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Fossil Soils and Completeness of the Rock and Fossil Records

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INTRODUCTION

> Forests may be as dense and lofty as those of Brazil, and may swarm with quadrupeds, birds and insects, yet at the end of thousands of years one layer of black mould a few inches thick may be the sole representative of those myriads of trees, leaves, flowers and fruits, those innumerable bones and skeletons of birds, quadrupeds, and reptiles . . .   (Lyell, 1877, p. 21)

The contrast between the exuberance of life on land and the paucity of its fossil record is striking, and Lyell's pessimism concerning the completeness of the fossil record remains justified, as we shall see. However, there is usually more than just 'black mould' remaining from where forests once grew. There are remains of the soils in which they were rooted and drew sustenance. Paleosols can be regarded as trace fossils of ecosystems, just as footprints in sandstone are trace fossils of a passing dinosaur. Paleosols are the result of a variety of processes such as weathering, root penetration and burrowing acting over the time during which the ecosystem thrived. Viewed in this way, paleosols are records of past environments independent of associated fossils and sedimentary rocks. The fossil record of soils now allows estimates of the completeness of both the rock and fossil records (Retallack, 1984, 1986).

For example, a paleosol with a subsurface horizon enriched in clay skins and with stout woody root traces is an indication of trees and other forest biota, even if leaves and trunks of the trees are not preserved. In some cases fossil trees and leaf litters are found in paleosols (Retallack, 1976; Gastaldo,

1986; DiMichele and DeMaris, 1987; Retallack and Dilcher, 1988; Taylor *et al.*, 1992; Taylor and Taylor, 1993), but the paucity of such fossiliferous paleosols is a measure of the incompleteness of the fossil record. These formerly forested paleosols also represent times of non-deposition or gaps in the sedimentary record. The duration of that hiatus in sedimentation can be estimated to an order of magnitude from the degree of the development of paleosols by comparison with well-dated Quaternary soils (Leeder, 1975; Retallack, 1986; Bown and Kraus, 1987, 1993; Bown and Larriestra, 1990; Kraus and Bown, 1993a). These gaps in sedimentation are a measure of the incompleteness of the sedimentary record.

Some years ago I addressed such issues of completeness of the rock and fossil record using Eocene and Oligocene paleosols in Badlands National Park, South Dakota (Retallack, 1984, 1986). Subsequent studies (Towe, 1987; Bown and Beard, 1990) and my own reports of more than a thousand Mesozoic and Cenozoic paleosols (Retallack, 1975, 1976, 1977, 1979, 1983a,b, 1984, 1986, 1994a; Retallack and Dilcher, 1981a,b; Retallack and Ryburn, 1982; Retallack *et al.*, 1995, 1996, 1997, 1998) emphasized again pH, Eh and time for development of paleosols as important constraints in preservation of fossils in paleosols. Further studies have also showed how paleosols can be used to find the big gaps in non-marine sedimentary successions, because they can be guides to sequence stratigraphic architecture (Kraus, 1992; Wright, 1992; Wright and Marriott, 1993).

COMPLETENESS OF THE FOSSIL RECORD

After an organism dies, its remains must survive a variety of destructive processes in order to be preserved as part of the fossil record. The case of an antelope dying on an East African savannah is an appropriate model for preservation of fossils in paleosols (Shipman, 1981). Initially, predators and scavengers of all kinds, ranging from lions and hyenas to blowflies and carrion beetles to fungi and bacteria, devour the flesh and disarticulate the skeleton. Bones are destroyed by trampling, and by cracking and splitting during weathering at the surface. As the bones are overgrown by plants, covered by dust, fall down cracks and burrows or are trampled into the soil, they are destroyed by a new set of processes related to soil formation. Fossil assemblages in paleosols are further modified during late diagenesis, exposure and collecting. This is a complex chain of events and the prospects of reconstructing each aspect of it are daunting.

Paleosols come to the rescue by offering information on three important taphonomic variables: Eh, pH (Figure 6.1) and time of soil formation (Figure 6.2). The redox status of paleosols can be determined from colour and mineral composition. Chemically oxidized paleosols are reddish-coloured
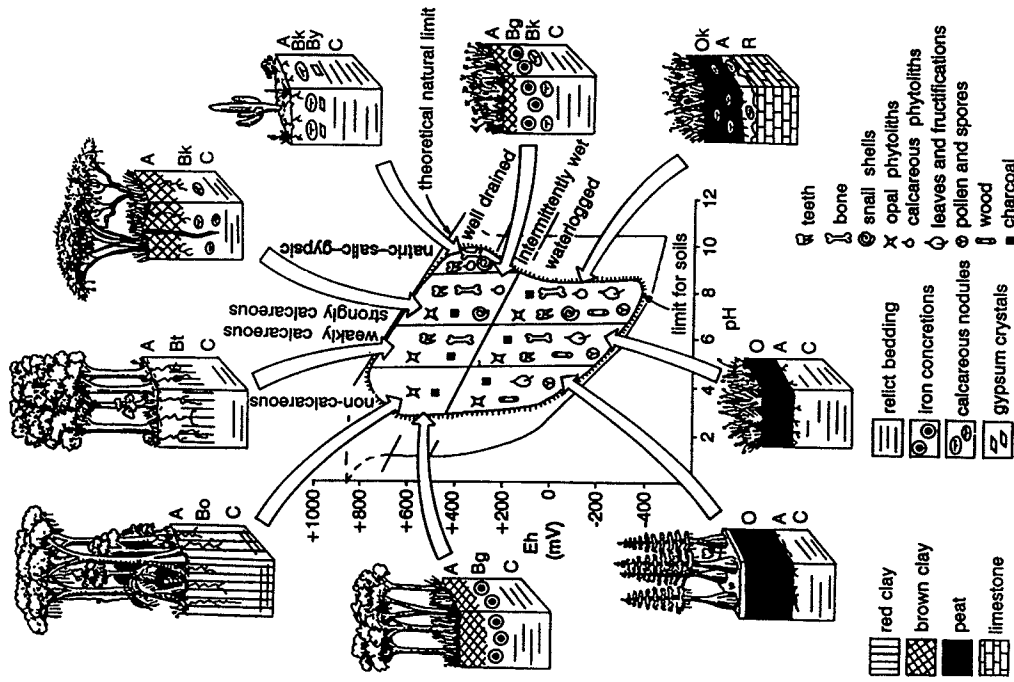
Figure 6.1 Theoretical Eh–pH stability fields for common kinds of terrestrial fossils preserved in fossil soils and representative kinds of soils. Soil horizon shorthand is from Soil Survey Staff (1990). Scales on the soil columns are about 2 m and for forest vegetation about 10 m. (After Retallack, 1984).

with ferric oxide minerals, and also have deeply penetrating root traces and burrows. Chemically reducing paleosols, on the other hand, are drab-coloured and have minerals such as siderite, as well as coal layers, aquatic fossils and tabular root systems (Retallack, 1976, 1990; Fastovsky and McSweeney, 1987; Besly and Turner, 1989; Blodgett *et al.*, 1993; PiPujol and Buurman, 1994).

