Compared to other branches of earth sciences, soil is known as a fossil of the Earth's surface. The study of soils provides insights into historical processes and environmental changes. Soils are the product of long-term interactions between living organisms and their physical environment. They form a unique layer of the Earth's surface that can serve as a record of past environmental conditions and biological activity. Soils are crucial for agriculture, as they provide nutrients and support plant growth. Understanding soil formation and evolution is essential for sustainable land management and conservation efforts.

INTRODUCTION

CREG HETTELACK

TERRESTRIAL ENVIRONMENTS

FOSSIL SOILS: INDICATORS OF ANCIENT

NEW YORK, P.55-102; PREHISTORIC AND PALEOBIOGEOGRAPHY AND EVOLUTION


soils, particularly those older than Pleistocene, that a review of them does not cover an impossibly large literature. This review is biased toward my personal conviction that interpretation of ancient environments is the most promising future direction for studies on fossil soils. Pleistocene buried soils and altered rocks at major geological unconformities are the best known fossil soils, but they are discussed here in less detail than well-preserved fossil soils within thick sedimentary sequences that also preserve other kinds of fossils. Because of difficulties peculiar to Pleistocene fossil soils and geological unconformities, the study of older fossil soils has often been approached timidly or avoided in the past. Caution is certainly needed, especially in unraveling the complex effects of sedimentation, volcanism, diagenesis, and metamorphism from ancient soil-forming processes. However, more and more studies of older fossil soils are overcoming these obstacles. It is now apparent that careful studies of fossil soils can provide evidence for many features of ancient environments that were previously indeterminable and can also support and integrate conclusions from a number of other earth sciences into surprisingly detailed reconstructions of the past. It is also becoming apparent that fossil soils are much more abundant in nonmarine rocks than generally realized. Many enigmatic kinds of rocks, masquerading under a variety of uninformative names are now turning out to be (at least partly) fossil soils. Among these are redbeds, variegated beds, badlands, cornstone, ganister, tonstein, underclay, and fireclay (Williamson 1967; Steel 1974; McBride 1974; Retallack 1977a, 1979).

What are fossil soils and how are they recognized? The most practical definition of a fossil soil (also called a paleosol) is a former soil buried by later deposits. The main difficulty with this definition arises, not from its fossil nature, but from the concept of modern soil, which is different for engineers, agriculturists, geologists, and soil scientists (Ruhe 1965; Hunt 1972). I prefer to broadly define soil as material on the surface of a planet altered by physical or chemical weathering, the action of organisms, or all of these. Fossil soils can be recognized by any of the features of modern soils. For older fossil soils the most diagnostic feature is the remains of fossil roots preserved in growth position. Other features include leached or reddened, massive-looking and clay-rich layers, prismatic or blocky jointed layers, and a variety of trace fossils, mottles, nodules, and concretions. The micromorphology of the fossil soil in thin section and its clay mineralogy and geochemistry are also useful in the study of older fossil soils, if interpreted with care.

THREE MAJOR KINDS OF FOSSIL SOIL

Fossil soils occur naturally in three different geological settings. Each has been studied from different perspectives, related to their particular problems and possibilities.


Walkden, G. M. 1974. Palaeokarstic surfaces in upper Visean (Carboniferous)
The problems with interpreting ancient aquatic ecosystems are largely due to the scarcity of fossils. They can be made clear by considering the number of fossils that are likely to be present in the sedimentary rocks. However, when we look at the fossil record, we see that the number of fossils is much lower than we might expect. This suggests that the environment was not as conducive to the preservation of fossils as we might have thought.

One reason for this is that the processes that create fossils are not always the same. For example, the type of sediment in which a fossil is found can affect the chances of it being preserved. If the sediment is too loose, the fossil may be washed away. If it is too hard, the fossil may be too difficult to extract. Additionally, the environment in which the fossil was formed can also affect its chances of survival. For example, if the fossil was formed in a riverbed, it may be more likely to be preserved than if it was formed in the ocean.

Despite these challenges, we can still learn a lot from the fossil record. By studying the fossils that do exist, we can gain insights into the history of life on Earth. We can also use these insights to predict how life might change in the future.

In summary, fossils provide valuable information about the history of life on Earth. While the fossil record is incomplete, it is still a powerful tool for understanding the past. By studying fossils, we can learn about the evolution of life and the processes that shape the environment.
original geological unconformity, first recognized by Hutton in 1787, shows several features of Siluro-Devonian soil formation. The surface has topographical relief of at least 400 m and is reddened and fissured, with fissure fills of red, calcareous, sandy breccia (Friend, Harland, and Gilbert-Smith 1970). Other examples of paleosols at unconformities are the "lateritic" paleosols which have been widely recognized at the unconformable contact between Cretaceous and early Tertiary rocks in many parts of the western United States (Wanless 1923; Pettyjohn 1966; Abbott, Minech, and Peterson 1976; Thompson, Fields, and Alt 1977).

Although easy to recognize, because they indicate millions of years of erosion and nondeposition, this in itself is a problem for their interpretation. Many features of these paleosols may be relics of soil formation under a climate and vegetation very different from those just before burial. A more serious problem with such paleosols arises from the way unconformities commonly juxtapose rocks of different porosity, mineralogy, and other characters. Unconformities are especially susceptible to later modification by hydrothermal alteration, diagenetic or metamorphic changes involving reaction between the contrasting materials, and leaching or precipitation of minerals by intrastratal solutions or groundwater. The difficulties of unequivocally distinguishing between later modification and original weathering are well illustrated by the disagreement of Lewan (1977) and Kalliokoski (1977) over the nature of altered rocks underlying the 1-billion-year-old Jacobsville Sandstone, north of Marquette, Michigan. The need for caution can also be seen from the following example. In the driftless area of southwestern Wisconsin, successive early Paleozoic sandstones may have strongly silicified and ferruginized crusts and mottled and pallid zones immediately below each capping carbonate unit. Evidence presented by Dury and Haberman (1978) indicates that these are not early Paleozoic paleosols, but were more likely produced by weathering in the late Cretaceous and early Tertiary.

