The Supercontinent Cycle

Several times in earth history the continents have joined to form one body, which later broke apart. The process seems to be cyclic; it may shape geology and climate and thereby influence biological evolution

by R. Damian Nance, Thomas R. Worsley and Judith B. Moody

Is plate tectonics a random process or is it orderly? According to the theory of plate tectonics, the earth's rigid outer layer, called the lithosphere, is a mosaic of slablike plates that move with respect to one another at speeds averaging a few centimeters per year. The plates float on a hot, plastic layer of the earth's mantle called the asthenosphere. Most of the plate movements are driven by a process known as sea-floor spreading, in which molten material from the asthenosphere rises through the lithosphere at high ridges on the ocean floor, where it cools to become the crust that makes up the ocean bottom. Newly created oceanic crust moves steadily away from the mid-ocean ridges toward the continents. If the sea floor and the adjacent continent are on the same lithospheric plate, the continent is carried along by the conveyor belt of oceanic crust. Alternatively, the oceanic crust may sink under the continent to rejoin the mantle, in a process known as subduction.

The continents are generally viewed as passive objects that are ferried about by sea-floor spreading. They are not entirely unchanged by the processes of plate tectonics, however. Separate blocks of continental crust can collide and merge, forming new, larger continents. Conversely, continents can be torn apart by deep rifts that eventually become the centers of new ocean basins. Indeed, there is evidence that several times in the history of the earth the continents have undergone these processes on a grand scale: several times most or all of the continents have gathered to form a single supercontinent, which has later split into many smaller continents only to rejoin and form a supercontinent again.

What governs the formation and destruction of supercontinents? Do they appear and disappear simply by chance, because of the random shifting of continental plates? Various regularities in the geologic record have led the three of us to believe that a much more orderly, even cyclic, process must be at work. Drawing on the ideas of Don L. Anderson of the California Institute of Technology and on the prescient observations of the Dutch geologist J. Umgrove (set out in his 1947 book *The Pulse of the Earth*), we have devised a theoretical framework that describes what may be the underlying mechanisms of such a "supercontinent cycle."

In our theory the dominant force comes from heat. It is generally understood that tectonic plates are driven by convective motions in the underlying mantle, which are powered by heat from the decay of radioactive elements. The radioactive decay (and the resulting production of heat) is a continuous process whose rate has declined smoothly with time, and so the production of heat cannot in itself account for the episodicity inherent in an alternation between continental assembly and continental breakup.

The key phenomenon, we think, is not the production of heat but rather its conduction and loss through the earth's crust. Continental crust is only half as efficient as oceanic crust at conducting heat. Consequently, as Anderson has pointed out, if a stationary supercontinent covers some part of the earth's surface, heat from the mantle should accumulate under the supercontinent, causing it to dome upward and eventually break apart. As fragments of the supercontinent disperse, heat can be transferred through the new ocean basins created between them. After a certain amount of heat has escaped, the continental fragments may be driven back together.

In other words, we think the surface of the earth is like a coffee percolator. As in a coffee percolator, the input of heat is essentially continuous. Because of poor conduction through the continents, however, the heat is released in relatively sudden bursts.

This theoretical framework and its corollaries make it possible to tie together a number of observations in widely disparate fields. They make it possible, for example, to understand the timing of the extreme changes in sea level that have taken place in the past 570 million years. The framework also helps to explain and link many other events of the past 2,500 million years, such as periods of intense mountain building, episodes of glaciation and changes in the nature of life on the earth. The supercontinent cycle, in our view, is a major driving process that has provided the impetus for many of the most important developments in the earth's history.

The Opening of Oceans

Our model builds on an earlier description of episodic plate motions known as the Wilson cycle. Named for J. Tuzo Wilson of the Ontario Science Center, the Wilson cycle is the process by which continents rift to form ocean basins and the ocean basins later close to reassemble the continents. In the first stage of the Wilson cycle volcanic

