PALEOSOLS

Record and Engine of Past Global Change

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Soils, like people, both control and are controlled by their environment. Different kinds of soils reflect different environments, from dry grassland to fetid salt marsh. But soils, by their fertility and stability, also determine what can grow in a given site, be it lichens, redwoods, or grass. Soils have played this dual role for hundreds of millions of years. Paleosols record environmental changes of the past, but they also can be considered engines of global change.

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From this perspective, paleosols may reveal both the impact of soils on the atmosphere and the impact of the atmosphere on soils. The balance of oxygen and carbon dioxide in the atmosphere has changed as soils have both added and removed these gases from the air.

Oxygenation of the atmosphere owes much to soils. Photosynthesis by trees, grasses, and other plants produces oxygen from carbon dioxide. Carbon is stored in the chemical makeup of plants, and in humus and other organic matter in soils. Carbon dioxide is also removed from the atmosphere as bicarbonate in ground water through the weathering of silicate minerals by natural carbonic acid in surface waters.

Soils contribute carbon dioxide to the atmosphere through the respiration of roots, worms, and microbes. Atmospheric carbon dioxide also comes from burning of biomass and the erosion and degradation of organic matter in soils. Reduced weathering (caused by cold or dry conditions or by the depletion of minerals in the soil) and the corresponding reduction in carbonic acid consumption leaves carbon dioxide in the air.

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Quarry for the fossil ape Kenyapithecus *near Fort Ternan, Kenya, shows the dark paleosols of short-grass wooded grasslands with the soil structure of a true sod (hammer rests on layer). Middle Miocene in age, these paleosols provide the oldest evidence for such ecosystems in East Africa. Changes in the carbon cycle to accommodate the increased internal surface area and carbon storage of sod grasslands may have contributed to global climate change known from deep sea records as the Monterey event.*

(Photo on page 25)
The hackly layer is a Late Ordovician paleosol near Potters Mills, Pa. The isotopic composition of its carbonate nodules indicates an early Paleozoic atmosphere rich in carbon dioxide (18-19 times the present level). The early Paleozoic greenhouse may have been due in part to a high ratio of animal-to-plant productivity. This paleosol, for example, shows abundant burrows but little trace of plants.

Recorders of Global Change

Scientists have used paleosols to reconstruct changes in atmospheric composition over the past 3.5 billion years. Heinrich Holland (Harvard University) devised a physicochemical model for weathering that estimates the ratio of the partial pressures of oxygen and carbon dioxide from the chemical composition of paleosols. A surprising early finding was that Precambrian paleosols developed on granite were oxidized while soils of the same geological age on basalts were chemically reduced. This finding indicates that Archean and early Proterozoic atmospheres had at least some oxygen, more than previously thought. Oxygen levels, however, were still too low to oxidize the abundant iron liberated by hydrolysis of iron-rich materials such as basalt.

Work with Holland's weathering model has also identified a trend toward oxygenation of the atmosphere around 2 billion years ago. By 850 million years ago, red paleosols were widespread (a sign of abundant atmospheric oxygen), as were glacial deposits and the enigmatic Ediacaran organisms.

Researchers are using the carbon isotopic composition of carbonate in paleosols to reconstruct Paleozoic atmospheres. Atmospheric carbon dioxide is isotopically heavier than carbon dioxide produced by plant respiration and decay. It should have diffused further into the soil at times when the partial pressure of carbon dioxide was high.

From isotopic data, Claudia Mora, Steven Driese (both University of Tennessee), Crayton Yapp, Henry Poths (both University of New Mexico), and I have shown that the early Paleozoic greenhouse effect of high atmospheric carbon dioxide began to subside as early as the Silurian, and continued to fall until the onset of late Devonian to early Permian forests and ice ages.

Similar isotopic studies document a decrease in atmospheric carbon dioxide during the late Miocene Messinian salinity crisis in the Mediterranean when the sea's opening to the Atlantic closed and its waters evaporated. Isotopic lightening of $\delta^{13}C$ in carbonate of paleosols from this time in Pakistan, Kenya, Bolivia, and Nebraska has been attributed to the spread of grasses that used the C_4 photosynthetic pathway. (This pathway provides the most efficient carbon dioxide utilization of the three photosynthetic carbon processes.)

Thure Cerling (University of Utah) and Jay Quade (University of Arizona) first discovered this dramatic isotopic shift. They argue that it reflects a decline in greenhouse gas because, when carbon dioxide levels are low, C_4 plants are more competitive than plants using the C_3 pathway. This negative shift in greenhouse gas during the late Cenozoic ushered in the Quaternary Ice Age.

Engines of Global Change

These studies assume that paleosols provide records of the rise and fall of atmospheric carbon dioxide. But there are reasons to think that soils also played a role in causing global atmospheric changes.