In Thick Terrestrial Sedimentary Successions

The ideal situation for the preservation of fossil soils is in sedimentary basins subsiding at such a rate that soils are covered and sink below the water table shortly after reaching the greatest differentiation possible, given the parent material, vegetation, and climate at the time. As discussed by Allen (1974b), this may occur without episodic basin-wide subsidence and sedimentation. The covering of soils at long intervals is a natural consequence of the restricted supply route of sediment, such as mudflows and streams, in many terrestrial environments. Streams constantly change course or meander laterally, but any given portion of their floodplains is infrequently reworked by the stream channel or covered by thick near-channel

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—. 1977b. Triassic paleosols in the upper Narrabeen Group of New South


Kidston, R., and Lang, W. H. 1921. On Old Red Sandstone plants showing structure from the Rhynie chert bed, Aberdeenshire. Part V. The thallogypha occurring in the peat bed; the succession of the plants through a vertical section of the bed and the conditions of accumulation and preservation of the deposit. Trans. R. Soc. Edinb. 52:855–902.


Ložek, V. 1967. Climatic zones of Czechoslovakia during the Quaternary. In

Series paleosols of the Triassic near Sydney, Australia, the best evidence that siderite nodules were formed in place during soil formation was the rare occurrence of sand-filled insect burrows approaching the nodules from above, but sidling right around them, rather than passing through them (McDonnell 1974; Retallack 1977a). After detailed consideration of all their features, these Triassic paleosols proved impressively well preserved for their age and the few diagenetic alterations found were not critical to interpretation of the paleosols.

METHODS OF STUDY

Although theoretically recognized by all the features of modern soils, different methods of study are needed for older fossil soils than for Quaternary and modern soils. As a general rule, mineralogy and geochemistry, although necessary to consider, are the features of paleosols most susceptible to later alteration and should play a subordinate role to detailed field observations, the nature of horizons and soil pedds, micromorphology, and associated fossil plants and animals in the study of older fossil soils.

Fieldwork

There is no substitute for detailed fieldwork in the study of fossil soils. The most striking feature of fossil soils from a distance is often their color, especially bright red and brown horizons. The most diagnostic feature is evidence of fossil roots in place. Other features include clayey, leached, massive prismatic, blocky-jointed or slickensided layers, and a variety of trace fossils, mottles, nodules, and concretions. Some concepts of paleosol horizons’ parent material, and of special features, such as later fills of surficial holes left by felled trees (Fig. 3.3), need to be assessed in the field, before they can be confirmed by laboratory studies. Color should also be taken in the field, using a Munsell or other soil color chart, rather than any of the existing rock color charts.

For interpretative, as opposed to stratigraphical, studies of fossil soils, I have found that the soil mapping units of the United States Department of Agriculture (Soil Survey Staff 1951, 1962) are best for several reasons. The names do not imply anything of the nature or origin of the fossil soil and are not dependent on modern soil classification, whose criteria cannot always be applied to paleosols or unequivocally distinguished from diagenetic modifications. A separate name can be given to each particular paleosol. Part of the name relates it to other paleosols of a similar kind in the same area. The paleosols can be interpreted at several conceptual levels within a hierarchy of classification. There is no confusion between paleosols from different areas.


such as sepic plasmic fabrics (Figs. 3.4, 3.5), may be diagnostic of soils and soil-forming processes. The terminology developed by Brewer (1964) for micromorphological features of soils has been widely accepted in studies of older fossil soils (Terrugi and Andreis 1971; Allen 1974b; Retallack 1977a; McPherson 1979).

Well-consolidated and cemented fossil soils may be difficult to disaggregate accurately for analysis of the proportions of sand, silt, and clay at different levels of the profile (Spalletti and Mazzoni 1978). Such quantitative information is of great value in assessing the nature of soil horizons and degree of illuviation, and also in naming paleosols. Grainsize distribution is best determined by counting measured grains under a microscope using a point counter. Friedman (1958, 1962) has shown that counts of the long axes of about 500 grains gives results very close to that of sieving fractions of unconsolidated sediments, and that even more accurate statistical parameters of the distribution can be obtained by converting the data with regression equations. Be aware, though, that the widely used Wentworth grainsize scale of geologists is not the same as that usually used by soil scientists. The grainsize scale and textural classes used by the United States Department of Agriculture (Soil Survey Staff 1975, p. 470) are better suited to textural studies of fossil soils.

FIGURE 3.4. Cline-trimasepic plasmic fabric from the A horizon of a well-differentiated paleosol in the latest Eocene to early Oligocene lowermost Chadron Formation (11.6 m in Figure 3.13); Pinnacles area, Badlands National Monument, South Dakota. × 50.

Acknowledgments

This work was funded by National Science Foundation EAR-9700898.

References
for consistency and to determine which are due to original soil formation and which due to later alteration.

Fossils

Trace fossils, bones, shells, coprolites, plant fossils, or any other vestige of former life associated with fossil soils should be collected and prepared by appropriate techniques. Fortunately, a great deal of basic paleontological work has already been done on terrestrial and near marine organisms, and this may only need to be integrated with study of the fossil soil, in order to reconstruct the soil, its setting, and the ecosystem it supported.