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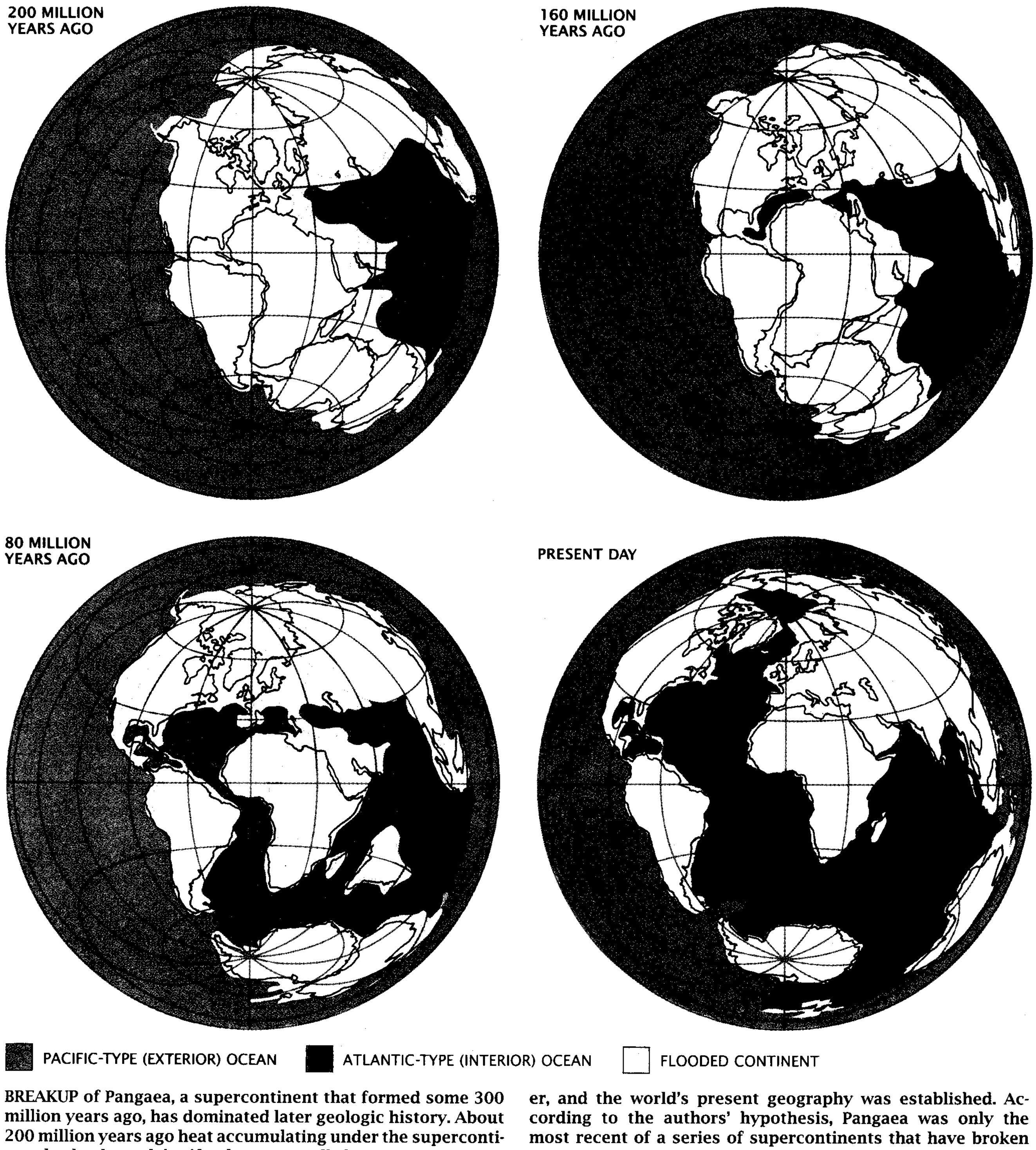
"hot spots" form in a continent's interior; the hot spots are then connected by rift valleys, along which the continent eventually splits. When the continent fragments, the rift valleys grow to become a new ocean as hot mantle material wells up through the rifts to form the sea floor. The continental fragments move apart, sliding away from these elevated "spreading centers" as mantle material wells up.

As the material making up the ocean floor ages, it cools, becomes denser and subsides, increasing the depth of the ocean. Eventually, about 200 million years after the first rift formed, the oldest part of the new ocean floor (the part directly adjacent to the continental fragments) becomes so dense that it sinks under the continental crust: it is subducted. The processes of subduction then close the ocean, bringing the continents back together. Eventually the continents collide and



