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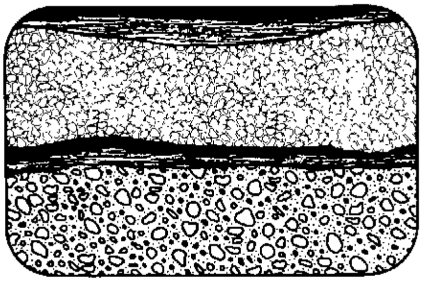
Résumé de l'article

Paleosols, particularly buried paleosols, have proved valuable stratigraphie markers in many Quaternary studies. They are most commonly found buried by loess in central Europe and the United States, and by volcanic ash in the Pacific margins. Within their morphologies are recorded evidence of past climates and vegetations. The understanding of paleosols has paralleled our comprehension of contemporary soils and hence the methods of investigation of paleosols are those that have found common usage in the study of the soils of today. The recognition of paleosols is thus largely based on the identification of characteristics known in contemporary soils.

The usefulness of paleosols as stratigraphic indicators is in part due to their extensive and recognisable occurrence over large areas and because they often contain material suitable for absolute dating by the 14C method. Wood, charcoal, peat and soil organic matter have all been employed in the dating of paleosols. 14C dating of secondary carbonates or oxalates and of plant opal phytoliths, whilst more difficult than the dating of wood, etc., are also possibilities for the Quaternary paleopedologist. Relative dating techniques, particularly changes in the composition of organic matter after burial, have also proved useful in some studies.

The reconstruction of paleo environments from paleosol morphology presents many problems and conclusions must be derived from as many lines of evidence as possible. Pollen, opal phytoliths, faunal remains, micro morphology and mineralogical composition should all be investigated and the results integrated to provide a consistent picture of past climates and vegetations. A lack of understanding of pedology can often lead to erroneous conclusions.



Dating Methods of Pleistocene Deposits and Their Problems: VII. Paleosols

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Summary
Paleosols, particularly buried paleosols, have proved valuable stratigraphic markers in many Quaternary studies. They are most commonly found buried by loess in central Europe and the United States, and by volcanic ash in the Pacific margins. Within their morphologies are recorded evidence of past climates and vegetations. The understanding of paleosols has paralleled our comprehension of contemporary soils and hence the methods of investigation of paleosols are those that have found common usage in the study of the soils of today. The recognition of paleosols is thus largely based on the identification of characteristics known in contemporary soils.

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The reconstruction of paleoenvironments from paleosol morphology presents many problems and conclusions must be derived from as many lines of evidence as possible. Pollen, opal phytoliths, faunal remains, micromorphology and mineralogical composition should all be investigated and the results integrated to provide a consistent picture of past climates and vegetations. A lack of understanding of pedology can often lead to erroneous conclusions.

Introduction
Part of the voluminous and varied record of the Quaternary is contained within soils that have themselves been buried by geologically significant events ascribable to the Quaternary. Part of this record is expressed in the morphology of soil profiles that show different degrees and stages of horizon development that in turn correspond to the varying lengths of time the soil forming materials had been exposed to pedological processes (Thorp, 1965). These ancient soils are generally referred to as paleosols (from Greek, *palaeo* ancient, and Latin, *solum* soil), and their study as paleopedology.

Paleosols are increasingly becoming the subject of study of many branches of the natural and earth sciences, including pedology, biology, stratigraphy, sedimentology, geomorphology, etc. It is the purpose of this paper to present a general introduction to the study of paleosols, with particular reference to their use in Quaternary studies. Aspects of their recognition, techniques used for their dating, and problems associated with with their use as stratigraphic markers will be considered.

Three general types of paleosols are recognised. These are 1) *buried soils*, which are formed on pre-existing landscapes but have become buried by subsequent geological processes, 2) *relict soils* which occur on relatively stable ancient land surfaces and have not been buried by younger sediments, and 3) *exhumed soils*, which are found on existing landscapes but were originally buried and have become re-exposed on the land surface by erosion of the covering material (Ruhe, 1965). As buried soils have found the greatest application in Quaternary studies this review will concentrate almost exclusively on this type of paleosols.