COMMON DIAGENETIC MODIFICATIONS

Unraveling the effects of diagenesis and original weathering can be a major stumbling block in the interpretation of older fossil soils. It is helpful to be aware of diagenetic modifications common in older paleosols. The following is my own list of troublesome diagenetic modifications. Undoubtedly others will be added as research continues.

Reddening of Ferric Oxide Minerals

The diagenetic inversion of yellow and brown ferric gel and goethite to brown or red limonite and hematite causes an appreciable reddening of fossil soils. The reason why paleosols of the last interglacial are commonly redder than those presently forming in the same areas may be partly because of higher temperature and humidity when they formed (Ruhe 1965). However, it is probably also partly due to long-term diagenetic inversion to redder ferric oxide minerals (Walker 1974). In most pre-Tertiary paleosols with horizons stained with ferric oxide, this is mostly hematite. Even the B horizons of humic gleys (fibrists) paleosols from the Triassic near Sydney, Australia (Retallack 1977b), are brightly colored. These fossil soils may not have originally been as red as they appear today. Such paleosols may have originally been a variety of pale yellowish, brownish or pinkish colors, and were not necessarily oxisols or lateritic podzolic soils.

Siderite Pseudogley

Siderite nodules may form in waterlogged portions of modern soils (Kanno 1962; Degens 1965) and were evidently an original feature of the B horizons of gleysed podzolic (aquod) paleosols from the Triassic near Sydney, Australia (Retallack 1977a, 1977b). However, even previously

1967; Hardan 1971; Conry and Mitchell 1971). More could be done, particularly with older fossil soils associated with Miocene, Pliocene, and Pleistocene hominoid fossils. Spectacular new finds of such fossils are changing concepts of our own evolution as a species (Johanson and Taieb 1976; Leaky et al. 1976; Bishop 1978), but many questions remain. How and when was the evolution of Homo sapiens related to forest, savanna, and prairie environments? To what extent can the spread of grasslands be attributed to the use of fire by hominoids? Did the giant beasts of the Pleistocene become extinct because of overkill by hominoids, because of their effect on the ancient environments or because of other environmental changes? Detailed studies of fossil soils addressing these questions have not yet been forthcoming, but enough is now known of the geological occurrence of early hominoid fossils to indicate their potential. In the Middle Silts and Gravels Member of the Kapthurin Formation of Kenya, between 700,000 and 230,000 years old, Tallon (1978) reported hominoid remains (probably Homo erectus) and stone artifacts scattered over the surface of a fossil soil, which had a calcrite 2 m below the surface. This occupation site was evidently on lakeside flats just south of the nose of a trachyte flow, which was used to quarry the artifacts. Further studies are needed to establish the nature of the calcrite and the different kinds of lakeside vegetation and soils. A variety of fossil soils have also been found in association with hominoid remains, perhaps up to 2 million years old, in the Chesowanga area of the northern Rift Valley of Kenya (Bishop, Hill, and Pickford 1978), and also in association with hominoid remains 9 to 12 million years old (mid-Miocene) in the central Kenyan Rift Valley (Pickford 1978). Paleosols may also be useful in evaluating the habitats of Miocene hominoids from the Siwalik deposits of Pakistan (Pilbeam et al. 1977a, 1977b; Behrensmeier, personal communication 1979).

CONCLUSIONS

The study of fossil soils is just beginning. Compared to other branches of earth sciences there are still few researchers, although their ranks are growing. There are innumerable projects unattempted, many involving major aspects of the evolution of terrestrial ecosystems. Undoubtedly, more will be revealed as work progresses.

Although useful in stratigraphical mapping, fossil soils also provide evidence for interpretation of ancient terrestrial environments. These interpretations are particularly effective when integrated with existing paleontological and geological studies. Such an approach promises to become an important additional way of understanding the past.
could not have supported the vegetation indicated by the fossil soils. In
the Madison Formation (Eocen), these deposits are confined to the
western part of the state, where they form a narrow band along
the Mississippi River. Here, the deposits are thicker and more abun-
dant than in the eastern part of the state. The deposits consist of
coarse-grained sediments, including sandstone, siltstone, and mud-
stone. The sediments were deposited in a lake or river environment,
and the fossils are representative of a diverse community of plants
and animals. These deposits provide evidence of the climate and
environment of the Madison Formation during the Eocene period.

Smith (1978) has shown that the study of terrestrial fossil soils can
provide important insights into past environments. Fossil soils are
formed when the organic matter in the soil is preserved under anaerobic
conditions, resulting in the formation of distinct layers. These layers
are often preserved in the rock record and can be used to
reconstruct past environments. Smith's work has demonstrated that
the study of fossil soils can provide valuable information about past
environments and the evolution of plant and animal communities.

The Importance of Fossil Soils in Geologic History

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their present indurated state. From my study of Triassic ganisters from near Sydney, Australia (Retallack 1977a), I concluded that the silica cement was derived largely from the early diagenetic mobilization and reprecipitation of opal phytoliths from plants, fecal pellets, and airborne dust in the original soil.