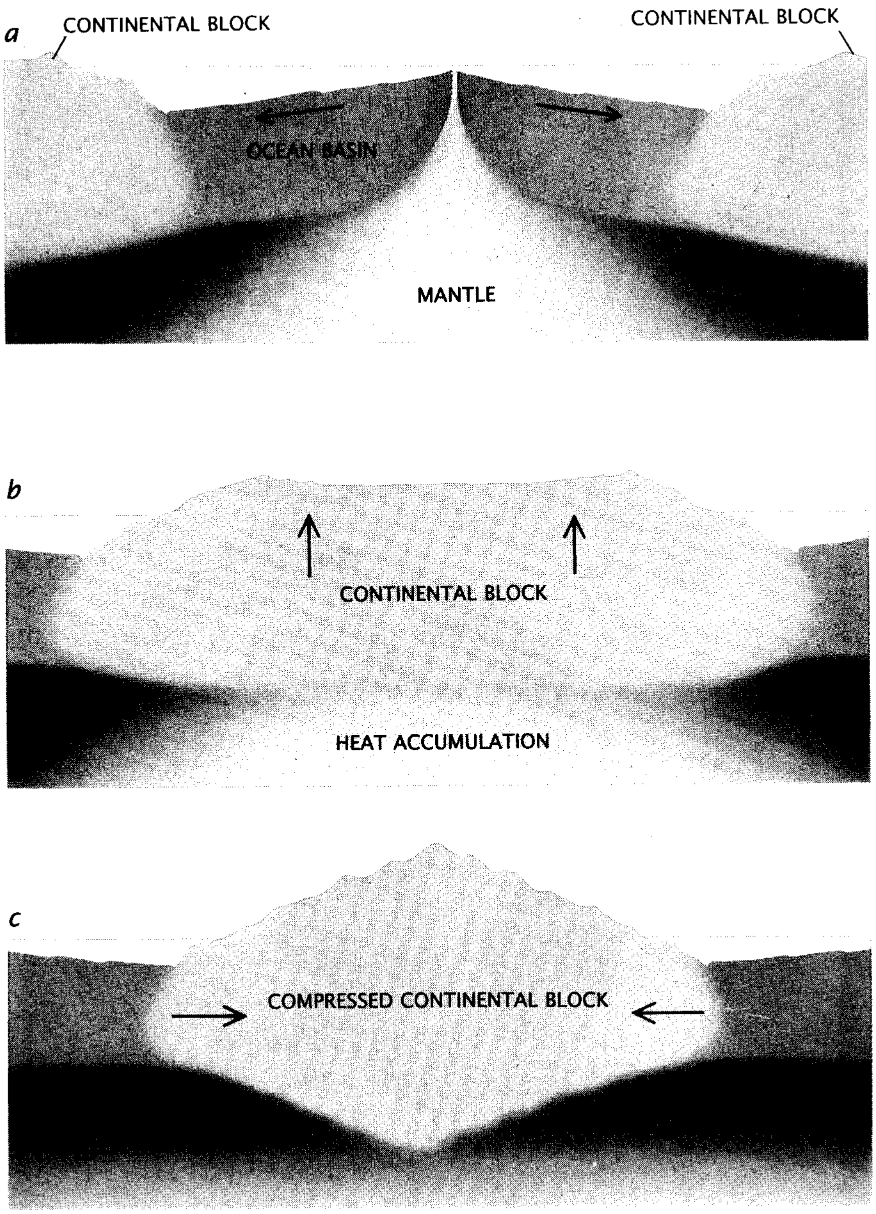
BREAKUP of Pangaea, a supercontinent that formed some 300 million years ago, has dominated later geologic history. About 200 million years ago heat accumulating under the supercontinent broke through in rifts that eventually became oceans. The growth of these shallow oceans at the expense of the older and deeper superocean raised the sea level, partially drowning the continents. Sea level rose to a maximum about 80 million years ago; then it fell, as the new oceans became older and deeper, and the world's present geography was established. According to the authors' hypothesis, Pangaea was only the most recent of a series of supercontinents that have broken up and reassembled during the past 2,600 million years; this supercontinent cycle has shaped the geology and climate of the earth and provided a force for biological evolution. These maps are based on work by A. G. Smith of the University of Cambridge and J. C. Briden of the University of Leeds.

rejoin, and the compressive forces of collision create mountain belts.

When viewed in terms of Wilson cycles, there is a striking contrast between the evolution of the continental margins surrounding the North Atlantic and the margins of the Pacific. The margins of the North Atlantic have undergone a series of Wilson cycles during the past billion years; the regions bordering the Pacific have apparently undergone none. In other words, oceans have repeatedly opened and closed in the vicinity of the present-day North Atlantic, while a single ocean has been maintained continuously in the vicinity of the Pacific.

In our model, then, the Pacific is the descendant of the oceanic hemisphere that has surrounded each incarnation of the supercontinent; each of the Wilson cycles that took place in what is now the North Atlantic region occurred as part of the breakup and reassembly of a supercontinent. The Atlantic should therefore be expected to close again, once more reuniting the continents in a supercontinent surrounded by a single superocean.

At present the sea-floor crust of the Pacific is being subducted under all the continents that surround it, whereas the floor of the Atlantic generally butts up against surrounding continental blocks. In our framework this means that the continents are still in the process of dispersing after the breakup about 200 million years ago of the most recent supercontinent, which Alfred Wegener, the father of the theory of continental drift, christened Pangaea, or "all earth" [see "The Breakup of Pangaea," by Robert S. Dietz and John C. Holden; SCIENTIFIC AMERICAN, October, 1970]. The continents are now approaching their maximum dispersal. Soon (on a geologic time scale) the crust of the Atlantic will become old and dense enough to sink under the surrounding continents, beginning the process that will close the Atlantic ocean basin.