Buried soils are commonly found near the periphery of the furthermost extent of glacial ice and are thus usually covered by loess or, less frequently, by glacial till. They are often also associated with destructive plate margins and are thus covered with volcanic ash. Buried soils associated with glacial deposits are thus frequently encountered in the northeastern region of the United States, the central parts of northern Europe and the central regions of the Soviet Union. Paleosols covered with volcanic ash are commonly encountered in Japan, New Zealand and the western fringes of North America. Paleosols, such as those found in Saskatchewan, can also be associated with the rapid migration of sand bodies (Turchenek *et al.*, 1974) or, as in Ireland, with the rapid development of peat (Carey and Hammond, 1970).

Many paleosols occurring in similar stratigraphic positions have characteristic features, such as distinctive horizons, that often permit consistent recognition over considerable areas and thus their use as stratigraphic tools for Quaternary deposits has become firmly established. Paleosols have been one of the primary criteria for separation of the Nebraskan, Kansan, Illinoian and Wisconsin deposits of North America. The possibilities of paleopedology in Quaternary studies have been discussed by Frye (1949), Ruhe (1965), Yaalon (1971), Buurman (1975) and Catt (1979).

The methodology and techniques used to describe and characterize paleosols are those that have found common usage in the study of contemporary soils. Hence many of the soil properties that are measured during routine soil survey are the same properties that have often proved useful in paleopedological studies. The climate, vegetation and moisture condition under which the paleosol developed can often be inferred from a study of such soil properties as colour, depth to carbonates, mineral alteration and solum development.

Historic Review
Historically the Sangamon soil is one of the most thoroughly studied paleosols of any region. Located beneath the Wisconsinian loess sheet and above the Illinoian till sheet, it has proved to be a valuable stratigraphic marker in many parts of the mid-western United States. Soils of Sangamon age have been traced from Ohio through the type area in Illinios to southwestern Texas, a distance of some 3,300 kilometres (Fry and Leonard, 1965). The Sangamon soil was first described by Leverett (1898). The present status of the Sangamon soil has recently been reviewed by Follmer (1978).

In Europe, buried soils extending from East Germany to the Soviet Union have been studied over many years and many are believed to have formed during the Riss-Wurm Interglacial. Examples of these paleosols are the Stillfried in Austria, the Paudorf in Czechoslovakia and the Mezin in the Soviet Union. The majority of these soils are covered by loess and their use as stratigraphic markers has been discussed by Kukla (1975).

Since these early studies on paleosols, further investigations have been pursued

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in Europe (Icole, 1971; Muchenhausen, 1973), the Soviet Union (Morozova *et al.*, 1979), the United States (Simonson, 1954; Ruhe, 1965), Canada (Rutter, 1969; Dormaar, 1978), New Zealand (Leamy *et al.*, 1973) and South America (Folster *et al.*, 1977). In addition to these studies on Pleistocene paleosols, paleosols of Tertiary age have also been reported on in Belgium (Buurman, 1972), Brazil (Mabesoone and Lobo, 1980), Mexico (Abbott *et al.*, 1976) and the United States (Abbott, 1981).

The evolution of the concepts of buried soils has paralleled current developments in pedology and early confusion on the use of such terms as gumbotil and accretion gley have largely been resolved (Frye *et al.*, 1960). Problems of horizon nomenclature for paleosols however still remain (Bos and Sevink, 1975), and recently Catt (1977) has suggested that the term paleosol be restricted to buried soils of at least 10,000 years of age and the term neosol be used for soils of more recent burial.

Recognition of Paleosols

Recognition of paleosols is generally based on the difference in morphology between the paleosol and the materials above and below and much care is needed in the interpretation of these differences before a positive identification can be made. As many different lines of investigation as possible need to be pursued before the presence of a paleosol can be unequivocally established. A recent paper by Brown and Kraus (1981) outlines many commonly used identification techniques in paleopedology.

Buried soils generally occur at the contact between two different types of surficial materials, e.g., loess/till, and have developed in the underlying material. There will be an unconformity between the top of the paleosol and the overlying material. Pedological processes will have imparted to the soil parent material visual characteristics that are recognisable in the form of horizons. Both horizons of loss (eluviated) and gain (illuviated) are generally present in soils. A diagrammatic representation of a paleosol is shown in Figure 1.

