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# *Field recognition of paleosols*

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## ABSTRACT

**Three main features of paleosols are useful for distinguishing them from enclosing rocks: root traces, soil horizons, and soil structures.**

**Fossil root traces are best preserved in formerly waterlogged paleosols. In oxidized paleosols their organic matter may not be preserved, but root traces can be recognized by their irregular, tubular shape, and by their downward tapering and branching. Often root traces are crushed like a concertina, because of compaction of the surrounding paleosol during burial. The top of a paleosol may be recognized where root traces and other trace fossils are truncated by an erosional surface. Root and other trace fossils are not useful for recognizing paleosols of middle Ordovician and older age, since large land organisms of such antiquity are currently unknown.**

**Soil horizons usually have more gradational boundaries than seen in sedimentary layering. Commonly these gradational changes are parallel to the truncated upper surface of the paleosol. Some kinds of paleosol horizons are so lithologically distinct that they have been given special names; for example, cornstone (Bk) and ganister (E); the letter symbols are equivalent horizon symbols of soil science.**

**Compared to sedimentary layering, metamorphic foliation, and igneous crystalline textures, soil structure appears massive, hackly, and jointed. The basic units of soil structure (peds) are defined by a variety of modified (for example, iron-stained or clayey) surfaces (cutans). Peds may be granular, blocky, prismatic, columnar, or platy in shape. Concretions, nodules, nodular layers, and crystals are also part of the original soil structure of some paleosols.**

**Complications to be considered during field recognition of paleosols include erosion of parts of the profile, overlap of horizons of different paleosols, development of paleosols on materials eroded from preexisting paleosols, and the development of paleosols under successive and different regimes of weathering.**

## INTRODUCTION

This chapter presents a personal view of the fundamental problem of recognizing paleosols in outcrop. It is not meant as a comprehensive discussion of field methods in paleopedology, nor as an outline of a "paleopedological paradigm," nor as a program for further research. The terminology and concepts used are largely those of the U.S. Department of Agriculture (Soil Survey Staff, 1951, 1962, 1975; Guthrie and Witty, 1982), with a liberal sprinkling of ideas from Brewer (1976), Buol and others (1980), and Birkeland (1984). The three main field features of paleosols are root traces, soil horizons, and soil structures. Consideration of these features forms the bulk of this account. Also considered are complications that may affect paleosol recognition, field names for paleosols, a list of basic field equipment, and a collage of diagrams and tables useful for field reference.

## ROOT TRACES

One of the most diagnostic features of paleosols is evidence of root traces in their place of growth. Even if there are no other indications of ancient soil formation, root traces are evidence that the rock was exposed to the atmosphere and colonized by plants, and thus a soil by almost anyone's definition (Buol and others, 1980; Retallack and others, 1984). A gray shale with clear bedding may appear to be an ordinary sedimentary deposit, but a few fossil root traces penetrating the shale means that it was probably an alluvial paleosol similar to a Fluvent (in the classification of Soil Survey Staff, 1975).

The top of a paleosol can be recognized as the surface from which root traces emanate. Concentrations of other trace fossils, such as burrows, also can be used, a technique long recognized as an indication of omission surfaces and hardgrounds in marine sedimentary rocks (Seilacher, 1964). There are, however, situations in which sedimentation keeps pace with burrowing and vegetative growth. Where breaks in sedimentation cannot be discerned easily, paleosols are not usually developed to the extent that they can be regarded as good indicators of paleoenvironment or stratigraphic level, and so are not of great concern.

In cases where little original organic material of the root has been preserved, its remains can be considered a kind of trace fossil (Sarjeant, 1975). Unlike other trace fossils such as burrows, root traces mostly taper and branch downward. They are also very irregular in width, commonly with irregular longitudinal creasing. Large vertical roots characteristically have a concertina-like outline, because of compaction of enclosing sediments. Outward flexures of the concertina may be located at large lateral rootlets extending into the matrix. The distinction between root traces and burrows is not always easy. Roots may spread out laterally over hardpans in soils, and some kinds of roots branch upward and out of the soil (Fig. 1). Furthermore, a number of soil insects and other creatures burrow around and into roots to feed, a practice that appears to be at least as old as Triassic (Retallack, 1976).

Paleobotanical research has unearthed fossil examples of most of the major kinds of root traces; particularly well-documented examples of fossil root traces are cited herein as a guide to paleobotanical literature. Roots are downward growing plant axes, often with numerous finer branches or rootlets (Fig. 2). Both roots and rootlets are more anatomically conservative than other parts of the plants. Usually a central woody cylinder (stele) is separated by a zone (cortex) of fleshy cells (parenchyma) from a tough outer coat (epidermis) to the root (Fig. 1A; as, for example, in Late Devonian roots of *Archaeopteris*: Beck, 1981; Eocene roots of *Metasequoia*: Basinger, 1981). The central woody cylinder (stele) and tough outer layer (epidermis) often withstand decay much longer than the intervening zone (cortex) of soft cells (parenchyma, as in Late Triassic root traces studied by Retallack, 1976). Root hairs are elongate cells that gather water and nutrients from the soil. They are concentrated in zones along the finest rootlets and are preserved only under exceptional circumstances (see for example, Fig. 3, Late Carboniferous *Austroclepsis*; see also Sahni, 1929, 1932). Some very early (Silurian and Devonian) land plants and modern mosses and liverworts lack true roots. They have fine hairlike organs (rhizoids, Fig. 1E) that perform a similar function. Like root hairs, these also are preserved under exceptional circumstances (as in Devonian *Rhynia*: Kidston and Lang, 1917).

Various kinds of roots are named for their patterns of branching and botanical origins. Many plants have several roots of equal size extending outward and downward from their base, but some have a single, thick, vertical root (tap root) similar to a carrot or turnip (Fig. 1T; a fossil example is Late Devonian *Eddya*: Beck, 1967). Other plants, especially living grasses and quillworts, have numerous fine roots (Fig. 1R, fibrous roots) radiating from the base of the plant or from a thickened stem base (a corm or rhizophore, Fig. 1G; as in Early Triassic *Pleuromeia*: Retallack, 1975). If the roots arise from the stem of the plant, rather than from its base or from other roots, they are called adventitious roots. They may arise from stems lying in or along the ground (rhizomes, Fig. 1I; as in Late Carboniferous *Calamites*: Eggert, 1962), stems scrambling along and above ground (runners or stolons, Fig. 1F; as in Pennsylvanian *Callistophyton*: Rothwell, 1975) or from erect stems and their aerial branches (prop roots, Fig. 1M; as in Early Cretaceous *Weichselia*: Alvin, 1971).

In some cases, such as modern tree ferns, a very weak stem is completely encased in numerous adventitious roots, which form a thick, soft "false trunk" (Fig. 1H, N; as in Pennsylvanian *Psaronius*: Morgan, 1959; and Early Cretaceous *Tempskya*: Andrews and Kern, 1947). Potato-like underground storage structures branching from roots or rhizomes are called tubers (Fig. 1I; as in Cretaceous *Equisetites*: Seward, 1898; Rushforth, 1971). Some plants, especially mangroves, have rootlets that extend ver-

Figure 1. Kinds and distribution of roots found in soils and paleosols. Plant species (and sources of these and further illustrations) follow. A, generalized dicotyledonous angiosperm morphology and anatomy; B, crack willow, *Salix fragilis* (Kawase and Whitmoyer, 1980); C, mangrove, *Avicennia marina* (Chapman, 1976); D, mangrove, *Sonneratia alba* (Chapman, 1976); E, liverwort, *Hymenophytum flabellatum* (Scagel and others, 1984); F, strawberry (*Fragaria x ananassa*) (Raven and others, 1981); G, quillwort, *Isoetes echinospora* (Seward, 1910); H, tree fern, *Dicksonia fibrosa* (Heath and Chinnock, 1974); I, horsetail, *Equisetum sylvaticum* (Andrews, 1947); J, tropical dicot, *Cariniana pyriformis* (Jenik, 1978); K, mangrove, *Avicennia germinans* (Jenik, 1978); L, tropical dicot, *Mitragyna stipulosa* (Jenik, 1978); M, screw pine, *Pandanus candelabrum* (Jenik, 1978); N, oil palm, *Elaeis guineensis* (Jenik, 1978); O, short grass prairie, southeast of Colorado Springs, Colorado, dominated by blue grama, *Bouteloua gracilis* (b), with threeawn grass *Aristida purpurea* (a) and the forbs *Artemisia frigida* (r), *Psoralea tenuiflora* (p), *Chrysopsis villosa* (c), and *Yucca glauca* (y: Weaver, 1919); P, lowland, tall grass prairie near Lincoln, Nebraska, dominated by bluestem, *Andropogon furcatus* (a), switchgrass, *Panicum virgatum* (p), and Kentucky bluegrass *Poa pratensis* (b), with cordgrass *Spartina cynosuroides* (s) and forbs *Glycyrrhiza lepidota* (g) and *Solidago altissima* (o: Weaver, 1920); Q, mountain forest near Pikes Peak, Colorado, dominated by Engelmann spruce *Picea engelmanni* (p), with limber pine *Pinus flexilis* (i), and small dicots *Chamaenerion angustifolium* (c), *Fragaria virginiana* (f), *Haplopappus parryi* (h), and *Rosa acicularis* (r: Weaver, 1919); R, threeawn grass *Aristida purpurea* (Weaver, 1919); S, mountain sage, *Artemisia frigida* (Weaver, 1919); T, 16-yr-old sugar maple *Acer saccharum* (Biswell, 1935).