Similarly, the induration and complete silicification of petrified peats is probably also partly diagenetic. Kidston and Lang (1921) regarded the dead areas, wound reactions, and unequal enlargement of cells in otherwise well-preserved stems of *Rhynia major* from the early Devonian Rhynie chert of Scotland, as responses of living plants to the infiltration of silica-rich groundwaters from nearby fumaroles. Substantial influx of silica into this petrified peat was probably coincident with more aquatic conditions which destroyed the *Rhynia* marshes. The peaty substrate with well-preserved remains of these plants in growth position is overlain by layers with abundant crustaceans, algae, and the more aquatic vascular plant *Horneophyton* (emended from the original name of Kidston and Lang, by Barghoorn and Darrah [1938]). The living plants probably did not live in extremely high silica concentrations, nor in the indurated chert of today. The chert must have been silicified and indurated very early in diagenesis. This is apparent from the exceptional preservation of uncrushed herbaceous remains, and anatomical detail, in this and other petrified peats of various geological ages (Schopf 1970; Ting 1972; Basinger and Rothwell 1977; Runnegar 1977).

**Sharpened Boundaries**

The delineation of nodules, concretions, and horizons is often much sharper in older fossil soils than in modern soils. This may be in part a diagenetic segregation of chemically incompatible parts of the paleosol. Particularly noticeable is the often sharp delineation of gray reduced areas around fossil roots within horizons stained red with ferric oxide minerals, in older paleosols (Fig. 3.6).

The superficial appearance of sharp contacts can also be due to differential weathering of more indurated portions of a paleosol. In the Avalon and Warrigwood Series paleosols of the Triassic of the Sydney Basin (Retallack 1977a), the lower boundaries of the silicified A horizons (ganisters), never prove to be as distinct in polished slabs as they appear in the field.

**Physical Compaction**

Depending on the depth and other conditions of burial, fossil soils may be flattened or develop jointing or other structures. According to Roesch-
Copper, Uranium, and Water Abundance

To be discovered in orogen (Reid, 1997).
solutions and also some of the organic layers which have been mineralized, are also probably fossil soils. The minerals are thought to have been dissolved in groundwater draining from uranium-bearing crystalline or volcanic rocks in uplands, and precipitated at a "redox front" (a transitional zone from positive to negative Eh or oxidizing to reducing conditions) in the lowlands (Stanton 1972; Granger and Warren 1978). This may have occurred during the formation of the fossil soils in these deposits, as well as during their later diagenesis. Basin-wide studies of these fossil soils, and particularly interpretations of their ancient water tables, may prove to be a powerful exploration tool. To my knowledge, this has not yet been suggested or attempted.

INTERPRETATION

Some aspects of ancient terrestrial environments can only be interpreted from the study of fossil soils. For other aspects, the study of fossil soils may be a valuable independent check on conclusions reached by other kinds of research. The study of fossil soils has lagged far behind other geological and paleontological studies, such as analysis of sedimentary basins, sedimentary petrography, heavy mineralogy, sedimentology, palaeocurrents, palynology, paleobotany, paleontology, and paleoecology. In areas where these other studies have already been completed, a study of fossil soils may serve as a critical focus to integrate other information into a more detailed concept of a particular ancient terrestrial ecosystem than was hitherto possible.

Water Table

The nature and depth to the B horizon of some kinds of paleosols is a reasonable guide to the depth of the water table, or at least the zone about which it most commonly fluctuated. Frequent wet periods are indicated by siderite nodules or spherulites in the B horizon (as with all these features they must be demonstrated to be original), by aspic or undulic plasmic fabrics, by an apedal or massive structure, by shallow root systems with thicker roots spreading laterally rather than downward, and also by more humified organic matter at the surface. More frequent dry periods may be indicated by reddish mottled or nodular B horizons stained with ferric oxide minerals, by well-differentiated pods, by animal burrows, by deeper root systems, and by less humified organic matter at the surface. Even better drained and more arid conditions are indicated by soils without a clear B horizon or with other indicators, such as caliche nodules. It is also possible that this last kind of paleosol was so immature before burial that there was on a pre-Oligocene surface in a deep drill hole in the Ross Sea, Antarctica (Ford and Barrett 1975).

Forests would have had a greater stabilizing effect on the landscape than preexisting kinds of vegetation. Even today, forests have not achieved total cover of the landscape, but they were probably much less effective in controlling upland erosion during the Devonian and Carboniferous. Schumm (1968) has pointed out that the Euramerican Carboniferous coal measures have more and thicker clastic partings than the spectacularly thick early Tertiary coals of North America, Germany, and southeastern Australia. He suggested that this is due to greater erosion of less vegetated uplands during the Paleozoic. Further study of woodland and other fossil soils in sedimentary basins should refine this hypothesis considerably.

Tertiary Emergence of Grassland Soils

The development of savanna, steppe, prairie, and pampas vegetation on the plains, and of grassy vegetation above the snowline in alpine regions, also had a major effect on landscapes of the world. On the plains, new kinds of soils formed under the grassy swards, mollisol (of the U.S. Dept. of Agriculture), or chernozem, prairie soil, black earth, rendzina, and wiesenhoden of older nomenclature. Evidence from fossil plants indicates that monocotyledonous angiosperms probably evolved during the early Cretaceous (Doyle 1973), but true grasses do not appear until the early Tertiary (Litke 1968). The best known megafossil record of grasses is in the Miocene to present sediments of the Great Plains of North America (Elias 1942; Thomassen 1979). Other than this the fossil record of grasses is generally poor. The emergence of grasslands within the interior of all the major continents at various times during the Tertiary is better indicated by other fossil plant remains and fossil mammals. In particular, the high crowned (hypodont) teeth of grazing mammals indicate that coarse grassy fodder was widely available. On such grounds, savanna or pampas may have appeared in Argentina as early as the Eocene (Patterson and Pascual 1972). In Africa, there were probably considerable areas under savanna vegetation during the Oligocene, and it was probably more extensive during the Miocene and Pliocene (Tanner 1978; Axelrod and Raven 1978). In North America, savanna began to emerge as a vegetation type during the Oligocene, with steadily increasing numbers of trees culminating in prairies as extensive as those of today by Pliocene times (Webb 1977). Savanna and steppe of central Asia appears to have become widespread during the Miocene, expanding into western Europe and China by the Late Miocene (Osborn 1910). In Australia, savanna may have been present during the Pliocene, but there is little evidence of savanna and grassland until the Pleistocene (Kemp 1978; Martin 1978).