The dark colours of soil surface horizons generally result from the accumulation of organic matter and are probably the most distinctive and initial indicators of the presence of paleosols. Subsequent analysis of organic carbon contents and the depth distributions of clays, iron and aluminum oxides/hydroxides, or carbonates may substantiate the presence of a paleosol. As the presence of plant material is ubiquitous in the surface horizons of soils, the presence of pollen, together with insect remains, at some considerable depth within dark coloured horizons, should confirm the presence of a paleosol. Changes in the infrared spectra of humic acids and the presence of plant opal phytoliths (see below) have also been suggested as useful indicators for the presence of paleosols (Dormaar and Lutwick, 1969). The presence of archaeological artifacts such as pottery, tools or arrow heads may also prove useful in some specific instances.

Soil surface horizons are generally zones of maximum mineralogical weathering. Hence a change in the clay mineral composition with depth or the disappearance of easily weatherable minerals may indicate relict pedological processes. Similarly, the illuviation of soil constituents in paleosols can lead to characteristic features recognisable in thin sections (Dalrymple, 1958). The presence of orientated clay (argillans), accumulations of iron or manganese (glaebules), secondary carbonates (calcans) or presence of charcoal (α - anthracons) are micromorphological features that have been recognised in paleosols (Bullock *et al.*, 1973; Griffey and Ellis, 1979; Sturdy *et al.*, 1979; Valentine *et al.*, 1980).

Special problems arise in paleosols that have been truncated during burial, or where a buried soil horizon exists within the solum of a contemporary soil. Gould *et al.* (1979) used the presence of opal phytoliths and increased enzymatic activity at depth within a soil profile to establish the presence of a buried horizon, while Sturdy *et al.* (1979) used a combination of micro-morphology, particle size distribution, clay mineralogy and depth distribution of soil constituents to identify a similar horizon as a paleo feature in a contemporary soil of England.

Absolute Dating Techniques

Probably the most widely used dating technique in the study of paleosols, and for soils in general, is ^{14}C dating, introduced into paleopedology by Felgenhauer *et al.* (1959). The use of this technique has been reviewed recently by Scharpenseel and Schiffman (1977). Radiocarbon dating depends essentially upon examination of material produced by the photosynthetic fixation of atmospheric ^{14}C by autotrophic organisms. Once incorporated, it is assumed that there is no exchange with the environment and the progressive decay of the radioactive isotope in situ can be used, with certain assumptions, to measure the age of the sample. With a half-life of 5,730 years, ages can reasonably be measured to 50,000 years.

Wood (Forsyth, 1965), peat (Borchardt *et al.*, 1973), charcoal (Sorenson *et al.*, 1971; Valentine *et al.*, 1980) and extracted fractions of soil organic matter (Griffey and Ellis, 1979; Mahaney and Fahey, 1980) from paleosols have all been dated. Both wood and charcoal samples are susceptible to transport, adsorption of organic compounds and penetration by recent fungal mycelia (Godwin, 1969; Geyh *et al.*, 1971), and suitable precautions and pretreatments are often required prior to analysis (Scharpenseel *et al.*, 1968). Limmer and Wilson (1980) suggest that the amino acid composition of paleosols should be examined before ^{14}C dating, as the presence of certain amino acids would indicate recent contamination.

Goodwin *et al.*, (1957) comment that "uncritical investigators, incompetent to recognise unsuitable material or unwilling to reject it are increasingly submitting for dating samples that bring nothing but