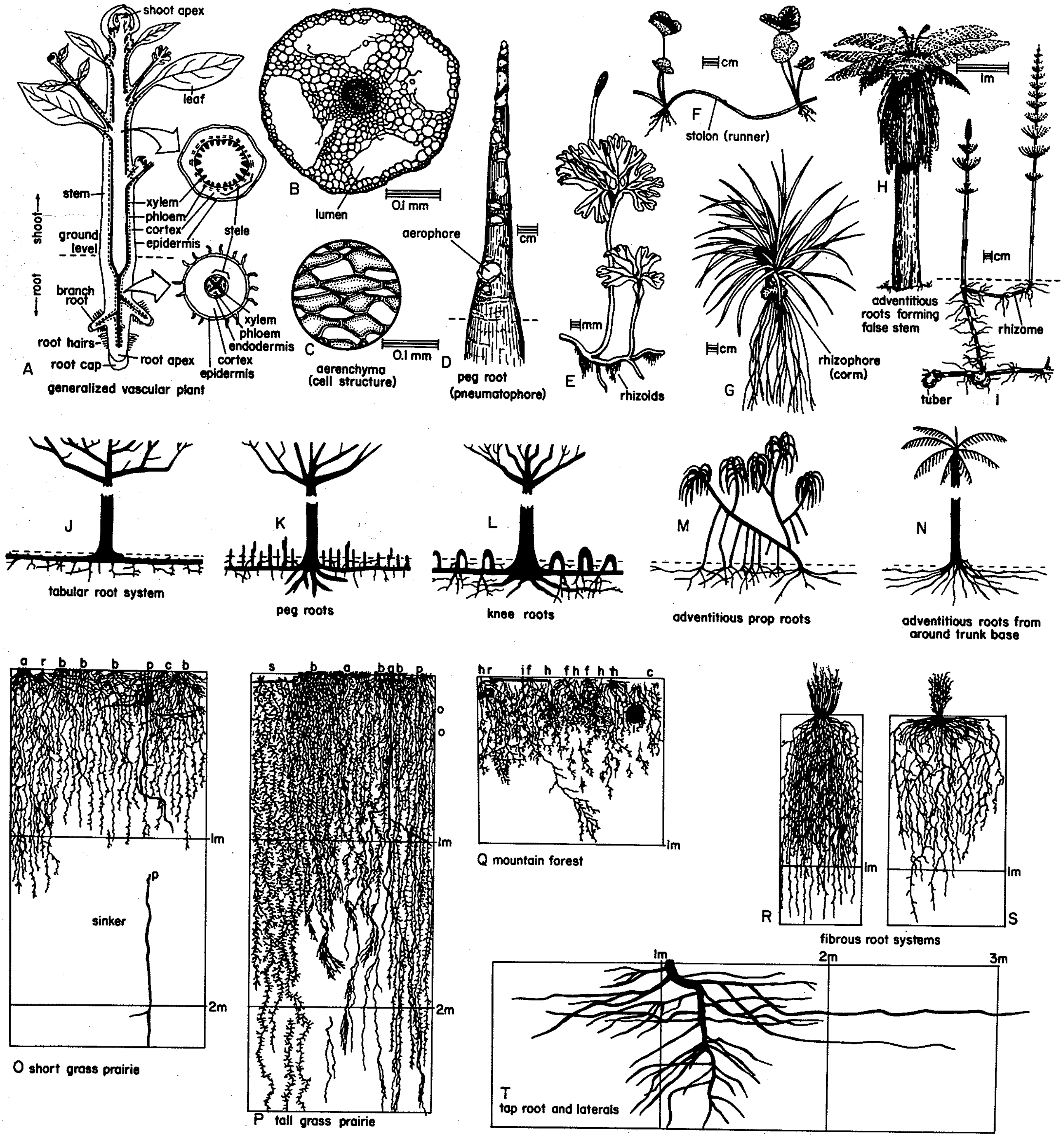
shoot apex
leaf
stem
xylem
phloem
cortex
epidermis
stele
shoot
ground level
root
branch root
root hairs
root cap
root apex
xylem
phloem
endodermis
cortex
epidermis
A
generalized vascular plant
B
lumen
0.1 mm
C
aerenchyma (cell structure)
0.1 mm
aerophore
cm
D
peg root (pneumatophore)
E
mm
rhizoids
F
cm
stolon (runner)
G
cm
rhizophore (corm)
H
1m
adventitious roots forming false stem
cm
rhizome
tuber
I
J
tabular root system
K
peg roots
L
knee roots
M
adventitious prop roots
N
adventitious roots from around trunk base
a r b b b p c b
1m
p
sinker
2m
O short grass prairie
s b a bab p
o
o
1m
2m
P tall grass prairie
hr if h fhf h h c
1m
Q mountain forest
1m
R
1m
S
fibrous root systems
1m
2m
3m
T
tap root and laterals

Figure 2. Fossil roots and rootlets from Early Miocene, Molalla Formation on High Hill, near Scotts Mills, Oregon (Retallack specimen R261). Their original organic matter has been weakly ferruginized. Scale in both centimeters (figures) and millimeters (fine gradations).

Figure 3. Petrographic thin section of silicified root hairs radiating from hollow, adventitious root seen in transverse section in false stem of tree fern *Austroclepsis australis*, from Early Carboniferous Caroda Formation, opposite Glenidle Homestead, near Caroda Post Office, New South Wales (Retallack specimen P5580C). Scale bar = 0.1 mm.

tically upward into the air (peg roots, Fig. 1D, K; as reported from Miocene paleosols: Whybrow and McClure, 1981). Peg and prop roots often have thin-walled openings to the inside of the root (aerophores, Fig. 1D; as in Early Cretaceous *Weichselia*: Alvin, 1971), and spongy porous tissue (aerenchyma, Fig. 1C; and in Pennsylvanian *Amyelon*: Cridland, 1964). Hollow cavities in roots (lumina, Fig. 1B; as in Pennsylvanian *Stigmaria*: Stewart, 1947; and Permian *Vertebraria*: Gould, 1975) allow circulation of oxygen needed for plant respiration in waterlogged, reducing environments. Root structures such as this not only indicate the existence of paleosols, but are evidence of soil conditions.

The various kinds of roots can most easily be recognized when their original organic matter is preserved. This occurs mostly in paleosols formed in waterlogged lowland environments where the activity of microbial decomposers is limited by lack of oxygen. Many kinds of roots also are recognizable in well-drained paleosols. Rarely is there organic matter remaining in root traces of such red and variegated paleosols. All that remains are irregular tubular features filled with material different from the surrounding paleosol matrix. This filling may include several generations of clay and silt washed into the hole left by the decaying root (Fig. 4). In some cases, only soft tissues (such as the cortex of a root) may be replaced by clay within more decay resistant parts (such as the epidermis and stele: an example is figured by Retallack, 1976). Root holes also may be filled with minerals such as crystalline calcite, chalcedony, or zeolite.

Poorly preserved root traces may be accentuated by encrustations that formed around them during their growth. Roots take in water by osmosis and by maintaining a negative pressure (water potential) in their thin conducting tubes (xylem) by loss of water from leaves (transpiration). Nutrients are absorbed the same way, aided by materials exuded by roots that favor mineral weathering. The area of active nutrient uptake around a root (rhizosphere) is a gelatinous zone (mucigel) rich in bacteria and fungi. Many nutrient cations are released from soil minerals by replacement with hydrogen ions in mildly acidic solutions maintained by organic acids, and by carbonic acid arising from carbon dioxide of microbial and root respiration. Other nutrients, such as iron, are dissolved by organic reductants, such as caffeic acid, or are bonded to large organic molecules (chelates) produced by plants. This does not mean that the rhizosphere is uniformly or always chemically acidic and reducing, as was once thought (Keller and Fredericksen, 1952). Most of the time the root zone is near-neutral in pH and Eh, allowing for normal activity of both roots and microbes (Nye and Tinker, 1977). Conditions can change over short intervals of time following rainfall or nutrient starvation (Olsen and others, 1981).

With repeated cycles of wetting (making the soil mildly acidic), then drying (neutral to alkaline), plant roots growing in calcareous, friable materials such as coastal sand dunes can become heavily encrusted in thick tubes of aragonite-cemented sandstone. These calcareous rhizoconcretions become so thick and unyielding that the root eventually dies and the remaining hole fills with other materials (Semeniuk and Meager, 1981; Bown, 1982; Cohen, 1982). Similarly, iron mobilized in the drab, ferrous state within the rhizosphere may be oxidized to yellow or red ferric oxides near the root to form ferruginous rhizoconcretions (Bown, 1982). Root traces encrusted with carbonates and iron oxides are among the most prominent found in paleosols. With heavy encrustation they become increasingly difficult to distinguish from nodules and burrows.

