

The Dynamic Earth

Presenting an issue on the earth as a system of interacting fluids, including living matter. Some of the flows are fast, others slow, but overall the planet is maintained in a remarkably steady state

by Raymond Siever

Scientists who study the earth are accustomed to working with many different scales of space and time. The physical dimensions of their subject range from the global to the submicroscopic, from volumes of matter measured in cubic kilometers to interatomic gaps measured in angstrom units. Often a given research topic will encompass widely disparate scales of length, as when an earthquake triggered by a slippage of a few centimeters along a fault generates seismic waves that travel for thousands of kilometers through the earth's interior. Similarly, the temporal dimensions of geology include not only short-lived phenomena such as earthquakes, volcanic eruptions and meteorite impacts but also events recorded in units of tens or hundreds of years (for example the meandering of a river), thousands of years (glaciation), millions of years (continental drift) and even billions of years (the formation of the present, oxygen-rich atmosphere). Again a single process, notably weathering, can be studied over a wide range of time scales: from the minutes and hours of a laboratory experiment measuring the dissolution rate of a mineral to the thousands of years needed to form a soil. Taken in various combinations, the parameters of geologic space and time define the scope of this single-topic issue of *Scientific American*: the multitude of great and small changes that have taken place—and continue to take place—in the history of the earth.

Most geologists, oceanographers and other earth scientists tend at one time or another to think of the earth as a machine, or perhaps as a living organism. The metaphor of the machine captures an important aspect of the earth's dynamism: in spite of all the changes that are observed at many different scales

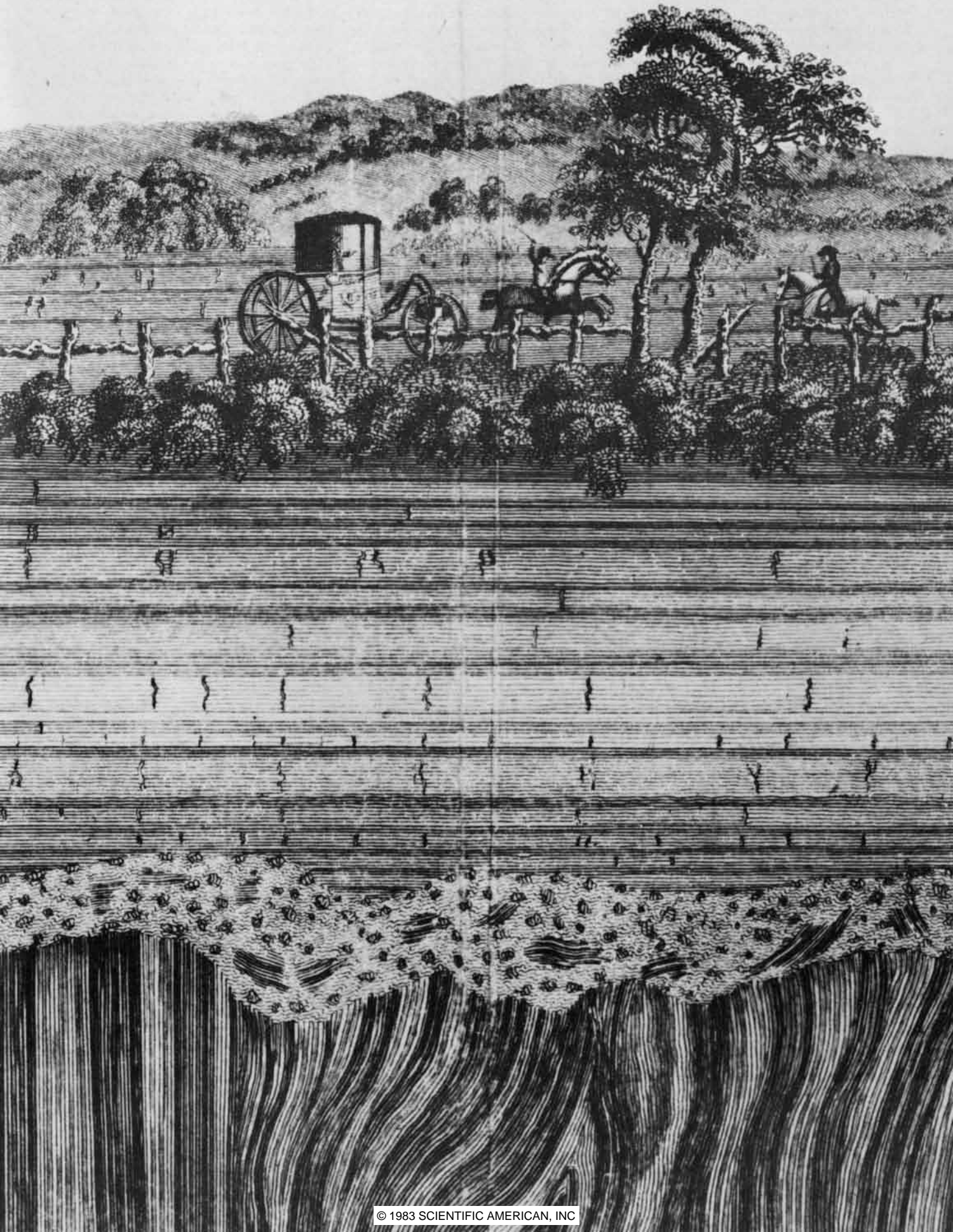
of space and time, the earth as a whole stays remarkably constant. In particular, it has become apparent in recent years that major parts of the globe—the core, the mantle, the crust, the oceans and the atmosphere—can be profitably viewed as a complex, interacting system in which there is a cyclic flow of material from one reservoir to another. The mechanistic model of the earth as a vast recycling system has its counterpart in the physiological model of dynamic equilibrium known as homeostasis.

The hierarchy of scales that pervades the work of the earth scientist is perhaps best exemplified in the making of a geologic map, an artifact that can be described in somewhat nongeologic terms as a graph of the position on a coordinate system at the earth's surface of rock formations of different ages. The first step in geologic mapping is the job of the field investigator, who determines two major properties of the rocks at a given site: age and composition. At a typical rock outcrop one can see only small-scale relations, usually over distances measured in meters. From an assemblage of such observations the final map of the region is constructed, like any other graph, by interpolation and extrapolation, showing forms appropriate to its

scale. On a map with an area of, say, 200 square kilometers one can see patterns of river valleys and the characteristic folds and faults of bedrock. The wealth of information at the outcrop level is sacrificed in favor of grosser features. On a map that covers a region of many thousands of square kilometers one begins to see even larger features: plateaus, mountains, plains, entire river systems, the outlines of a rift valley, the distribution of glacial lakes. As the map gets to continental or global proportions one sees the largest structures of the continental surface, principally mountain chains. Whenever detailed information is sacrificed for patterns that show up only on a large-scale map, the trick is to recognize what details to leave out. In other words, the essence of this kind of geologic analysis is always to separate the "signal" from the "noise."

