Soils of the Past

An introduction to paleopedology

Gregory J. Retallack
University of Oregon
Eugene
USA

SECOND EDITION

Blackwell
Science

Soils of the Past

An introduction to paleopedology

Dedicated to Ken and Wendy Retallack, for letting me be

Soils of the Past

An introduction to paleopedology

Gregory J. Retallack

University of Oregon
Eugene
USA

SECOND EDITION

Blackwell
Science

Published by
Blackwell Science Ltd
Editorial Offices:
Osney Mead, Oxford OX2 0EL
25 John Street, London WC1N 2BS
23 Ainslie Place, Edinburgh EH3 6AJ
350 Main Street, Malden
MA 02148-5018, USA
54 University Street, Carlton
Victoria 3053, Australia
10, rue Casimir Delavigne
75006 Paris, France

Other Editorial Offices:
Blackwell Wissenschafts-Verlag GmbH
Kurfürstendamm 57
10707 Berlin, Germany

Blackwell Science KK
MG Kodenmacho Building
7–10 Kodenmacho Nihombashi
Chuo-ku, Tokyo 104, Japan

Iowa State University Press
A Blackwell Science Company
2121 S. State Avenue
Ames, Iowa 50014-8300, USA

First published 1990 by
Unwin-Hyman
Reprinted 1991 by
Harper Collins Academic
Second edition 2001 by
Blackwell Science Ltd

Set by Best-set Typesetter Ltd., Hong Kong
Printed and Bound in Great Britain
at the Alden Press Ltd,
Oxford and Northampton

DISTRIBUTORS

Marston Book Services Ltd
PO Box 269
Abingdon, Oxon OX14 4YN
(*Orders*: Tel: 01235 465500
Fax: 01235 465555)

USA
Blackwell Science, Inc.
Commerce Place
350 Main Street
Malden, MA 02148-5018
(*Orders*: Tel: 800 759 6102
781 388 8250
Fax: 781 388 8255)

Canada
Login Brothers Book Company
324 Saulteaux Crescent
Winnipeg, Manitoba R3J 3T2
(*Orders*: Tel: 204 837 2987)

Australia
Blackwell Science Pty Ltd
54 University Street
Carlton, Victoria 3053
(*Orders*: Tel: 3 9347 0300
Fax: 3 9347 5001)

A catalogue record for this title
is available from the British Library

ISBN 0-632-05376-3

Library of Congress
Cataloging-in-publication Data

Retallack, Greg J. (Greg John), 1951–
Soils of the past. an introduction to paleopedology/
Gregory J. Retallack. — 2nd ed.
p. cm.
Includes bibliographical references and index.
ISBN 0-632-05376-3
1. Paleopedology. I. Title.
QE473.R473 2000
552'.5—dc21 00-045445

For further information on
Blackwell Science, visit our website:
www.blackwell-science.com

Contents

Part 3: Fossil record of soils

Preface to the second edition

In the years since first publication of this book, paleopedology has grown from a long childhood into gawky adolescence. Paleopedology's infancy was well captured on the opening page of Vladimir Nabokov's (1955) *Lolita*, in which it is offered as the epitome of an obscure scientific interest of Humbert. Now, it is no longer a surprise to find a paleosol or a paleopedologist. Emphasis now is on interpretation of large suites of paleosols, for example, tracking past fluctuations in atmospheric carbon dioxide from the isotopic composition of carbonate nodules in paleosols. Such isotopic studies of paleosols demonstrate that they really were soils of the past. Their message about former environments and ecosystems goes beyond their surface appearance. The study of these remarkable rocks is now in a phase limited mainly by human ingenuity. Isotopy, cathodoluminescence, magnetic susceptibility, X-radiography and microtomography are opening new vistas into the formerly hidden world of paleosols.

The first edition of this book was mainly ideas and questions. This edition is devoted more to procedures and answers. The way of paleopedology is currently being mapped out on several fronts. Global change, coevolution, mass extinctions and comparative planetary geology are some of the currently important topics informed by paleosols. In pursuit of these broader objectives, procedures for recognition and study of paleosols are becoming routine. Much of the first edition outlining such procedures has now been consigned to tables. I have also written another book (Retallack 1997a) as a source book of terminology and procedures for professionals. Here, however, emphasis remains on what paleosols can tell us of the way the world works. The theory and issues of paleopedology continue to grow in the quirky, sometimes upsetting and sometimes inspiring, manner of adolescence. In another 10 years, perhaps the field will have settled into comfortable middle age. For the moment, however, as the Chinese proverb has it, we live in interesting times.

Gregory J. Retallack
Eugene, Oregon, 2000

Preface to the first edition

Landscapes viewed from afar have a timeless quality that is soothing to the human spirit. Yet a tranquil wilderness scene is but a snapshot in the stream of surficial change. Wind, water and human activities constantly reshape the landscape by means of catastrophic and usually irreversible events. Much of this change destroys past landscapes, but at some times and places, landscapes are buried in the rock record. This work is dedicated to the discovery of past landscapes and their life through the fossil record of soils. A long history of surficial changes extending back almost to the origin of our planet can be deciphered from the study of these buried soils or paleosols. Some rudiments of this history, and our place in it, are outlined in a final section of this book. But first it is necessary to learn something of the language of soils, of what happens to them when buried in the rock record, and which of the forces of nature can be confidently reconstructed from their remains. Much of this preliminary material is borrowed from soil science, but throughout emphasis is laid on features that provide most reliable evidence of landscapes during the distant geological past.

This book has evolved primarily as a text for senior level university courses in paleopedology: the study of fossil soils. It is not the usual view of this subject from the perspectives of soil science, Quaternary research or land use planning. It is rather the view of an Earth historian and paleontologist. Compared with the elegant outlines of a fossil skull or the intricate venation on a fossil leaf, fossil soils may at first appear unprepossessing subjects for scientific investigation. These massive, clayey and weathered zones are fossils in their own way. Their identification within a classification of modern soils presupposes particular past conditions, in the same way as the lifestyle that can be inferred from modern relatives of a fossil species of skull or leaf. Particular features of paleosols also may reflect factors in their formation in the same way as ancient diet can be inferred from the shape of fossil teeth, or former climate from the marginal outline of a fossil leaf. This book is an exploration of the idea that paleosols are trace fossils of ecosystems.

Examples in this book are drawn largely from my own work on fossil soils, some of it not yet published elsewhere. Theoretical concepts have been borrowed more widely from allied areas of science including geomorphology, coal petrography, plant ecology, astronomy and soil science, to name a few. The fossil record of soils is a new focus for integrating existing knowledge about land surfaces and their biota. Paleopedology remains an infant discipline, hungry for theory and data of the most elementary kinds. This book is one attempt to partially quell the growing pains.