Finally, time for development of paleosols can be estimated from the degree of expression of pedogenic structures compared with original structures such as sedimentary bedding (Bown and Kraus, 1987, 1993; Retallack, 1990, 1991; Kraus and Bown, 1993a). There are recognizable stages in the degree of subsurface enrichment in clay or carbonate and in the surface accumulation of peat that correspond to broad classes of development for humid, arid and waterlogged environments, respectively (Figure 6.2). The point here is that Eh, pH and time for development can be estimated from paleosols independent of their fossils. The role of these variables in fossil preservation in paleosols can thus be assessed from field studies of paleosols and the fossils in them.

A New Compilation

Much of the initial inspiration for this work came from a study of 87 paleosols of Eocene and Oligocene age in Badlands National Park, South Dakota (Retallack, 1984, 1986). Even at that time it was apparent that preservational preferences were statistical or probabilistic, rather than absolute, so that a larger data set was desirable. During the past decade I have been able to study several thousand paleosols of all geological ages. Those of early Palaeozoic and Precambrian age are not considered here because not all the different kinds of potential terrestrial fossils had evolved by then. Published reports of late Palaeozoic, Mesozoic and Cenozoic profiles now include 1478 paleosols, all studied within long stratigraphic sections using uniform field protocol (for example, Figure 6.3; Retallack, 1988a). The paleosol descriptions have been published elsewhere. In order of geological age these include late Permian and early Triassic paleosols of the Sydney Basin, Australia (Retallack, 1998), of southern Victoria Land, Antarctica (Retallack et al., 1997) and at Graphite Peak, Antarctica (Retallack et al., 1998); early Triassic paleosols near Sydney, Australia (Retallack, 1975, 1976, 1977); middle Triassic paleosols of New Zealand (Retallack, 1979, 1983a; Retallack and Ryburn, 1982); mid-Cretaceous paleosols of Kansas (Retallack and Dilcher, 1981a,b); late Cretaceous and Paleocene paleosols of Montana (Retallack, 1994a); early Eocene paleosols of Wyoming (Figure 6.3); late Eocene and early Oligocene paleosols of the Clarno and Painted Hills areas of Oregon (Bestland and Retallack, 1994a,b) and of Badlands National Park, South Dakota (Retallack, 1983b, 1984, 1986); and Miocene paleosols of Pakistan and Kenya (Retallack, 1991; Retallack et al., 1995). These paleosols represent a variety of different kinds of biological and physical environments, including humid and arid paleoclimates; swamps and deserts; high and low latitudes; forests and grassland; therapsid, dinosaur and mammal communities; uplands and lowlands; volcaniclastic and
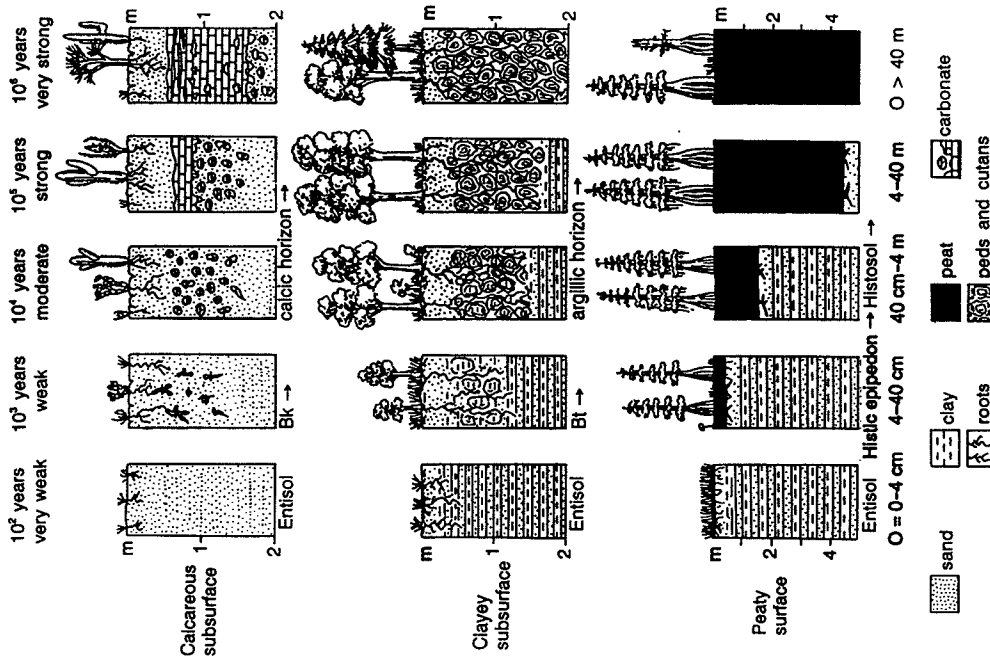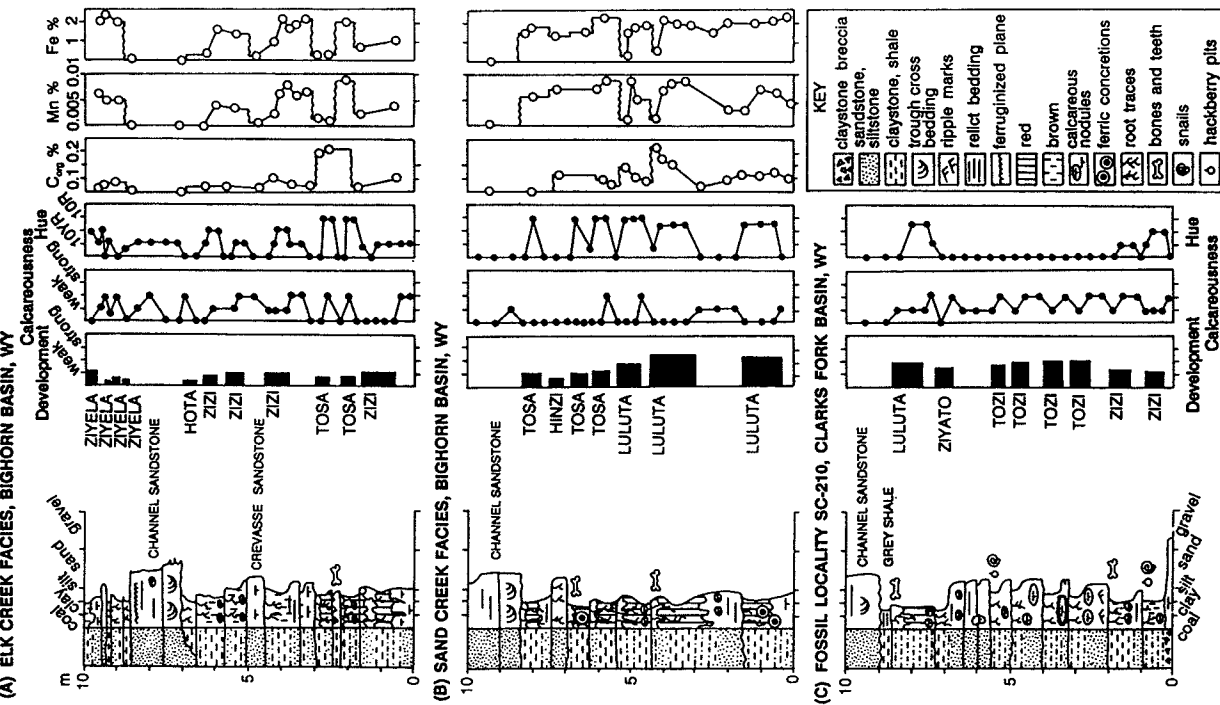
Figure 6.2 Soil features used for estimating degree of development of paleosols. The scale for cartoons of ecosystem type differs from those on the soil columns. (Data from Retallack, 1990, 1991)