An additional distinctive feature of root traces found in red colored paleosols is a diffuse, drab colored (bluish or greenish gray) halo extending out into the surrounding paleosol matrix (Fig. 4). Superficially, these drab, haloed root traces are similar to krotovinas and to surface-water gley in modern soils (as described by Duchafour, 1978, and Knapp, 1979). A krotovina is a tongue of material washed down into burrows and root traces from an overlying horizon of the soil or from the surface. This kind of structure differs from drab haloes in containing material of a texture different than the soil matrix, from which it is separated by a sharp boundary. Surface-water gley forms when water is perched on the surface of a clayey or indurated soil for some time, so that it becomes stagnant, and anaerobic bacterial activity initiates chemical reduction of the margins of cracks, root holes, and burrows in the soil. Surface gleying may also produce rims of iron or manganese stain around root traces, or mineralization with pyrite or sphaerosiderite, and is often found in soils with carbonaceous surface horizons. Fossil examples of both krotovinas (metagranotubules of Retallack, 1976) and surface-water gley (in Ogi Series paleosols of Retallack, 1983b) have been recognized, but these are far less common and widespread than drab-haloed root traces (Retallack, 1983b, 1985).

There are two especially promising hypotheses to explain the origin of drab-haloed root traces. Perhaps they represent the rhizosphere: the chemical microenvironment established by the living root and its associated halo of mucigel, microorganisms, and soil water. By this hypothesis it is difficult to reconcile the rarity of such features in modern red soils with their abundance in red paleosols. A second explanation for drab haloes around root traces is as gley features associated with anaerobic microbial decay of organic material soon after burial of the paleosol below the water table. Also formed in this way is the gleying of surface horizons of paleosols, which commonly are bluish or greenish gray. This color is seldom seen in modern soils, even those with quite carbonaceous surface horizons. The contrast between drab-haloed root mottles and surface horizons and the red remainder of the paleosol may have been enhanced by dehydration of yellow and brown ferric oxyhydrates to brick red hematite during deep burial (Walker, 1967). Drab-haloed root traces are important not just as a common kind of root trace, but also as indicators of vegetation just before burial. They can be especially useful in distinguishing between woodland, savanna, and open grassland of the past (Retallack, 1983b). Roots and rhizospheres rapidly decay and oxidize in an exposed soil, so by either hypothesis of their origin the drab-haloed root traces represent the last crop of a paleosol.

Figure 4. Petrographic thin section oriented parallel to former land surface in horizon BA of type Long Reef clay paleosol from Early Triassic, Bald Hill Claystone at Long Reef, New South Wales, showing deeply iron-stained soil matrix (dark), drab halo around root trace (light and granular), and silty clay infill of root hole (light with concentric lamination). Scale bar = 1 mm.

While searching for fossil root traces it is useful to consider their arrangement (Figs. 1J–T), as this may give important clues

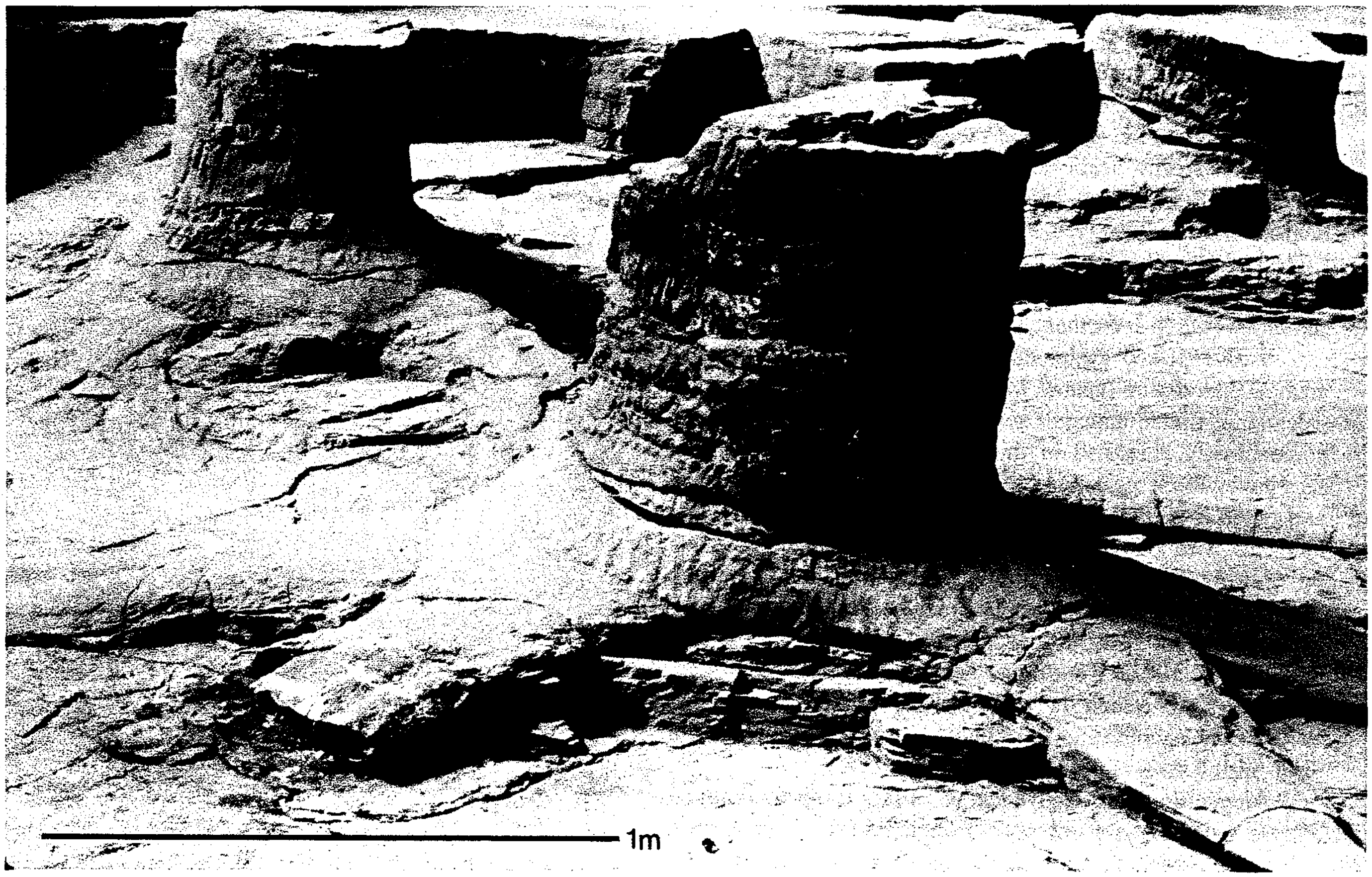

Figure 5. Tabular root systems of large arborescent lycopods, *Stigmaria ficoides,* in the Early Carboniferous, lower Limestone, and Coal Group, in Victoria Park, Glasgow, Scotland. Scale bar = 1 m, for foreground only.

to the nature of former drainage, vegetation, and originally indurated parts of a paleosol. Because roots need oxygen in order to respire, they seldom penetrate permanently waterlogged parts of soils. Laterally spreading (tabular) root systems are characteristic of plants growing in swampy ground (Jenik, 1978). This is a very common configuration for fossil stumps found in sedimentary rocks (Fig. 5), and is a part of the reason why many seat earths to coal seams contain few root traces. In contrast, well-drained paleosols may be penetrated by roots to great depths (Sarjeant, 1975). In seasonally dry climates there may be a more complex pattern: a copious surficial network of roots active in the wet season, together with a few deep roots (sinkers) tapping deep ground water during the dry season (Van Donselaar-ten Bokkel Huininck, 1966). This is a typical pattern for root traces of savanna ecosystems in which trees are scattered among widespread grasses. The roots of grasses are mostly of the fibrous type, and are less than 2 mm in diameter. They tend to become less copiously branched and more clumped in distribution (under individual tussocks) in open grasslands of very dry climates (Weaver, 1968). Root traces avoid or run along the margins of cemented horizons or nodules, and can be an important indication that these were originally indurated in the soil. This pattern of root traces is the best line of evidence for recognizing duripans and fragipans (lithified horizons in soils, Soil Survey Staff, 1975) in paleosols that are now entirely lithified. Furthermore, root traces may be better preserved and less compacted within nodules (especially those of siderite) than in the surrounding matrix (Retallack, 1976). This is an indication that the nodules at least predate compaction, and may be an original part of the soil. Many soil nodules are initiated as unindurated chemical aggregations, easily penetrated by roots. Later they may become hard and indurated (Gile and others, 1966).

One limitation on the use of root traces to recognize paleosols is that they have not yet been definitely found in rocks older than the Devonian period, when the first large woody vascular plants appeared. There are trace fossils that may have been produced by small vascular plants in some Late Silurian paleosols (Retallack, 1985) and reduction spots, possibly from plant or-

Figure 6. Sharp upper contact (top left) and diffuse nodular and lower horizons of modern grassland soil (upper left) and two comparable paleosols from Miocene-age (about 14 Ma) Fort Ternan Beds, in the main excavation at Fort Ternan National Monument, Kenya. Hammer handle is 25 cm.