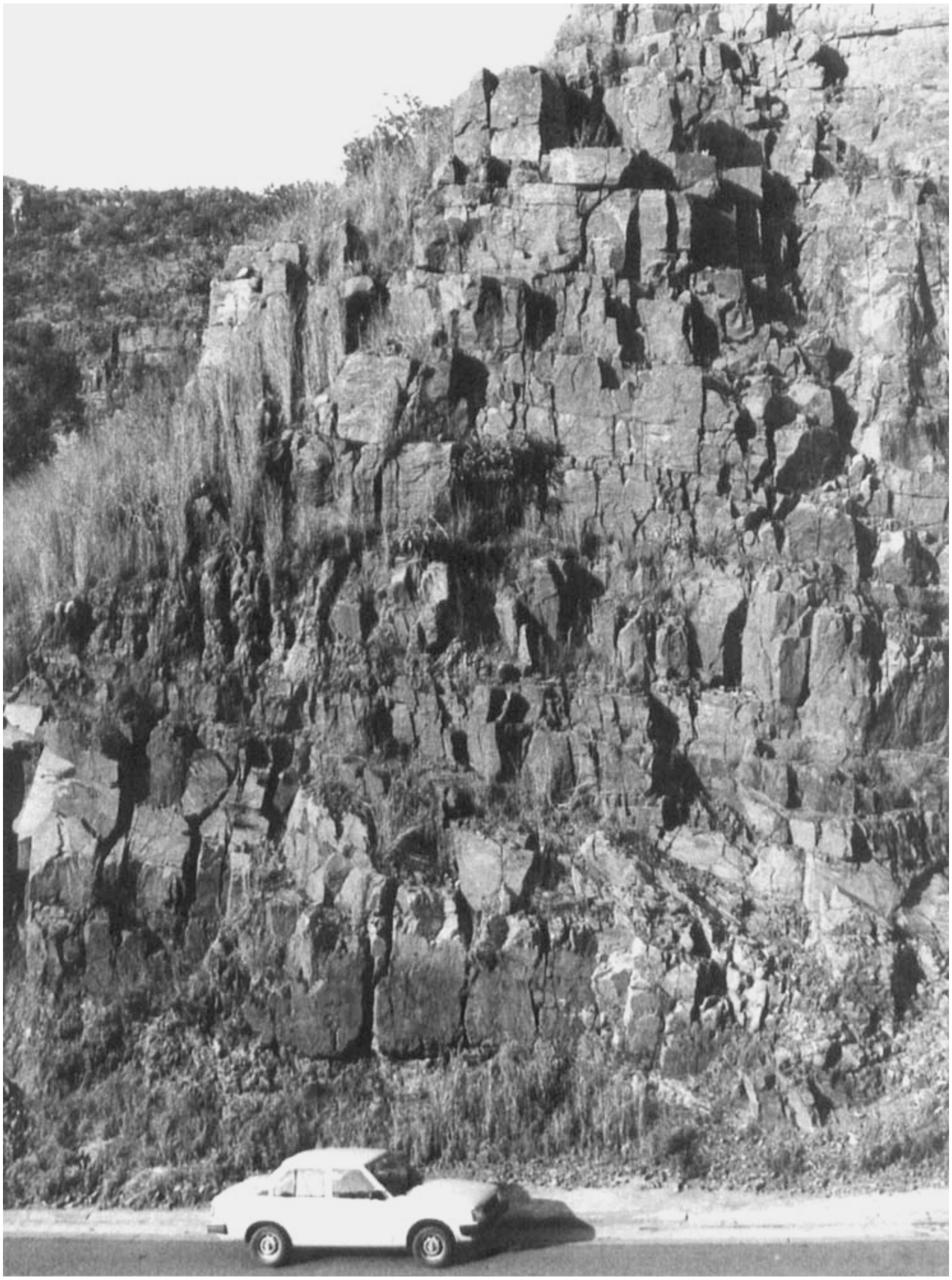
Gregory J. Retallack
Eugene, Oregon, 1989

Acknowledgments

This book on paleosols would be slender indeed without extensive borrowing of facts, experiments, ideas and inspiration from allied areas of science. I have been fortunate to be able to draw upon the wise counsel of prominent sedimentologists (J.R.L. Allen, A. Basu, D.R. Lowe, R.M.H. Smith, E.F. McBride and L.J. Suttner), paleontologists (R. Beerbower, A.K. Knoll, J.W. Schopf and P. Shipman), geochemists (G.G. Goles, J.M. Hayes, H.D. Holland, W.T. Holser and T.E. Cerling) and soil scientists (P.W. Birkeland, S.W. Buol, L.D. McFadden, P.F. McDowell, L.R. Follmer, D.L. Johnson and A.J. Busacca). Among the emerging cadre of paleopedologists concerned with rocks older than Quaternary it is a pleasure to acknowledge stimulating discussions with D.E. Fastovsky, M.J. Kraus, W.R. Sigleo, V.P. Wright and S.G. Driese. Last and certainly not least, many of my ideas have been reshaped by students at the University of Oregon (E.A. Bestland, D.P. Dugas, C.R. Feakes, P.R. Miller, J.A. Pratt, S.C. Radosevich, G.S. Smith, G.D. Thackray, E.S. Krull, J.G. Wynn and N.D. Sheldon). They gave real meaning to the Socratic dictum that the unexamined life is not worth living.

Photographs, specimens and other illustrative materials were generously and promptly provided by H.J. Anderson, J.B. Adams, T.M. Bown, J. Gray, R. Greeley, M.J. Kraus, S.C. Morris, NASA Space Science Center and C.J. Percival. Others graciously acquiesced in my adaptation of their published work. For several fine photographs, I thank Sean Poston. The writing would not have proceeded nearly so much to my satisfaction without the happy home life created by Diane, Nicholas and Jeremy.

Part 1
Soils and paleosols



2200 million year old paleosol (light colored zone) near Waterval Onder, South Africa.

Chapter 1 **Paleopedology**

Paleopedology is the study of ancient soils, and is derived from an ancient Greek word (πεδον, πεδου) for ground. It has nothing to do with pedestrians (Latin *pes, pedis*) or pediatricians (Greek παις, παιδος). Soils of the past, either buried within sedimentary sequences or persisting under changed surface conditions, are the main subject matter of paleopedology. In this book, it is seen as a historical perspective on soil genesis and as a way of reconstructing the geological history of land surfaces on Earth. Soils, like organisms, sediments and surface environments, have changed over the past 4566 myr of recorded Earth history.

The concept of fossil soils can be traced back to the Scottish physician James Hutton (1795). His insistence on arguing past causes from those that can be observed today was a prerequisite to making a connection between soils of today and those of the distant geological past. Red rocks along angular unconformities exposed along the course of the River Jed and at Siccar Point, southeast of Edinburgh, he regarded as comparable to surface soils and sediments on the modern landscape (Fig. 1.1). 'From this it will appear, that the schistus mountains or vertical strata of indurated bodies had been formed, and had been wasted and worn in natural operations of the globe, before horizontal strata were begun to be deposited in these places . . .' (Hutton 1795, Vol. 1, p. 438). These ideas were reiterated in John Playfair's (1802) *Illustrations of the Huttonian Theory of the Earth*, which, because of its conciseness and clarity of expression, was more influential than Hutton's original two volumes. Playfair also cited a 1799 record of a fossil forest in Lincolnshire, now covered by tidal flat sediments. This is the oldest record of a Quaternary fossil soil.

The oldest record of buried soils within consolidated sedimentary rocks was the 'dirt beds' (Fig. 1.2) and fossil stumps reported in latest Jurassic limestones of the Dorset coast by Webster (1826) and popularized by Buckland (1837) in a volume widely known as the *Bridgewater Treatise*. Other fossil forests were discovered in the late 19th century, and their stumps and associated fossil plants described, but little was made of their substrates as fossil soils. Examples include the Eocene *Sequoia* forests of Yellowstone National Park, USA, and Carboniferous stumps of tree-lycopsids at Clayton (Yorkshire) and in Victoria Park (Glasgow), both UK. A summary of these early discoveries of pre-Quaternary fossil soils was given in introductory chapters of Albert C. Seward's monumental work *Fossil Plants* (1898). He appreciated the significance of fossil soils as evidence for the immensity of geological time and as indicators of past worlds. Study of the paleosols themselves had to await the development of soil science.