Similarly, pH can be estimated from the mineral and chemical composition of paleosols. Unlike acidic paleosols, alkaline paleosols are calcareous and enriched in alkali and alkaline earth elements (Retallack, 1976, 1990; Percival, 1986; Hughes et al., 1992). Surface environments can be geochemically characterized within a grid of Eh and pH (Krumbein and Garrels, 1952; Baas-Becking et al., 1960), and so can the stability of different kinds of fossils in soils and paleosols (Figure 6.1).

are of greater significance for fossils in soils than in sediments because of the long time during which they are exposed to weathering, and because of the great range of Eh and pH conditions found in soils (Baas-Becking et al., 1960).

Biogenic opal phytoliths and sponge spicules are stable in the widest range of Eh and pH, and accumulate in a variety of modern soils (Wilding and Drees, 1972; Wilding et al., 1979). Their distribution may also be related to Eh because silica phytoliths become enriched as a concentrate in soils in which associated organic matter is destroyed by oxidation. Opal phytoliths and spicules are very weakly soluble at pH < 9, although appreciably more soluble than quartz, but both quartz and opal are dissolved at pH > 9 (Krauskopf, 1979).

The occurrence of calcareous phytoliths in soils has been little studied, although they have been obtained from prehistoric human coprolites (Bryant and Williams-Dean, 1975). The endocarps of hackberry, Celtis occidentalis, may contain 25–64% calcium carbonate by dry weight of the whole fruit and 2–7% silica (Yanovsky et al., 1932). This may account for the favoured preservation of fossil hackberry endocarps in oxidized, calcareous paleosols of Tertiary age in North America and Kenya (Retallack, 1983b, 1991).

Aragonite (rarely calcite) shells of land snails are not found in acidic, non-calcareous soils, but are common in alkaline (pH 7.5–8.0) soils and paleosols (Evans, 1972; Pickford, 1986). Dissolution of shells in acidic soils proceeds rapidly once the organic periostracum decays (within about a year in non-waterlogged soils). Although the distribution of fossil land snails is to a certain extent due to differential preservation, many species have larger living populations in areas of calcareous soils.

Preservation of bones and teeth is also controlled more by pH than Eh, because these phosphatic fossils are prone to dissolution by acid (Chaplin, 1971; Pickford, 1986). In seasonally dry, subtropical Zimbabwe, bones in 700 year-old human graves were well preserved under alkaline (pH 6.2–7.9) termite mounds, but had been completely destroyed in adjacent acidic (pH 4.1–5.4) soils (Watson, 1967). In cool temperate, humid, north-western Europe, human bodies interred in acid, reducing peats for thousands of years (mostly from 100 BC to 500 AD) showed varying degrees of bone decalcification and in one case complete loss of bone within preserved skin and other soft tissues (Glob, 1969). Large bones have a lower surface to volume ratio than small bones and so persist preferentially in paleosols (Retallack, 1988b). This and their weaker mineralization may also explain the rarity of bones of young compared with old animals (Gordon and Buikstra, 1981; Carpenter, 1982). Teeth persist in more acid conditions and for a longer time than bones, and are found in Quaternary paleosols without associated bones (Evans, 1972). This may be because of the greater density and lesser permeability of teeth compared with bone (Shipman, 1981). Under extremely alkaline conditions (pH 9–10), the growth of salts may promote cracking of bone (Behren-

Figure 6.4　A new compilation of the relative abundance of different kinds of fossils in paleosols of varied Eh, pH and time for development. Percentage values represent the proportion of all the studied paleosols of that category that yielded examples of a particular kind of fossil. (Data from Retallack, 1975, 1976, 1977, 1979, 1983a,b, 1984, 1986, 1991, 1994a,b; Retallack and Dilcher, 1981a,b; Retallack and Ryburn, 1982; Bestland and Retallack, 1994a,b; Retallack et al., 1995, 1997, 1998)

smeyer, 1978). Even unpolluted rain is acidic (pH 5.6), so bones at the surface of the soil weather according to the following sequence: stage 1, superficial longitudinal cracking; stage 2, flaking of outer surface and cracking 1–1.5 mm deep; stage 3, exposed patches of fibrous bone; stage 4, very deep flaking and cracking; stage 5, bone falling apart in places and like a pile of splinters (Behrensmeyer, 1978).

Coprolites have varied original compositions, including fibre, pollen, spores, calcareous phytoliths, shells, scales, arthropod exoskeletons, bones and teeth. They can also be permineralized with calcite, siderite or silica (Bryant and Williams-Dean, 1975; Edwards and Folk, 1979). Organic matter of coprolites is preserved where aerobic bacterial decay is limited by freezing in permafrost, by strong acidity in peat bogs, by excessively reducing water-logged environments or by extreme desiccation in deserts (Heizer and Nap-ton, 1969). Coprolites of birds and carnivorous mammals contain appreciable amounts of bone (Mellet, 1974) and other materials of similar phosphatic composition (Edwards and Folk, 1979). Avian guano is not obviously cop-rolitic because it is amorphous, but its composition becomes similar to that of bone as its organic matter decomposes or is leached. Fresh excrement of the captive pelicans has only 4% P_2O_5, but this has been enriched to 19% in modern Peruvian accumulations of pelican guano, and 29% in old Peruvian guano (Hutchinson, 1950). Similar conditions and processes may account for the reduction in volume, shrivelling and then (after a few weeks or months) bleaching, cracking and powdering of the dung of domestic dogs (Edwards and Yatkola, 1974). Like bone, calcium phosphates are generally stable under alkaline conditions, but the degree of acidity at which they dissolve depends on their crystallinity and chemical composition (Lindsay and Vlek, 1977).