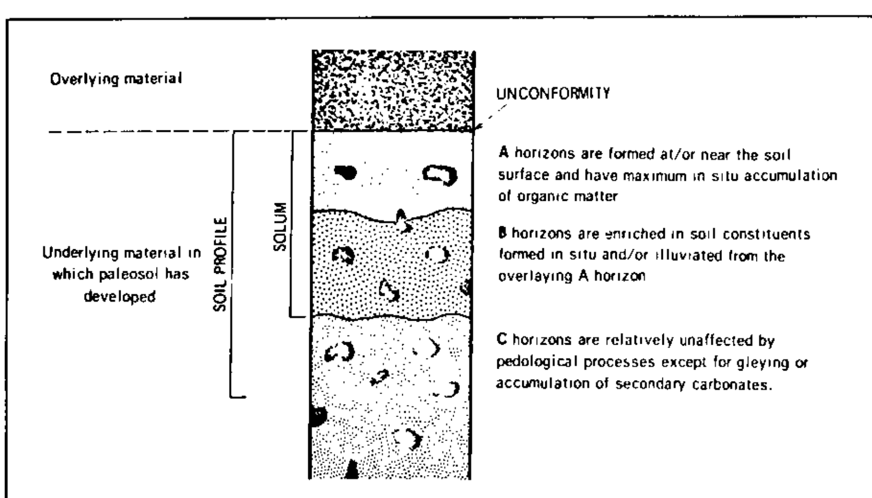

Figure 1 *Diagrammatic representation of a Paleosol.*

confusion and irritation to the literature of Quaternary research". It is believed that only in peats consisting of plant remains in situ that unique ages can be ascribed by the ^{14}C dating method (Perrin *et al.*, 1964) and then only if root penetration from recent plant growth is negligible. Nichols (1969), for instance, has shown that the ^{14}C ages of basal peats in Canada correspond to the dates already established for climatic changes, and dating of peat layers in eastern Oregon has proved useful in correlating deposits of Mazama volcanic ash (Borschardt *et al.*, 1973).

The extraction and dating of various fulvic, humic and humin fractions of soil organic matter, whilst revealing an increasing resistance to breakdown from fulvic to humin fractions, has proved of limited value in providing absolute ages of contemporary soils and has merely confirmed the rapid turnover of soil organic matter (Martel and Paul, 1974). However, with buried paleosols the method is potentially more promising and David (1966) used ^{14}C dates of soil humus to establish the age of the Prelate Ferry paleosol in Saskatchewan. The exclusion of atmospheric oxygen by burial should effectively inhibit any biological breakdown of organic matter. A number of problems can arise, however, including contact with oxygen-rich ground water, illuviation of younger organic matter from above and deep penetration by plant roots. Polach and Costin (1971), for instance, found a consistently younger age for soil organic matter extracted from four paleosols when compared to wood remains from the same soil profiles.

Some attention has been given to the possibility of ^{14}C dating of secondary carbonates in soils and paleosols, although the results to date have been disappointing. Williams and Polach (1969), for instance, found radiocarbon dates for secondary soil carbonates 3,600 years older than anticipated and ascribe this to the low ^{14}C content of ground water - the 'limestone dilution effect' of Broeker (1965), sometimes called the "hard water effect". On the other hand, Bowler and Polach (1971) found some dates younger than the presumed age of the sediment in which the carbonates had formed. They suggested exchange with modern ^{14}C in percolating water as a possible explanation of the results. These differences in ages became more significant in humid regions. Mean residence times for soil carbonates have also been shown to increase with increasing particle size and St. Arnaud (1979) has concluded that it is only for clay-sized secondary carbonates precipitated at some depth in the soil profile that realistic dates can be obtained. It would therefore seem that secondary carbonate ^{14}C dating is most useful for paleosols from arid and semi-arid areas in which there is no evidence of contamination from fluctuating ground water, and in which the secondary carbonates can be distinguished from inherited carbonates by their presumed smaller particle size.

The possibility also exists of using organic matter occluded in plant opal phytoliths as a source of ^{14}C (Jones and Beaver, 1963). Opal phytoliths are silica bodies formed in the epidermal cells of plants, particularly grasses, and these phytoliths accumulate in soils after the vegetation has decomposed (Geis and Jones, 1973). Pretreatment of the phytoliths with boiling chromic acid or hydrogen peroxide is usually necessary to remove contaminants from the phytoliths prior to dating (Wilding *et al.*, 1967). The major problems with using phytoliths in dating are: 1) their low content in most soils, ranging from 0.1 to 3% for many soils (Wilding *et al.*, 1977); 2) difficulties in their separation from soils; and 3) their low carbon contents (approximately 1%). Wilding (1967) required 45 kg of soil to obtain 60 g of phytoliths, which in turn contained 0.75 g of carbon and gave a ^{14}C age of 13,300 ± 450 years B.P. The logistical problems of using opal phytoliths are thus obvious.