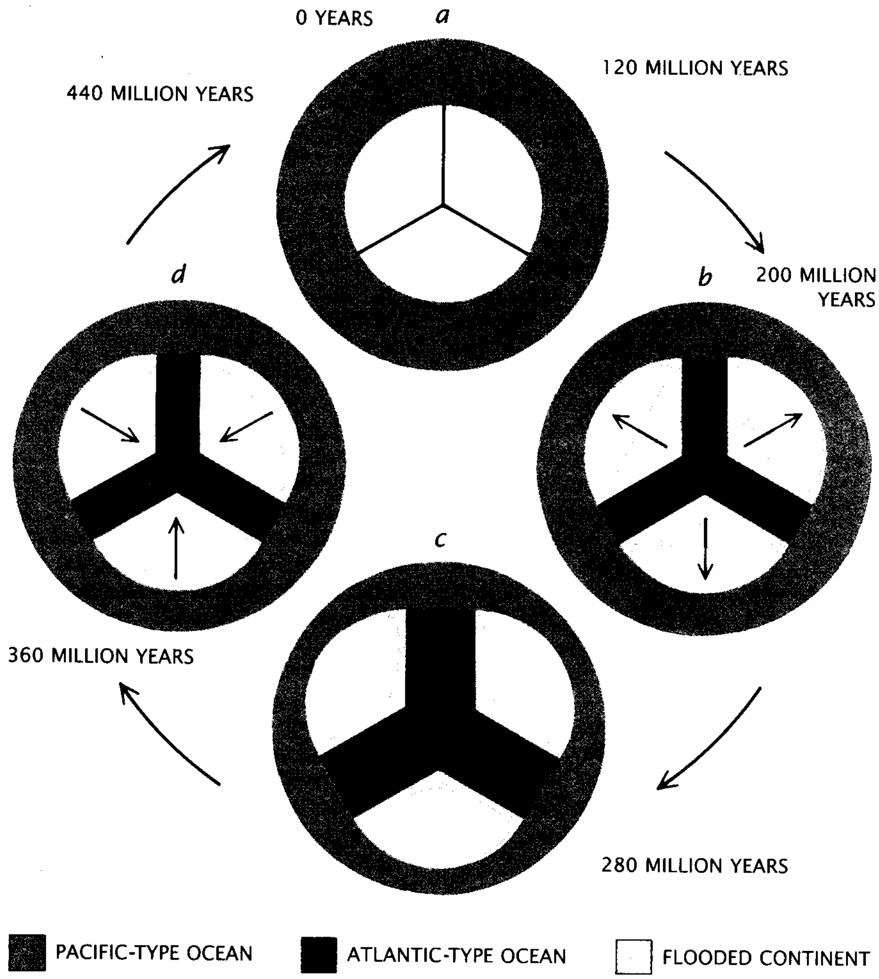
SEA LEVEL with respect to the continents is controlled by several tectonic factors. One is the age of the sea floor, which is created by the upwelling of hot material from the earth's mantle at mid-ocean "spreading centers" (*a*). As the sea floor spreads it cools, becomes denser and sinks; older ocean is therefore deeper, and so sea level becomes lower when the average age of the world's oceans increases. The accumulation of heat under stationary continental crust (*b*) alters sea level by buoying the continent upward. Sea level is also affected by compression (*c*) or extension (not shown) of continents. When continents are compressed, the total area of the world ocean increases while the volume of water remains constant: sea level is lowered.

Surprising Regularity

A second underpinning of our supercontinent-cycle hypothesis is the timing of various episodes of mountain building and episodes of rifting. The ages of mountain ranges that could have been produced by the compressive forces that accompany continental collisions reveal a surprising regularity. This kind of mountain building was particularly intense, occurring in several parts of the world, during six distinct periods. The periods were broadly centered on dates about 2,600 million years ago, 2,100 million years ago, a time between 1,800 and 1,600 million years ago, 1,100 million years ago, 650 million years ago and 250 million years ago. The timing shows a certain periodicity: the interval between any two of these periods of intense compressive mountain building was about 400 to 500 million years.

What is more, about 100 million years after each of these periods of mountain building there appears to have been a period of rifting. Large numbers of mantle-derived rocks—rocks that may have been produced when magma welled up into cracks created by rifting—date from times broadly centered on 2,500 million years ago, 2,000 million years ago, a time between 1,700 and 1,500 million years ago, 1,000 million years ago and 600 million years ago. The mountain building of 250 million years ago, of course, was followed by the rifting and eventual breakup of Pangaea.

These regularities indicate to us that supercontinents are created in a cyclic process, in which one complete cycle takes about 500 million years. By examining these geologic records and others, and by taking into account such factors as the rate at which sea-floor spreading takes place in present-day oceans, we have calculated a more precise timetable for the supercontinent cycle. After the fragments of a supercontinent first separate—probably some 40 million years or so after rifting begins—we estimate that it should take about 160 million years for the fragments to reach their greatest dispersal and for subduction to begin in the new oceans. After the continents begin to move back together, another 160 million years or so should elapse before they re-form a supercontinent. The supercontinent should survive for about 80 million years before enough heat accumulates under it to cause rifts to form. Forty million years later that rifting will lead to another breakup, 440 million years after the previous one.



SUPERCONTINENT CYCLE is depicted schematically. A supercontinent (*a*) can survive for about 80 million years before the accumulation of heat causes rifts to form, and for another 40 million years or so before it is torn apart into separate continents. The continents drift apart (*b*) until they reach their greatest degree of dispersal, about 160 million years later (*c*). Then they move back together (*d*), eventually re-forming the supercontinent (*a*). The entire cycle takes about 440 million years.

Effects on Sea Level

How can one test whether the supercontinent cycle proceeds as we have described? The cycle is likely to have striking effects on sea level, for which there are clear geologic records covering the past 570 million years. Assuming a constant amount of water in the world oceans, sea level (in relation to continental mass) is largely determined by two factors: the total volume of the world's ocean basins, which depends in part on the average depth of the sea floor, and the relative elevation of continents. The supercontinent cycle would involve the creation and destruction of ocean basins and the thermal uplifting of continents, and so it should have a profound influence on both factors.

As the material making up the ocean floor moves away from mid-ocean ridges during sea-floor spreading, it cools and subsides, its depth increasing as the square root of its age. Wolfgang H. Berger and Edward L. Winterer of the Scripps Institution of Oceanography have calculated how the average age of the world ocean floor should change during the breakup of a supercontinent. Before the breakup the average age of the ocean should remain constant, because in the superocean surrounding the supercontinent new sea floor is created at about the same rate as old sea floor is destroyed by subduction under the landmass. During the breakup, the subducting, "Pacific type" superocean will be replaced by an increasing proportion of non-subducting, "Atlantic type" oceans. Later, when the supercontinent begins to reunite, these "interior" oceans will be destroyed by subduction and replaced by Pacific-type ocean again. These processes affect the average age of the world ocean floor.