During the late 19th century, buried soils also were recognized within surficial deposits of loess and till. These 'weathered zones', 'forest zones' and 'soils', as they were variously termed, were found in Russia by Feofilatkov (in the 1870s, as recounted by Polynov 1927), in the midcontinental USA by McGee (1878), and in New Zealand by Hardcastle (1889). By the turn of the century such observations had been used for stratigraphic subdivision of glacial deposits (Chamberlain 1895).

Despite these discoveries, the origin of paleopedology as a discrete field of inquiry can be traced back to the late 19th century development of soil science (Tandarich & Sprecher 1994). Since classical times, soils have been studied from the point of view of plant nutrition. It was not until 1862 that the Saxon scientist Fredrich A. Fallou first published the term 'pedologie' for the study of soil science, as opposed to what he termed 'agrologie', or practical agricultural science. The foundations of modern soil science were laid by Vasily Dokuchaev with a detailed account of the dark, grassland soils of Russia (1883). This monograph demonstrated that soils could be described, mapped and classified in a scientific fashion. Furthermore, their various features could be related to environmental constraints, of which climate and

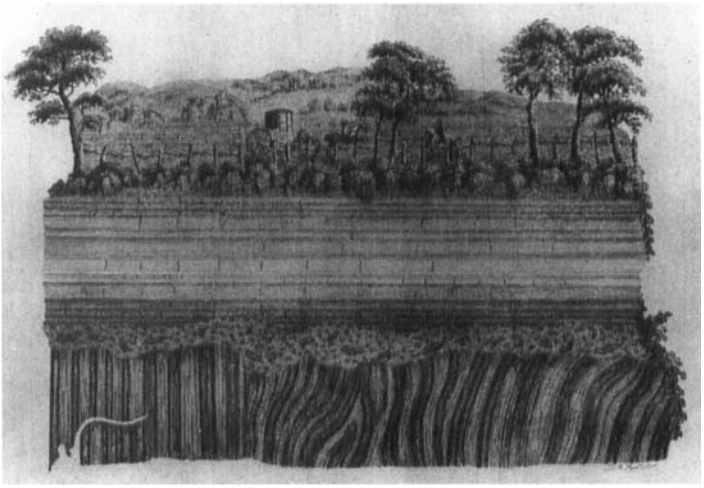
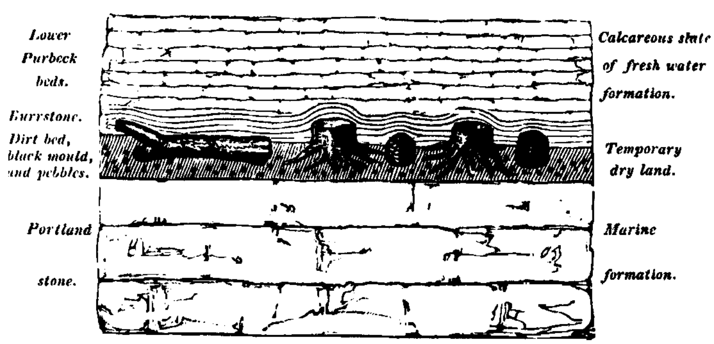


Figure 1.1 Angular unconformity between Lower Silurian (430 Ma) Hawick Rocks and Upper Devonian (360 Ma) Upper Old Red Sandstone along the River Jed in south-eastern Scotland (from Hutton 1795).

vegetation were considered especially important. By the early part of the 20th century there was an established scientific tradition of research on soil geography, classification and genesis in Russia, as summarized in the influential general works of K. D. Glinka (1927).

In the course of these early Russian investigations, certain soils were found to be anomalous in that their various features did not fit the general relationship between soil type and their climate and vegetation. It had long been suspected that these were very old soils, perhaps products of past environments. In 1927, Boris Polynov summarized Soviet observations of this kind. His short paper, which introduced the term paleopedology, can be considered the foundation of this branch of science. Polynov included the study of four kinds of materials within paleopedology. 'Secondary soils' encompass those formed by two successive weathering regimes, such as grassland soils degraded by the advance of forests after retreat of glacial ice. 'Two-stage soils' were recognized to have an upper horizon of recent origin, but deeper horizons of more ancient vintage. 'Fossil soils' were defined as soil profiles developed on a surface and subsequently buried. Polynov's final category of 'ancient weathering products' included the redeposited remnants of soils such as laterites and china clays. Polynov and his colleagues established a logical framework for the paleoenvironmental study of paleosols of all ages that continues in Russia.

Modern soil science in North America can be traced back to Eugene W. Hilgard's (1892) monograph



Section of the Dirt-bed in the Isle of Portland, shewing the subterranean remains of an ancient Forest. De la Beche.

Figure 1.2 'Dirt beds' (paleosols) in a stratigraphic section through the uppermost Jurassic (Tithonian, 150 Ma) Purbeck Formation on the Isle of Portland, Dorset, England (from Buckland 1837).

on the relationship of soil and climate. This, and the first large-scale mapping and classification of North American soils by Milton Whitney (1909), were largely independent of comparable research carried out by Russian soil scientists. Soviet influence first appeared in the work of Curtis Marbut, particularly his monumental soil survey of the USA (1935). Paleopedology also was introduced into North America through a Soviet connection. Constantin Nikiforoff completed doctoral studies at the University of St Petersburg in pre-revolutionary Russia, but by 1943 was a scientist with the US Department of Agriculture (USDA) Soil Conservation Service, when he published a short essay outlining the role and scope of paleopedology. A supporting study of paleosols in the same journal of 1943 by Kirk Bryan and Claude Albritton made clear the practical application of such studies.

Ideas on the classification and origin of soils have been especially useful for studies of Quaternary stratigraphy and geomorphology. Such studies are now conducted in most parts of the world, coordinated by a Commission on Paleopedology established in 1965 at the Seventh Congress of the International Association for Quaternary Research, in Denver, USA. An early result of the commission's activities was the publication, in a volume of research papers edited by Dan H. Yaalon (1971), of recommendations for recognizing and classifying paleosols. Mapping units for Quaternary paleosols have been incorporated into official stratigraphic codes (e.g. North American Commission on Stratigraphic Nomenclature 1982). Modern research on Quaternary paleosols can be found in books and journals on soil science, geography, archeology and Quaternary research (Catt 1990; Holliday 1992, 1994; Follmer *et al.* 1998).

In contrast to a steady level of interest in Quaternary paleosols, studies of older paleosols have been slow to gain momentum. In many sequences now known to contain them in abundance, paleosols were not recognized or their features were explained as diagenetic phenomena. Little was made of those few cases where paleosols were explicitly recognized (Barrell 1913; Collins 1925; Allen 1947; Thorp & Reed 1949). Beginning in the 1960s, interest in pre-Quaternary paleosols has been increasing on several fronts, as they were discovered in many nonmarine sedimentary sequences (Retallack 1997a) and even in deep-sea cores (Ford 1987; Holmes 1992). The study of paleosols is especially compatible with the overall aims of sedimentology to reconstruct ancient environments and geological processes. Paleosols now regularly appear in accounts of sedimentary geology (Esteban & Klappa 1983; Wright 1986a) and of weathering processes (Martini & Chesworth 1992; Ollier & Pain 1996).