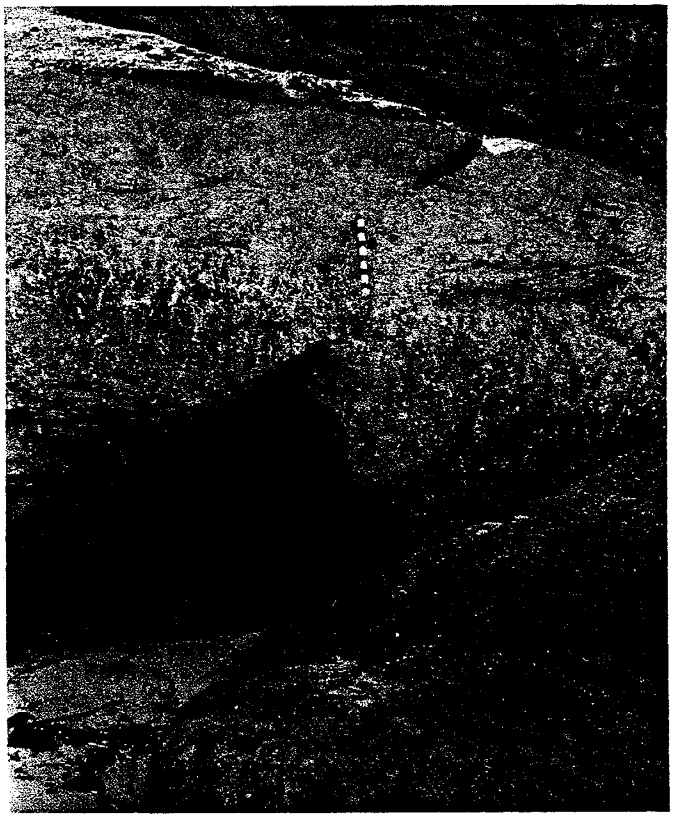

Figure 7. Sharp upper contact and diffuse lower horizons, and drab haloed root traces (in upper part of red B horizon), in forested paleosol, type Long Reef clay paleosol (of Fig. 4). Black and white scale is 1 ft, graduated in inches.

ganic matter in Late Ordovician paleosols (Boucot and others, 1974). Other Late Ordovician paleosols have been recognized from the concentrations of burrows at specific levels, but it is only the association of these with other soil features (caliche nodules and mineral and chemical weathering trends) that allows these to be distinguished from marine trace fossils (Retallack, 1985). Nonmarine metazoan trace fossils are unlikely to be much older than this, but their antiquity has received little serious scientific attention.

## SOIL HORIZONS

A second general feature of paleosols is their soil horizons. The exact nature of paleosol horizons varies considerably, but there are some consistent features useful for recognizing them in the field. The top of the uppermost horizon of a paleosol is usually truncated sharply by an erosional surface. Below that, by contrast, boundaries between different horizons and the underlying parent material are usually gradational (Figs. 6, 7). The distinction between sharp and diffuse contacts can be made only in outcrops at least a few tens of centimeters wide. If there are no extensive sea cliff or roadcut exposures, as in a weathered badlands slope, some digging may be needed to improve exposure. It is worth considerable effort to be sure of the nature of the boundaries of soil horizons in the field, as this will determine where samples are taken, and is something that cannot be redeemed by later laboratory studies.

Exceptions to the sharp top of the upper horizon and gradational boundaries to other horizons are not common in my experience, but do occur. Some lowland soils receive thin increments of sediment through which vegetation continues to grow (a cumulative horizon of Birkeland, 1984). These cumulative surface horizons are more bioturbated than a purely sedimentary shale or siltstone. Usually, however, they are less bioturbated than most of the paleosol just below. Generally, there is a more or less abrupt change in the density of bioturbation that can be taken as the approximate top of the profile. Other exceptions to the generalization of gradational horizon boundaries are sharp contacts between layers within a paleosol. Most commonly these are relict beds from sedimentary parent material, not yet obliterated by soil formation. Associated sedimentary features, such as bedding, ripple marks, or load casts, allow confident identification of such relict bedding. There also may be erosional surfaces within a profile, where a preexisting paleosol has been substantially eroded, and soil development proceeded on an additional layer of sediment. These cases may be more difficult to detect in the field, but may be revealed by chemical or petrographic anomalies.

In some cases, soil horizons are so striking that they have specific geological names, such as cornstone (a nodular calcareous, usually Bk horizon; Steel, 1974) and ganister (a silicified sandy, usually E horizon; Retallack, 1976). Strongly contrasting colors from one horizon to the next are common. Successions of paleosols with grey green near-surface (A and E) horizons and red to purple subsurface (Bt and Bs) horizons form especially scenic sequences, as gaudy as a barber pole or candy cane (Retallack, 1984). Sequences of calcareous paleosols are often more subdued and lighter in color, with alternating brown surface (A) and cream subsurface (Bk) horizons (Retallack, 1983b). Some Precambrian paleosols have surface (A) horizons of a very distinctive lime green color (Retallack and others, 1984).

A wide variety of horizons are recognized in modern soils, and these are labeled with a system of letters and numbers (such as A and Bt) in a kind of shorthand system of description (Table 1). Although laboratory reassessment may force changes in a horizon designation, it is best to interpret paleosol horizons in the field. Such field observations will determine the way a paleosol is sampled, and perhaps ultimately its interpretation and identification in classifications of modern soils. Compared to the numerous systems for classification of soils, the field nomenclature for soil horizons has remained fairly stable over the years. Some minor changes are now being proposed in revision of the U.S. Department of Agriculture's Soil Survey Manual (Guthrie and Witty, 1982). These are contrasted with nomenclature of an earlier edition of the Soil Survey Manual in Table 1. A distinctive feature of the new scheme is its conflation of accumulations of carbonate, clay, sesquioxides, and humus as equally valid indicators of B horizons. Thus, horizons formerly labeled "Cca" should now be "Bk."

In order to characterize soil horizons, their grain size, color, reaction with acid, and the nature of their boundaries must all be recorded in the field. Grain size can be reassessed by laboratory studies, but color cannot. Samples of well-indurated or partly metamorphosed paleosols may hold their color well, but little-altered clayey paleosols of the kind widespread in scenic badlands of Mesozoic and Cenozoic rocks in the western United States change color on exposure and laboratory storage. In the Badlands of South Dakota, rock samples became paler (Munsell value became higher) after a few hours of drying in the sun, and after six months of laboratory storage, greenish gray parts of the samples became discernibly more yellowish (change in Munsell hue) because of oxidation of their reduced iron-bearing minerals (Retallack, 1983b). It is best to record color using a comparative chart (Munsell Color, 1975) on fresh rock within a few minutes of exposure. In some cases it is useful to take the weathered color of the adjacent unexcavated exposure of color-banded badlands, because these colors are useful for locating similar paleosols in unexcavated weathered slopes.

The carbonate content of a horizon, as a guide to its base saturation, can be determined in the laboratory, and may be useful in identifying the paleosol within a classification of modern soils. It also is helpful to determine carbonate content in the field by applying drops of dilute (about 10%) hydrochloric acid. In recent fieldwork, I was especially interested in carbonate content as a guide to the preservation of bone (following general models of Retallack, 1984), and used an expanded scale of acid reaction to approximate carbonate content (Table 2). A final feature of horizons that must be recorded in the field is the nature of their contact with adjacent horizons. Only one contact needs to be specified for each horizon—the upper one if systematically describing a profile up section or the lower one if working downward. Two aspects of the contact are of interest: whether one horizon changes into another within a narrow (abrupt) or broad (diffuse) vertical distance, and whether the contact is laterally planar (smooth) or somehow disrupted (broken). The U.S. Department of Agriculture has adopted official terms for the National Cooperative Soil Survey to describe these various degrees of sharpness and lateral continuity (Table 3). I have used these in published descriptions of paleosols, but have often found my memory of them uncertain in the field and measured the transition distances and spacing of irregularities. Such measurements can easily be translated later into categories.

The nature of soil horizons provides important clues to past vegetation of paleosols and the time available for formation. As a soil develops so does the complexity of its vegetation and the degree of differentiation of its horizons. Soils of young land surfaces, such as recent flood deposits, or landslide debris, have persistent features betraying their origin, such as bedding. They support early successional vegetation and have only an organic (A) horizon over mildly weathered parent material (C horizon). This simple structure (A horizon over C) is also seen in some grassland soils (Fig. 6). These also may have a calcareous subsurface horizon (Bk) that is closer to the surface in grassland soils of progressively drier climates (Jenny, 1941; Arkley, 1963) and that becomes thicker and more massive with time (Table 4). A full sequence of horizons (A–Bt or Bs–C) is formed under stable, mature woody vegetation. Leached (eluvial or E) horizons form under closed canopy forest, woodland, and heath, in which rainfall leachates from the leaves, as well as root action and other agents, translocate organic matter, clay, or sequioxides of iron into a distinctive subsurface (Bt or Bs) horizon (Fig. 7). With time this subsurface horizon becomes thicker and more enriched in organic matter, clay, or sesquioxides. The differentiation horizons can be used to assess the relative degree of development of paleosols (Table 5). Rough estimates in years can be gleaned from current studies of modern soils of various ages (chronosequences: Birkeland, 1984).

Soil horizons are also the basis for most classifications of soils. Because each system of classification has its own strengths and weaknesses, it is best to identify paleosols within several classifications. The classification used by the National Cooperative Soil Survey of the United States (Soil Survey Staff, 1975) is based largely on experience with young glacial, alluvial, and volcanic soils of North America; its many new terms and concepts are now gaining widespread currency (Table 6). The classification of the Food and Agriculture Organization (FAO) of UNESCO (summarized by Fitzpatrick, 1980) is based on experience of soils in tropical regions. The classification prepared by the Australian CSIRO (Stace and others, 1968) is based on the soils of the stable and largely unglaciated continent of Australia, and employs many old and familiar soil names, such as Podzol and Chernozem. Tentative field identification of paleosols within such classifications serves to focus attention on those features that are diagnostic.

## SOIL STRUCTURE

A final field characteristic of paleosols is soil structure. This forms at the expense of bedding, crystal structure, and schistosity of parent materials, because of bioturbation by plants and animals, wetting and drying, and other soil-forming processes. Compared to sedimentary, metamorphic and igneous textures, soil structure appears massive or hackly at first sight. On closer inspection it can be seen to be complexly organized, with particular structures indicative of particular soil conditions.