Immediately after the breakup of a supercontinent the world ocean floor should, on the average, become progressively younger and shallower as young, Atlantic-type oceans begin to replace the older, Pacific-type ocean. When the Atlantic-type oceans reach the same average age as the Pacific-type ocean, the trend should reverse: the growth of increasingly old Atlantic-type oceans should cause the world ocean floor to age and deepen. The maximum average depth should occur when Atlantic-type oceans reach their greatest average age, just before they begin to be subducted. Then, as the oldest areas of the Atlantic-type oceans are subducted and the oceans close, the world ocean floor should become younger and shallower again.

Calculations of sea level based on these parameters alone suggest that a supercontinent's continental shelves should be flooded, because the ocean basin surrounding a supercontinent is younger and shallower than, for example, the floor of today's world ocean. A second factor, however, must be added to the analysis: the degree to which a supercontinent would be uplifted by the heat that would accumulate under it. If the supercontinent is lifted high enough, sea level in relation to the continental mass could still be low even if the sea floor is comparatively shallow.

One way to estimate how much a supercontinent might be uplifted thermally is to consider present-day

Africa. Africa has remained essentially stationary for at least the past 200 million years, during which time a good deal of heat from the mantle has accumulated under it. (Some of that heat is being released in the rift valleys now forming in various areas of the continent.) By comparing the height relative to sea level of Africa's shelf break (the true edge of the continent) with the height of the shelf breaks of other continents, we can estimate that thermal uplifting has buoyed Africa by about 400 meters. As a lower limit, then, one can expect that a supercontinent would be thermally uplifted by at least 400 meters.

Other factors should also cause the supercontinent to be emergent (elevated in relation to sea level). For example, the collisions that take place during the assembly of the supercontinent should compress and thicken continental crust, decreasing the earth's total land area. This would add to the total area of the ocean basins and thereby lower sea level. Conversely, the stretching and extension of crust that accompanies the breakup of a supercontinent should lower the total area of the world ocean basin, thereby raising sea level.

By adding together all these components, it is possible to determine how sea level should change in the course of every phase of the supercontinent cycle. As we have noted, during the existence of a supercontinent sea level should be relatively low. As the supercontinent breaks up, sea level should rise, both because the continental fragments will stretch and subside thermally and because the breakup will replace old, Pacific-type ocean with young, Atlantic-type ocean. Sea level should continue to rise for about 80 million years, as the younger oceans make up a greater fraction of the world ocean. Then, as the Atlantic-type oceans age and expand, sea level should decline for another 80 million years or so, until the Atlantic-type oceans begin to be subducted.

When the continents begin to come together, sea level should rise, as older Atlantic-type crust is subducted. That rise in sea level should continue for another 80 million years, until the supercontinent begins to be reassembled. Then, as continents collide and the growing supercontinent is uplifted thermally, sea level should decline for about 80 million years. Once the supercontinent has been formed, sea level should remain static for another 120 million years, until the supercontinent breaks up again.

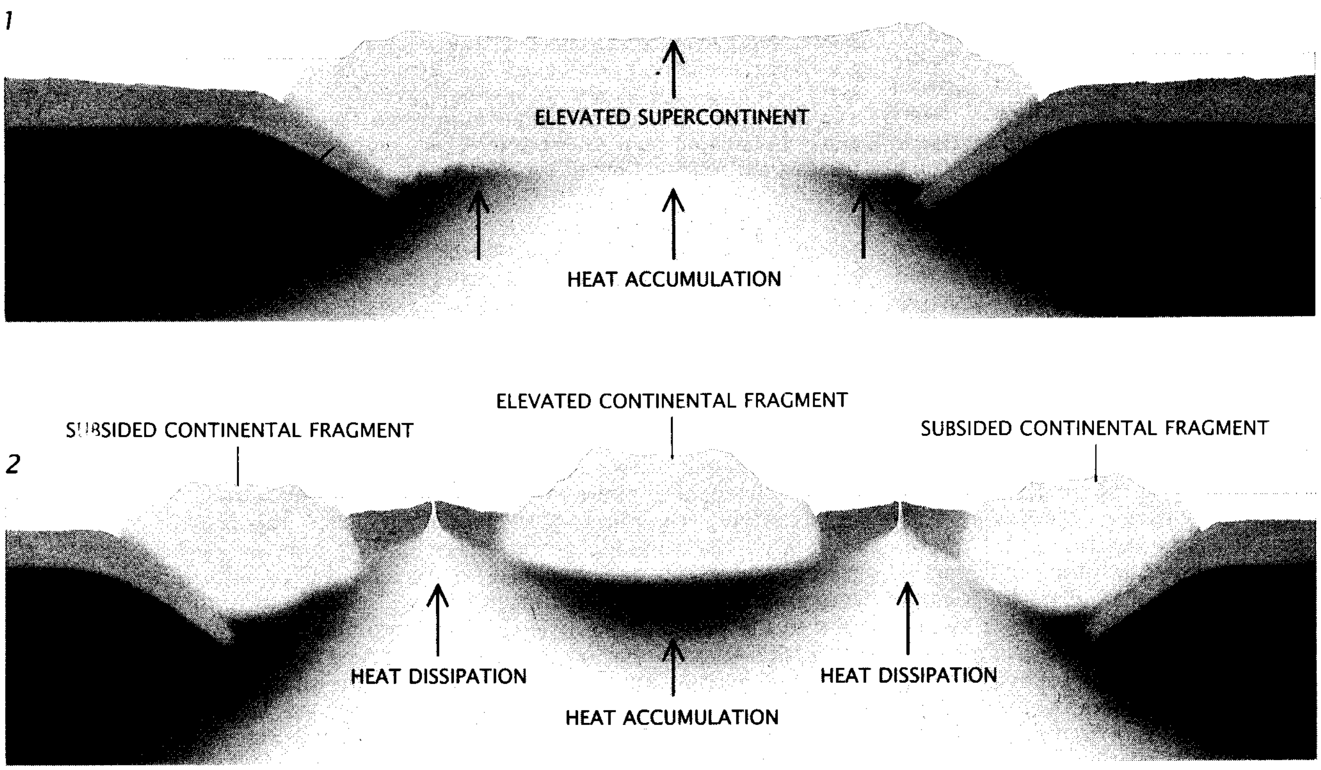
These predictions of changes in sea level match the geologic record of the past 570 million years, which is as far back as sea level can be determined with any reliability. In particular, the timing and the relative magnitudes of sea-level changes predicted by the model match the preserved record. The absolute values, of course, always vary from continent to continent; the model gives only global averages.