Paleontological research has always been concerned with reconstructing past biotas, their ecology and the ways in which they are preserved in the rock record. Paleosols can be regarded as both trace fossils of past ecosystems and as preservational environments for many kinds of fossils (Retallack 1975, 1976, 1977). Paleontologically oriented accounts of paleosols are appearing now in a variety of books and journals concerned with paleoecology, paleoclimatology, and other paleontological subjects (Retallack 1991a; Parrish 1998; Stanley 1998).

A final area of geological sciences now contributing to paleopedology is geochemistry. The chemical study of weathering by Samuel S. Goldich (1938), from which was derived his well-known mineral stability series, dealt with Cretaceous paleosols in Minnesota. Paleosols also were used as indicators of atmospheric conditions and the nature of weathering processes in the very distant geological past (Sharp 1940; Sidorenko 1963). Such studies are now more common in journals and books concerned with geochemistry and Precambrian geology (Holland 1984; Schidlowski *et al.* 1992).

Looking toward the future, fossil soils may be used as stratigraphic markers in the continuing inventory and mapping of the geological resources of this and other planets. Particular features of paleosols may aid in locating especially valued resources. For example, changes in degree of development and mineral content of paleosols reflect former time for formation and degree of waterlogging, and can be used to guide exploration for petroleum, coal and uranium ores. Coal and uranium accumulated in parts of the landscape where groundwater was poorly oxygenated. Uranium is more likely to be found in and near paleosols that are variegated and that formed on the margins of uplands of uraniferous granites (Kimberley 1992). Coal is associated with paleosols that are gray and formed in swamps, rather than paleosols that are red and were formerly well drained (Retallack & Krull 1999). Paleochannel sandstones, located by following lateral trends in paleosol development and waterlogging, can be local petroleum reservoirs (Kraus & Bown 1993).

Fossil soils also provide historical validation for theories about how soils form. The geological history of soils can be viewed as a long-term natural experiment in which many fundamental conditions of soil formation, such as vegetation and atmospheric composition, have changed. Information from fossil soils can strengthen ideas about how soils form and how they should be classified. Because such ideas form the basis for much agricultural and engineering activity and their modification in the face of accelerating global change, it is all the more important that they have a firm scientific basis (Retallack 1996a).

Finally, fossil soils are evidence for reconstructing past terrestrial ecosystems and environments. They can be used to bring particular times and places into sharper focus as evidence independent of associated fossils and sedimentary structures. They are a record of the evolution of ecosystems and of their interaction with environments on land, and provide a perspective on our place on Earth.

Chapter 2 **Soils on and under the landscape**

Difficulties in defining 'fossil soil' arise not so much from its fossil nature as from confusion over what is meant by soil. A fossil soil or paleosol, like other kinds of fossils, is the remains of an ancient soil. It may have been buried by later deposits or it may be at the surface but no longer actively forming in quite the same way. The word soil on the other hand, like other commonly used words such as love and home, means different things to different people. For farming purposes, soil is fertile, loose, tillable ground. In engineering specifications, soil is any material that can be excavated without recourse to quarrying or blasting. By both these practical definitions, unaltered sediments, such as dune sands or flood silt, are regarded as soil. Yet some extremely altered soil materials, such as hard laterites, are not.

To some soil scientists, soil is the medium in which vascular plants take root (Buol *et al.* 1997). This narrow definition includes rock crevices supporting large plants. Yet it excludes rocks colonized by plant-like microbes and rootless plants such as mosses and liverworts. It also excludes hard-setting parts of soils and parts of soils below the level of roots (Hole 1981).

Taking an even wider view, what are we to call lunar, Venusian and Martian land surfaces that have been altered in place by surficial processes? The Moon and Venus are lifeless. Mars probably is also. Should calling their altered land surfaces soils necessarily imply that life is present? Or should an alternative label such as regolith imply that they are barren of life? Similar problems beset naming fossil soils older than Ordovician, before the advent of large land plants. If one takes the view that soils are a medium of plant growth, then both the terms Precambrian soil and Precambrian regolith beg the question of the antiquity and nature of life on land. Like the question of life on Mars, the origin of life on land is an important scientific issue in its own right and should not be confused by semantic considerations.

For paleopedology a wider definition of soil is needed. In this book I take soil to be material forming the surface of a planet or similar body and altered in place from its parent material by physical, chemical or biological processes. This is close to Nikiforoff's (1959) concept of soil as the 'excited skin of the subaerial part of the Earth's crust', and its more functional description by Colin *et al.* (1992) as a 'geomembrane filter'. Soil can be envisaged as a zone of interaction between the atmosphere and crust of a planetary body. A flux of energy from the Sun, water, snow or living creatures continually alters rocks or sediments into what we call soil.

A part of the problem with defining soils is their intrinsically intermediate nature. Soils are complex zones of interaction between sediment or solid rock and the ecosystem or atmosphere. Because of the varying levels of interaction down from the land surface, it is usual to study soils in profiles that show the layering of alteration, or soil horizons. Solum is a technical word for that part of the soil profile most altered by soil processes (Fig. 2.1). In many cases it is riddled with roots of plants. The soil solum also may be dark, red, clayey or massive, and so is very different from its underlying parent material. Weathered material between the solum and underlying sediment or bedrock has a mix of soil and inherited features, and is called saprolite, or alterite (Nahon 1991). Saprolite may be soft, oxidized, clayey or otherwise altered like a soil, but not to the same extent as the soil solum. Some saprolites show clearly the bedding, schistosity and deformation of parent rock. The distinction between saprolite and solum is a matter of degree of alteration.

Soils and paleosols on the landscape

Soils blanket most of the landscape except for areas covered by rivers or lakes or areas freshly uncovered by erosion and human excavation. Conditions of sunshine, moisture and other soil-forming factors vary in different parts of the landscape, and so do the soils forming there. The fundamental unit of soil is a column of soil material,

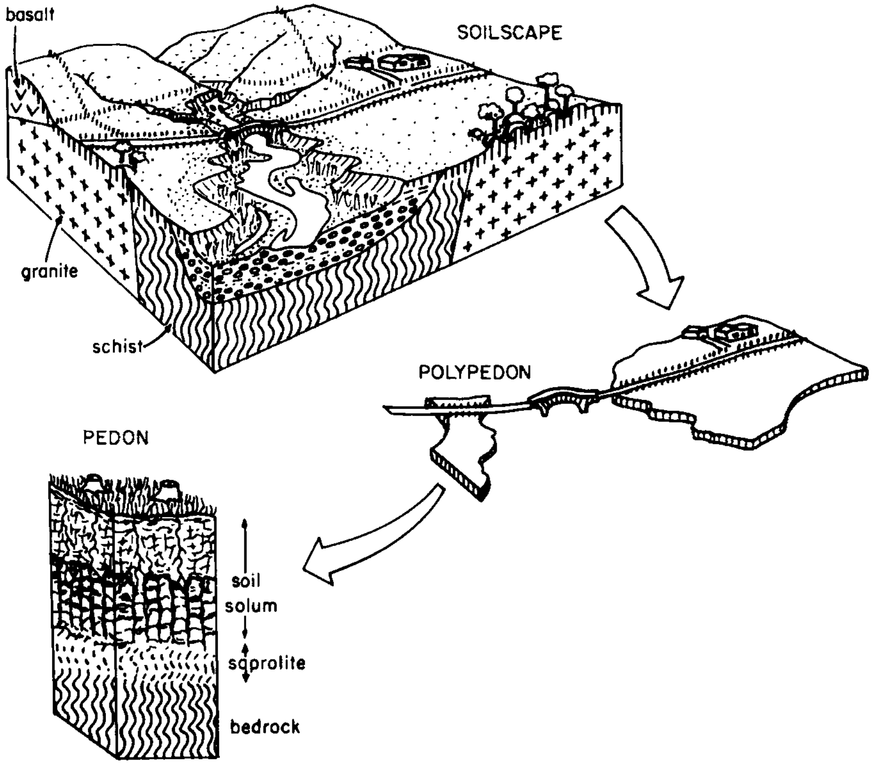


Figure 2.1 Technical terms for soils and their relationship to landscapes.