The preservation of organic matter, such as wood, leaf cuticle, plant fructifications, spores and pollen, is controlled more by Eh than by pH. This is mainly because of the activity of aerobic microbial heterotrophs, such as fungi and bacteria, rather than because of direct chemical oxidation (Elsik, 1971; Havinga, 1971; Scheihing and Pfefferkorn, 1984; Burnham, 1985). To a lesser extent, microbial activity also appears to be related to pH. Havinga (1971) observed greater microbial destruction of pollen and spores in the A horizon of a calcareous (3% $CaCO_3$), alkaline (pH 7.1), alluvial clay, than in the A horizon of an acidic (pH 4.6), podzolized sand. Others have observed that mildly alkaline soils (pH 6.5–8.1) are often barren of recognizable pollen and spores (Dimbleby, 1957), although in very alkaline soils (pH 9 or more) microbial activity may be inhibited and allow pollen preservation (Potter and Rowley, 1960). High alkalinity and a tendency to set like Portland cement may also explain the preservation of insects, millipedes, spiders, and the skin and tongues of lizards in carbonatite–nephelinite volcanic ash (Hay, 1986; Retallack, 1991; Retallack et al., 1995).

Charcoal (or fusinite in the jargon of coal petrography; Diessel, 1992) can

Table 6.1　Criteria for distinguishing between fossil charcoal and coalified wood fragments (after Cope and Chaloner, 1980)

Fossil charcoal	Coalified wood
Equant shape	Usually elongate splinters
Sharply broken or rounded ends	Irregular or frayed ends
Black and opaque	Brown to black
Broken surface fibrous	Broken surface conchoidal
Broken surface showing cell structure	Broken surface structureless
No middle lamella between cell walls as seen under SEM	Middle lamella visible between crushed cells under SEM
Resistant to oxidation	Easily oxidized
Found in oxidized and gleyed paleosols	Found in gleyed paleosols
Glows on burning	Burns with bright flame

be distinguished from unburnt coalified wood by a variety of criteria, the best of which is the homogenization of adjacent cell walls visible under the scanning electron microscope (SEM) (Table 6.1). Charcoal is appreciably more resistant to microbial and chemical degradation, and has a longer residence time in soils, than other kinds of organic matter. Organic materials can be ranked in order of resistance to decay, with starch and fructose very easily degraded, but suberin, cutin, resin and amber less easily degraded, and lignin and sporopollenin decay-resistant (Tegelaar et al., 1991). Never-theless, charcoal is more prominent in oxidized than in reduced paleosols, where it is masked by associated uncharred organic material. Charcoal has been widely used for radiocarbon dating of late Quaternary paleosols, which appear to have formed under a wide range of Eh and pH conditions. A dedicated compilation of such data is in order, because pre-Quaternary records remain too sparse to be representative.

Time for Soil Development as a Factor

The destruction of potential fossils by processes controlled by Eh and pH in soils takes time. Fossils favoured for preservation should also increase in relative abundance within the soil through time. Apart from this study is microbial accumulation through time in paleosols of land snails, bones and teeth, and perhaps also of poorly represented calcareous phytoliths, phosphatic cop-rolites and charcoal (Figure 6.4). This is true also of organic matter ac-cumulating within soils as peat. In contrast, there is declining representation of individual plant fossils in increasingly well-developed paleosols (Figure 6.4). Almost all non-peaty terrestrial ecosystems are oxidizing to some extent.

Without intervention of sedimentary cover characteristic of very weakly developed soils, individual fossil plants are bound to decay eventually.

Few studies document temporal trends in fossil preservation in soils and paleosols. In Zimbabwe, corrosion and flaking was notable in bones that were 20 years old, but 800 year-old graves no longer preserved skeletons (Watson, 1967). Accumulation of fossils in soils under favourable conditions also takes time. Surveys of bone accumulation in Amboseli National Park, Kenya (Behrensmeyer, 1982) indicated that thousands to tens of thousands of years are needed to accumulate a fossiliferous paleosol with 10–1000 bones per 100 m², representing the 10 major herbivores. Such processes give a time-averaged assemblage with a resolution of tens of thousands of years (Kowalewski, 1996).

Fossils freshly incorporated in the soil during burial may not have been affected by processes within the soils that tend to destroy fossils of that kind. Thus, fossil snails may be preserved in or on paleosols that were formerly acidic, although their remains are rare compared with those kinds of fossils favoured for preservation. Completely articulated skeletons are usually from animals overwhelmed by catastrophe in mudflows, stream channels or very weakly developed paleosols. In the Eocene Willwood Formation of Wyoming, there is greater representation of complete skeletons in weakly rather than strongly developed paleosols and prospecting has naturally focused on these deposits (Bown and Beard, 1990). Exceptionally preserved, articulated skeletons dominate museum displays, but are rare in paleosols (Retallack, 1988b, 1991).

COMPLETENESS OF THE ROCK RECORD

Ager (1973, p. 100) has well characterized the sedimentary record, which, 'like the life of a soldier, consists of long periods of boredom and short periods of terror'. The short periods of terror are events of sedimentation such as flooding, mudflows and volcanic ash falls. The periods of boredom are times of soil formation, and their duration can be estimated from the degree of development of the paleosols. Paleosols are thus important indicators of gaps in the sedimentary record of geological time. They can be helpful in assessing rates of evolution of mammals, and the duration and discreteness of biostratigraphic zones.

Palaeosols are often an obvious record of the completeness of stratigraphic sections. As soils develop, roots and burrows destroy bedding, schistosity or crystalline structure of parent sediments and rocks. Parent materials also are disrupted by cracking, frost heave and other processes. Weathering in the soil converts silt and sand grains of feldspar to clay and of magnetite to goethite. In this way a bedded silty sediment can be converted into a massive

red claystone. Even at a glance over the spectacularly gullied cliffs of Badlands National Park, South Dakota, the purple-pink, clayey Chadron Formation can be seen to have much better developed soils, and thus a more incomplete record of geological time, than the silty and bedded Brule Formation. Similarly, the Elk Creek facies of the Willwood Formation of Wyoming is temporally more complete than the Sand Creek facies of that formation (Figure 6.3; Bown and Kraus, 1981; Retallack, 1984). The Dhok Pathan Formation of the Siwalik Group of Pakistan is temporally more complete (has more weakly developed paleosols; Retallack, 1991, 1995) than those mentioned above from Wyoming and South Dakota or the Chinji Formation of the Siwalik Group of Pakistan (Behrensmeyer et al., 1995).