The hackly appearance of much soil structure (for example, Fig. 8) is caused by a network of irregular planes (cutans, in soil terminology) surrounding more stable aggregates of soil material (peds). A common kind of cutan is clay skins (or illuviation argillans, in the terminology of Brewer, 1976), formed where clay has washed down into and lined cracks within the soil. These should be restricted to a pedogenic, clayey B horizon, as opposed to a subsurface clayey bed in the parent material of the soil. Cutans also can be ferruginized planes (diffusion ferrans), manganese encrusted surfaces (mangans) or cracks filled with sand (skeletans of soil science, which is the same thing as "sandy clastic dikes" of geological nomenclature). Soils may also contain sheets of crystalline calcite, barite, or gypsum. The network of cutans found in soils, especially if mineralized with crystals such as barite, may appear simlar to the boxwork veining of some hydrothermal ores. In general, however, cutans are less regularly boxlike, less sharply bounded (on one side at least), and are restricted to narrow, stratabound horizons of considerable lateral extent.

Stable aggregates of soil material (peds) are bounded by both cutans and open spaces (voids) in the soil. Since open spaces are usually crushed or filled within paleosols, recognition of fossil peds in them depends on recognizing cutans. In cases where peds have been strongly compressed against each other during burial, slickensides form. These also form in surface soils of clayey texture with shrinking and swelling of clay on wetting and drying. Unlike slickensides associated with faults, those around peds are randomly oriented and restricted to particular (usually clayey) horizons. Peds are classified according to size and shape (Fig. 9). It is best to classify fossil peds in the field. Many kinds of peds are difficult to sample because they are only weakly defined or disrupted by jointing formed during burial.

Local concentrations of specific minerals (glaebules, in the terminology of Brewer, 1976) are also common in soils. Usually they are hard, distinct, calcareous, ferruginous, or sideritic lumps. These are the same as the nodules and concretions of sedimentary geologists. If they have a homogeneous internal texture, they are termed nodules. Those with concentric internal lamination are termed concretions (Brewer, 1976). Nodules also may be composed of clay. Brewer has proposed calling these "papules," a noncommital name for those cases where it is unclear whether they were clay clasts of a partly brecciated parent material or whether they were cavity fills or other local pedogenic accumulations of clay. If aggregations of material are especially diffuse, irregular, or weakly mineralized, they are termed mottles. Both mottles and glaebules can be categorized in terms of their visibility and abundance (Table 7). As with other such classifications used by the U.S. Department of Agriculture (Soil Survey Staff, 1975), this provides a degree of uniformity for published descriptions. Glaebules and mottles are irregularly shaped and have minerals that are either amorphous or very finely crystalline. Tubular mineral segregations (pedotubules) and a variety of crystals are found in soils and have a terminology of their own (Brewer, 1976). Glaebules, tubular features, and crystals are found in marine sedimentary rocks as well as in soils, and so are not as diagnostic of paleosols as peds and cutans. Nevertheless, glaebules, tubular features, and crystals are abundant and varied in paleosols, and form an important part of their structure.

Soil structures are important to the interpretation of paleosols, especially their drainage and chemical behavior. Clay skins, for example, form in soils in which the water table is below the surface for some part of the year. Soils formed under waterlogged swampy conditions may lack soil structure, showing little more than root traces. Granular and crumb structures are indications of copious biological activity. This is evidence for high soil fertility, and is characteristic of the surface (A) horizons of grassland soils (Mollisols). Domed columnar peds form in soils in which the clays are saturated with sodium cations. This structure is most commonly found in marine-influenced soils of mangal and salt marsh, and also in desert soils formed around salt pans. The mineralogy of nodules and related features may be a guide to former pH and Eh of the paleosol (using the well-known stability fields for minerals proposed by Krumbein and Garrels, 1952), provided these features can be shown to be original from their relationship to root traces and burrows. In general, ferric nodules and concretions form in well-drained, oxidized soils. Siderite nodules are characteristic of neutral to alkaline, waterlogged soils. Some waterlogged soils, especialy those which are marine-influenced, may have pyrite nodules. Calcareous nodules are found in well-drained alkaline soils. Consideration of these various interpretative possibilities may be useful in framing and further field-testing hypotheses about paleosols.

## COMPLICATIONS IN FIELD-SETTING OF PALEOSOLS

The recognition of root traces, soil horizons, and soil structure in paleosols may seem complex enough, but there are additional general complications that need to be considered during field examination of paleosols. These have to do with the way in which paleosols fit into rock sequences (Fig. 10).

In subsiding river valleys and coastal plains, of the sort in which many thick sedimentary sequences accumulate, soils are periodically covered by sediment. If a flood is especially catastrophic, and vegetation or engineering works are unable to contain it, a considerable amount of flood alluvium (a meter or so) may cover the soil. It then becomes a buried soil, a term I regard as synonymous with "fossil soil" and "paleosol."

If only thin increments (a few millimeters or centimeters) of sediment are deposited on a soil, most plants continue to grow and incorporate this material into the soil. Such cumulative horizons may blur the upper boundary of a paleosol, but these kinds of paleosols commonly show a break in the density of bioturbation, which can be taken as the top of the profile.

A more serious problem is the covering of a soil with an intermediate thickness of sediment (a few tens of centimeters) so that the younger soil that developed on the surface above the paleosol overlaps the paleosol. The remaining structures of the older surface (A) horizon in the subsurface (B) horizon of the younger soil are called pedorelicts. This is a general term for soil features believed to have formed in a soil (or paleosol) different from the one in which they are present (Brewer, 1976). Other examples of pedorelicts include nodules weathered out of older soils and incorporated into and persisting within the parent material of younger soils.

A pedorelict is not the same as a relict soil, which refers to a whole or partly eroded profile. Relict soils are surface soils in which the same soil material appears to have been modified by several different regimes of soil formation. This can be because the soil was buried and then uncovered by erosion at a later date (exhumed soil), or because it simply remained at the surface while climate, vegetation, or other soil-forming factors changed. Most fossil soils below major unconformities involving millions of years of nondeposition are relict soils to some extent. This, as well as the possibility of subsurface modification by ground water running along the unconformity, should be considered in interpreting their paleoenvironment (Pavich and Obermeier, 1985). For all paleosols it is prudent to consider the kind of paleoenvironment indicated by root traces, soil horizons, and soil structure in the field. Conflicting indications may arouse suspicion that the soil or some features are relict, and stimulate the search for evidence of the order of environmental change. The distinction between relict and exhumed soils may be difficult to determine, but can be settled by tracing the paleosol laterally to where it is buried (Ruhe, 1965). Thus, it is best to keep general the term relict paleosol, and to use the term exhumed paleosol only for those paleosols in which burial and uncovering can be demonstrated.

Soil material is not only eroded, but also deposited. The term pedolith (in the sense of Gerasimov, 1971) is convenient for deposits with a sedimentary organization, such as bedding or ripple marks, but with individual grains of soil mineralogy and microstructure. Most sediment is ultimately derived from soil, and so is pedolithic in a strict sense. In many sedimentary sequences (such as those discussed by Retallack, 1976, 1977), however, sediment from distant sources is quite distinct from that eroded out of local soils. In such cases, the term and the concept of pedolith are useful.

## FIELD NAMES FOR PALEOSOLS

Many names for particular paleosols and kinds of paleosols are now finding their way into print. While some regard these names as an intolerable burden to already overloaded geological nomenclature, experience with other materials, such as trace fossils, has shown that informal number or letter designations tend to be ignored by future scientists working with comparable material.

Three systems for naming paleosols are available for the three different purposes of stratigraphic correlation, geological mapping, and paleoenvironmental interpretation of paleosols. It is not necessary to decide on final names during fieldwork, but potential names and relevant data for the particular system of naming should be considered in the field.

Paleosols have long been used for stratigraphic correlation in Quaternary sediments (Morrison, 1976); this technique is now being applied to much older rocks (Ortlam, 1971). The basic units of this technique have been called a number of different names in the past, but are now widely called geosols; for example, the Sangamon Geosol (North American Commission on Stratigraphic Nomenclature, 1982). A geosol defines a recognizable land surface. It may consist of different kinds of paleosols along strike, but is recognized by a comparable degree of development and other regionally consistent (especially climate-related) features.

Some paleosols, especially the thick remnants of paleosols at major unconformities such as laterite, silcrete, and caliche, are so widespread and well developed that they cover significant areas of geological maps. These also have been names after localities where they are best exposed and given the name profile, as in Curalle silcrete profile (Senior and Mabbutt, 1979).

For interpretative studies of paleosols, names are needed for kinds of paleosols as well as for selected specific profiles. Often in paleosol sequences, many examples of the same kind of paleosol may be found, reflecting persistence of broadly similar soil-forming conditions as the sequence accumulated (Retallack, 1983a,b). In situations such as this, I have used conventional soil mapping units (Soil Survey Staff, 1951, 1962). The basic field unit is termed the series, representing a consistently recognizable kind of paleosol. Series are named after a locality, or other feature if localities are not available (for example, Zisa and Gleska Series paleosols mean "red" and "mottled" series in the local Sioux Indian language: Retallack, 1983b). Each series is based on a representative paleosol (type profile), which should be carefully studied and documented. Individual paleosols may be named from the petrographic texture of their surface horizon or from other features (for example, the type Zisa clay and Gleska silty clay loam thick petrocalcic phase paleosols of Retallack, 1983b). There is also scope for grouping series of paleosols into larger units (associations) based on shared features, such as similar parent material. Paleosol series names are not yet formal geological names in the same way as geosols, but some effort should be made to avoid names that could be confused with other soil or rock units by checking compilations of these names (for example, by Luttrell and others, 1986; by Huddleston, 1979; or the computer data base available from the offices of the U.S. Soil Conservation Service).