Testing the Model

Evidence for the supercontinent cycle can also be found by examining the isotopes of sulfur and carbon found in certain marine sediments. (Isotopes are atoms of the same element that have different atomic weights.)

During the early stages of breakup, a supercontinent is likely to include a number of marine rifts that, like the modern Red Sea, are weakly connected to the world ocean. These rifts can undergo a continuous process of partial evaporation, in which certain elements, such as sulfur, precipitate out of the seawater to form minerals. When seawater containing sulfur is evaporated, heavy sulfur (which has an atomic weight of 34) precipitates out more readily than light sulfur (which has an atomic weight of 32).

If an evaporating marine rift contin-



HEAT controls the elevation of a supercontinent and its fragments. A supercontinent (*1*), surrounded by subduction zones (where sea-floor material sinks under the continent), remains stationary in relation to the underlying mantle. Heat accumulates under it, buoying it upward. After the supercontinent breaks up (*2*), fragments subside as they drift away. A fragment that stays in place (*center*) remains elevated. Present-day Africa is one example of such a stationary fragment.

ues to mix with the world ocean, it should act as a sink for heavy sulfur: it should tend to pull heavy sulfur from the ocean as a whole and bury it in evaporitic sediments. Then the world ocean should become relatively depleted in heavy sulfur and enriched in light sulfur. Hence in sediments derived from the world ocean as a whole during the period of the supercontinent, we should expect to see relatively high levels of light sulfur and low levels of heavy sulfur. This is indeed what is found in open marine sediments formed about 200 and 600 million years ago—that is, during the past two instances of the supercontinent.

Carbon isotopes also give evidence of supercontinents. The lighter isotope of carbon (carbon 12) diffuses in solution faster than a heavier isotope (carbon 13). As a result light carbon is more likely to be taken up by organisms and incorporated into their biomass. Organisms are therefore a sink for light carbon. During periods of low sea level the rate of organic productivity in the world ocean should be high, because greater amounts of nutrients such as phosphorus and nitrogen—eroded from continental crust and carried to the sea by rivers—will be available when more continental crust is exposed.

Thus when sea level is low, more carbon (particularly light carbon) will be incorporated into organisms, and the water of the world ocean will be comparatively depleted in light carbon and enriched in heavy carbon. When examining such seawater-derived sediments as limestone (calcium carbonate), then, we should expect to find relatively high levels of heavy carbon and low levels of light carbon if the sediments were produced during a period of low sea level. In similar sediments produced during a period of high sea level, we should expect to find relatively more light carbon and less heavy carbon. And indeed, the ratio of heavy carbon to light carbon in such sediments closely matches the predictions of our model for the past 600 million years.

Climate and Life

Perhaps the most important effects of the supercontinent cycle are its influences on climate and life. What should those effects be? Most of the climatological effects of the supercontinent cycle will be driven by the changes in sea level that are caused by the processes of continental breakup, dispersal and reassembly.

When sea level is low—that is, when the world is dominated by a single emergent supercontinent or when individual continents are widely dispersed (as they are now) and the world ocean floor is at its oldest—large amounts of silicate minerals in the continental crust, such as calcium silicates, are exposed to weathering and erosion; they are dissolved in rivers and carried into the world ocean. When these dissolved silicates are mixed into seawater, they combine with dissolved carbon dioxide to produce solid precipitates [see "How Climate Evolved on the Terrestrial Planets," by James F. Kasting, Owen B. Toon and James B. Pollack; SCIENTIFIC AMERICAN, February]. For example, calcium silicates may combine with carbon dioxide to produce calcite (limestone) and quartz. This process draws down carbon dioxide from the atmosphere.