These general impressions can be quantified by drawing on information from a growing literature on times for development of Quaternary soils (Bockheim, 1980; Harden, 1990). Such studies aim to generate chronofunctions, which are mathematical relationships between soil variables such as clay enrichment and time for formation. Chronofunctions are based on carefully selected suites of soils for which the other variables of climate, vegetation, parent material and topographic setting are comparable. Such a group of soils is called a 'chronosequence'. Commonly these are soils on fluvial terraces at various elevations in incising river valleys, or on morainal ridges increasingly distant from retreating glaciers. Accurate dating of the surfaces is a major shortcoming of such studies, and includes radiocarbon dating and analysis of archaeological artefacts, fossil mammals and palaeomagnetism.

A qualitative scale of development also has been recognized (Birkeland, 1984; Retallack, 1990). This can be envisaged to proceed on three parallel tracks (Figure 6.2) representing humid well-drained soils (pedalfers of Marbut, 1935), aridland well-drained soils (pedocals of Marbut, 1935) and poorly drained soils (peat swamps in the geological sense). Development of pedalfers proceeds by obliteration of bedding or other original features of the parent material. With time, cracks are lined with clay that creates an increasingly clayey and thick subsurface horizon (Harden, 1982, 1990; Markewich et al., 1990). For pedocals, the accumulation of carbonate proceeds through a series of stages from dispersed wisps to nodules and then massive to laminated layers (Gile et al., 1966, 1980; Machette, 1985). In swamps, peat accumulates at rates of some 0.5–1 mm per year because slower rates allow oxidative decay of organic matter and faster rates create anoxic conditions that kill the roots of the trees supplying the organic debris (Falini, 1965; Moore and Bellamy, 1974). Because of the natural tempo imposed on soil formation by Pleistocene advances of ice sheets, moderately developed soils on the modern landscape are those that formed after the retreat of northern hemisphere ice some 15000 years ago (Birkeland, 1984). These are pedalfers with clay enriched to about 8% more in subsurface than surface horizons of

the soil, pedocals with carbonate accumulation to the nodular stage and peat accumulated to a thickness of about 40 cm. These are the limits used by the US soil taxonomy for argillic and calcic horizons, and for Histosols (Soil Survey Staff, 1975, 1990). Weakly and strongly developed soils can be calibrated to orders of magnitude less or more time. This order of magnitude scale lacks precision, but has the advantage of wide applicability.

Such a yardstick of paleosol development can be used to estimate both resolution and completeness of stratigraphic sections. Resolution is a question of scale or the time interval in years for which a sequence can be considered to have a relatively complete record of events. Completeness, on the other hand, is a measure of the reliability of a sequence at a given resolution. A complete sequence at a resolution of 1000 years should have on average a bed, paleosol or other record of geological time for every interval of 1000 years. A sequence of paleosols can be regarded as complete at a resolution that is equivalent to the average time of formation of its individual paleosols. Completeness can be estimated for finer resolutions as a fraction or percentage of that resolution (Retallack, 1990).

A more complex way of estimating stratigraphic completeness is by comparing rates of sediment accumulation of a sequence with rates usual for that environment and time span, as estimated from a large compilation of rates (Sadler, 1981; Anders et al., 1987). Rates of sediment accumulation can be distinguished from rates of rock accumulation (Kraus and Bown, 1986, 1993a), with rock accumulation converted to sediment accumulation by compensating for burial compaction using standard curves (Sclater and Christie, 1980; Baldwin and Butler, 1985). Such conversions are not necessary for using the compilations of Sadler (1981) and co-workers (Anders et al., 1987), because their long-term rates were calculated for rock sections uncompensated for compaction. A shortcoming of this probabilistic approach using typical sediment accumulation rates is that it fails to demonstrate the exact position and duration of the gaps, as is potentially possible using paleosols (Retallack, 1994b).

A Tale of Two Sections

Whether a sequence of paleosols was the best for time or the worst for time can be illustrated by comparison of late Eocene and early Oligocene paleosols of Badlands National Park, South Dakota and Painted Hills National Monument, Oregon (Figure 6.5; Table 6.2). These two terrestrial sequences of paleosols can be correlated using mammalian biostratigraphy, palaeomagnetic stratigraphy and numerous ^{39}Ar/^{40}Ar radiometric dates (Prothero and Rensberger, 1985; Swisher and Prothero, 1990; Prothero and Swisher, 1992; Prothero, 1996; Tedford et al., 1996; Bestland et al., 1997), and these force

	Chadronian		Orellan		Whitneyan	
	Painted Hills	Badlands	Painted Hills	Badlands	Painted Hills	Badlands
Thickness (m)	12	23	98	38	114	46
From paleosol minimum times — Time (years)	229 000	106 005	454 900	80 135	469 700	65 920
Rate (m/1000 yrs)	0.052	0.213	0.215	0.479	0.243	0.701
Resolution (years)	14 313	5889	3273	3339	2973	2535
Completeness (% of 1000 yr intervals)	7	17	31	30	34	39
From paleosol maximum times — Time (years)	645 000	930 500	1 396 500	648 500	1 385 500	307 000
Rate (m/1000 yrs)	0.019	0.024	0.070	0.059	0.082	0.150
Resolution (years)	40 313	51 694	10 047	27 020	8769	11 808
Completeness (% of 1000 yr intervals)	2	2	10	4	11	9
From radiometric times — Time (years)	1 700 000	1 700 000	2 000 000	2 000 000	2 000 000	2 000 000
Rate (m/1000 yrs)	0.007	0.013	0.049	0.019	0.057	0.023
Resolution (years)	1 700 000	1 700 000	2 000 000	2 000 000	2 000 000	1 700 000
Completeness (% of 1000 yr intervals)	0.9	1.6	6.1	2.4	7.1	2.9