Evidence from fossil soils is likely to give a much clearer idea of the age
The special curve mentioned in the previous paragraph is a curve used to determine the age of fossils. This curve is based on the assumption that the rate of radioactive decay is constant over time. The curve is used to calculate the age of fossils by comparing the amount of radioactive material in the fossil to the amount of the same material in a modern sample of the same type of organism.

Soil Profile

Soil horizons are the layers of soil that form above the bedrock. The top layer, known as the A horizon, is the most recent layer to form and is typically rich in organic material. The B horizon, or subsoil, is the next layer down and is characterized by a higher content of clay and minerals. The C horizon, or parent material, is the layer below the B horizon and is composed of the original rock or sediment from which the soil formed.

Soil Chemistry

The chemistry of soil is determined by the chemical composition of the parent material, the climate, and the biological activity of the soil. The pH of the soil is an important factor in determining the availability of nutrients to plants. The C:N ratio, which is the ratio of carbon to nitrogen in the soil, is also important in determining the availability of nutrients.

Paleobotany, Paleozoology, and Evolution

The study of ancient plants and animals is known as paleontology. By examining the fossil record, scientists can gain insights into the history of life on Earth. The study of evolution, the study of how species change over time, is based on the fossil record. By examining the evolution of species, scientists can gain insights into the processes that drive evolution.
more than 10 m deep in the early Miocene Harrison Formation of northwestern Nebraska (Fig. 3.7) have even been found with entombed skeletons of burrowing rodents. The *Daemonelix* burrows indicate that the water table in these soils was seldom closer than 10 m below the surface, for otherwise the rodents would have drowned. The nature and occurrence of traces of soil fauna can supply useful constraints in the interpretation of fossil soils. Further studies of these traces can be expected to reveal much about the evolution of such animals as earthworms and ground-dwelling social insects and rodents.

**Vegetation**

The former vegetation of some fossil soils, particularly gleyed and organic soils, may be preserved in or around their upper surface. Plant material is usually not preserved in more oxidized fossil soils. However, poorly preserved pollen in oxidized Triassic fossil soils proved sufficient to gain an idea of its vegetation (Retallack 1977b). As a general rule, fossil plants are much better preserved in flood, pond, or lake deposits than in direct association with fossil soils. More detailed understanding of fossil plants gained from such better preserved material is often useful also in interpreting fossil soils. The fossil plants may indicate whether the vegetation was a forest, savanna or grassland, and also show adaptations to conditions such as aridity, salinity, or waterlogging. This may serve as an independent check on deductions from their likely fossil soil. The study of fossil soils and plants can be combined to gain a better understanding of both.

**FIGURE 3.7.** *Daemonelix*, burrow system of a rodent from the early Miocene Harrison Formation of Nebraska. Reduced onetenth natural size. (Redrawn from Barbour [1897].)

**FIGURE 3.11.** Later Early or earlier Middle Triassic type Long Reef clay paleosol north of Sydney, Australia. The ferruginized lower B horizon of the type profile includes pedorelicts of the A horizon of an underlying paleosol.

soft volcanic sand grains better preserved lower in the profile. The reddish material with isotic fabric in lower horizons is mainly hematite and goethite, with some siderite. Soil-forming processes have resulted in considerable accumulation of total iron (Fe₂O₃ + FeO) in the B horizon, a moderate accumulation of Al₂O₃ in the A and B horizon, and loss of CaO, MgO, Na₂O, and K₂O throughout the profile. These paleosols were identified as gray brown podzolic (of Stace et al. 1968), ferrods (of Soil Survey Staff 1975), and Uf2 (of Northcote 1974).

I have seen similar fossil soils, not yet studied in detail, in the late Mississippian or early Pennsylvanian Manning Canyon Formation, across Utah Lake, from Provo, Utah; in the early Permian uppermost Opeche Formation, near Boulder Park, in the Black Hills of South Dakota (Fig. 3.3); in the late Triassic Lockatong Formation of the Newark Basin, near Phoenixville, Pennsylvania; in the Late Triassic Chine Formation of the Petrified Forest National Monument, Arizona; in the early Cretaceous Otway Group of southern Victoria, southeastern Australia; in the mid-Cretaceous upper Dakota Formation in Russell County, Kansas; and in the Eocene Clarino Formation, on Camp Hancock, near Clarno, Oregon. Other aspects of the geology and paleontology of these various places are discussed by Tidwell (1967), Tranter and Petter (1963), Olsen (1978), Wycoff et al. (1972), Douglas (1969), Hattin, Seimers, and Stewart (1978), Baldwin (1976), and references therein. Similar well-differentiated reddish paleosols have also been reported from the Pennsylvanian of Colorado (Hubert 1960); the Permian and Triassic of southern Germany (Ortlam 1971); the Permian...
structures. Humans are capable of understanding and processing the patterns and relationships within these structures to make predictions and decisions based on past experiences. The ability to recognize and interpret these patterns is a key aspect of human intelligence and is essential for tasks such as learning, problem-solving, and decision-making in various domains.