Carbon dioxide in the atmosphere helps the earth to retain the heat it gains from solar radiation. When carbon dioxide is drawn down into oceanic deposits, this "greenhouse" warming effect is diminished, and the world climate becomes colder. If there is an emergent continental landmass near enough to the pole, glaciers will form (as they have on modern-day Antarctica and Greenland).

Glaciation has several important effects on the global climate. For one thing, it removes water from the ocean basins, causing sea level to drop still lower. Glaciation also amplifies circulation and mixing in the world ocean. Much of the ocean circulation of the present-day earth, for example, is driven by a global "heat engine," in which warm, salty water from the Tropics and the subtropics flows toward the pole, where it gives up its heat, sinks to the bottom and flows back toward the Equator [see "Polynyas in the Southern Ocean," by Arnold L. Gordon and Josefino C. Comiso; SCIENTIFIC AMERICAN, June]. By mixing surface water into the deep water, the heat engine distributes oxygen and other nutrients throughout the ocean. Ice at the pole keeps the polar waters cold, helping to maintain the temperature difference that drives the heat engine.

Such vertical circulation combines with the increased supply of continent-derived nutrients to raise the level of biological productivity at times of low sea level. High productivity should trap still more carbon in organic matter, further lowering levels of atmospheric carbon dioxide.

The environments that are most hospitable to marine life are the continental shelves, where continent-derived nutrients are abundant and shallow depths allow sunlight to penetrate to the sea floor. When biological productivity is high, however, these shelf environments are unavailable, exposed by the low sea level. As a result many established species will become extinct, and new, innovative species will be favored. This does not mean, however, that life will be particularly diverse. On the contrary, such conditions—high nutrient levels but few available environmental niches—lead to ecosystems in which a large amount of biomass is concentrated in relatively few successful species.

Climate after Breakup

Thus the effects of low sea level include a propensity toward glaciation, strong vertical circulation in the world ocean, high biological productivity, biological innovation and a low degree of biological diversity. What should be the effects of high sea level, which would be expected just after a supercontinent breaks up or just before it is reassembled?

When continents are drowned, a relatively small amount of silicates will be available to sequester atmospheric carbon dioxide in sea-floor deposits. Meanwhile carbon dioxide will be released into the ocean and from there into the atmosphere by the hot mantle material that wells up at sea-floor spreading centers. Also, the subduction of oceanic crust and the resulting melting of limestone deposits in the subducted sediments will release still more carbon dioxide into the atmosphere at the volcanoes that mark subduction zones.

Atmospheric levels of carbon dioxide will therefore rise and the earth's climate will become warmer. Polar ice caps should melt, raising sea level still higher and further drowning the continents. The absence of polar ice will reduce vertical and horizontal circulation of the world ocean, causing it to begin to stagnate: oxygen and nutrient levels in ocean waters will decline, and with them biological productivity. On the other hand, the drowned continental crust will provide a large area for the shallow seas that are most hospitable to life. The resulting ecosystems will resemble those of the present-day Tropics, where the climate is warm, nutrient levels are low and a relatively large number of environmental niches are available. Like today's Tropics, these ecosystems would be characterized by low productivity and great species diversity.

How well does the record of past climates and life forms bear out these predictions? One of the most impressive confirmations of our model is found in records of glaciation. All the known episodes of glaciation in the history of the earth took place at times when according to our model sea levels should have been low. The converse is not true. That is, not every period when sea levels should have been low had an episode of glaciation: probability dictates that in some periods there would not have been an emergent continent near the pole.