Inevitably earth scientists face the problem of reconciling scales. For example, structural geologists and geophysicists are currently trying to relate the large-scale collisions of tectonic plates that throw up high mountains such as the Alps and the Himalayas to the small-scale folds and faults that can be seen on an individual mountainside. The aim is to learn how to go in the opposite direction: to infer from small-

EVIDENCE OF ANCIENT UPHEAVALS underlies the pastoral scene on the opposite page. The engraving is from James Hutton's *Theory of the Earth*, published in 1795. It shows an exposed riverbank of the river Jed in southern Scotland. The vertical beds of rock at the bottom of the bank were originally laid down as oceanic sediments. They subsequently underwent metamorphosis to become schist and were deformed and uplifted to become part of a mountain chain. The band of mixed material just above them is erosional debris dating from that period. The metamorphic rocks were then submerged again, and the horizontal sedimentary beds of sandstone were deposited above them. Finally the entire formation rose above sea level once more and the new soil layers were formed at the top. Hutton cited such examples from his wide-ranging field trips as evidence both of the earth's antiquity and its dynamic activity. In modern terminology a rock formation of this type is called an angular unconformity.



scale folds and faults what an older, obliterated mountain chain was like and how it might have been created by ancient plate motions.

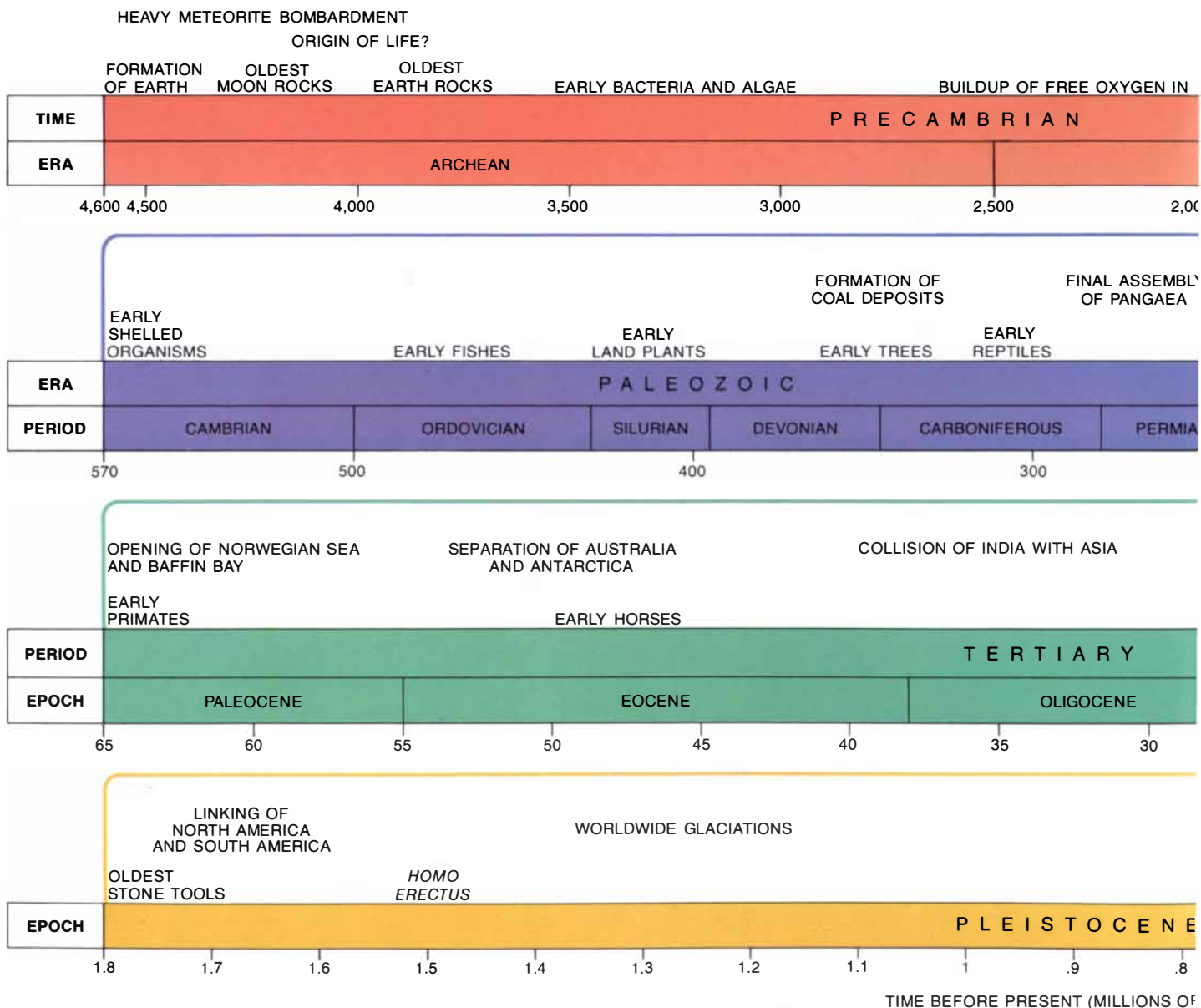
Scales of time involve additional subtleties. A river flowing at several centimeters per second moves at roughly the same speed as a fault block slipping in an earthquake. Yet the distribution of these two movements over a longer period is quite different. The river runs more or less steadily for months or years, whereas the movements along the fault are episodic, with intervals of little or no movement extending over as much as hundreds of years. The distinction between steady and episodic change is central to the current debate over the rate of biological evolution: the key question

here is whether or not the geologic time scale embodied in fossil-bearing rocks is precise enough to resolve the issue between the "gradualist" and the "punctuated equilibrium" models of the evolution of species.

Generations of geologists have relied primarily on a biological clock: the sequences of fossils that by their evolutionary changes mark the major divisions of geologic history. In the 19th century that was the only choice; in the 20th century, however, it became possible to calibrate the fossil clock by another timekeeper: the radioactive-decay clock, which depends on the known decay rates of radioactive isotopes of carbon, uranium, potassium, rubidium and neodymium. The scales of the events the

two clocks date are apt to be different, as is the nature of the events timed. Working with both clocks is a little like arranging to meet someone at a certain time when one person relies on his pulse to count seconds and the other has a watch with only an hour hand.

Geologists refer to the apparent motion of the sun (or what might be called everyday time) to time comparatively fast processes such as the weather, floods, landslides, volcanic eruptions and earthquakes. They invoke radioactivity alone to time very slow processes such as the evolution of the atmosphere. In between lies the scale of geologic time over which continents move, mountain chains rise, the earth's magnetic field reverses, fossil species evolve



GEOLOGIC TIME SCALE, originally constructed by 19th-century naturalists solely on the basis of fossil evidence, has been calibrated by means of modern radioactive-dating techniques. In this representation the top line shows the full sweep of geologic time from the origin of the earth some 4.6 billion years ago to the present. The com-

paratively short span of Phanerozoic time, during which fossils of shelled organisms have been abundant in the geologic record, is enlarged in the second line from the top, and successively shorter time segments are enlarged in the next two lines. The three eras of Phanerozoic time (Paleozoic, Mesozoic and Cenozoic) are divided in turn

and glacial epochs last. Over this intermediate time scale reference is made primarily to the specific rock sequences that constitute the geologic record.

For example, in order to study the meandering of a river one can rely on historical records if they go back far enough, perhaps supplementing this information with data drawn from the relicts of prehistoric terraces. To study the long-term evolution of the river, from the early cutting of its valley into bedrock to its later broadening into a characteristic floodplain, however, one has no alternative but to consult the geologic record. The rise in sea level since the retreat of the glaciers some 10,000 years ago is also revealed in the geologic record, which yields information both on

the rate of change of the ice sheets and their relation to the sea and on an important property of the earth's interior. As the ice retreated it unloaded the crust, and from the crust's "rebound" it is possible to estimate the viscosity of the mantle material that flowed under it in order to accommodate the rise.