or pedon, of the kind that could be dug out of the wall of a trench. Soils vary in such complex ways that few pedons are exactly alike. Some pedons are sufficiently similar that they are recognized as a discrete kind of soil, different from others in the area. One or more of these similar pedons covering an area of ground is called a polypedon (Soil Survey Staff 1993). These are like tiles in a mosaic of soils over the landscape. The assemblage of polypedons mantling the landscape is called a soilscape.

Soils form over many years until covered by sediment or removed by erosion. In river valleys, for example, deposits of sand and silt left behind by an especially powerful flood, or the rubble of a landslide, may cover soils and drive off or destroy plants and animals (Fig. 2.2). Deep burial is a common way in which paleosols are formed. The covering deposits provide a surface for recoloniza-

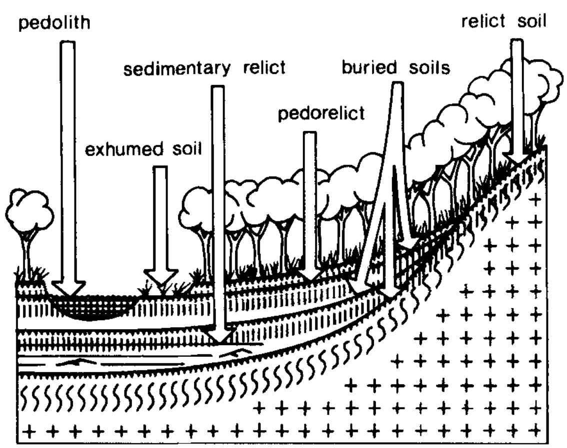


Figure 2.2 Technical terms for fossil soils (paleosols) and their relation to sediments (from Retallack 1983a; reprinted with permission from the Geological Society of America).

tion by plants and animals, and soil begins to form anew. Soon the bare surface is dry and cracked and small plants are taking root. With the advent of plants come worms and other burrowing invertebrates as well as herbivorous mammals. In humid regions, these early successional plants and animals are followed by shrubs and ultimately there is reconstituted the kind of woodland and soil that existed before.

As a soil is burrowed, penetrated by roots and otherwise altered, the ripple marks and bedding planes of original alluvium are progressively destroyed. Such sedimentary relicts persist in many weakly developed bottomland soils and paleosols. Their persistence is a reflection of the degree to which the soil has been able to form and does not negate the identification of these materials as soils or paleosols. It is not difficult to recognize that paleosols developed during times of peace and quiet between deposition of thick sedimentary layers.

Sequences of paleosols can become very difficult to decipher, however, if the intervening sedimentary layers are too thin to separate them effectively (Woida & Thompson 1993; Olson & Nettleton 1998). A common situation that may cause confusion is overprinting of the upper horizon of an older soil by development of a lower horizon of a younger soil with a slightly higher surface. The older near-surface horizon, then, is not genetically related to the younger subsurface horizon. From the point of view of the younger soil, it can be considered a pedorelict of the older soil. Other common pedorelicts are nodules or clasts of pre-existing soils within sediments on which later soils have formed. Distinguishing these older nodules or clasts from nodules or clods of the younger soil may be difficult unless they have sharp, ferruginized or truncated boundaries.

Some sedimentary layers are very distinctive because they are composed entirely of a particular kind of soil material. Such a bed, with clasts of soil minerals and appearing like a soil but with sedimentary organization, may be called a soil sediment (Catt 1998) or pedolith (Gerasimov 1971). The term pedolith was originally coined by Erhart (1965) for redeposited laterites of Tertiary age. These remain a good example because such locally derived soil material forms brightly colored red beds distinct from enclosing alluvium. Pedolith is useful only for such clear cases, where soil-derived sediments are distinct, because most sediment ultimately is derived from soils and so is pedolithic in some sense.

Surface soils can also be considered relict paleosols if they are of a kind completely different from those forming under prevailing conditions. Good examples of relict soils are lateritic and bauxitic paleosols remaining at the surface in the deserts of Australia from early Tertiary deep weathering (Ollier & Pain 1996). The true soils of deserts are not lateritic, bauxitic, red, clayey and deeply weathered, but thin, sandy and little altered from the color of their parent materials: as can be seen from soils of eastern Oregon, southern California, Nevada, the Middle East and Central Asia (Birkeland 1999). The term relict paleosol should be used only for such clear anomalies, because environmental change can be rapid, and most soils can be considered relicts of different past conditions to some extent.

Quaternary paleosols

By current estimates (Van Couvering 1997), the Quaternary geological period is the past 1.8 myr. Thousands to millions of years are the time spans it takes to form soils, so those of Quaternary age are important evidence for the way in which soils form. The study of factors in soil formation usually involves a carefully constrained analysis of soils and paleosols of varying age or situation. In the earthquake-prone Transverse Ranges of California, river terraces are uplifted and tilted by folding that is still continuing (Fig. 2.3A). The youngest surfaces are those nearest the streams, where they are still disturbed by annual floods. Older terraces, dated by radiocarbon and other means, are at higher levels. This stepped landscape includes successively older surfaces at higher levels and these in turn bear progressively better-developed soils (Fig. 2.3B). Many such sequences of alluvial terraces and their soils have been studied to document changes in soil formation with time (Harden 1990). Another favorite landscape for such studies is areas around the terminus of retreating glaciers (Birkeland 1992). This kind of research provides basic information about the way in which soils form that is vital to the interpretation of paleosols.

Studies of Quaternary soils and paleosols reveal clearly what complex things soils are and how many factors enter into their formation (Johnson & Watson-Stegner 1987; Phillips 1993). Not all these complications are relevant to interpretation of older paleosols. Among these are human impacts such as increased incidence of

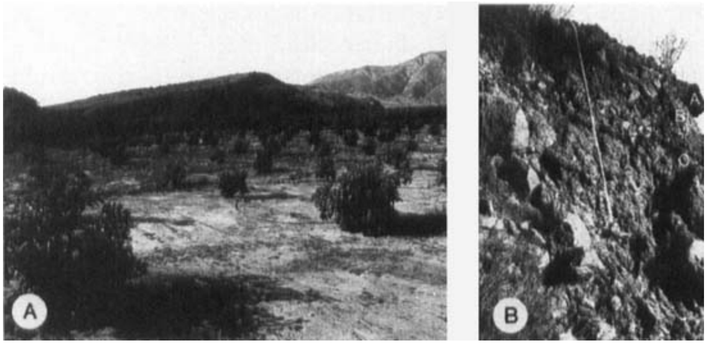


Figure 2.3 Tectonically tilted Pleistocene (*c.* 160–200 Ka) terraces disrupted at Culbertson Fault (Rockwell *et al.* 1985) on left skyline and the Tertiary rocks of Santa Paula Ridge in central Timber Canyon, north of Santa Paula, California, USA (A), and a thick, well-developed soil (Typic Palexeralf in US taxonomy) on the central tilted terrace (B); soil horizons are indicated by standard shorthand and tape is 2 m long.

fires, forest clearance and paving. Some of the difficulty in understanding Quaternary paleosols also has been exacerbated by focusing study on those found in outcrops or shallow trenches rather than in deep boreholes. Paleosols of uplifted terraces or stable continental regions are likely to have been influenced by a greater variety of weathering regimes than those subsiding below the zone of weathering shortly after formation.