Table 6.2 Resolution and completeness of late Eocene and early Oligocene sequences of Badlands National Park, South Dakota and Painted Hills National Monument, Oregon, estimated from maximum and minimum times of paleosol development (see text) and from radiometric rates of sediment accumulation (following Sadler, 1981)
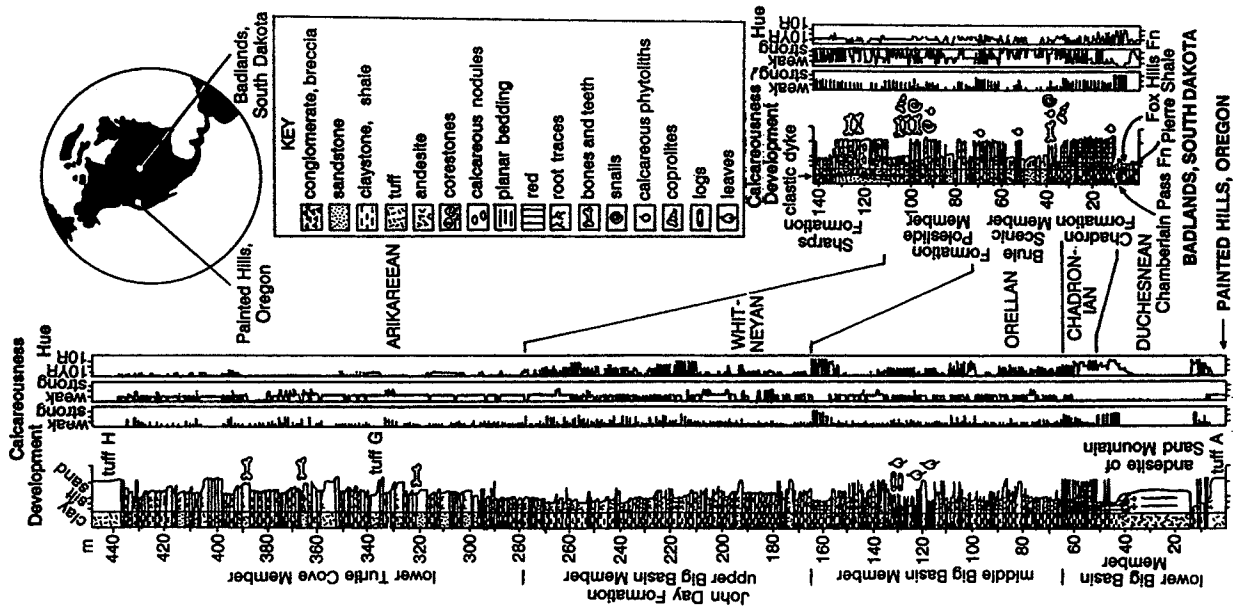
minor revision in previous estimates of completeness (Retallack, 1984, 1986). The Painted Hills sequence is thinner than the Badlands sequence for an interval correlated with the Chadronian North American Land Mammal 'Age', but thicker for the succeeding Orellan and Whitneyan North American Land Mammal 'Ages'. This indication of an inferior completeness of the Orellan and Whitneyan in Chadronian, but a superior completeness of the Orellan and Whitneyan in the Painted Hills, is confirmed by the nature of paleosols in each section. The Painted Hills have more weakly developed paleosols than the Badlands (generally shorter temporal resolution from paleosols in Table 6.2). In both areas resolution and completeness increase up-section, regardless of whether minimum or maximum rates of soil formation are used (Table 6.2). Palaeosols give a more detailed impression of these relative changes than radiometry.

These estimates help to resolve an important area of doubt remaining from earlier analysis of completeness of the Badlands section (Retallack, 1984). In that study it was shown that rates of sediment accumulation estimated from paleosols were much higher than rates estimated from radiometric data, as can be seen here (Table 6.2). Estimates of completeness and resolution thus remain more optimistic from paleosols than from radiometry. This discrepancy indicates that there are more gaps than meet the eye in these paleosol sections.

The hundreds of thousands of years of time missing are unlikely to be lost in underestimated soil development due to the paleosols reaching a steady state in age-diagnostic features, because this has not been found in recent analysis of adequately resolved chronosequence data used to estimate times of development of the paleosols (Harden, 1990). The missing time is only partly compensated by estimated maximal times of paleosol development, as recommended by Kraus and Bown (1986). Even with generous maximum times of soil formation, rates of sediment accumulation are still two to four times greater than rates estimated from radiometric data (Table 6.2).

Nor is much time likely to be lost in paleosol overprinting. By this is meant the obscuring of one soil by development of a later soil on the same material. Cases of overprinting have been detected in the Painted Hills where clasts or relict horizons of moderately to strongly developed pre-existing soils indicate an unusual degree of weathering in a paleosol (Bestland et al., 1996). One cate an unusual degree of weathering in a paleosol (Bestland et al., 1996). One moderately to strongly developed paleosol overprinting another is rare in my experience, but has also been noted elsewhere (Gardner et al., 1988; Hughes et al., 1992). The more usual case of a strongly developed soil

Figure 6.5 (opposite) *A comparison of late Eocene and early Oligocene sequences of paleosols in Badlands National Park, South Dakota and Painted Hills National Monument, Oregon. (From Retallack, 1983b, and Bestland and Retallack, 1994b, with addition of 'Redcap paleosols' at the top of the Orellan-equivalent interval in the Painted Hills)*

(hundreds of thousands of years) overprinting weakly developed ones (tens of years) involves too little time to be significant.

Instead, the time seems to have disappeared in major disconformities between packages of similar paleosols. The similarity of purple-pink clayey paleosols in the Chadron Formation and their strong contrast with brown silty paleosols in the Brule Formation is probably a reflection of a relatively short duration of accumulation of each formation compared with the gap in time between formations. Palaeovalleys and other erosional discontinuities at the base of the Chadronian and Duchesnean sequences have recently been mapped throughout the Badlands of South Dakota (Terry and Evans, 1994). Erosional gaps at the base of the Orellan and Whitneyan sequences in the Badlands of South Dakota have now been demonstrated by truncation of magnetic reversals along strike of these discontinuity surfaces compared with sections further west (Prothero et al., 1985; Prothero, 1996; Tedford et al., 1996). Completeness of the record within members and formations in the Painted Badlands may be superior to that within comparable units in the Painted Hills, but the Painted Hills overall provides the more complete record, because the discontinuities between units are less profound.

This discovery has important implications for studies of mammalian evolution based on the fossil record of Badlands National Park. Because the sequence is a succession of high-resolution subsequences, separated by profound temporal gaps, it is not surprising that it has been used to support the concept of evolution by punctuated equilibrium (Heaton, 1993; Prothero et al., 1998). Mammal fossils within the successive sedimentary units show little morphological change, interpreted as evolutionary stasis, and they appear and disappear abruptly near the boundaries of the units. Thus, it has become even clearer with this analysis than during initial studies (Retallack, 1984, 1986) that the Badlands of South Dakota are a poor choice for evolutionary studies. Even though the Painted Hills sequence has greater temporal completeness than the Badlands of South Dakota, paleosols in the Painted Hills are non-calcareous and unsuitable for bone preservation except at the very top of the sequence where mammal remains are fragmentary and poorly preserved. Better sequences for the study of mammalian evolution are in the Willwood Formation of the Bighorn and Clarks Fork Basins of Wyoming (Figure 6.3; Gingerich, 1976, 1980, 1985, 1987; Bown and Kraus, 1993; Gingerich and Gunnell, 1995), and in the Siwalik Group of Pakistan and India (Barry et al., 1990, 1991; Retallack, 1991, 1995). These sequences were deposited under sustained high rates of sediment accumulation, and have long seccessions of weakly to moderately developed, calcareous paleosols. Nevertheless, it is doubtful that, even in these sections, major discontinuities can be assumed to be negligible, as implied by methods that allot geological time in proportion to the development of paleosols (Bown and Larriestra, 1990; Bown and Kraus, 1993; Kraus and Bown, 1993a). Such approaches assume a

degree of completeness that is unrealistic. The degree of completeness of any section should be determined, not assumed.