In essence, the study of complex processes, such as those operating in the brain, involves understanding the interaction and interplay of different components and variables. By integrating knowledge from various disciplines, including cognitive science, neuroscience, and artificial intelligence, researchers can gain deeper insights into the nature of these processes and develop new technologies and tools to support human learning and decision-making.

As the field continues to evolve, there is a growing recognition of the importance of interdisciplinary approaches and the need for collaboration across different domains. This approach is essential for addressing the complexity of human cognition and for harnessing the full potential of artificial intelligence in enhancing human capabilities and improving our quality of life.
Frarey and Roscoe 1970; Rankama 1955). Other more subtle kinds of extinct paleosols may be discovered in the future.

Some kinds of fossil soil horizons such as caliche and laterite have been widely identified in the past on too little evidence, without any indication of the nature of the profiles or any attempt to demonstrate that the features observed were original rather than diagenetic. This is especially apparent from reexamination of so-called laterites of the area around Sydney, Australia by Hunt, Mitchell, and Paton (1977). Close attention to detail is necessary if studies of fossil soils are to realize their evident potential.

Basin Tectonics

The nature of fossil soils and their distribution within sedimentary sequences may give otherwise unattainable information on rates of sedimentation, subsidence, uplift, and basin topography. In my work on Triassic paleosols north of Sydney, Australia (Retallack 1977a, 1977b), the distribution of paleosols indicated all these things. The Bald Hill Claystone, 18 m thick, at the base of the succession contains about eight confusingly superimposed and well-differentiated paleosols. The area probably received little sediment for 16,000 years or more because it was very slowly subsiding, freely drained, rolling land. By contrast, the paleosols are completely separated by sediment in the overlying Garie Formation. These humid gley (fibrist) paleosols indicate increased subsidence culminating in deposition of subaqueous lagoonal shale. In the overlying Newport Formation, paleosols are also well separated by sediment, but show several indications of immaturity, such as widespread sedimentary relics within the profiles. This would indicate a steady subsidence rate of about a meter every 2,000 years. Higher within the Newport Formation, paleosols are seldom preserved. Paleosols are very rare in the overlying braided stream deposits of the Hawksbury sandstone. This probably is due to very low subsidence rates, allowing extensive lateral migration of streams and almost total reworking of floodplain deposits.

Allen (1974b, 1974c) has developed several theoretical models to explain the distribution of paleosols and channel deposits expected under varying conditions of subsidence, stream behavior (lateral migration as opposed to channel avulsion), and climatic fluctuations. Slow subsidence of the order of a meter every 5,000 years and periodic channel avulsion may best explain the distribution of paleosols in the Anglo-Welsh outcrop of the Siluro-Devonian Old Red Sandstone.

Climate

Temperature and rainfall are such important factors in forming modern soils that many modern soils are restricted to particular climatic zones. animals. They were evidently vegetated, at least sparsely. Much has been learned of the evolution, anatomy, and morphology of the primitive plants associated with these paleosols (Banks 1968), but it is too early yet to say what kinds of plant communities vegetated these various fossil soils.

McPherson (1979) has made a detailed study of similar fossil soils from the Late Devonian (probably Famennian) Aztec Siltstone of southern Victoria Land, Antarctica. These are riddled with small root casts and burrows, calcareous nodules, and vein networks, and also show tepee structures and color mottling. Sepic plasmic fabrics (as in Fig. 3.4) are common in these paleosols. The down profile decrease in SiO₂ and increase in Al₂O₃, K₂O, and TiO₂ indicates that there was significant illuviation of clay. Increasing total iron (Fe₂O₃ + FeO), CaO, and MnO with depth, is related to a down profile increase in hematite and carbonate. These changes indicate very rudimentary development of A and B horizons, as found, although much better differentiated, in modern forested soils. McPherson compares these Devonian paleosols with red or brown clays, red brown earths, calcareous red earths, and red earth soils of the Australian classification (Stace et al. 1968). Only a few fragmentary lycophod fossil plants have been found in Devonian rocks of Antarctica (Plumstead 1964). Judging from later representatives of this group of plants, these probably colonized wetter habitats than these fossil soils, whose vegetation is still unknown.

As discussed by Schumm (1968), the emergence of a land flora had a great effect on stabilizing stream channels, particularly in promoting meandering rather than braided stream courses. It also served to delay and lessen the devastation of flash flooding after rains in some parts of the landscape. As a result, soil formation on the interfluvies was less frequently and less critically interrupted by sedimentation.

Mid-Paleozoic Appearance of Woodland Soils

The first woodlands and forests would have had a considerable impact on the world’s land surfaces. In some ways their greater biomass would have
ABOVELOPE OF THE PRECAMBRIAN

For the Pioneer

fossil soils are found in the lower Proterozoic rocks of the world. The oldest known examples of these deposits are from the Lower Proterozoic of South Africa and Australia. These soils are remarkable for their resemblance to modern soils in that they contain well-developed horizons, including a well-developed A horizon. The well-developed horizons of these soils are due to the action of weathering processes, which resulted in the accumulation of minerals and organic matter. The presence of these soils indicates that the Earth was capable of supporting plant life at an early stage in its history.

DIAGNOSTICATION OF SOILS THROUGH TIME

The study of fossil soils helps us understand the evolution of soil formation and the development of plant life. The earliest known examples of fossil soils date back to the late Proterozoic era, around 1.2 billion years ago. These soils were formed in conditions similar to those of modern tropical rainforests. As we move forward in time, the complexity and diversity of soil types increase, reflecting the evolution of plant life and the changing environments. By studying fossil soils, we can gain insights into the environmental conditions of the past and the evolution of terrestrial ecosystems.
recognized to date have been below major unconformities. The many problems of this kind of geological setting have already been discussed. There is a need for more earnest theoretical modeling of the likely weathering effects of different hypothetical Precambrian atmospheres and also for more detailed micromorphological and geochemical studies of Precambrian paleosols.