Paleosols at major unconformities

Many unconformities show evidence of paleosols. Not all do because some have been scoured clean by fluvial or marine erosion before being covered by later sediment. Examination of geological maps for unconformities remains a productive method for locating paleosols, especially in Precambrian rocks, where they are difficult to recognize otherwise. Paleosols at major geological unconformities include thick, well-differentiated layers of rock enriched in ferric oxide (laterite), in alumina (bauxite), in silica (silcrete) or in calcium carbonate (calcrete). The origin of these distinctive materials is a complex issue for at least two reasons. First, they take so long to form that conditions originally encouraging their formation are almost certain to have changed in some way before their burial and preservation (Vasconcelos *et al.* 1992; Chadwick *et al.* 1995). Second, these are all indurated and weather-resistant materials that can withstand subsequent erosional events (Thiry 1999; Valeton 1999). A brief consideration of some of the leading theories for the formation of one kind of duricrust serves to illustrate some of these complexities.

Thick (10 m) laterites are thought not to form within the soil solum, but within deeper and thicker zones of saprolite below (Ollier & Pain 1996). Especially appropriate sites for the accumulation of ferric oxides to such a concentration are places on the side of plateaux where groundwaters enriched in iron dissolved in swamps within depressions on the plateau are oxidized within a zone of seepage around the plateau margin (McFarlane 1976). Lateritic profiles may reach considerable thickness in such geomorphological positions (Fig. 2.4). Such zones of concentrated ferric oxide are soft and easily excavated within the ground, but once exposed to air they become indurated like a brick. Their excavation and drying for construction stone on the Indian subcontinent is the source of their name from the Latin *later* (*lateritis* in genitive) for brick. Indurated laterites may armor hillsides against further erosion or may persist as pebbles of conglomeratic material similar to pisolitic or nodular original laterite (Tardy & Roquin 1992). Once formed, laterites are very persistent.

From this brief account of laterites, they can be seen to involve more than just soil formation. Erosional landscape lowering, reorganization of pre-existing soil horizons, changing flow of groundwater and progressive modification of the landscape also occur (Valeton 1999). The overlapping effects of so many processes make interpretation of such old surfaces of weathering difficult and controversial. Interpretation of buried examples is confounded by additional difficulties. Along major erosional unconformities it is difficult to be sure that the entire pre-existing profile has been preserved. Modern duricrusts form the surface of many landscapes because the soil under which they formed has been eroded. Many paleosols at major unconformities are likely to represent saprolite or other deep layers rather than the surface solum (Schau & Henderson 1983). A

Figure 2.4 Laterite (dark lower zone) with pockets of china clay (white) and mottled zone (variegated middle zone) of a Miocene paleosol (Plinthic Paleudult of US taxonomy) overlain unconformably by sand capped with a modern soil (Hapludoll of US taxonomy) at north end of Long Reef beach near Sydney, Australia (laterites discussed by Faniran 1971).

second difficulty with unconformities is the way in which they juxtapose materials of very different chemical and physical characteristics. Commonly clayey impermeable paleosols are overlain by gravelly or sandy, permeable fluvial deposits. Passage of groundwater through overlying sediments could substantially alter the underlying paleosol with effects becoming less marked downward from the unconformity in a manner difficult to distinguish from former soil formation (Pavich & Obermeier 1985). Examples of formerly well-drained paleosols that are mineralized with sulfide or uranium minerals characteristic of reducing environments (Mossman & Farrow 1992) are indications of such modifications.

Despite these problems, paleosols at major unconformities often present soil formation so extreme as to be unmistakable. The accumulated alteration of ages is not easily erased by later events of lesser duration. As evidence of the antiquity and geological history of deep weathering and of duricrusts, they are of interest in themselves.

Paleosols in sedimentary and volcanic sequences

Paleosols are abundant in some sedimentary and volcanic successions (Fig. 2.5). In many cases paleosols have masqueraded under nongenetic terms such as red

Figure 2.5 Alluvial–volcaniclastic sediments including a long sequence of superimposed paleosols of Eocene and Oligocene age in the Pinnacles area of Badlands National Park, South Dakota, USA (from Retallack 1983a; reprinted with permission from the Geological Society of America).

beds, variegated beds, tonstein, ganister and cornstone. Unlike conglomerates and sandstones, which are readily identifiable as hardened gravel and sand, these other rock types do not resemble modern kinds of sediment. Their similarity to modern soils was unrecognized as long as they were compared with sediments and rocks rather than soils.

Ganisters, for example, are rocks found in Euramerican Carboniferous coal measures. The word was coined by Cornish miners for hard, silicified quartz sandstone that is so chemically and physically inert that it is used for lining furnaces. Ganisters commonly are penetrated by carbonaceous root traces and underlie coal seams. It is now recognized that these were upper horizons of moderately well-drained soils. Their quartz-rich composition was produced in part by destruction of easily weathered associated minerals and their silicification by diagenetic mobilization of accumulated plant opal (Retallack 1977; Gibling & Rust 1992).

Another kind of rock that seemed puzzling from a sedimentary perspective has been called cornstone: red rock riddled with yellowish nodules of calcium or magnesium carbonate, irregular to rounded in shape and several centimeters in diameter. Marine rocks commonly contain calcareous, sideritic and other kinds of nodules presumed to have formed after burial of the sediment (Boggs 1995), and cornstone also was thought to be produced by burial diagenesis. Some of the classical cornstone sequences of the Old Red Sandstone in Britain contain fossil freshwater fish but no marine fossils. From this it could be argued that they formed after burial, but in lake sediments. Careful evaluation of the associated sandstones revealed that cornstones were more commonly associated with rocks thought to have formed in ancient rivers and that they resemble calcareous nodules of modern soils of dry climates (Allen 1986a). Carbonate nodules formed by burial diagenesis are less complexly cracked, less micritic and do not show displacive fabrics. The differences between calcareous nodules of marine rocks and of paleosols are now sufficiently well established that nodular paleosols can be recognized as evidence of low sea level within shallow marine limestones (Wright 1982).

Several general problems with the study of paleosols in sedimentary successions are apparent from these two examples. Foremost among these is their alteration upon deep burial. Cornstone was most easily understood because it is indurated and similar in appearance to modern soil nodules. Few modern soils are colored as brightly as red beds nor are many soils hard and flinty like ganisters. The likelihood of some changes after burial should not be taken to mean that all features of these rocks formed during burial. Careful attention to relationships with unquestionably original structures, such as fossil root traces and burrows, allows discrimination between original features of a paleosol and those formed during burial. A second problem is caused by the confused boundaries of some paleosols in sedimentary successions as a result of overlapping of successive paleosols. Erosion and redistribution of soil material also can be confusing. These complications can obscure the expression of soil horizons or other features that would be more obvious indications of paleosols. A third problem has been the application of inappropriate conceptual models to the interpretation of these rocks. Many nonmarine sedimentary rocks include evidence of soil formation as well as sedimentation. Each needs to be considered in interpreting geological history.