Another possible pedogenetic source of ^{14}C is calcium oxalate. Graustein *et al.* (1977) have shown that both naturally occurring forms of calcium oxalate (weddellite and whewellite) are probably more widespread in soils than previously believed, and Jones *et al.* (1980) and Wilson *et al.* (1980) have reported on the occurrence of both calcium and magnesium oxalates in weathering environments. To date there have been no reported occurrences in paleosols and so their possible usefulness in dating has yet to be pursued.

Relative Dating Techniques

Whereas ^{14}C dating techniques will give absolute ages for soils, or fractions separated from them, many soil properties are known to change with time and these properties are frequently used for relative dating techniques. Amongst those soil properties that change with time are composition of organic matter, mineralogical composition, content of major and minor elements and nature of the iron oxides/hydroxides.

Several studies have considered the changes in the chemistry of soil organic matter in paleosols and their use in paleopedological dating techniques. Yoshida and co-workers in Japan have studied the changes in the chemistry of humus fractions of paleosols after burial by volcanic ash. They found that the contents of fulvic and humic acids decreased with time but reached a steady state at 3,000 to 4,000 years for fulvic acid and at approximately 10,000 years for humic acid (Yoshida *et al.*, 1978). The most significant relationship with time was the amount of humus extracted by NaOH and $Na_2P_2O_7$. Significant increases in C/N ratio were also found, particularly after approximately 3,000 years of burial for the humic acid fraction (Yoshida and Kumada, 1978). Humic acids in the paleosols were also found to differ appreciably from humic acids in contemporary soils in having higher O contents and O/C ratios, and lower H contents (Yoshida and Kumada, 1979).

Limmer and Wilson (1980) have examined the fate of amino acids in paleosols and advocated their use in dating paleosols beyond the range of ^{14}C dating. They found that after 80 years of burial fourteen amino acids were detectable in the paleosols, after 7,000 years of burial lysine and histidine were no longer detectable, at 20,000 years isoleucine, leucine, tyrosine and phenylalanine had disappeared and by 40,000 years only six amino acids remained - arginine, aspartic acid, serine, glutamic acid, glycine and alanine. Logarithmic plots of the ratios of the remaining amino acids showed excellent relationships with time and indicated the potential usefulness of this technique in dating paleosols with ages up to 200,000 years. Because soil type and climate would have a significant bearing on the rate of decomposition of amino acids, Limmer and Wilson suggest calibration of this technique for other areas. Such techniques depend on relatively constant first order kinetics of breakdown, i.e., a relatively constant climate.

The mobility of elements varies during pedogenesis and, of the major elements, Mg, Ca, Na and K are considered relatively mobile and the elements Si, Al and Fe are relatively immobile. With increased time of weathering the mineralogical composition of a soil will tend towards a residua system dominated by the minerals quartz, gibbsite, goethite, hematite and kaolinite (Chesworth, 1973). The relative predominance of these minerals in paleosols has thus been used to suggest extended periods of weathering before burial, or to indicate a climate and/or vegetation favouring accelerated mineral weathering. The presence of kaolinite in a paleosol from the Front Range, Colorado led Mahaney and Fahey (1980) to suggest that the soil was developed during warmer conditions than exist currently, and similarly Wang *et al.* (1981) has used the presence of gibbsite to suggest a possible pre-Wisconsin land surface in New Brunswick. Kukla (1975, p. 113), however, has pointed out that the presence of a poorly developed paleosol does not necessarily rule out an interglacial age, particularly if the interglacial interval was relatively arid.

A number of attempts have been made to use the changes in the relative amounts of amorphous to crystalline iron oxides/hydroxides as a relative dating technique. Iron released on weathering is presumed to be initially amorphous but convert to a crystalline form with time. The so-called 'Fe-ratio' is measured by determining the amount of Fe dissolved by ammonium oxalate with that dissolved by a mixture of dithionite-citrate-bicarbonate (McKeague *et al.*, 1971). Studies on Quaternary river terraces in Nevada by Alexander (1974) and in Pakistan by Ahmad *et al.* (1977) have shown that the Fe-ratio is initially high but decreases with time to a constant value. Attainment of this value may take many hundreds or thousands of years. Evans and Cameron (1979) for instance reported a high value even after some 125,000 years for some arctic soils. Schwertmann (1966) has indicated that the presence of even small amounts of organic matter can greatly inhibit the crystallisation of amorphous iron hydroxides. Thus although Fe-ratios are not sufficiently unequivocal alone for placing associated Quaternary deposits in sequence, they may be useful supplements to other criteria.