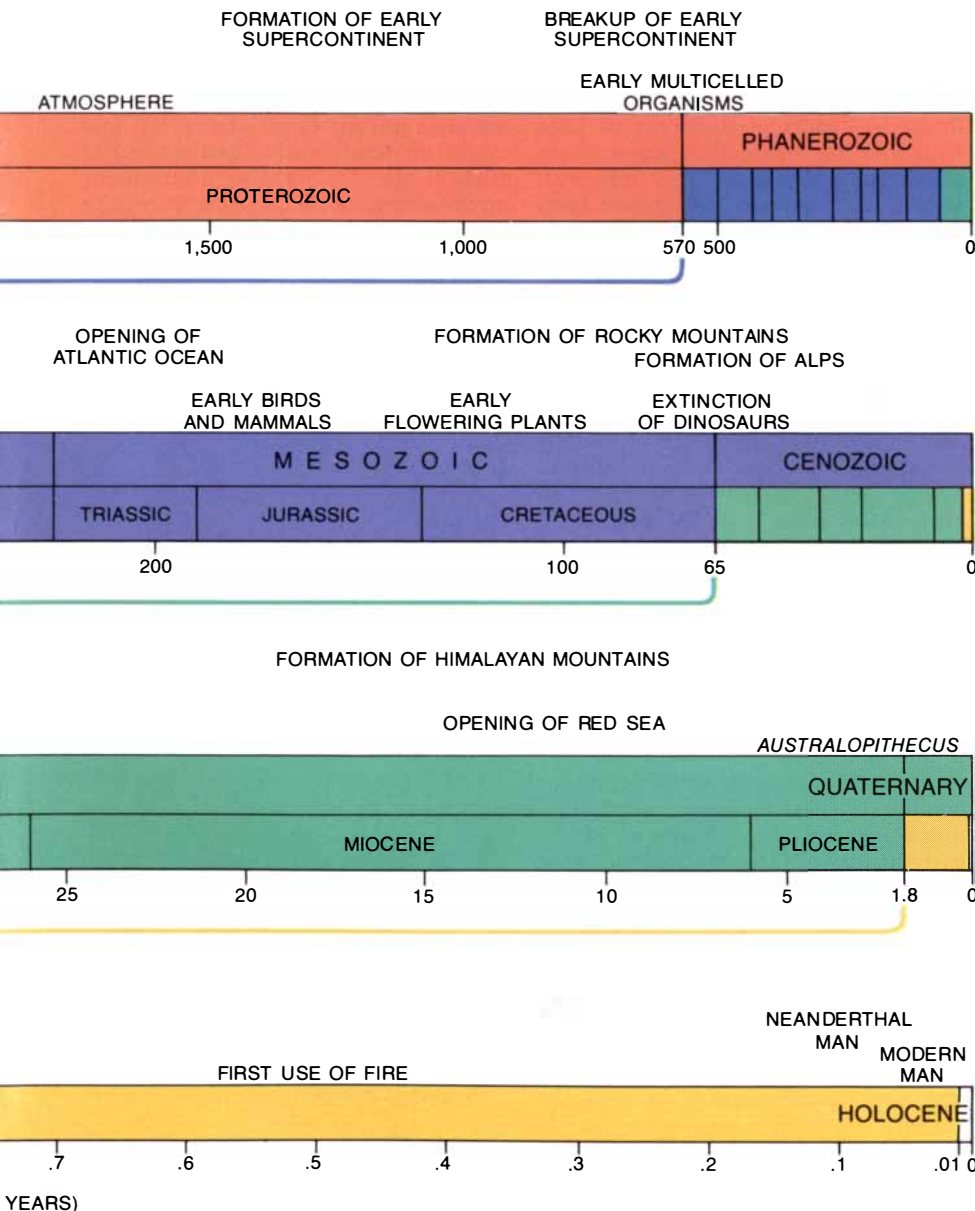
The history of the earth is studied not only for its own sake but also for economic reasons: to explore for oil, gas, metallic ores and other useful substances formed at a specific time and place in the distant past. Simple curiosity, however, is what drives most geologists to want to know just what happened when. They want to know about the last ice age both for what it can reveal about the next one and for a

glimpse of what the conditions of life were for early man. Finally, there are those geologists who specialize in the search for evidence that the history of the earth is not just one random thing after another but rather the playing out on a long time scale of the cycles of a great machine.

If earth history is cyclic, over what periods of time does it repeat itself, and how does one keep track of the process? The hydrologic cycle serves as a model of the cyclic flow of material between different parts of the earth. Water from one major reservoir, the atmosphere, falls on the land and the sea. Some of the precipitation is stored temporarily in the ground and in lakes. The rest follows various routes back to the other major reservoir, the sea. Evaporation from the sea and the land back to the atmospheric reservoir completes the cycle.

The hydrologic cycle is global. Hence by adding up all the water in all the world's reservoirs and flow paths one can arrive at an estimate of the total water content of the system and its major parts. Bypassing analysis of individual reservoirs has the effect of removing heterogeneity: one finds that the global balance is quite steady from year to year. In other words, there is always about the same amount of water in the atmosphere, in the oceans, in the polar ice caps and on the continents. Over periods of less than a year the system may not be so steady, and over periods of a few years the global balance may shift somewhat from one reservoir to another. Indeed, perturbations of the system can elucidate the operation of the cycle. The ice ages represented one such shift in the cycle: water was removed from the ocean and stored in the ice reservoir, and the flows from one reservoir to another were adjusted accordingly; the result was a drastic change in the climate and a lowering of the mean sea level, which exposed much of the area of the continental shelves. The continuing discussion of this major perturbation centers on the possible reasons for the shift and how rapidly the glacial ice caps expanded and then shrank as the earth returned to the comparatively unglaciated stage that prevails today. Polar ice and mountain glaciers still exist, of course, and so it is not possible to know from firsthand evidence what the hydrologic cycle was like when the earth was completely free of ice.

The movement of carbon dioxide through the atmosphere, the ocean and the solid earth provides another opportunity for following the large-scale flow of chemical elements from one part of the earth to another. The carbon dioxide of the atmosphere is taken up by plants in photosynthesis and by rocks in weathering. Photosynthesis manufac-



into 11 periods; the Tertiary period is divided into five epochs, and the Quaternary period consists of the Pleistocene and Holocene epochs. The calibration of the geologic clock by radioactive dating is a continuing concern. For example, according to a recent review of the radiometric evidence by an international group headed by the French geochronologist G. S. Odin, the beginning of the Cambrian period may have been between 540 and 520 million years ago.

tures the earth's supply of organic carbon and weathering accounts for the calcium carbonate of limestones, a major product of the transformation of igneous rocks into sediments. Dead plant and animal matter, together with the calcium carbonate shells of mollusks and other organisms, immobilizes the carbon. As these materials are buried in the form of sediment and incorporated into the crust of the earth, carbon is removed from the surface reservoir. At the same time ancient organic matter and limestones are eroded and chemically weathered. By the oxidation of organic matter and the dissolution of calcium carbonate, carbon dioxide is returned to the dynamic system, keeping it in balance.