Declines in carbon dioxide and climatic coolings coincide with the evolution of new kinds of ecosystems on land: late Precambrian lichenlike fossils, middle Ordovician nonvascular land plants, early Silurian vascular land plants, mid-Devonian forests, Oligocene rangelands, mid-Miocene sod grasslands, and late Miocene tall grasslands. Conversely, the onset of greenhouse conditions may correspond to the evolution of new kinds of consumers on land: late Ordovician myriapods, early Devonian insects, early Permian herbivorous reptiles, and late Triassic termites.

Such observations have prompted Paul Olsen (Lamont-Doherty Earth Observatory) to propose that the composition of the atmosphere is controlled by an "arms race" between plants and animals. When plants evolved substances that made them less palatable to animals (substances such as the chitin of lichens, the lignin of vascular plants, and the silica phytoliths of grasses), they sequestered more carbon. Such biological innovations may have led to ice ages.

When animals evolved ways to digest refractory, toxic, or carcinogenic plants more efficiently, the balance shifted, releasing more carbon dioxide to the atmosphere. Thus, millipedes, termites, and giant herbivorous reptiles may have initiated greenhouse climates of the past. The evolution of hypsodont teeth in mammals has not yet curbed the runaway expansion of grasslands or Quaternary advances of ice sheets. However, farming and the burning of fossil fuels may do the trick, at least in the short term.

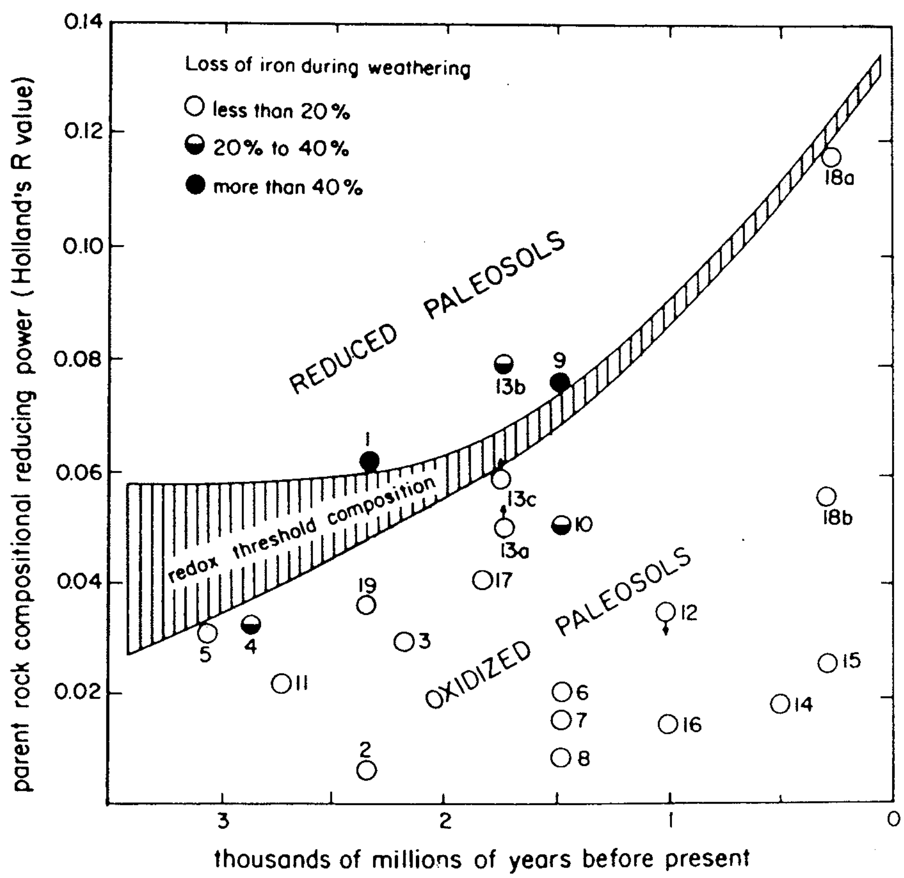
Major events in the evolution of plants on land toward bulkier, more carbon-rich communities are matched by comparable changes in soils. These changes include increased storage of carbon in biomass and soil organic matter and increased consumption of carbonic acid for weathering.