Collins (1925), Roscoe (1968), and Frarey and Roscoe (1970) have described a fossil soil, about 2.45 billion years old, developed on pre-Huronian crystalline rocks underlying the various basal formations of the Elliot Lake Group in the area between Sudbury and Elliot Lake, north of Lake Huron, Canada. This is a zone, up to 16 m thick, of altered biotite granite and greenstone on the pre-Huronian surface. Above unaltered pink biotite granite, there is a thick white rock with granitic texture containing highly altered mafic minerals, plagioclase almost entirely altered to sericite, and scattered inclusions of unaltered granite. Higher in the profile granitic texture is no longer present, even microcline is partly replaced by sericite and only quartz grains persist unaltered. The highest part of the profile is a greenish rock with quartz grains and remnants of microcline floating in a structureless matrix of sericite (mica-illite). Accessory minerals persisting in the altered rock include hematite, magnetite, pyrite, rutile, zircon, monazite, thorogummite (probably thorite originally), garnet, and amphibole. Thinner (about 1 m) profiles, developed on greenstone, consist of a greenish, gray or pale yellowish rock with a high sericite content. Pyrrhotite (or sometimes other sulfide minerals) may form a thin layer, up to 3 cm thick, immediately below the unconformity on these greenstone profiles. The pre-Huronian land surface was evidently leached of most of its CaO, SrO, and MnO, much of its MgO, Na2O, FeO, and Fe2O3, and perhaps a little SiO2 and Al2O3. Strangely, water, Rb2O, and K2O appear to have accumulated. Other aspects of this alteration are comparable with modern weathering, apart from the general loss of iron, the greater loss of Fe2O3 than FeO, and the extreme loss of MnO. These differences are probably due to the absence of oxygen in the atmosphere at that time. An anoxic atmosphere is also indicated by pyritic conglomerates containing placers of detrital uranium minerals, such as uraninite and brannerite, in the overlying Elliot Lake Group. Lack of oxygen is in good accord with modern theory that the Precambrian atmosphere was largely derived from degassing of the earth's interior from volcanic vents and so consisted largely of gases such as CH4, NH3, CO2, H2, H2O, H2S, and N2 (Berkner and Marshall 1965).

Another paleosol, possibly formed in an oxygen-poor atmosphere about 1.8 billion years ago, has been found in the Tampere area of Finland (Rankama 1955; Eskola 1963). This is a breccia of diorite with a gray schist matrix developed on fresh diorite and overlain unconformably by varved mica schist. Analysis of all these rocks showed a preponderance of FeO over Fe2O3, as in the pre-Huronian paleosols north of Lake Huron.

...jasper-bearing paleosol (McBride and Folk 1977). Finally, Microcodium is a widespread microfossil commonly preserved in caliche-bearing paleosols. Klappa (1978) has interpreted it as a fungus, possibly mycorrhizal, and has discussed numerous occurrences dating back to Jurassic times.

Early Paleozoic Advent of Soils of Vascular Land Plants

The study of fossil soils may make a fundamental contribution to the current debate on when the first vascular land plants appeared. Some (Gray and Boucot 1977) feel that dispersed trilet spores, trachyde-like bodies, and cuticle fragments found in rocks as old as late Ordovician are the first evidence of vascular land plants. Others (Banks 1975a, 1975b; J. M. Schopf 1978; Edwards, Basset, and Rogerson 1979) are only prepared to accept as evidence of the first vascular land plants the complete megafossils of late Silurian age. The debate has opened some very difficult, perhaps insoluble, questions. To what extent do specific structures of fossil plants necessarily indicate their affinities or paleoenvironment? Is the adaptive value of such structures in living plants the same as it was to the first land plants? Which and how many features are important indicators of terrestrial habitat? Were some of the earliest land plants adapted to partial or periodic exposure to the air? Studies of the fossil substrates supporting these early plants should give a more definitive and detailed perspective on the problem. The holdfasts, rhizoids, rhizomes, and roots of primitive plants may be well-preserved in aquatic shales and cherts. Although not preserved as well in more oxidizing environments, such structures may significantly modify soil material. They promote the obliteration of relic structures from the parent material and development of sepic plasmic fabrics, cutans, and glaebules, or leave more obvious pedotubules (this terminology is after Brewer 1964).

Early Paleozoic redbed sequences should be examined in more detail with this aim in mind. First on my list are the Ordovician and Silurian paleosols described by Boucot et al. (1974) from the Arisaig area of Antigonish County, Nova Scotia. Here paleosols cap several columnar-jointed andesite flows in the late Ordovician Dunn Point Formation. The 1.3 m thick profiles consist largely of a homogeneous aggregate of granular hematite and clay, which extends deeper into cracks within the spheroidally weathered andesite (Fig. 3.9). The lower portion of this altered zone contains upward fining andesite corestones. This is overlain by an horizon with poorly developed spherulitic texture. The upper portion of the red material is blocky, with nodules and irregular patches of chaledony and carbonate. Near the surface of the profile there are small white reduction spots and irregular pockets, about 1 m wide and 20 cm deep, filled with bedded, redeposited red material. Plastically deformed fragments of the red paleosols are commonly entrained in overriding andesite and ignimbrite flows. The
1970s, a number of new findings emerged that challenged the prevailing models of ocean chemistry. The Redfield ratio, which had been established as a fundamental constant, was found to vary significantly in different environments. This led to the development of more complex models that incorporated the variable nature of nutrient cycling in the ocean. These models took into account the spatial and temporal variations in nutrient availability and the impact of factors such as temperature, salinity, and light intensity on phytoplankton productivity.