In much the same way one can construct cycles of all the elements and their isotopes. For example, from the rate at which dissolved calcium enters the ocean from rivers (about 10^{13} moles per year) and the total amount of calcium in the oceans (about 10^{19} moles) one can estimate how long an ion of calcium can be expected to remain in the ocean: about a million years. On the average that is how long it takes before the calcium combines with a carbonate group and settles out of the reservoir as a part of some limestone. The calcium ion may then be buried, perhaps ultimately to be incorporated into a silicate-bearing metamorphic rock. Alternatively, it may go deeper still, becoming part of a magma that will return to the surface in a congealed form as an igneous rock, there to be weathered, dissolved and sent back to the ocean by a river.

These chemical cycles are different versions of the grand geologic cycle that James Hutton, the founder of modern geology, enunciated almost 200 years ago. In Hutton's original version rocks are weathered to form sediment, which is then buried. After deep burial the rocks undergo metamorphosis and/or melting. Later they are deformed and uplifted into mountain chains, only to be weathered again and recycled. In spite of many arguments and theories about the mechanisms of Hutton's rock cycle its basic outlines remain intact as the geologist's way of viewing an earth of constant change.

The continental crust, the repository of the geologic record of the past 3.8 billion years, is engaged in its own cycle of destruction and renewal. Each year some 10^{16} grams of solid and dissolved products of the erosion of the land surface are removed by rivers, wind and glacial ice. Much of the solid detritus is deposited on the continental shelves, but a good deal is lost to the ocean basins. The return is by way of subduction zones, where some of the sediments of the deep-sea basins are scraped off as the oceanic lithosphere plunges into the mantle [see "The Oceanic Crust," by

Jean Francheteau, page 114]. The oceanic sediment, which is found in front of oceanic island arcs and along continental margins where the subduction zone borders a continental mass, is plastered back onto the continent. The igneous rocks generated at subduction zones are also added to the continents. Thus over geologic time the continental masses remain in a steady state, even though there are frequent rises and falls in sea level that periodically flood and bare the continental shelves and the lower parts of the continents proper. The sediments and igneous rocks that are added to the continents are welded to them mainly as mountain chains associated with plate boundaries [see "The Continental Crust," by B. Clark Burchfiel, page 130]. Old mountains, then, are the remnants of a past recycling of the continents brought about by the motions of the lithospheric plates.

The recycling story extends deep into the mantle, as crustal materials are thrust to depths of hundreds of kilometers at the subduction zones where plates converge. There they mix with some materials that have never been part of the crust and others that have reached the surface before in their history. Geologists are just beginning to understand how the materials of the earth mix under the conditions of high temperature and pressure prevailing in the interior. The chief tracers of this mixing are the radioactive isotopes of rubidium and neodymium, which are helping to reveal the relations between age and mixing [see "The Earth's Mantle," by D. P. McKenzie, page 66]. Studies of the behavior of the core and the mantle over various time scales will determine to what extent they too can be viewed as parts of the great recycling machine.

If the machine has been going for billions of years, including some violent perturbations at times, how was it built in the first place? By what series of steady states did it evolve to its present condition? These are the questions that link a fragmentary rock record of the early history of the earth and the other planets to deductions drawn from the astronomy of the formation of the stars and the evolution of the solar system.

Theories of the formation of the solar system out of a nebula of gas and dust are still being refined, but they all have in common the central idea that about 4.6 billion years ago the earth grew to roughly its present size by a combina-

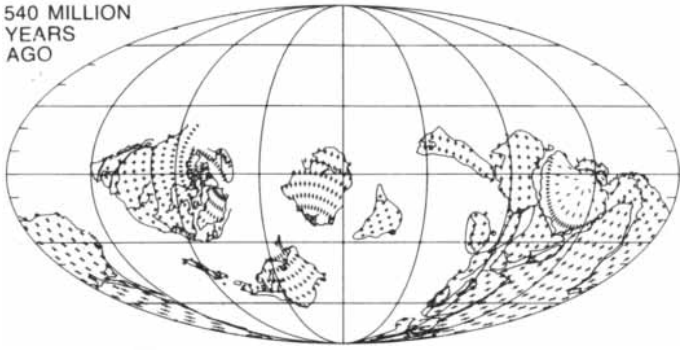
tion of two processes: the condensation of primitive solar-nebula material and the accretion of bits and pieces of other planetary matter in the vicinity. The early history of the earth was marked by continued accretion and by a rapid increase in temperature, due to a combination of three effects: heating from the radioactive elements abundant in the early condensate, heating from the impact of infalling material and heating from the contraction of the young planetary body. The rise in temperature, according to the now conventional view, led to widespread melting and a massive differentiation of the earth into a core, a mantle and a crust. All these ideas, proposed long before the exploration of the solar system by spacecraft, were refined in recent years by studies of the moon and of other planets. This was particularly true of the moon, where astronauts were able to sample a body whose history was frozen at an early stage. The moon, with no atmosphere or oceans, suffered no chemical weathering that could obliterate earlier generations of rock. It also did not offer a hospitable environment for life to begin. Viewing it emphasizes how vital the fluid envelope of water and gas was to the earth's machine. The composition of the gas, however, was not the same as that of the atmosphere of today. In its earliest stages the primitive atmosphere was free of oxygen and contained reduced gases such as methane and ammonia [see "The Atmosphere," by Andrew P. Ingersoll, page 162].

How the dynamics of the earth machine worked in the early days is a deductive study, because no mountains or sediments are preserved to give any hint of the products. The radioactively dated rock record begins in a fragmentary way about 3.8 billion years ago, which is the age of metamorphism by pressure and temperature of a series of originally sedimentary rocks in southwestern Greenland. The record clearly demonstrates that the essential operations of the geologic machine were similar to those in effect today. Iron formations and other types of sedimentary rocks such as sandstones and shales can be recognized in their metamorphosed forms in the Greenland rocks. Igneous rocks found at the site seem to have been created by much the same kind of melting that can be seen operating today. The deformation of rocks is also similar to the deformations of later times.

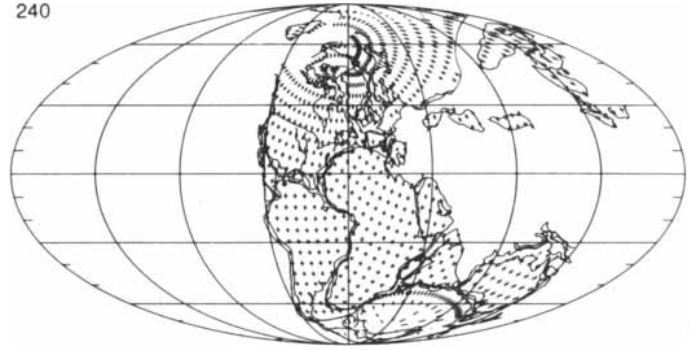
Nevertheless, there are differences be-

CHANGING FACE OF THE EARTH is portrayed at 60-million-year intervals from the Cambrian period to the present in the 10 computer-generated maps on the opposite page. The sequence documents the assembly and breakup of the supercontinent of Pangaea, the two chief episodes of continental drift leading up to the present arrangement of the earth's land masses. The maps were assembled by Alfred M. Ziegler and Christopher S. Scotese of the University of Chicago's Paleographic Atlas Project mainly on the basis of paleomagnetic evidence.