Recent high-precision radiometric dating and magnetostratigraphic correlation show that the big temporal gaps in the Badlands sequence coincide with temporally lesser gaps in the Painted Hills, and these are synchronous with marine regressive lowstands in shallow marine rocks of late Eocene and early Oligocene age (Bestland et al., 1997). This is a remarkable set of coincidences, considering that during the late Eocene and Oligocene the Badlands of South Dakota were at least 1600 km north of the Gulf coast of that time, and 1300 km east of the Painted Hills, which were separated from the former Pacific coast by a 300 km wide volcanic mountain range now preserved in the Western Cascades. It is difficult to imagine sea level having such long-distance effect into continental interior basins. Cratonic South Dakota and volcanic Oregon were also very different tectonic provinces and had dissimilar subsidence regimes. The common thread between these two sections is variation in climate, which has already been shown to be the principal control on sedimentation in the Badlands in a multifactorial comparison (Retallack, 1986).

Sequence Stratigraphy for Palaeosols

Possible explanations for the distribution of gaps in paleosol sequences can be gained by studying the pattern of development of paleosols (Figure 6.6), in an approach analogous to sequence stratigraphy of marginal marine rocks (Posamentier and Vail, 1988; Wilson, 1991; Emery and Myers, 1996). Two contrasting patterns of development of successive paleosols are evident in the Badlands and Painted Hills (Figure 6.5). The Painted Hills sequence has a sinuous pattern where development rises and falls in successive paleosols. One exception is the probable Chadronian portion of the Painted Hills sequence, which is like the Badlands sequence in showing a sawtooth pattern of development. Sawtooth patterns show a steady increase in development of successive paleosols until a sudden switch to weakly developed paleosols, then build up again to better-developed paleosols higher in the next sequence. The sawtooth pattern shows ageing-upwards sequences of paleosols, whereas the sinuous to irregular pattern has alternating ageing-upwards and younging-upwards sequences. Other examples of sinuous patterns are in the Siwalik Group of Pakistan (Retallack, 1991, 1995), the Hiwegi Formation of Kenya (Retallack et al., 1995), and the Fremouw Formation of Antarctica (Retallack et al., 1997b). Other examples of the sawtooth pattern are in the Clarno Formation of Oregon (Retallack et al., 1996), Chinle Group of Arizona (Kraus and Middleton, 1987), Beaufort Group of South Africa (Smith, 1990), Illawarra Coal Measures of Australia (Retallack, 1998) and Buckley Forma-
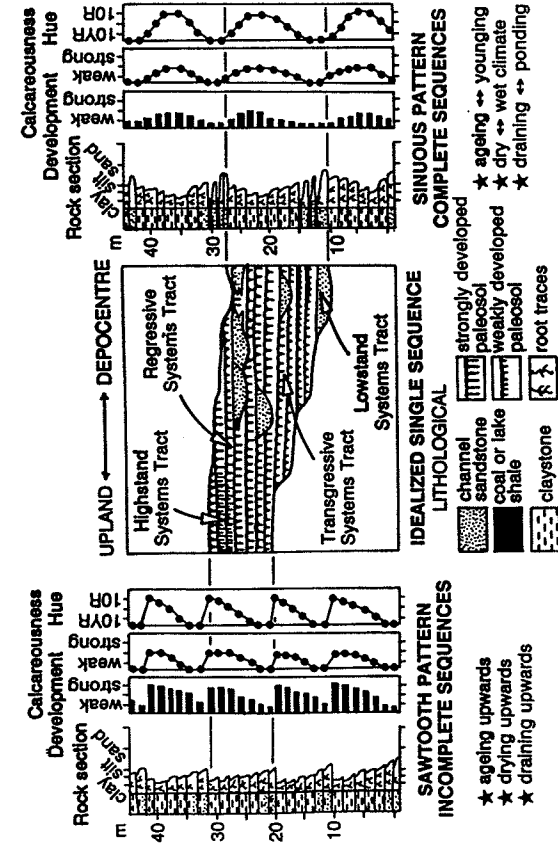
Another sedimentary explanation for ageing-upwards sequences of paleosols is palaeochannel migration (Kraus, 1987; Smith, 1990; Kraus and Bown, 1993b). However, the Whitneyan, Orellan and Chadronian sequences described herein (Figure 6.5) each include numerous levels of palaeochannels, and are cycles of longer duration (millions of years; Table 6.2) than alluvial cycles (thousands of years). Both the Badlands and Painted Hills, as well as other paleosol sequences (Wright, 1992), include paleosols traceable laterally for distances of many kilometres, indicating major regional pauses in sedimentation.

Another common explanation is tectonic uplift of the source area (Kraus, 1992). Source-area uplift has been discounted in the Badlands of South Dakota for two out of three sequence boundaries by unchanging or decreased proportions of far-travelled clasts in lower compared with upper portions of the sawtooth developmental pattern of paleosols (Retallack, 1986). Uplift of the sedimentary basin is a plausible explanation for disconformities at the breaks in the sawtooth pattern, but not for the increased stability indicated by paleosols below the break. Declining subsidence upsection is also possible, but how would this be synchronized in 2-Myr pulses in such distant places as Oregon and South Dakota? Milankovitch-scale periodicity of 21 000, 41 000, 95 000, 123 000 and 413 000 years has been found in many paleosol sequences: in the Miocene of Pakistan (Retallack, 1991), Oligocene of Oregon (Bestland and Swisher, 1996), Cretaceous of Switzerland (Strasser, 1988), Triassic of United States (Olsen, 1986), and in the Pennsylvanian of United States (Cecil, 1990). This periodicity in paleosol sequences more likely has orbital or palaeoclimatic than tectonic explanations (Olsen, 1986). The role of tectonics can be envisaged as analogous to that of a tape recorder. If relative subsidence rates are high, then the sequence records palaeoenvironmental signals with high fidelity. If subsidence rates are low, then the recording is less faithful to the signal. High-fidelity recording is facilitated by active subsidence, but the message comes from elsewhere.

Yet another explanation is increased volcanic input in lower compared with upper parts of sawtooth developmental patterns. It is true that the weakly developed paleosols of the lower parts of sequences are separated by less-weathered volcaniclastic sediments in Oregon (Retallack et al., 1996) and Kenya (Retallack, 1991). However, the really big eruptions, such as lava flows and ash-flow tuffs, are underlain and overlain by similar paleosols, leaving unaffected the sawtooth developmental pattern (Figure 6.5). Big eruptions can override the pattern, but small eruptions are either preserved or weathered away depending on their timing within the pattern. In the Badlands of South Dakota, volcanic ash either decreases or is unchanging across sequence boundaries despite an overall increase up-section (Retallack, 1986). The Milankovitch periodicities widely observed in paleosol sequences (Ol-

Figure 6.6 A sequence stratigraphic model for paleosols

tion of Antarctica (Retallack et al., 1998). The sawtooth pattern is especially common in coal measures where clastic deposition declines up-sequence to allow accumulation of thick sequence-capping coal seams (Arditto, 1991; Hampson, 1995; Herbert, 1995; Holdgate et al., 1995; Hampson et al., 1996; Retallack, 1998).