## A PERSONAL FIELD KIT

A good deal of equipment is now available to aid geological fieldwork. The following checklist outlines my own basic kit.

1. My digging and sampling equipment always includes a geological hammer. Some Quaternary paleosols may be too friable to sample directly with a hammer, but a hammer is still useful for forcing opened tin cans or pipe into the outcrop for extraction of samples showing soil fabric. If eroded badlands are to be sampled, it may be necessary to dig through the weathered surface to fresh rock using picks, shovels, or backhoes.

2. Recording equipment includes cameras, lenses, pencils, pencil sharpener, pens, and a field notebook. I prefer to make copious longhand notes and pencil sketches. This requires a larger-than-usual field notebook; quarto-sized, hardbound exercise books, with pages ruled into half-centimeter squares have proven best. The manner of describing sections of paleosols is just as it would appear in publications (Table 8), using my own modifications of the graphic presentation recommended by Selley (1978; Fig. 11).

3. The best available soil color charts are manufactured by Munsell Color (1975). Because diagenetic reddening of ferric oxyhydrate minerals and diagenetic pseudogley are so widespread in paleosols, the additional pages for tropical (hues 7.5R and 5R) and gley (chroma of 1) soil colors are strongly recommended. Soil color should always be taken on fresh rock within minutes of exposure, because colors change as rock samples dry and oxidize.

4. Dilute (about 10%) hydrochloric acid carried in an eyedropper bottle is needed for testing the carbonate content of samples by their effervesence of reaction (Table 2).

5. Marker pens with felt tips are useful for labeling hand specimens of different parts of a paleosol. It is also advisable to mark the top of hand specimens so that oriented petrographic thin sections can later be prepared. This is best marked by drawing a large (3 to 4 cm in diameter) circle on the upper portion of the sample in such a way that it forms a plane parallel to the top of the paleosol.

6. My measuring equipment includes tape and ruler. A Brunton compass may be useful for measuring dips and strikes of surfaces, and orientation of special features. Long sections designed to show the setting of paleosols within a sequence may be measured by the method of eye heights using a Brunton compass or other leveling device, such as an Abney level.

7. Packaging materials are needed for protection of samples of soil horizons, soil structures, and associated fossils during transport from the field. Newspaper is useful for wrapping. Small, delicate items may require boxes, bottles, or film canisters to prevent crushing.

8. Also useful are reminder sheets of information, such as the collage of diagrams included here (Figs. 8 through 11 and Tables 1 through 8). When working in a field camp, the following few books serve as an excellent research library: those by Stace and others (1968), Soil Survey Staff (1975), Buol and others (1980), Fitzpatrick (1980), and Birkeland (1984).

## CONCLUSIONS

The basic question addressed in this chapter is an apparently simple one. Is it a paleosol? To deal with even such a simple question, some concept of the characteristic features and settings of paleosols is needed. As discussed at length, fossil root traces, soil horizons, and soil structures are especially characteristic. The settings of paleosols include unconformities of all kinds, from major erosional gaps in the rock record to minor breaks between beds of alluvial sediments. More than any other piece of field equipment, it is these concepts that enable the field recognition of paleosols. Even in finding paleosols, which are much more abundant than generally suspected, fortune favors the prepared mind.

Another question is worth asking in the field, and has not been addressed in detail here. What else could it be, if not a paleosol? A number of geologic phenomena may mimic some features of paleosols: mylonitized and brecciated fault zones; reaction rims around and on top of pillow lava; graded beds that fine upward from conglomerate or sandstone to claystone; strongly bioturbated marine or lacustrine sediments; or marine hardgrounds. These have only a superficial resemblance to paleosols and are very different in setting. As dissimilar as they may seem in comparison to paleosols, these other phenomena can appear similar, especially on first inspection and in small outcrops. It is possible also for a particular outcrop to show a combination of a paleosol and one of these other phenomena, for example, a paleosol developed on an alluvial graded bed or a paleosol altered by ground-water flow beneath an impermeable capping rock. There has been no attempt to catechize these various alternatives here, because each case is different and provides its own challenge to one's powers of observation and reason.

Other questions also arise during fieldwork. In terms of modern soil classification, what kind of soil was this paleosol? What was its former climate, vegetation, topographic position, parent material, or time for formation? How should it be mapped and named? My own answers to some of these questions have been scattered through this description of basic features of paleosols in an attempt to show why these things are of interest. Complex interpretative questions also can be tested by field observations. Later, laboratory data on grain size, mineralogy, and chemical composition may provide invaluable quantification or validation of field ideas. Since samples analyzed are collected on the basis of field observations, such laboratory data may considerably refine field observations, but only rarely will overturn all the assumptions made then. Thus, the most crucial phase in the investigation of a natural phenomenon as complex as a paleosol is its field examination and description. Take care then, for paleopedology is fundamentally a field science.

## ACKNOWLEDGMENTS

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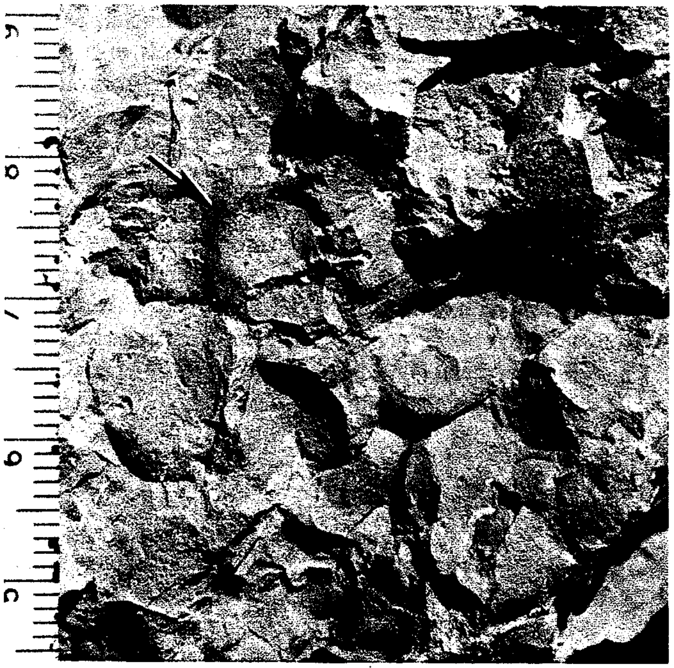


Figure 8. Granular ped structures outlined by clay skins (argillans, especially prominent at arrow) from type Conata clay paleosol of mid-Oligocene (Orellan or about 32 m.y.), Scenic Member of Brule Formation, in Pinnacles area, Badlands National Park, South Dakota. Scale in both centimeters (figures) and millimeters (fine gradations).

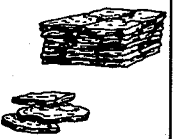
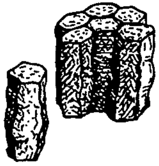
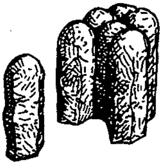
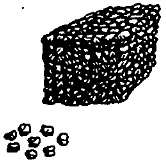
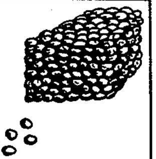
| TYPE | PLATY | PRISMATIC | COLUMNAR | ANGULAR BLOCKY | SUBANGULAR BLOCKY | GRANULAR | CRUMB |
|---|---|---|---|---|---|---|---|
| SKETCH |  |  |  |  |  |  |  |
| DESCRIPTION | tabular and horizontal to land surface | elongate with flat top and vertical to land surface | elongate with domed top and vertical to surface | equant with sharp interlocking edges | equant with dull interlocking edges | spheroidal with slightly interlocking edges | rounded and spheroidal but not interlocking |
| USUAL HORIZON | E,Bs,K,C | Bt | Bn | Bt | Bt | A | A |
| MAIN LIKELY CAUSES | initial disruption of relict bedding; accretion of cementing material | swelling and shrinking on wetting and drying | as for prismatic, but with greater erosion by percolating water, and greater swelling of clay | cracking around roots and burrows; swelling and shrinking on wetting and drying | as for angular blocky, but with more erosion and deposition of material in cracks | active bioturbation and coating of soil with films of clay, sesquioxides and organic matter | as for granular; including fecal pellets and relict soil clasts |
| SIZE CLASS | very thin < 1 mm | very fine < 1 cm | very fine < 1 cm | very fine < 0.5 cm | very fine < 0.5 cm | very fine < 1 mm | very fine < 1 mm |
| | thin 1 to 2 mm | fine 1 to 2 cm | fine 1 to 2 cm | fine 0.5 to 1 cm | fine 0.5 to 1 cm | fine 1 to 2 mm | fine 1 to 2 mm |
| | medium 2 to 5 mm | medium 2 to 5 cm | medium 2 to 5 cm | medium 1 to 2 cm | medium 1 to 2 cm | medium 2 to 5 mm | medium 2 to 5 mm |
| | thick 5 to 10 mm | coarse 5 to 10 cm | coarse 5 to 10 cm | coarse 2 to 5 cm | coarse 2 to 5 cm | coarse 5 to 10 mm | not found |
| | very thick > 10 mm | very coarse > 10 cm | very coarse > 10 cm | very coarse > 5 cm | very coarse > 5 cm | very coarse > 10 mm | not found |

Figure 9. Classification of soil peds (simplified from Soil Survey Staff, 1975; Birkeland, 1984).