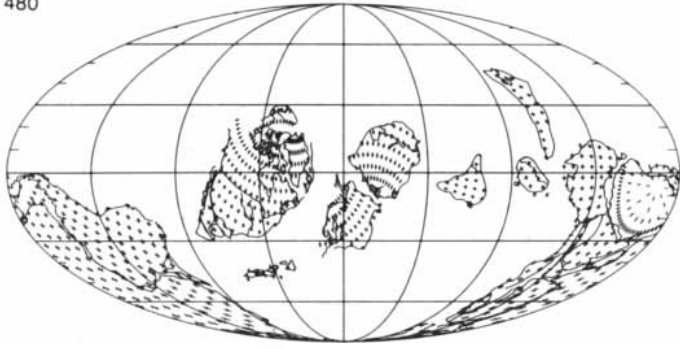
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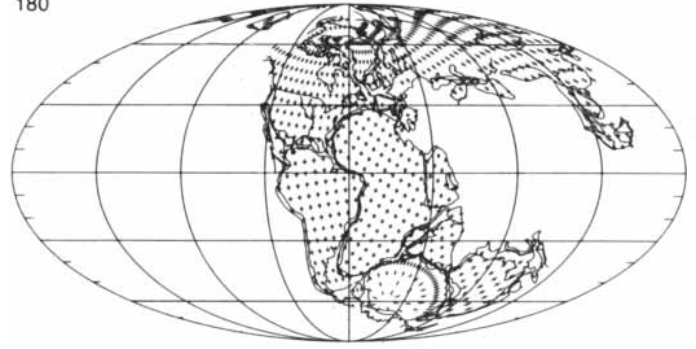
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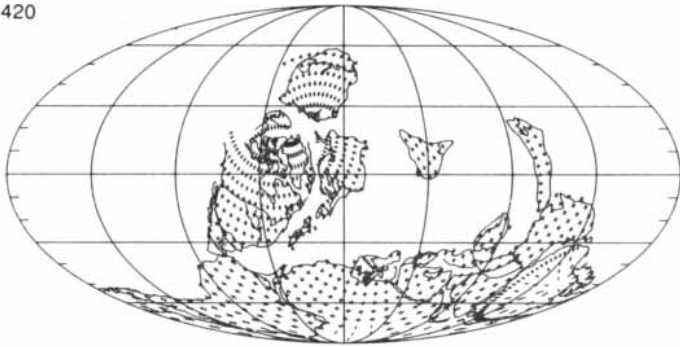
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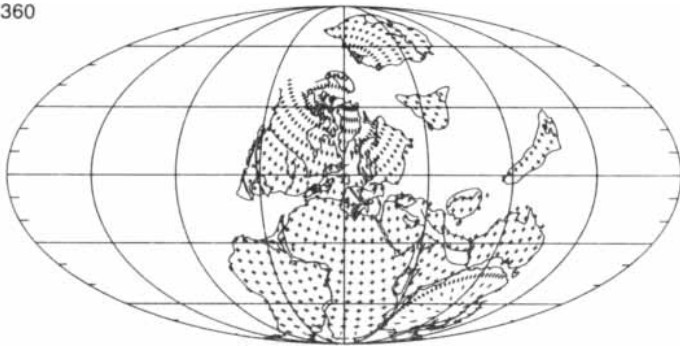
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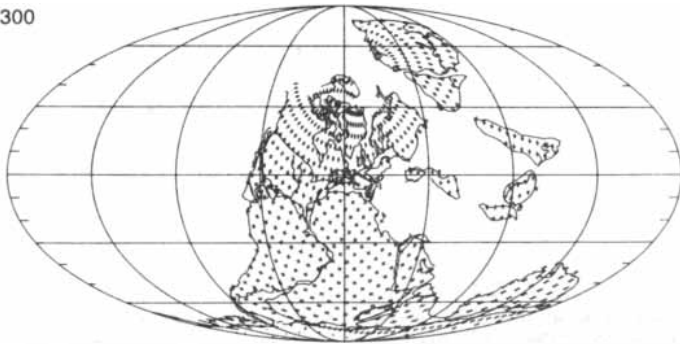
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tween these early rocks and more recent ones. Although no fossils have been found in the Greenland rocks (perhaps because the rocks have been so altered by metamorphism), evidence of primitive life is found in somewhat younger ones [see "The Biosphere," by Preston Cloud, page 176]. Some of the basalts found in the earliest earth rocks have compositions that reflect much higher melting temperatures, as if the rate at which the temperature increased with depth in the earth were much greater than it is now; this is not surprising in view of the earth's early thermal history. Moreover, before about 2.5 billion years ago there were few large masses of granitic rocks and the kinds of sediments formed on shallow continental shelves.

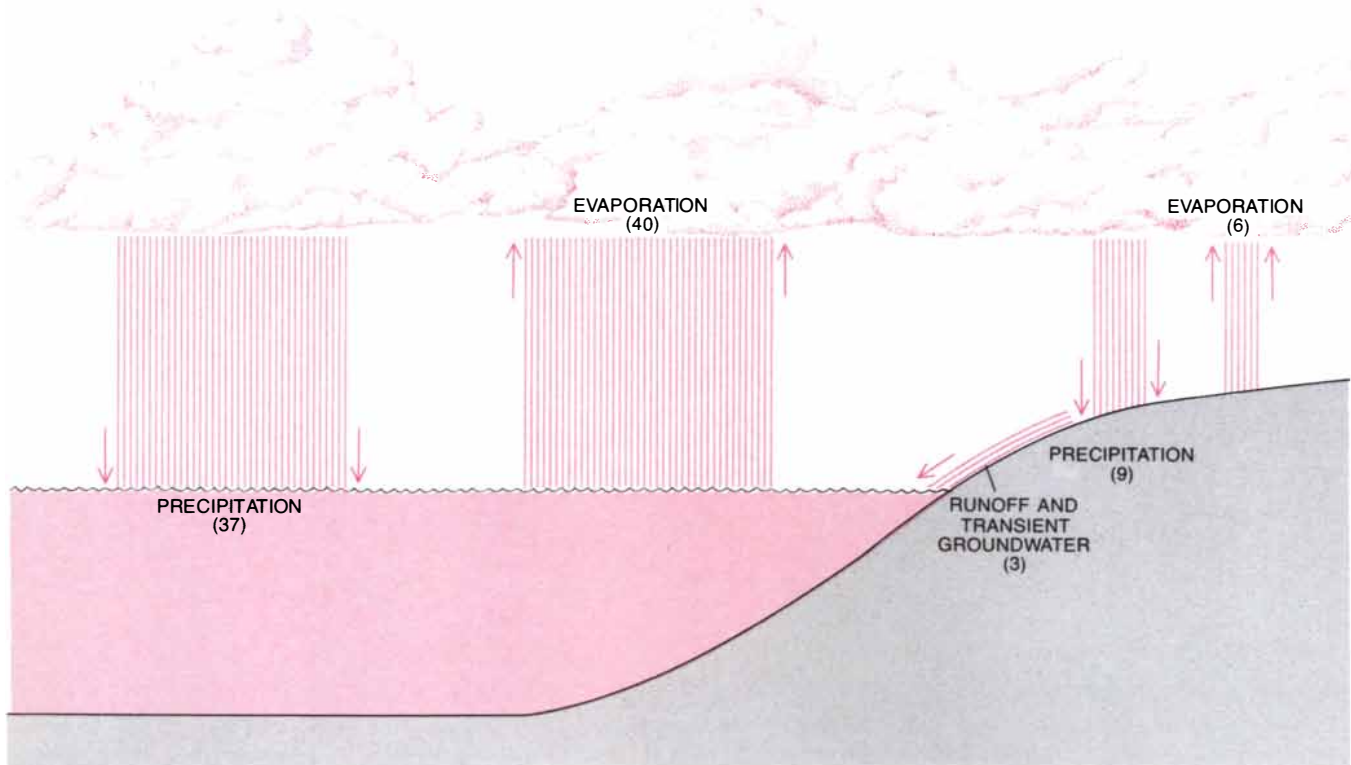
The differences indicate a machine whose internal temperatures were higher, whose atmosphere and oceans were deficient in oxygen and whose land masses were isolated, smaller areas rather than large continents. Yet at all times the average compositions of the rocks and their similarities from one place and time to another demonstrate that the recycling machine was operating at something like the same rate and with the same general character as it does today. It undoubtedly underwent