Problems

The methodology and techniques used to describe the morphology of paleosols are those that have found common usage in modern pedology and it is generally considered that soils developing under similar climatic, biotic and drainage conditions for similar intervals of time should consequently have similar morphologies and that morphological development should increase with time. Paleoenvironments are thus often inferred by comparing the morphology of a paleosol with that of a contemporary soil. However, such practice has been the cause of many of the problems in the interpretation of the paleo-environment of buried soils. A lack of understanding of pedology can lead to erroneous conclusions in the reconstruction of paleo-environments from simple considerations of the morphology of the buried soil. Morrison (1978) has discussed many of the problems encountered by both European and U.S. Quaternary geologists in interpreting various paleosols.

For example, reddish colours are common in many tropical and sub-tropical soils, e.g., Oxisols and Ultisols, and hence reddish colours in paleosols are often believed to be indicative of warmer paleoclimates (Thorp *et al.*, 1951). Reddish colours however may also originate at moderate climates but over considerable periods of time (Simonson, 1954; Pawluk, 1978). Similarly, reddish colours are absent from soils that have undergone periods of waterlogging and hence the presence or absence of reddish colours in paleosols may or may not be indicative of a warmer paleoclimate or a long interval of weathering (Ruhe, 1965).

Schwertmann and Lentze (1966) have shown that the reddish colour of soils depends on both the type of iron oxides/hydroxides present (hematites being generally redder than the other forms of iron) and the content of organic matter. Each of the oxides/hydroxides has a considerable range in colour and so hematite need not necessarily be present for an intense red colour.

The presence of thick decalcified layers in paleosols is also used as evidence for considerable periods of pedological development (Flint, 1949). The rate of decalcification is, however, profoundly influenced by the nature and original content of carbonates, the amount of water movement through the soil and the efficiency of nutrient cycling of the original vegetation. Catt (1979) has commentated on the problems of using mineral weathering to infer paleoenvironmental conditions and hence correct stratigraphic interpretation. The absence of intense mineralogical weathering in paleosols believed to be of Tertiary age in Britain he suggests, may be due to the initial absence of easily weatherable minerals, mixing by Quaternary cryoturbation with the underlying calcareous parent material and continual input of fresh loess during the periods of weathering.

Finally, considerable controversy still remains on the origin of clay-with-flint soils of the Chalk uplands of southern England. Evidence for and against Tertiary weathering have been presented and Catt (1979) suggests that all the indirect evidence used to date pedogenesis can be interpreted in more than one way, and that it is clear that the only way of dating soil development in periods too early for direct radiocarbon dating is by careful stratigraphic interpretation.

Concluding Remarks

Paleosols have been the subject of investigation for many years and in that time techniques used for their recognition have remained remarkedly unchanged. The presence of soil organic matter, plant and insect remains, depth distribution of soil constituents and mineralogical composition are as useful today as they were in the past. Improvements however in the micromorphological examination of soil have aided considerably in paleosol recognition.

The ^{14}C dating method has proved the most useful radiometric dating technique for Quaternary paleosols both because of the common presence of organic remains and because of the range in ages to which the technique can be usefully applied. Relative dating techniques, whilst of lesser value, can often provide supplements to other criteria in placing paleosols in the correct stratigraphic sequence.

Problems in the use of paleosols can arise if an uncritical comparison is made between the morphology of a paleosol and the morphology of a contemporary soil. These problems often arise because of inadequacies in our understanding of pedology.

In conclusion, I have attempted in this paper to present an overview of the use of paleosols in Quaternary studies and indicate the strengths and weaknesses of their use. The perspective I have taken is that of a pedologist, although the study of paleosols is now undertaken by scientists from a wide range of disciplines.

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