TABLE 1. DESCRIPTIVE SHORTHAND FOR LABELING PALEOSOL HORIZONS

| Category | New Term | Description | Old Term |
|---|---|---|---|
| ***Master Horizons*** | O | Surface accumulation of organic materials (peat, lignite, coal), overlying clayey or sandy part of soil | O |
| | A | Usually has roots and a mixture of organic and mineral matter; forms the surface of those paleosols lacking an O horizon | A |
| | E | Underlies an O or A horizon and appears bleached because it is lighter colored, less organic, less sesquioxidic, or less clayey than underlying material | A2 |
| | B | Underlies an A or E horizon and appears enriched in some material compared to both underlying and overlying horizons (because it is darker colored, more organic, more sesquioxidic or more clayey) or more weathered than other horizons | B |
| | K | Subsurface horizon so impregnated with carbonate that it forms a massive layer (developed to stage III or more of Table 4) | K |
| | C | Subsurface horizon, slightly more weathered than fresh bedrock; lacks properties of other horizons, but shows mild mineral oxidation, limited accumulation of silica carbonates, soluble salts or moderate gleying | C |
| | R | Consolidated and unweathered bedrock | R |
| ***Gradations Between Master Horizons*** | AB | Horizon with some characteristics of A and B, but with A characteristics dominant | A3 |
| | BA | As above, but with B characteristics dominant | B1 |
| | E/B | Horizon predominantly (more than 50%) of material like B horizon, but with tongues or other inclusions of material like an E horizon | A&B |
| ***Subordinate Descriptors*** | a | Highly decomposed organic matter | — |
| | b | Buried soil horizon (used only for pedorelict horizons with paleosols; otherwise redundant) | b |
| | c | Concretions or nodules | cn |
| | e | Intermediately decomposed organic matter | — |
| | f | Frozen soil, with evidence of ice wedges, dikes, or layers | f |
| | g | Evidence of strong gleying, such as pyrite or siderite nodules | g |
| | h | Illuvial accumulation of organic matter | h |
| | i | Slightly decomposed organic matter | — |
| | k | Accumulation of carbonates less than for K horizon | ca |
| | m | Evidence of strong original induration or cementation, such as avoidance by root traces in adjacent horizons | m |
| | n | Evidence of accumulated sodium, such as domed columnar peds or halite casts | sa |
| | o | Residual accumulation of sesquioxides | — |
| | p | Plowing or other comparable human disturbance | p |
| | q | Accumulation of silica | si |
| | r | Weathered or soft bedrock | ox |
| | s | Illuvial accumulation of sesquioxides | ir |
| | t | Accumulation of clay | t |
| | v | Plinthite (in place, pedogenic laterite) | — |
| | w | Colored or structural B horizon | — |
| | x | Fragipan (a layer originally cemented by silica or clay, and avoided by roots) | x |
| | y | Accumulation of gypsum crystals or crystal casts | cs |
| | z | Accumulation of other salts or salt crystal casts | sa |

**Note**: This table has been adapted for use with paleosols from one by Guthrie and Witty (1982), showing proposed terminology from the new edition of the USDA *Soil Survey Manual*, compared to that of the 1951 edition. Some of the subordinate descriptors are considered more important than others; these letters (a, e, i, h, r, s, t, v, w) should all be written first after the master horizon if in combination with other letters, and they should not be used in combination with each other. Master horizons can be subdivided by numbers (e.g., B1, B2, B3). If the parent material of a paleosol consists of interbedded shale and sandstone, these will show different kinds of alteration in the same profile. Such different layers separated by discontinuities are numbered from the top down, without using the number 1; for example, A, E, E/B, Bt, 2Bt, 2BC, 2C, 3C. If you can form a clear mental picture of this profile, you are well on the way to mastering this pedological shorthand.

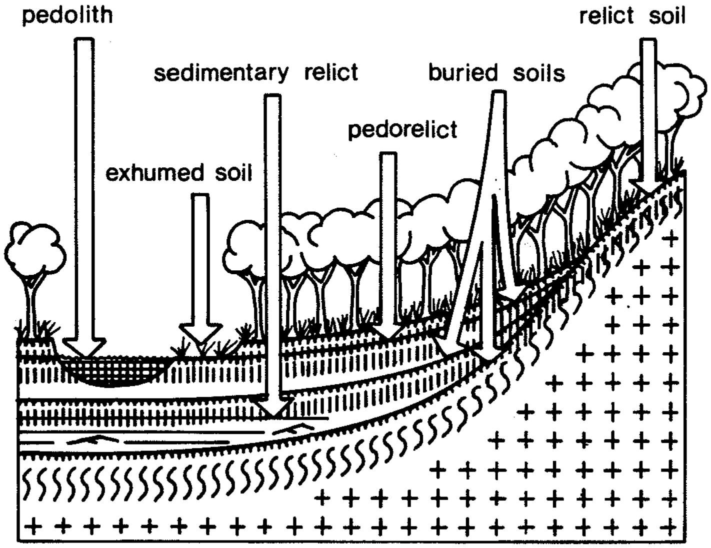


Figure 10. Important terms and concepts for recognition of fossil soils (from Retallack, 1983a, with permission from the Geological Society of America).

TABLE 2. SCALE OF ACID REACTION TO APPROXIMATE CARBONATE CONTENT OF PALEOSOLS

| Carbonate Content | Reaction with Dilute Acid |
|---|---|
| Noncalcareous | Acid unreactive; often forms an inert bead |
| Very weakly calcareous | Little movement within the acid drop, which could be flotation of dust particles as much as bubbles |
| Calcareous | Numerous bubbles, but not coalescing to form a froth |
| Strongly calcareous | Bubbles forming a white froth, but drop of acid not doming upward |
| Very strongly calcareous | Drop vigorously frothing and doming upward |

***Note:*** This table, developed during recent fieldwork, has been amplified from a scale proposed by Birkeland (1984).

TABLE 3. SHARPNESS AND LATERAL CONTINUITY OF PALEOSOL HORIZON BOUNDARIES

| Category | Class | Features |
|---|---|---|
| ***Sharpness*** | Abrupt | Transition from one horizon to another completed within 1 in (2cm) |
| | Clear | Transition completed within 1-2.5 in (2-5 cm) |
| | Gradual | Transition spread over 2.5-5 in (5-15 cm) |
| | Diffuse | One horizon grading into another over more than 5 in (15 cm) |
| ***Lateral Continuity*** | Smooth | Horizon boundary forms an even plane |
| | Wavy | Horizon boundary undulates; with pockets wider than deep |
| | Irregular | Horizon boundary undulates, with pockets deeper than wide |
| | Broken | Parts of the adjacent horizon are disconnected, e.g., by deep and laterally persistent clastic dikes in Vertisols |