gradual changes, and there are also records of abrupt episodic shifts. The first glaciation of the earth was recorded early in Precambrian time. A more significant change in the cycle came about 2.5 billion years ago, when there seems to have been a sudden rise in the production of granite and the appearance of large continental shelves.

Later in the Precambrian, about a billion years ago, the machine began to look much as it does today. Oxygen in the atmosphere started increasing as photosynthetic organisms grew in numbers and efficiency, and as the march toward more complex life forms accelerated. Although the land surfaces were populated only by algal, fungal and bacterial species, rock weathering in Precambrian soils and the formation of river and lake deposits were proceeding much as they are today; their rates, however, may have been lower. The interior of the earth had by now settled down to something like its present state and through partial melting some regions of the mantle were being differentiated and depleted in certain elements with respect to the mantle as a whole. Whether plate tectonics was the primary mode of heat loss at that time is an open question. The magnetism of ancient rocks gives evidence of continental drift and reversals in the polarity of the earth's

magnetic field, and so the dynamo in the earth's core that generates the field must have been in steady operation [see "The Earth's Core," by Raymond Jeanloz, page 56]. Perhaps the plates were too thin to act quite as they do today, and the average size of the plates was smaller. Geologic knowledge of the Precambrian is too fragmentary to give firm answers to these questions yet.

Most geologists working in the past two centuries would have agreed that the biggest change of all was the one at the boundary of Precambrian time and the Cambrian period, marking the beginning of the Phanerozoic eon: the "known" part of the geologic record. It was then that organisms with shells evolved; their fossils make it possible to date the rocks more precisely and to erect the stratigraphic time scale. Compared with the Precambrian there are many more areas of these younger rocks exposed in an unmetamorphosed state, and so one can more readily deduce the course of earth history since then. This change, which is generally believed to have taken place about 570 million years ago, was far more important for the life of the planet than it was for the working of most other parts of the machine, which by then had reached maturity. The parts most affected by the evolutionary development of higher or-



HYDROLOGIC CYCLE, represented quantitatively in this diagram, serves as a model of the cyclic flow of material between different parts of the earth. The numbers shown are multiples of a basic unit equal to 10,000 cubic kilometers of water per year. In spite of occasional short- and long-term perturbations, the global balance among the world's major water reservoirs—atmosphere, oceans, continents

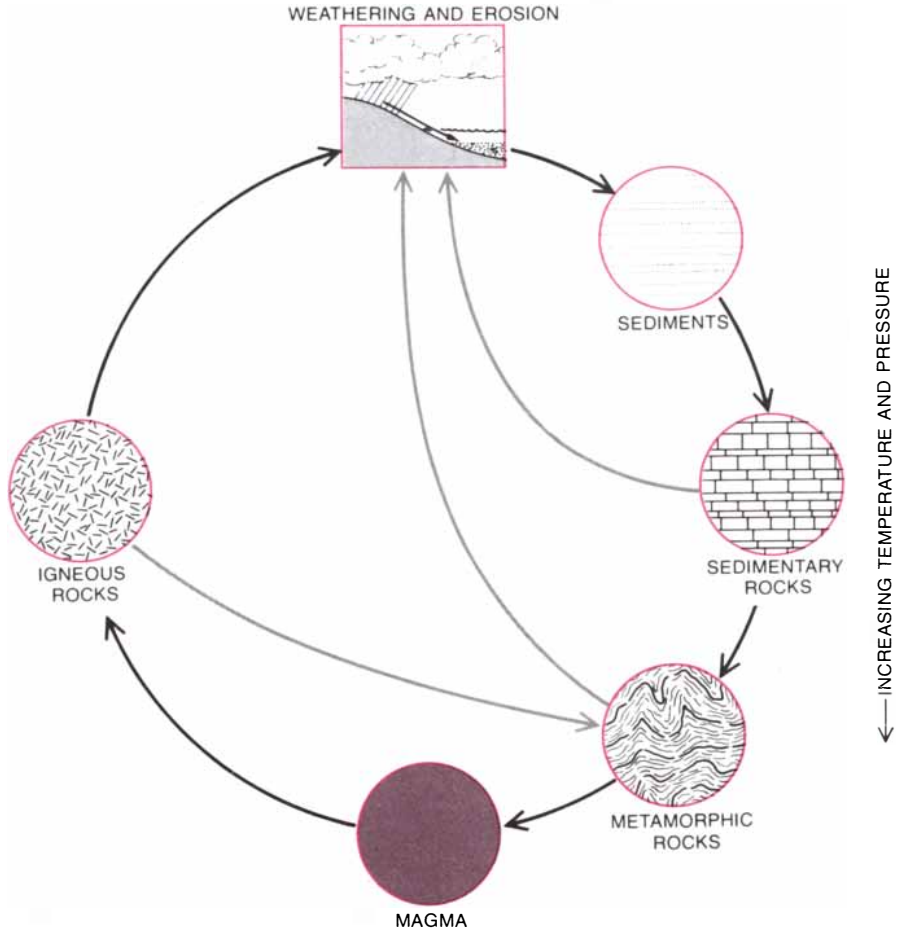
and polar ice caps—is quite steady from year to year. In addition to the amounts indicated here water is also brought to the surface of the earth by volcanism. This comparatively small increment consists of former surface water recycled through the interior by way of subduction zones as well as "juvenile" water, namely part of the original water of the mantle that has never escaped to the surface before.

ganisms were those at the surface, where the chemical influence of life processes is felt. The atmosphere arrived at something like its present oxygen level; the deposits of limestone became dominated by the shells of shallow marine organisms, and the chemical cycles of carbon dioxide, oxygen, phosphorus and nitrogen rather abruptly shifted to their present states.

Since that time changes in the rates and quantities of sediments controlled by organisms have been determined by the course of evolution. The vascular land plants first appeared about 400 million years ago and coal beds began to be widespread. The evolution of the flowering plants came about 120 million years ago. The siliceous algae (diatoms) and the pelagic foraminifera evolved about 130 million years ago and started to form the abundant siliceous and calcium carbonate oozes of the sea floor. Much biological sedimentation was shifted to the open sea floor, whose evolution can be understood only for the past 150 million years. The older record of sea-floor spreading has been swept into subduction zones and destroyed by metamorphism or melting.