Biological Evidence

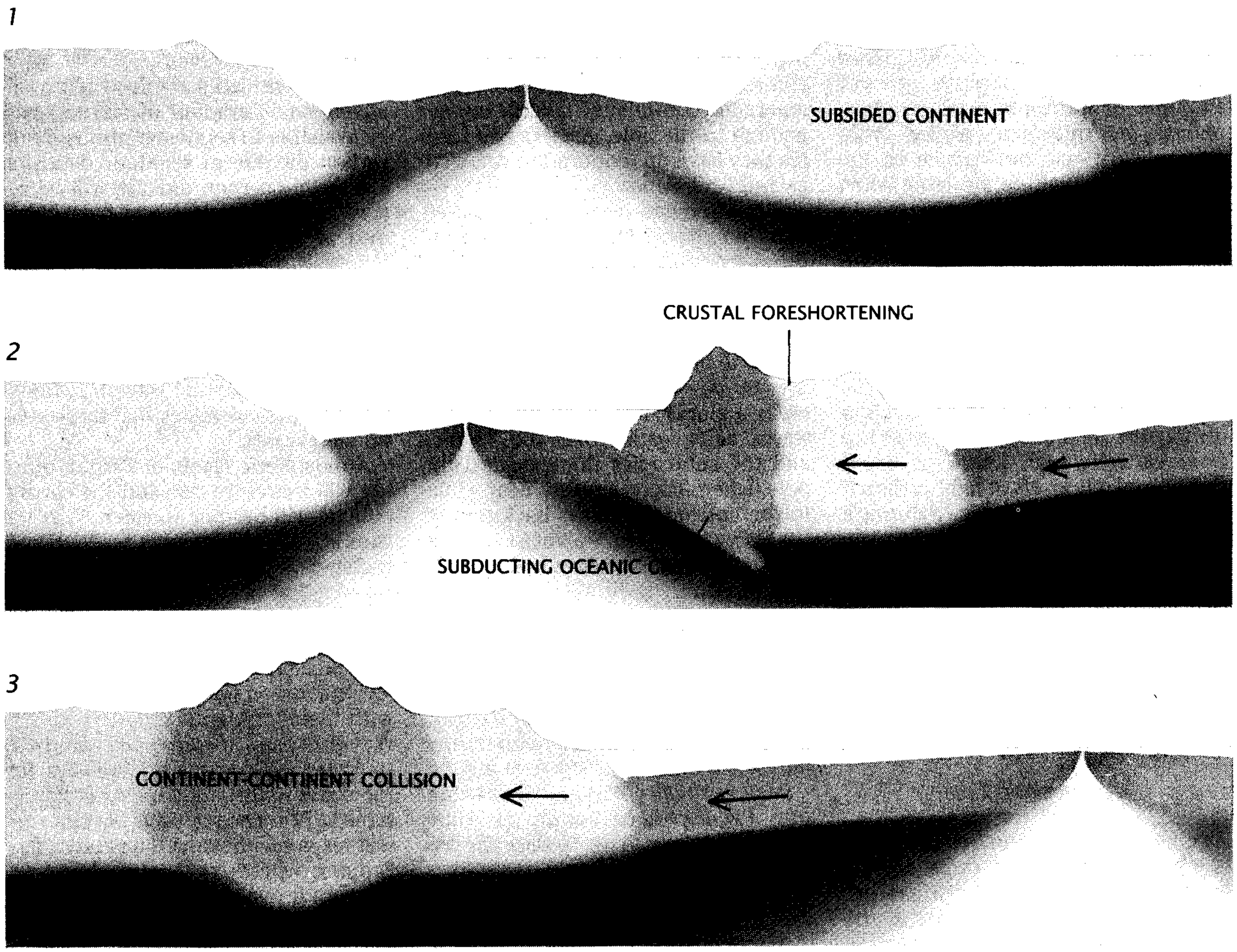
The biological record is a little more ambiguous, for a variety of reasons. Perhaps most important, the fossil record is not uniform throughout time. The record is based mainly on deposits buried on continental crust—buried when sea levels were high. When sea levels are low, marine organisms will generally live offshore, beyond the exposed continental shelves. Deposits recording these periods are rare: such deposits are likely to have been destroyed later, by subduction of the ocean floor. Nevertheless, the available evidence tends to confirm our hypothesis.

For example, the few geologic records of marine life during the existence of the most recent supercontinent, Pangaea, indicate low diversity of species, as we would expect when sea levels are low. In addition, the period of drowning that followed the breakup of Pangaea was characterized by high levels of species diversity.

Looking further back in time, the breakup of the previous supercontinent about 600 million years ago was marked by the first recorded appearance of shelled animals. During the period following this breakup there was what has been called an explosion of diversity [see "The Emergence of Animals," by Mark A. S. McMenamin; SCIENTIFIC AMERICAN, April, 1987]. In particular, shelled animals radiated into a highly diverse array.

Looking back still further, the first recorded multicellular animals are found in marine sediments that are about a billion years old. These sediments would have been deposited, according to our model, right after the breakup of a supercontinent. It is quite possible that this biological innovation occurred during the existence of the supercontinent but was not recorded until the continent broke up and sea levels rose, drowning the continental shelves.

A still older innovation may also be linked to the supercontinent cycle. About 2,100 million years ago, just prior to an assumed supercontinental breakup, blue-green algae first developed heterocysts, the organelles that



FORESHORTENING of continental blocks increases the total area of the world ocean and thereby lowers the global sea level. Just after the breakup of a supercontinent (*1*) the new sea floor (*left center*) butts up against continental fragments. Later, as the new ocean basin closes (*2*), the continent moves over the sea floor, subducting it; the resulting compressive forces foreshorten the continent and raise mountains, in the process lowering sea level. Still later, when continents collide during reassembly of the supercontinent (*3*), the continental crust is foreshortened even further, again lowering sea level.

make it possible to fix nitrogen (to crack apart nitrogen molecules and bind the constituent atoms to carbon in organic matter) even in the presence of atmospheric oxygen. Without heterocysts or similar organelles, the chemical reactions of nitrogen fixation can be interrupted by oxygen atoms that bind to the nitrogen atoms. The atmosphere was then just beginning to contain oxygen; the innovation made it possible for many later organisms—the predecessors of today's photosynthetic plants—to survive in the new, oxygen-bearing atmosphere, which otherwise could have been poisonous to them.

A New Framework

The supercontinent-cycle hypothesis represents a new framework, a new way to understand the geologic history of the earth. It suggests that the processes of plate tectonics on the largest scale are primarily governed not by chance but by a regular, cyclic process.

The supercontinent cycle also represents a new way of understanding the history of life on the earth. The large-scale climatological effects brought about by various phases of the supercontinent cycle—continental drowning or emergence, glaciation and ocean circulation, stagnation in the world ocean and other effects—drove many of the important biological innovations that have directed the later course of evolution. In a sense, then, the supercontinent cycle is indeed the pulse of the earth: with every beat the earth's climate, geology and population of living organisms are advanced and renewed.

FURTHER READING

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