***Note:*** This table is slightly modified from one of Birkeland (1984).

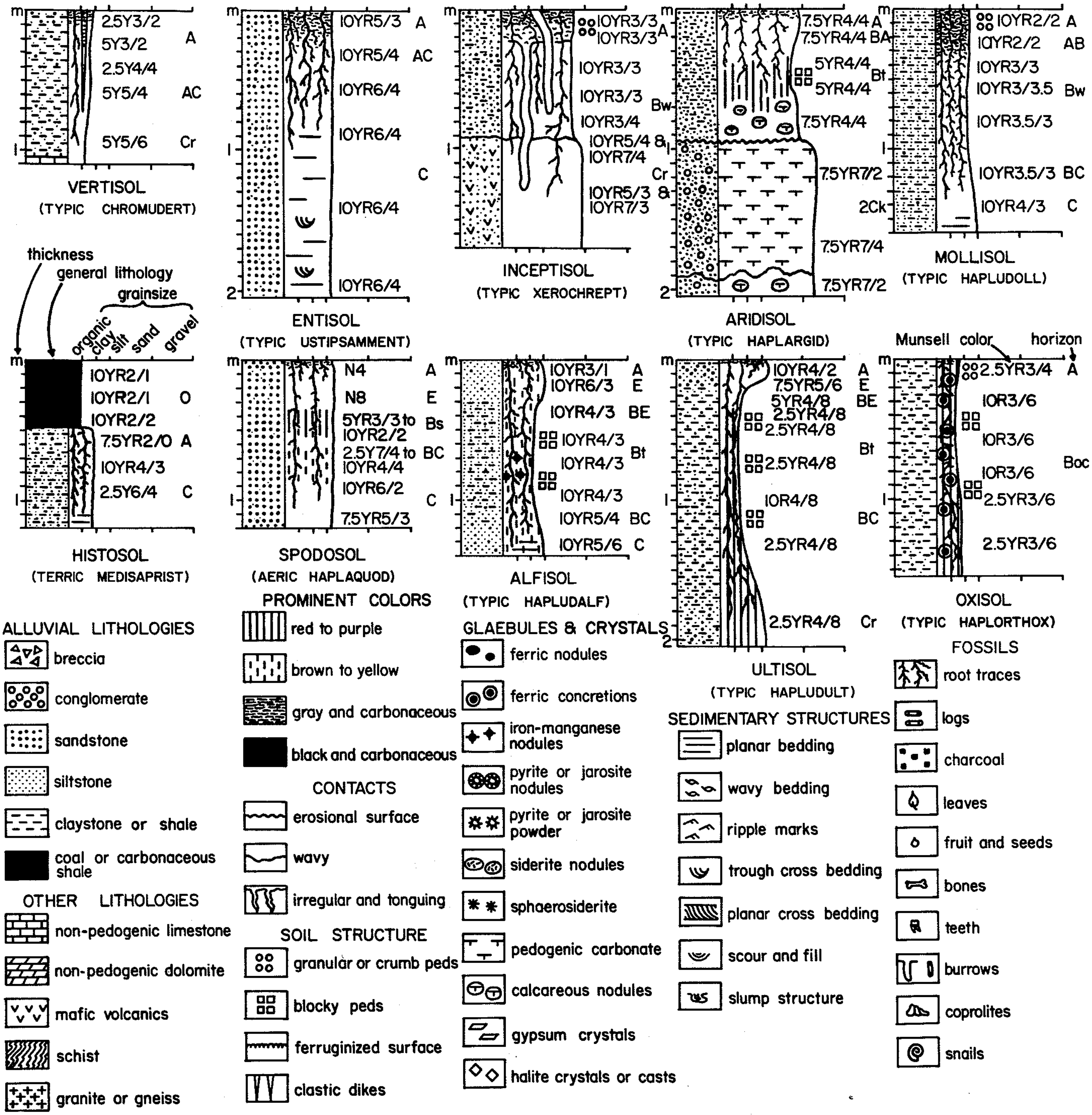


Figure 11. Suggested symbols and style for representing columnar sections of paleosols (adapted from scheme of Selley, 1978), with 10 profiles of modern soils thought to be representative of USDA taxonomic orders (by Buol and others, 1980, Appendix 1) as examples. Symbols not exhaustive; may need to be adapted or augmented to particular circumstances.
]

TABLE 4. STAGES OF CARBONATE ACCUMULATION IN PALEOSOLS

| Stage | Paleosols Developed in Gravel | Paleosols Developed in Sand, Silt, or Clay |
|---|---|---|
| I | Thin, discontinuous coatings of carbonate on underside of clasts | Dispersed powdery and filamentous carbonate |
| II | Continuous coating all around, and in some cases, between clasts: additional discontinuous carbonate outside main horizons | Few to common carbonate nodules and veinlets, with powdery and filamentous carbonate in places between nodules |
| III | Carbonate forming a continuous layer enveloping clasts: less pervasive carbonate outside main horizon | Carbonate forming a continuous layer formed by coalescing nodules; isolated nodules and powdery carbonate outside main horizon |
| IV | Upper part of solid carbonate layer with a weakly developed platy or lamellar structure, capping less pervasively calcareous parts of the profile | |
| V | Platy or lamellar cap to the carbonate layer strongly expressed; in places brecciated and with pisolites of carbonate | |
| VI | Brecciation and recementation, as well as pisoliths common in association with the lamellar upper layer | |

***Note:*** This table includes modifications (Machette, 1985) to the scheme proposed by Gile and others (1966).

TABLE 5. STAGES OF PALEOSOL DEVELOPMENT

| Stage | Features |
|---|---|
| Very weakly developed | Little evidence of soil development apart from root traces: abundant sedimentary, metamorphic, or igneous textures remaining from parent material |
| Weakly developed | With a surface rooted zone (A horizon), as well as incipient subsurface clayey, calcareous, sesquioxidic, or humic, or surface organic horizons, but not developed to the extent that they would qualify as USDA argillic, spodic, or calcic horizons or histic epipedon |
| Moderately developed | With surface rooted zone and obvious subsurface clayey, sesquioxidic, humic, or calcareous or surface organic horizons: qualifying as USDA argillic, spodic or calcic horizons or histic epipedon, and developed to an extent at least equivalent to stage II of calcic horizons (Table 4) |
| Strongly developed | With especially thick, red, clayey, or humic subsurface (B) horizons, or surface organic horizons (coals or lignites), or especially well-developed soil structure, or calcic horizons at stages III to IV (Table 4) |
| Very strongly developed | Unusually thick subsurface (B) horizons, or surface organic horizons (coals or lignites), or calcic horizons of stage VI: such a degree of development is mostly found at major geologic unconformities |

***Note:*** This scale is modified from a version of Retallack (1984) to include coal-bearing paleosols.

TABLE 6. A SHORT AND SUPERFICIAL KEY TO SOIL ORDERS OF THE U.S. DEPARTMENT OF AGRICULTURE FOR FIELD IDENTIFICATION OF PALEOSOLS

| Features | Order |
|---|---|
| ***If paleosol has:*** | ***It may be a(n):*** |
| • Abundant swelling clay (mainly smectite) to a presumed uncompacted depth of 1 m or to a bedrock contact, together with hummock and swale structure (mukkara), especially prominent slickensides or clastic dikes | Vertisol |
| • No horizons diagnostic of other orders, and very weak development (Table 5) | Entisol |
| • No horizons diagnostic of other orders, but weak development (Table 5) | Inceptisol |
| • Light coloration (high Munsell value), thin calcareous layer (calcic horizon) close to surface of profile and developed to stage II or more (Table 4), or evidence of pedogenic gypsum or other evaporite minerals | Aridisol |
| • Organic (but not carbonaceous or coaly), well-structured (usually granular) surface (A) horizon (*mollic epipedon*), usually with evidence of copious biological activity (such as abundant fine root traces and burrows) and with subsurface horizons often enriched in carbonate, sometimes enriched in clay | Mollisol |
| • Surface organic (O) horizon of carbonaceous shale, peat, lignite, or coal (*histic epipedon*) originally (before compaction) at least 40 cm thick | Histosol |
| • Thick, well-differentiated (A, Bt, and C horizons) profile, with subsurface (Bt) horizon appreciably enriched in clay (*argillic horizon*) and often red with sesquioxides or dark with humus, and also with evidence (such as effervescence in acid or calcareous nodules or abundance of easily weathered minerals such as feldspar) for high concentrations of nutrient cations (such as $Ca^{++}$, $Mg^{++}$, $Na^{+}$, and $K^{+}$) | Alfisol |
| • Thick, well-differentiated (A, Bt, and C horizons) profile, with subsurface (Bt) horizon appreciably enriched in clay (*argillic horizon*) and often red with sesquioxides or dark with humus, but also with evidence (such as lack of reaction with acid or abundant quartz or kaolinite) for low concentrations of nutrient cations | Ultisol |
| • Thick, well-differentiated (A, Bs, and C horizons), with sandy subsurface (Bs or Bh) horizon cemented with opaque iron or aluminum oxyhydrates or organic matter (*spodic horizon*), and always with little or no clay or carbonate | Spodosol |
| • Thick, well-differentiated to uniform profile, clayey texture, with subsurface horizons highly oxidized and red, and almost entirely depleted of weatherable minerals (*oxic horizon*) | Oxisol |

***Note:*** This key has been simplified for field observation. Precise identification of soils and their diagnostic horizons requires laboratory work and careful reference to Soil Survey Staff (1975).

TABLE 7. SIZE, ABUNDANCE, AND CONTRAST OF MOTTLES IN PALEOSOLS

| Category | Class | Features |
|---|---|---|
| ***Contrast*** | Faint | Indistinct mottles or glaebules visible only on close examination: both mottles and matrix have closely related hues and chromas |
| | Distinct | Mottles are readily seen, with hue, value, and chroma different from that of surrounding matrix |
| | Prominent | Mottles are obvious and form one of the outstanding features of the horizon; their hue, value, and chroma differing from that of the matrix by as much as several Munsell color units |
| ***Abundance*** | Few | Mottles occupy less than 2% of the exposed surface |
| | Common | Mottles occupy about 2 to 20% of the exposed surface |
| | Many | Mottles occupy more than 20% of the exposed surface. This class can be subdivided according to whether (a) the mottles are set in a definite matrix, or (b) the sample is almost equally two or more kinds of mottle |
| ***Size*** | Fine | Mottles less than 5 mm diameter in greatest visible dimension |
| | Medium | Mottles between 5 and 15 mm in greatest dimension |
| | Coarse | Mottles greater than 15 mm in greatest dimension |

***Note:*** These terms are little modified from those of Soil Survey Staff (1975). They may also be used for describing pedotubules and glaebules.

TABLE 8. SUGGESTED FORMAT FOR DESCRIPTION OF PALEOSOL HORIZONS

+0 cm, ...... (description of sediment overlying paleosol, using format below) ..... contact to

-0 cm, ...... (description of topmost horizon of paleosol, using format below) ...... contact to

-(depth to top of horizon) cm; horizon designation (Table 1); rock type (e.g., claystone, siltstone); fresh Munsell color of whole horizon and of special features; weathered Munsell color; nature of root traces (Fig. 1), soil structure (Fig. 9), or other features (Tables 4, 7); reaction with dilute acid (Table 2); mineralogy and microfabric (to be considerably amplified following laboratory work); nature of contact (Table 3) to

-(depth to top of horizon) cm, horizon designation ......

***Note:*** Examples of this kind of description are given in Retallack (1983b). Usually they are published as a sentence fragments connected by colons and semicolons, but I find it best in the field to write longhand paragraphs on each horizon, discussing field interpretations and subsequent efforts to test them.

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