The earth in old age is predictable from the present running of the machine. As the original supply of radioactive elements steadily decreases, the internal heat of the earth will diminish and simple heat conduction will slowly take over from the currently dominant mode of heat transfer by convection. As the earth cools, the rigid plates of the outer crust will thicken, and eventually they will congeal and become motionless. The "hot spots" that form volcanic centers will cool and solidify. With no internal forces to throw up mountains and move continents around, the external machine on the surface will take over, reducing much of the surface elevations of the land to plains elevated slightly above sea level. Sediment, the debris of erosion, will spread over land surfaces and sea bottom with no interruption by deep-seated rocks brought to the surface. A new balance of chemical elements based on a static tectonic system will lead to a shift in the composition of the atmosphere and the ocean, finally leading, as all mountain building and sedimentation ends, to a new steady state determined almost entirely by life's balance between photosynthesis and respiration.

That balance itself, together with the total mass of biological material, might change significantly as the nutrient reservoirs of the ocean and the atmosphere interact only with the thin surface skin of the earth. This brief essay at describing the future workings of the earth machine is enough to show how dependent the present workings of the planet are on interactions with the interior. No one



ROCK CYCLE, first proposed by Hutton almost 200 years ago, is still the basis of the geologist's view of the changing earth. In Hutton's version rocks are weathered to form sediment, which is then buried. After deep burial the rocks undergo metamorphosis and/or melting. Later they are deformed and uplifted into mountain chains, only to be weathered again and recycled. The modern theory of plate tectonics is in a sense an elaboration of Hutton's rock cycle.

is sure, however, of how such perturbations in the operation of the present machine can be predicted quantitatively, as is suggested by the current experience with carbon dioxide.

It has now been almost 100 years since Svante A. Arrhenius, the great Swedish chemist, called the attention of earth scientists to the effects of carbon dioxide on climate and its possible relation to glaciation. For much of that period some workers have been concerned about the steadily rising amounts of carbon dioxide in the atmosphere contributed by the burning of fossil fuels. As the pace of carbon dioxide emissions has increased dramatically in the latter half of the 20th century and as knowledge of the carbon cycle has grown, the issue has come to the point where government commissions and other national bodies estimate how much climatic change there is likely to be and what its effects might be. The comparatively small changes man has worked in the earth machine might have enormous consequences. Large as the earth is, the behavior of one of its biological spe-

cies may be enough to seriously disturb its balance.

In order to estimate the effects of increased carbon dioxide in the atmosphere one must consider all the fluxes and reservoirs. The human disturbance has been to change a single flux by increasing through coal mining and oil production the rate of return of buried organic carbon to the surface by orders of magnitude over the estimated preindustrial flux. To forecast the consequences one must follow through the entire system the changes that result. More carbon dioxide in the atmosphere leads to a slight increase in global temperatures as a result of the "greenhouse effect." An additional dissolution of calcium carbonate in the ocean and imperceptible changes in the balance of weathering and sedimentation of silicate and carbonate minerals will follow. The warming of the atmosphere will lead to some melting of the polar and glacial ice and a rise in the sea level, and very probably a shift in climatic belts. Reciting this list is only the beginning of a consideration of the innumerable ramifications of a shift in only one flux in

the system. It is this complexity that makes the estimation of the ultimate effects so difficult.

Burning fossil fuels is only the most recent perturbation of the earth machine. Geologic history is in one sense a recital of the many small shifts of the balance, some local and some global, that have characterized this otherwise smooth-running mechanism. The closer one looks at any complex machine, the more clearly one can detect fluctuations in its operation. In the midst of thousands of fluctuations that generate background noise—small shifts in sea level, plate-spreading rates and erosion rates, among others—one can see the signal of large and unusual events, infrequent and sometimes catastrophic. Near the end of the Miocene epoch, about 11 million years ago, the convergence of the African and European plates closed the mouth of the Mediterranean Sea. The Mediterranean dried up and thick layers of evaporites, principally salt and gypsum, were laid down. Soon afterward continuing plate motions reopened the Mediterranean to the Atlantic and it refilled. An immense waterfall existed for a time as water from the Atlantic spilled in to fill up the entire Mediterranean basin. Spectacular as the event was for this area of the world, it probably had a negligible effect on the global cycle; the evaporated water and salt removed from the ocean was minor compared with the huge volume of water in the world ocean.

Salt deposition at another time in the history of the earth was a part of a much more pervasive global cycle, one familiar to all geologists for its relation to massive extinctions of many biological species and almost complete withdrawal of the seas from every part of the continents. The end of the Paleozoic era, the boundary between the Permian and the Triassic periods, about 225 million years ago was marked by the complete assembly of the supercontinent Pangaea with the superocean Panthalassa surrounding it. Over a period of about 200 million years plate motions had gradually joined various pieces of continents into a single land mass. In the process evaporation from the narrow gulfs and bays of closing oceans and from arid regions led to great amounts of salt being withdrawn from the oceans, decreasing the salt content of the open ocean slightly and perhaps altering its density-driven circulation.

As the continents joined, their total perimeter shrank. As a result of mountain building caused by continental collisions in the course of the assembly the continents were dominated by high mountains. The ocean basins were enlarged by the slowing of plate-spreading rates and the lowering of midocean ridges as plate motions became largely

limited to the oceanic crust. The consequence of all these effects was a severe restriction of the area of the continental shelves. The diminished habitats of the shallow marine populations of the world and more variability in the climatic regimes of the land, which had recently gone through another glacial age, set the stage for the rapid evolution of new species and the extinction of old ones. A lot of guesswork is needed here because the rock record for the period is sparse. Most of the sediments deposited on the continents have since been eroded and the sea-floor record has been swept into the subduction zones.

Even this unusual time was soon superseded by a return to normal conditions as the supercontinent proved unstable. It began to rift into separate continental masses, and the Atlantic and Indian oceans opened. The seas transgressed the continents, salt beds were eroded, the salt returned to the ocean and the normal pattern of life resumed on the continental shelves. The episode demonstrates the machine's ability to right itself and settle down to a smooth operation after a violent shudder.

The glacial ages represent another kind of perturbation, one that primarily affected the surface and near-surface layers of the earth. The earth has been glaciated several times in its history, at least twice during the Precambrian, once in the early Paleozoic, once near the end of the Paleozoic and many times in the Pleistocene, which ended only about 10,000 years ago. Each of these events may have been triggered by continental-drift patterns that put a continent in a polar region and caused shifts in oceanic circulation. Perhaps there was a correlation with a wider than normal fluctuation of the carbon dioxide level. In each glacial period the periodicity of changes in the earth's orbit around the sun led to oscillations in the advance and retreat of the ice; the oscillations, called Milankovitch cycles, are now thought to account for the glacial and interglacial stages of the most recent ice ages. Each time, the postglacial earth returned to its preglacial state with little change, leaving behind a record of glacial sediment and grooved and striated bedrock, the pavement over which the ice moved.