The sinuous pattern is one of high sedimentation rates and high long-term completeness, whereas the sawtooth pattern is one of relatively low sedimentation rates and low long-term completeness. The sawtooth itself allows identification of the most profound gaps in the sequence. They are at the break between the most strongly and most weakly developed paleosols in the sequence. This can be true even if the most strongly developed paleosols with only moderately developed. Very strongly developed, thick paleosols with silcretes, laterites and bauxites show sedimentary hiatuses of millions of years, all by themselves (Retallack and German-Heins, 1994; Bestland et al., 1996).

The causes of long-term sawtooth sequences of paleosols can be discerned from evidence within the paleosols themselves. A common explanation for such patterns is marine transgression to a stillstand (Kraus, 1992; Hampson, 1995; Herbert, 1995; Holdgate et al., 1995; Hampson et al., 1996). This may play a role in some coastal sequences (Retallack, 1979, 1983b, 1994a, 1998; Percival, 1986; Strasser, 1988). Marine transgression does not account for other sawtooth sections such as the Eocene–Oligocene sequences of South Dakota and Oregon (Figure 6.5), which were very remote from the sea.

sen, 1986; Strasser, 1988; Cecil, 1990; Retallack, 1991; Bestland and Swisher, 1996) also are unlikely to have a volcanic cause.

An explanation that does appear to have some merit is that the sawtooth pattern of paleosol development follows variation in degree of drainage of paleosols. The lower parts of paleosol sequences are commonly drab in colour, with minerals such as siderite and pyrite (Cecil *et al.*, 1985; Cecil, 1990; Bown and Kraus, 1993). Root traces in these paleosols are tabular rather than vertically penetrating and animal burrows are rare. These are all indications of poorly drained paleosols (Retallack, 1990; PiPujol and Buurman, 1994). In contrast, the upper parts of sequences are commonly red in colour with minerals such as goethite and haematite, and have evidence of clays and silts washed down into deeper parts of the profile. They also commonly have deeply penetrating root traces and common burrows of non-aquatic animals such as termites and mongooses. These are all indications of well-drained paleosols (Retallack, 1976, 1990; Fastovsky and McSweeney, 1987; Besly and Turner, 1989). Differences in drainage may be more subtle in coal-measure sequences formed in very waterlogged terrains, but can still be inferred from petrographic measures of declining vitrinite content up-section within coal seams (Smyth, 1970; Cook, 1975; Shibaoka and Smyth, 1975). Such trends could reflect declining subsidence rate up-section, but could also be due to filling to a new dynamic equilibrium. These two alternatives are difficult to distinguish on a local level, but regional correlations tend to support the second alternative. The draining-upwards paleosol sequences of the North American Chadronian and Orellan are better drained at any comparable level in Nebraska compared with South Dakota (Retallack, 1992) and in Oregon's Picture Gorge compared with the Painted Hills (Bestland and Retallack, 1994b). Because the better-drained sequence is also thinner and closer to the source area, this supports the concept of filling to a new equilibrium rather than differential subsidence.

A final possibility is the tendency of paleosols that are higher within a sawtooth pattern of paleosol development to indicate a drier palaeoclimate. This is especially evident in sequences of calcareous paleosols like those of South Dakota's Badlands, where the mean annual rainfall is reflected by the depth to the calcareous nodular horizon of the paleosols (Schultz and Stout, 1980; Thompson *et al.*, 1982; Retallack, 1986, 1994b). In such cases the calcareous nodular horizons become shallower and shallower in each successive paleosol up-section, reflecting an increasingly dry climate. Such climatic change could also explain in part the common observation of draining-upwards sequences of paleosols, such as coals grading up through drab clayey to red clayey paleosols (Cecil *et al.*, 1985; Cecil, 1990; Bestland *et al.*, 1997). Climate is also a plausible link to marine regression and transgression. Warmer, wetter, greenhouse climates with little polar and glacial ice alternating with glacial advances during cooler, drier, oxygen-rich climates have

been a conspicuous feature of the Quaternary (Catt, 1986; Crowley, 1990). Drying-upwards sequences of paleosols may reflect such climatic variability on a variety of temporal scales ranging from millions to hundreds of years.

Whatever the cause in any given section, it is common for paleosols to form sawtooth developmental sequences that age upwards, drain upwards and dry upwards. The abrupt changes in development represent discontinuities in sediment accumulation that are not apparent from sequences of high sediment accumulation rate in which development of successive paleosols form a sinuous pattern. The discontinuities of sawtooth developmental sequences are major gaps in the sedimentary record, more significant than gaps between individual paleosols or created by overprinted soil development.

CONCLUSIONS

Palaeosols constitute a record of the past that is complementary to the fossil record. Palaeosols are in a sense trace fossils of ecosystems, which can be compared with the record of ecosystems from fossils. Former Eh and pH can be inferred from paleosols, and these are important variables in the preservation of different kinds of fossils. Fossils of organic matter such as leaves, logs, pollen and charcoal, for example, are preserved preferentially in chemically reducing (low negative Eh) environments such as bogs and swamps. This is because they are readily decayed by fungi and other aerobic decomposers under oxidizing conditions. Fossils of aragonite and calcite, such as snail shells, and of phosphate, such as bones and teeth, are relatively resistant to decay, but prone to dissolution by acid. They are seldom found in acidic soils and paleosols, and preferentially accumulate in calcareous alkaline soils of dry regions.

Palaeosols also can reveal breaks in sedimentation by their degree of development. Weakly developed soils and paleosols show little change from their parent materials other than rooting. Strongly developed soils, on the other hand, show considerable subsurface accumulation of clay or carbonate, or surface accumulation of peat. Each paleosol is in itself a break in sedimentation, but there are common patterns of development of successive paleosols that can reveal longer breaks in sedimentation. Sawtooth patterns of development have ageing-upwards sequences of paleosols, and major discontinuities are commonly located between the most strongly developed and the least developed paleosols. Because many incomplete sequences of paleosols accumulate by this pattern of punctuated equilibrium, it is perhaps not surprising that this would be an inferred pattern of mammalian evolution in them. Sequences of paleosols best for evolutionary studies are those that accumulated at high long-term sedimentation rates, with relatively weakly developed paleosols showing sinuous patterns of paleosol develop-

ment. Ageing-upwards sequences of paleosols commonly also are draining-upwards sequences and drying-upwards sequences, and in addition can be correlated with global changes in relative sea level. A common denominator of many of these changes is climate, which has a powerful influence in creating sequences of paleosols.

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