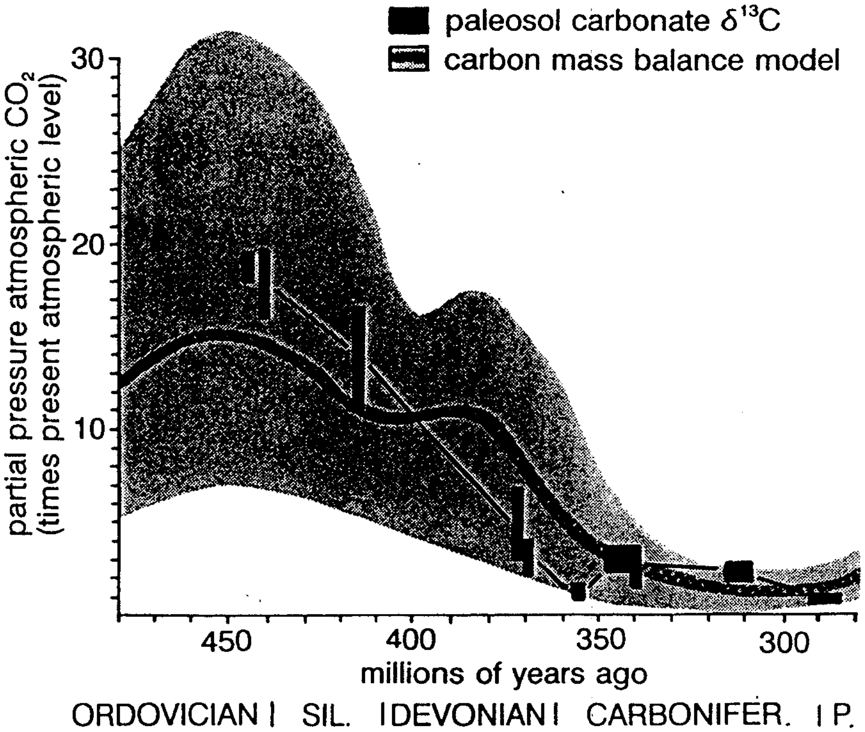
The appearance and rise of grasslands in the Cenozoic is recorded in a distinctive new kind of soil, Mollisol. The mollic surface horizon of these soils has an intimate mixture of clay and organic matter for subterranean carbon storage, and it is organized into fine (2-5 millimeter) clods that give an exceptionally high internal surface area for weathering.

In the Devonian through the Carboniferous, increasingly thick coals reflect the increased capacity of vegetation to create the histic surface horizons of Histosols. In the Devonian, deep woody roots appeared in soils. In addition, a subsurface horizon of clay, known as the argillic horizon of Alfisols, developed. Before that time, the most clayey part of soils was near the surface, which became thicker and more bioturbated by thalli and rhizomes during the late Precambrian to the Devonian. Carbon storage and carbonic acid consumption by soils escalated through time with several discernible thresholds.

Intervening episodes of greenhouse conditions and overgrazing by animals on land may also be recorded in the increasingly well-documented trace fossil record of paleosols. Late Ordovician millipede burrows and tracks and late Triassic termite nests are the most ancient records known of these organisms. Crayton Yapp and Henry Poths have demonstrated from variation in $\delta^{13}C$ within an Ordovician

Increased oxygenation of the atmosphere during the Precambrian is revealed by increased iron retention through time of paleosols with iron-rich parent materials.





*Declining atmospheric concentration of carbon dioxide through the Paleozoic is indicated by changing carbon isotopic composition of carbonate in paleosols (black boxes) and a mass balance model for sediments (shaded area). Data are from C.S. Yapp and H. Poths (*Nature, *v. 355, p. 342, 1992); G.J. Retallack (*University of Tennessee Department of Geological Sciences Stud. Geol., *v. 22, p. 33, 1993); C.I. Mora and others (*Science, *v. 271, p. 1105, 1996); and R.A. Berner, (*Science, *v. 261, p. 68, 1993).*

paleosol that atmospheric diffusion was countered by soil respiration comparable to that found in productive forest soils. Since the fossil records of plants and soils indicate that nothing larger than liverworts grew on land at that time, much of this soil respiration was probably due to animals. Termites and dinosaurs may have reintroduced communities with a low ratio of plant to animal production during the Mesozoic greenhouse. Thus Earth may have teetered from icehouse to greenhouse as first plants, then animals, gained the upper hand.

We are only beginning to appreciate paleosols as records and regulators of fundamental changes in the carbon cycle through geological time. They still have much to tell us about global change of the past.

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Retallack's interest in paleosols began 25 years ago on the beaches of Sydney, Australia. His early work in paleobotany drew paleoecological information from paleosols. He is still trying to understand those Triassic and Miocene profiles along with others ranging in age from Precambrian to Pliocene — profiles that promise a better understanding of life and landscapes of the past.

Additional Reading

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"Productivity of pre-vascular continental biota inferred from $Fe(CO_3)OH$ content of goethite" by C.S. Yapp and H. Poths. *Nature*, v. 368, p. 49-51, 1994.

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The GeoRef database contains many references on the author's topic. The following strategy was used to search GeoRef on CD-ROM through September 1995.

KEY WORDS	REFERENCES
paleosol* and (carbon dioxide or paleoclim* or paleoecol* or ecology or paleoenv* or global change) in de	655 (disk 3