath an isochronous deposit such as a volcanic ash bed, actual soilscapes can be reconstructed (Burggraf *et al.*, 1981).

### *Process Model Approach*

There has long been a conceptual framework for mathematical modelling of soil formation. Soils can be viewed as energy transformers, that is a body of material changed by the continuing efforts of natural processes (Runge, 1973). They can also be envisaged as open systems to the extent that they represent a boundary between earth and air through which materials move and are transformed (Simonson, 1978). Recent numerical models of the formation of carbonate horizons within soils provide examples of both these flux (Machette, 1985) and process models (McFadden and Tinsley, 1985; Mayer *et al.*, 1988). These particular models have not to my knowledge been applied to buried paleosols, although there is potential to do so.

Other models have been usefully employed in interpreting paleoenvironment from paleosols, such as one specifying atmospheric control of carbon isotopes in paleosol carbonates (Cerling *et al.*, 1989; Quade *et al.*, 1989; Cerling, 1991; McFadden *et al.*, 1991) and another estimating the partial pressures of atmospheric oxygen and carbon dioxide from chemical weathering of paleosol silicate minerals (Holland, 1984; Holland and Zbinden, 1988; Pinto and Holland, 1988; Zbinden *et al.*, 1988; Holland *et al.*, 1989; Holland and Beukes, 1990). Several excellent textbooks are available on numerical modelling of soil formation (Richter, 1987, 1990; Ross, 1989). Their application is bound to become more widespread as personal computers proliferate.

One problem with these models is gaining reliable input data from paleosols. In the model of Cerling (1991) for calculating atmospheric carbon dioxide, the isotopic composition of pedogenic carbonate in nodules and rhizoconcretions should be similar and reflect the balance of atmospheric carbon dioxide (isotopically heavy) and respired carbon dioxide (isotopically light). It has now been observed more than once that pedogenic nodules and rhizoconcretions in the same paleosol do not have same isotopic composition, and thus suggest different atmospheric carbon dioxide levels (Fig. 5). The sparry calcite of such paleosols may be isotopically even lighter and would thus indicate a different atmospheric composition or kind of vegetation (Driese and Mora, 1993). These differences may represent different degrees of biological productivity near nodules and rhizoconcretions, and for sparry cements an early burial decay of remnant organic matter (Retallack, 1992b). Thus, analyzing the bulk isotopic composition of paleosol carbonate can lead to erroneous results if close attention is not paid to the nature of different carbonate phases.

However, the principal problem with numerical modelling of paleosols is the assumptions on which they are based. The two models already mentioned (Cerling, 1991; Holland, 1984) are typical in requiring data on such conditions as original soil porosity, moisture content and biologically respired carbon dioxide (Fig. 5). Such information may not be obtained directly from paleosols. Reasonable values and limits can be applied from modern soils to force the models to perform, but how these values resonate through complex equations modelling development of a paleosol is not always clear. Many other models for modern soil formation are rate models, of the general form $\delta x/\delta t$, where $x$ is some measured feature of the soil, and $t$ is the time in years for its formation. Unfortunately, time for formation can usually be estimated only to an order of magnitude for paleosols, and such wide error limits are spread even wider within complex equations. In contrast, Jenny's (1941) formulation of time as an independent variable obviates this problem so that it is well suited to paleopedological studies, although Jenny's work has been criticized on this basis (Yaalon, 1975). Because of their assumptions, the results of modelling can only be cautiously accepted. This problem is likely to become more severe as models evolve into animated computer games, and the delight of playing obscures the underlying assumptions.

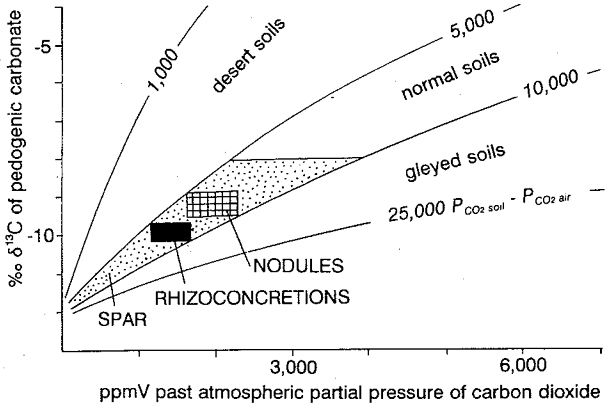

FIG. 5. Estimated partial pressure of carbon dioxide from the isotopic composition of pedogenic carbon in different carbonate phases within a Late Devonian paleosol from the Catskill Formation of Pennsylvania (data from Cerling, 1991; Driese and Mora, 1993).

## CONCLUSIONS

Although the approaches of taxonomic uniformitarianism, factor functions and process models are widely used in the study of paleosols, they are not unique to paleopedology. Classification, experimentation and modelling are approaches widespread in science. Individual preference for one of these approaches may have more to do with childhood love of stamp collections, chemistry sets or model trains than to their intrinsic merit. Adaptations of these approaches such as the principle of uniformitarianism, Walther's facies rule and use of relationships for postdiction are commonly used in historical geological sciences.

What is unique to paleopedology is the subject matter, the paleosols themselves. These distinctive layers of earth material really were soils formed in landscapes of the past. This definition of paleosols offered by Ruhe (1956) has shortcomings compared with more prosaic definitions (for example of Retallack, 1983a), but remains one of the most concise and evocative definitions. These ancient materials were once warmed by the sun, penetrated by roots, and loosened from bedrock as segments of former land surfaces over time spans long by human standards. Paleosols can thus be considered barometers of ancient atmospheric gas composition, rain gauges of past climates, trace fossils of former ecosystems, records of environmental work done to parent materials, indicators of past topography and tachometers of alluvial sedimentation. In recent years, the isotopic composition of pedogenic carbon has revealed such aspects of ancient environments as the partial pressure of atmospheric carbon dioxide and the proportion of past plant assemblages using the Calvin cycle ($C_3$) rather than Hatch–Slack ($C_4$) photosynthetic pathways (Cerling, 1991; Driese and Mora, 1993). Such discoveries from detailed analysis of paleosols are surprising, but they confirm what our eyes can see. These really were soils and they have much more to tell us about the past if we can learn to listen.

Given the diversity of views brought to the study of paleosols, it is surprising that only two general non-interpretive approaches have emerged. To some a paleosol is part of an ancient landscape, an extensive marker of a former land surface (Valentine and Dalrymple, 1976). From this perspective the geosol approach has great appeal. To others a paleosol is a product of its local environment, a unique individual profile with its own history (Retallack, 1990). From this perspective the pedotype approach is appealing. Neither approach can be claimed superior. Nor are they the only plausible views of paleosols. One could also envisage non-genetic naming systems of bioturbation (Droser and Bottjer, 1986), biomantles (Johnson, 1990) or developmental stages (Gile *et al.*, 1966; Retallack, 1988; Follmer, 1993). Our interpretations of paleosols matter less in the long run than clear and unequivocal characterization of them as objects in the field. Central to paleopedology should be descriptive databases on profiles and ancient landsurfaces, constructed according to generally accepted guidelines so that they can be reassessed and augmented by future generations.

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