Despite these problems, paleosols in sedimentary rocks are promising because of evidence for paleoenvironments that they contain. Evidence from fossil soils can be used not only to validate interpretations based on other lines of inquiry, but also to frame new kinds of interpretations. For example, fossil soils can be used as evidence of former vegetation against which can be assessed the degree of adaptation of limbs and teeth of associated fossil vertebrates (Retallack 1991a,b). Because of their unique problems and potential, the study of paleosols in ancient sedimentary successions is developing a research tradition of its own, distinct from that of paleosols at major unconformities and from that of Quaternary paleosols and soils.

Chapter 3 **Features of fossil soils**

Compared with cross-bedded sandstone or coarsely crystalline granite, paleosols at first sight may seem massive and featureless. Despite nondescript first impressions, paleosols do have distinctive features. For the most part these are characteristics also found in modern soils. Yet many paleosols are no longer loose, cracked and at the land surface. Important differences result from compaction and alteration upon burial, which change many of the diagnostic chemical properties of modern soils such as pH, Eh and base saturation. Thus, identification of paleosols can be a problem for both geologists and soil scientists alike (Wright 1992a; Birkeland 1999).

There are three main kinds of features by which paleosols may be recognized in the field and from laboratory studies: root traces, soil horizons and soil structure. Using these and other observations it is generally possible to distinguish paleosols from unaltered sedimentary deposits, volcanic flows or zones altered by faulting. Paleosols can be altered by groundwater, by hydrothermal activity or by metamorphism, and in these cases often have a mix of features difficult to disentangle. Alteration of paleosols after burial is the subject of a later chapter. This one is concerned with criteria to determine whether a rock is part of a paleosol or something else entirely.

Root traces

Fossil roots or root traces are one of the best criteria for recognition of paleosols in sequences of sedimentary rocks. They are evidence that plants once lived there, and that, regardless of the rock's other features, it was once a soil. A gray shale with clear bedding planes may look like an ordinary sedimentary deposit but the existence of a few fossil root traces in growth position means that it was once a soil. The fossil record of roots is now well documented (Pfefferkorn & Fuchs 1991; Bockelie 1994; Retallack 1997a; Elick *et al.* 1998) and will be reviewed after considering general aspects of fossil roots.

The top of a paleosol can be recognized as the surface from which root traces emanate (Fig. 3.1). Concentrations of other trace fossils such as burrows also can be used because they record periods of reduced or no deposition during which sediment was extensively modified at the surface. There are situations when sedimentation keeps pace with burrowing and vegetative growth, but irregularities in depositional processes are such that perfect balance between depositional disturbance and vegetative colonization is seldom attained. Usually there are zones of more than usual density of root traces and burrows that can be interpreted as horizons close to the top of a paleosol.

Under favorable circumstances the original organic matter of a fossil root may be well preserved. Even if only a trace of roots is preserved by an infill of clay or calcite, there are several distinctive features by which they can be recognized. Unlike other trace fossils such as burrows, most root traces taper and branch downward. They also are very irregular in width. Large, near-vertical root traces characteristically have a concertina-like outline because of compaction of surrounding sediments. Outward flexures of the concertina are located at large lateral roots extending out into the matrix. Despite these characteristics the distinction between root traces and burrows is not always easy. Root mats may spread laterally over hardpans or around nodules. Some kinds of roots, such as the pneumatophores of mangroves, branch upwards and out of the soil (Jenik 1976). Furthermore, a range of soil invertebrates, especially ants, termites and worms, form complex branching burrow systems (Ratcliffe & Fagerstrom 1980) that may have collapsed in places. The distinction between root traces and burrows is further blurred by soil invertebrates such as cicadas, which burrow around and into roots to feed on them (Retallack 1976). Another potentially confusing case is the preference of roots for the soft fill of fresh

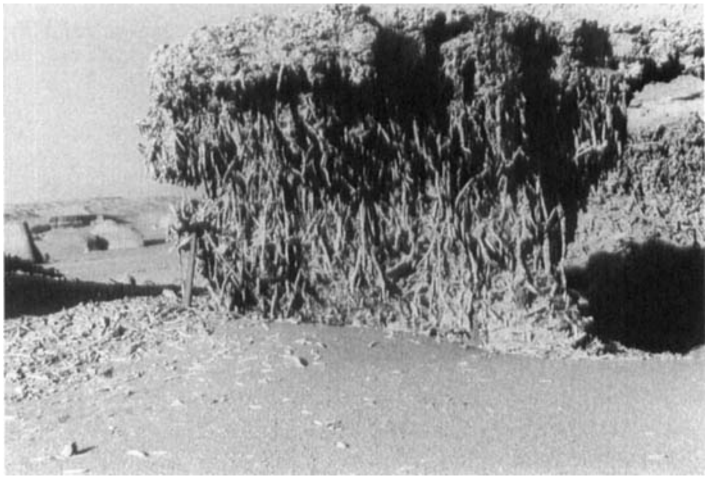


Figure 3.1 Calcareous rhizoconcretions emanating from the top of a mangal paleosol (Aquept) in the Upper Eocene (35 Ma) Birket el Qarun Formation near Madwar el Bighal, Faiyum depression, Egypt (photograph courtesy of Thomas L. Bown).

burrows rather than hard clayey soil matrix (Retallack 1991a).

Other structures that could be confused for root traces include gas escape structures (Neumann-Malkhau 1976) and tubular masses of soil fused by lightning strikes (Daly *et al.* 1993; Gifford 1999). These latter, called fulgurites, are lumpy masses of glass with exotic high-temperature minerals very different from ordinary soil matrix. Gas escape structures, such as those forming the conduit to sand volcanoes in alluvium covering methane-generating organic matter, are not so copiously branched or pervasive as root traces. In most cases, wispy tubular structures forming an irregular, dense network within nonmarine rocks are root traces.

One limitation on the use of root traces for recognizing paleosols is that they have not been found in rocks older than Silurian, when the first vascular land plants appeared (Retallack 1992a). There are burrows of invertebrates in paleosols as old as Ordovician (Retallack & Feakes 1987). For paleosols older than mid-Ordovician root traces and burrows are of no use for identifying ancient soils.

Kinds of roots

Fossil root traces are most easily recognized when their original organic matter is preserved. Paleobotanical research has now unearthed fossil examples of most of the major kinds of root now found (Retallack 1997a). Roots are downward growing plant axes. They have numerous fine branches or rootlets (Fig. 3.2). Both roots and rootlets are anatomically simple, unlike the anatomical diversity seen in aerial parts of plants. Usually a central cylinder (stele) of elongate woody cells (tracheids) is separated by a zone (cortex) of equidimensional fleshy cells (parenchyma) from a tough outer rim of thick-walled cells (epidermis). The central woody cylinder and tough outer rim withstand decay longer than the intervening zone of soft cells. Partly decayed root traces may show a central dark woody streak and a carbonaceous epidermis separated by a zone filled with mud, calcite or other minerals where the cortex has decayed (Retallack 1976). With further decay even the epidermal and stelar organic matter are replaced by other materials, but a concentric pattern of replacement may remain.