In the mid-1970s, the concept of the biological pump, which describes the process by which carbon is transferred from the atmosphere to the ocean, gained prominence. This process involves the uptake of carbon dioxide by phytoplankton during photosynthesis, which then sinks to the deep ocean as organic matter. The biological pump is a key component of the carbon cycle and plays a crucial role in regulating global climate.

The development of these new models and theories led to a reevaluation of the role of the ocean in the carbon cycle and the importance of understanding the complexities of ocean chemistry. This period marked a significant shift in the field of oceanography, with a greater emphasis on interdisciplinary approaches and the integration of data from different sources.

In the late 1970s and early 1980s, the International Biological Programme (IBP) and the later Joint Global Ocean Flux Study (JGOFS) were established to coordinate efforts in the study of the oceanic carbon cycle. These programs aimed to provide a comprehensive understanding of oceanic carbon fluxes and the role of the ocean in the global carbon cycle.

Overall, the 1970s were a period of significant progress in our understanding of ocean chemistry and the biogeochemical cycles that govern the Earth's climate. The development of new models and theories, along with the establishment of cooperative international efforts, paved the way for continued research and a deeper understanding of the Earth's oceans and their role in the carbon cycle.
FIGURE 3.8. One-billion-year-old fossil soil on Lewisian gneiss with prominent pegmatite veins, unconformably overlain by Torridonian conglomerate and sandstone, at Sheilgra, northwest Scotland. The reddish surface of the fossil soil is shown in heavier stipple. Hammer gives scale. (Redrawn from Williams [1968] with permission from the Scottish Journal of Geology.)

this profile, but all the original hornblende and most of the plagioclase have been altered to a pale green micaceous mass with patches of chlorite, carbonate, and iron oxide. Pegmatite veins were little altered. These and the foliation were bent at the unconformity in some outcrops, interpreted by Williams as evidence of Precambrian soil creep. Both the red and bleached portions of the profile on the biotite gneiss have lower SiO₂, FeO, CaO, and Na₂O and higher Fe₂O₃ and K₂O than fresh gneiss. In the red portion of the profile, Al₂O₃, Fe₂O₃, K₂O, TiO₂, and P₂O₅ are at maximum and SiO₂, FeO, and Na₂O at a minimum. Williams believed that the red portion of the profile was a remnant of a thicker, probably podzolic soil. There is no evidence of any different higher horizon, nor is it necessary. The accumulation of aluminium, iron and potassium and concomitant desilication was more likely produced by lateral flow of ground and surface water, rather than by illuviation more characteristic of modern forested soils. These paleosols were probably developed on freely drained, rolling parts of valleys in a warm, moderately humid climate and oxygenated atmosphere.

Kalliokosi (1975) has described comparable paleosols of similar age from Presque Isle, north of Marquette, Michigan, developed on granodiorite, diabase, and serpentinized peridotite, where these are unconformably overlain by late Keweenawan Jacobsville Sandstone. He interpreted the dolomite-quartz layers in these fossil soils as caliche horizons, indicating semiarid climate. The exact nature of these altered rocks has been disputed

(Lewan 1977; Kalliokosi 1977). Paleosols have also been found in several parts of the Grand Canyon of Arizona at the unconformity immediately below early and middle Cambrian sandstones (Sharp 1940; McKee 1969). Patel (1977) has reported another paleosol at the unconformity covered by early Cambrian rocks in the Saint John District of New Brunswick.

Compared to earlier times, these later Precambrian and Cambrian paleosols were leached of more silica and accumulated more iron, especially Fe₂O₃. This had a considerable effect on shallow marine sedimentation. Banded iron formations became much less common. Silicified shallow marine stromatolites, often including exquisitely preserved microorganisms, became more common (Hargraves 1976; Schopf 1975). More intense terrestrial weathering is probably also a partial explanation, besides long time of formation, for the supermature quartose sandstones deposited in rivers, beaches, and shallow marine continental shelves the world over during the late Precambrian and Cambrian.

Later Precambrian Microbially Influenced Soils

It is likely that the land was partly colonized by algae, bacteria, and viruses, and perhaps even fungi, lichens or liverworts long before the first vascular plants. The green slime of shallow Precambrian seas has been studied in some detail (J. W. Schopf 1978), but did it venture out to become the "scum of the earth"? There is little firm evidence for this idea, and still a need for more perceptive and detailed speculation.

Many of the kinds of microorganisms found in cyanobacterial mats of modern desert crusts were well represented in later Precambrian marine rocks (Campbell 1979). In modern deserts these organisms are capable of withstanding high salinity and long desiccation, with instant reactivation after rain. They are also capable of traveling overland by mechanical expulsion of trichomes during rehydration and by self-propelled gliding wherever there is moisture. Many are of a size easily transported by wind. Fischer (1965) and Sagan (1965) speculated that the high ultraviolet radiation during the earlier Precambrian prevented organisms from colonizing the surface of the ocean, the intertidal zone, and land. They also postulate that radiation was only reduced to tolerable levels by the increasing amounts of oxygen in the atmosphere. Schopf (personal communication 1980) doubts the severity of this radiation on the basis of very old stromatolites and likely planktonic organisms. But even allowing such radiation, microorganisms could have still survived on land below the surface in unconsolidated diaphanous materials and also in "shade oases" of crevices and overhangs. Small outposts of life on land may have been important centers of organic evolution.

The effects of the first soil organisms on soil formation would have been