In the past few years geologists have begun to evaluate disturbances of the earth's balance due to extraterrestrial sources. A thin bed of iridium-enriched clay has been found in a number of places around the world where sediments were deposited during the transition from the Cretaceous period to the Tertiary, about 65 million years ago. It has been proposed by Luis W. Alvarez, Walter S. Alvarez, Frank Asaro and Helen V. Michel of the University of California at Berkeley that this bed is the product of the impact of a large me-

teoritic body. Among the postulated consequences of the collision (with a body estimated to weigh about 10^{18} grams) were clouds of dust that obscured the sun, sudden cooling of the atmosphere and the ocean, changes in the chemistry of the atmosphere and the deposition of a thin layer of clay enriched in certain rare metals such as iridium. These changes are thought to have led to the extinction of many plant and animal species in the sea and the dinosaurs on the land.

Regardless of the durability of this hypothesis as an explanation of the geochemical and biological associations of the boundary between the Cretaceous and the Tertiary, geologists have come to recognize that collisions with asteroid-size bodies have been an important feature of the earth's history since its formation 4.6 billion years ago. Such heavy impacts may have come every 100 million years or so. Most of the events have left little trace because of erosion over the next few tens of millions of years, but some have left conspicuous circular scars.

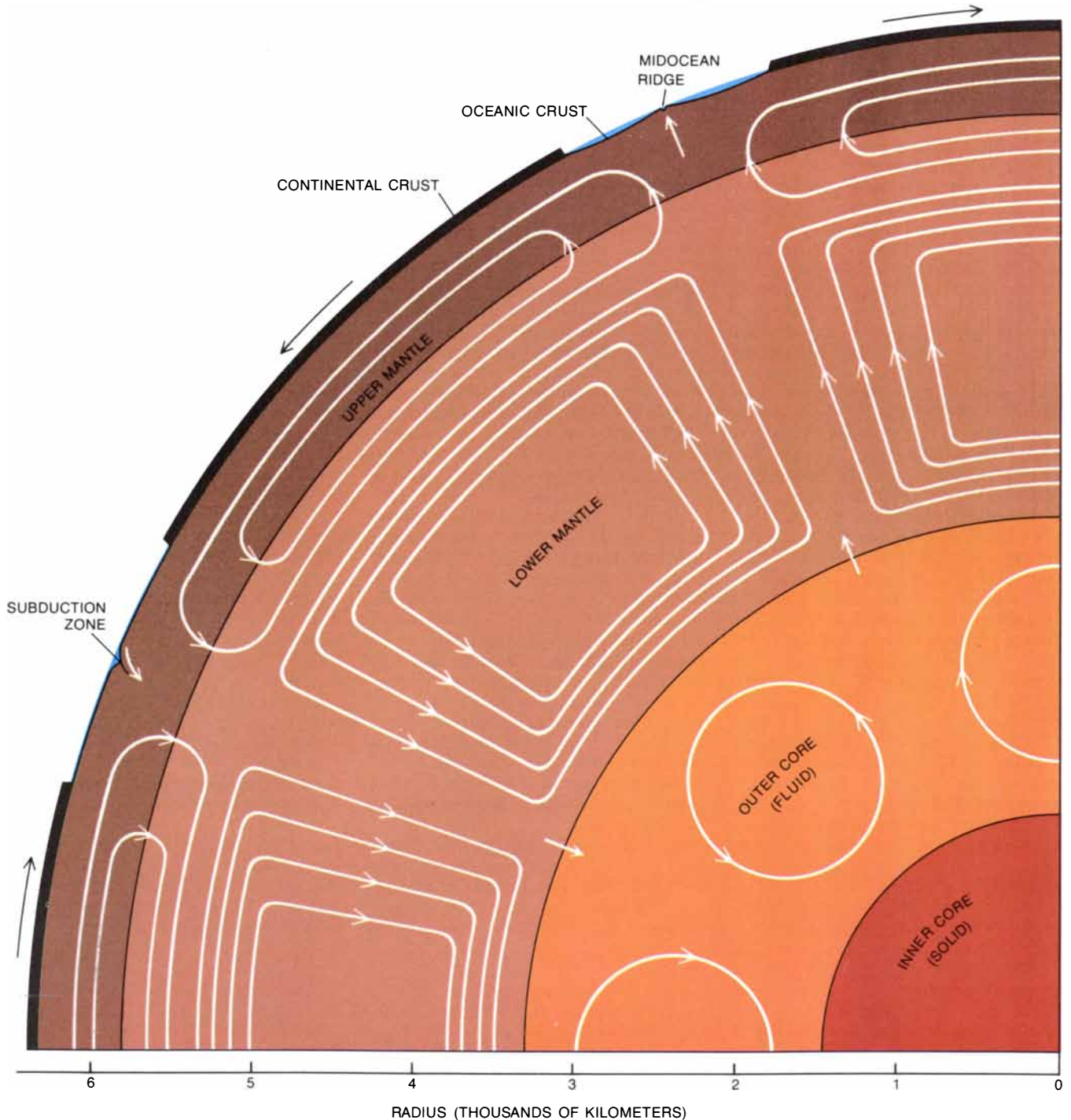
As the interconnectedness of the huge and complex earth system becomes more widely recognized, earth scientists are learning how to link up subsystems and explore new relations. Oceanographers have combined marine chemistry, marine biology and the geology of the sea floor, from midocean ridges to volcanic-island arcs, to see the oceans as an entire system. Indeed, it is the only way to estimate the interactions of the oceans with the carbon cycle and the carbon dioxide greenhouse [see "The Ocean," by Wallace S. Broecker, page 146]. With geologists and paleontologists they are now mapping the past of the oceans, particularly in relation to the recent glacial epoch. Predicting the operation of the surface part of the machine, powered by solar radiation, has become the business of oceanographers, geologists, atmospheric scientists and biologists. The ability to predict is dependent on devising ever more inclusive and sensitive models of the system and testing them against observations. Geophysicists working on the dynamics of the interior heat engine are engaged in correlating its structure and constitution, as revealed by earthquake waves, with its mineralogical and chemical constitution, as deduced from laboratory experiments on rock systems at high temperatures and pressures. Isotope-ratio studies of rocks derived from the interior and brought to the surface provide observations that tell about mixing mechanisms in the mantle. Theoretical studies of convection dynamics in plastically deformable solids at high pressures are showing how the mixing proceeds. The core, the mantle and the crust are no longer regarded as separate do-

mains but as interacting parts of a larger system whose properties and dynamics are modeled by geophysicists, geochemists and petrologists.

Earth scientists have long been familiar with the ways in which the actions of the interior affect the exterior through volcanism, mountain building, the flow of heat and the geomagnetic field. Now

they are seeing how chemical weathering and the differentiation of the materials of the interior as they are brought to the surface react on the interior as the altered material is plowed back into the mantle by subduction. In this way the surface machine is further coupled to the interior machine. As the subsystems are linked the earth may come to

be thought of more in the ways one thinks of a highly differentiated organism: as a system so complex that the ultimate reduction to simple forces and bulk compositions does not lead to a satisfactory understanding of the wonderful diversity and detail that can be observed directly at the surface and sensed remotely in the interior.



LARGE-SCALE MOTIONS of the major parts of the earth are indicated by arrows in this highly schematic diagram. Heat-driven convection in the fluid outer core has a dynamo effect that is responsible for the geomagnetic field. Convection in the upper mantle drives plate tectonics. Volcanism transports molten material to the surface at mid-

ocean ridges and other places. Solid material is returned to the interior at subduction zones. The degree of mixing between the upper mantle and the lower mantle is a subject of debate; in this case a model calling for separate convection cells has been adopted. Mixing of material between the lower mantle and the outer core is still speculative.