Root hairs are individual elongate epidermal cells found in zones near the tips of fine rootlets. Because of their increased surface area compared with that of older parts of root systems, they are especially significant in gathering water and nutrients from the soil. Silurian and Devonian land plants, like living mosses and liverworts, lacked true roots, but had functionally comparable rhizoids. Both root hairs and rhizoids are so small and delicate that they are preserved only by exceptional circumstances, such as cellular permineralization (Retallack 1997a).

Various kinds of roots are distinguished by their

Figure 3.2 Fossil root and rootlets from the Miocene Molalla Formation on High Hill near Scotts Mills, Oregon, USA. Their original organic matter has been weakly ferruginized (Retallack specimen R261).

pattern of branching and anatomical structure (Raven 1999). Many plants have a single, thick vertical root or tap root, as in Devonian *Eddya* (Beck 1967). Carrots and parsnips are familiar modern plants that have tap roots modified into large underground structures for the storage of carbohydrates. Another kind of root system is seen in living grasses (Gramineae) and quillworts (*Isoetes*). These have fibrous roots radiating from a thickened stem base known as a corm or rhizomorph, as in Triassic *Pleuromeia* (Retallack 1997c). If the roots arise from the stem of a plant rather than its base, they are called adventitious roots. These may arise from rhizomes, which are stems lying in or along the ground. They also may anchor stems scrambling above ground (runners or stolons) as in modern strawberries and Carboniferous *Callistophyton* (Rothwell 1975). Adventitious roots also form prop or stilt roots connecting erect stems and branches to the ground, as in Cretaceous *Weichselia* (Alvin 1971). In tree ferns, such as Carboniferous *Psaronius* (Morgan 1959), a very weak stem and leaf bases are completely enclosed by a mass of fine adventitious roots. They may look like tree trunks, but these masses of roots and leaf bases are best called false stems.

A variety of specialized structures of roots also are known from the fossil record. For example, tubers are underground storage organs branching from roots and rhizomes, as in the common potato and Cretaceous *Equisetites* (Watson & Batten 1990). Some plants of waterlogged soils have rootlets extending vertically into the air and these can be fossilized by deposition in swamp and intertidal habitats (Whybrow & McClure 1981). These peg roots (pneumatophores) may play a role in allowing access to air for root respiration. For similar reasons, some plants of waterlogged habitats have thin-walled openings to the inside of the root (aerophores) or spongy parenchymatous tissue (aerenchyma). The most obvious of these aerating adaptations are large hollow cavities (lumina) found in roots of some swampland plants, such as Permian *Vertebraria* (Retallack & Dilcher 1988). Rooting structures such as these not only indicate the existence of paleosols, but are also evidence of particular soil conditions.

From the known fossil record of roots, most kinds of rooting structures have been in existence since Carboniferous time (Pfefferkorn & Fuchs 1991). Extinct woody plants whose aerial parts were very different from those alive today showed surprisingly modern kinds of roots. Presumably this is because functional constraints on root evolution have been more important than phylogenetic constraints. Useful paleoecological interpretations can be made from fossil roots by comparison with modern studies of root ecology and arrangement.

Patterns of root traces

While digging for fossil root traces it is useful to consider their arrangement, because this may provide evidence for former drainage, vegetation types and originally indurated parts of a paleosol. Because roots need oxygen to respire they seldom penetrate permanently waterlogged parts of soils. Laterally spreading (or tabular)

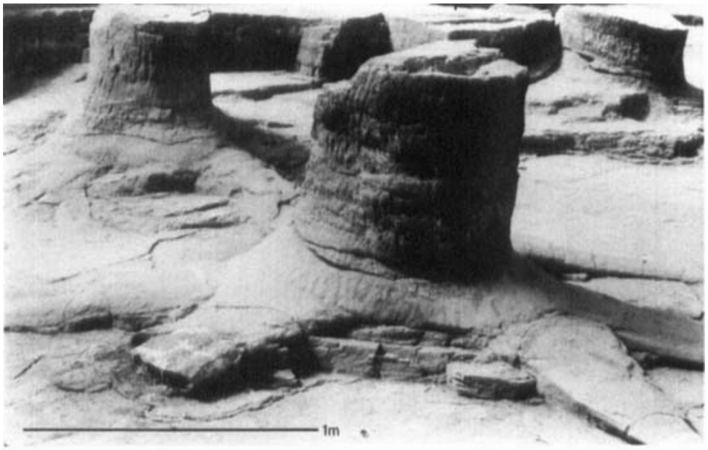


Figure 3.3 Tabular root system of a large, extinct arborescent lycopod (*Stigmaria ficoides*) of Early Carboniferous age (Namurian, 320 Ma) in the Lower Limestone Coal Group, Victoria Park, Glasgow, Scotland. The scale is 1 m for foreground only.

root systems are characteristic of plants growing in swampy ground (Jenik 1976) and are common among fossil stumps in sedimentary rocks of lowland environments (Fig. 3.3). On the other hand, well-drained paleosols may be deeply penetrated by root traces. Under wooded grassland, deeply penetrating and stout roots of trees and shrubs are scattered among a diffuse network of fine (<2 mm diameter) grass roots (van Donselaar-ten Bokkel Huinink 1966). In vegetation of drier climates the pattern of roots becomes shallower and more irregular as vegetation becomes more sparse and clumped. Under tall grass prairie a network of fine roots may extend as deep as 2 m below the surface (Fig. 3.4). Under short grass prairie grass roots are clumped under individual tussocks and interspersed with tubers and other rooting structures of desert perennials. Documentation of rooting patterns in modern soils is a laborious process that involves digging, erecting a supportive net for the excavated roots, and then carefully washing them out (Weaver 1919, 1920). Such research provides data against which fossil root systems can be compared.

Patterns of root traces also are clues for distinguishing original features of paleosols formed after burial.

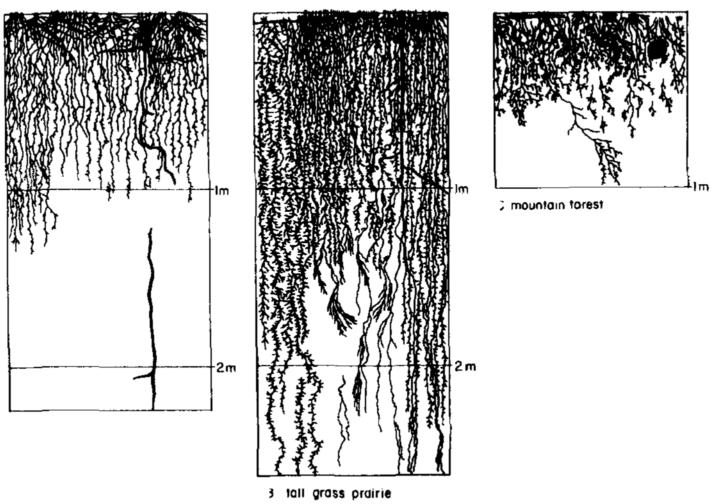


Figure 3.4 Scale drawings of excavated root systems of: (A) short grass prairie near Colorado Springs, Colorado, USA; (B) lowland tall grass prairie near Lincoln, Nebraska, USA; and (C) mountain forest near Pikes Peak, Colorado, USA (after Weaver 1919, 1920; with permission from the Carnegie Institution of Washington).