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Supercontinents

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Glossary

Continents have repeatedly collided and broken apart over geologic time. Supercontinents form when most continents are clustered in one part of the globe. Supercontinents have probably existed at several times in the past; the most recent one, Pangea, began to break apart about 180 Ma (million years before present). Its fragmentation led to the formation of the Atlantic and Indian oceans at the expense of the Pacific Ocean. The aggregation and breakup of supercontinents cause continental emergence and flooding, respectively, thereby exerting a strong influence on global climate.

I. Introduction

The idea that today's continents represent the dispersed fragments of an ancestral supercontinent, named Pangea, was first championed by Alfred Wegener (1880–1930), a German meteorologist, geophysicist, and Arctic explorer. His theory of continental dispersal was based on geological comparisons of the continents facing the Atlantic Ocean and of the southern continents. Although Wegener overestimated the rate of continental drift and was unable to propose a satisfactory mechanism, the geological consanguineity of the southern continents (South America, Africa, India, Antarctica, and Australasia) was substantiated by the South African geologist Alexander DuToit (1878–1948). In retrospect, we can see that the problem of mechanism was overcome by the Austrian geologist Otto Ampferer (1875–1947), who suggested in 1925 that continental drift might be driven by mantle convection currents, and by the British geologist Arthur Holmes (1890–1965), who reasoned that radiogenic heating in a supercontinent would insulate the underlying mantle and promote a convective upwelling that would ultimately weaken and disperse the supercontinent. Nevertheless, acceptance of Wegener's theory was delayed until the 1960s, after the predicted continental displacements had been verified paleomagnetically and seafloor spreading was inferred from the symmetrical disposition of magnetic anomalies with respect to midocean ridges. One of the early criticisms of Wegener's theory, that it did not account for geological events prior to the breakup of Pangea, fuels current speculation that there have been several cycles of aggregation and fragmentation of supercontinents, recurring at intervals on the order of 500 million years (m.y.)

II. Breakup and Dispersal of the Supercontinent Pangea

The relative motions of the continents since the breakup of Pangea are best deduced from seafloor magnetic anomalies. They show that continental dispersal was accompanied by growth of the Atlantic and Indian oceans at the expense of the Pacific Ocean, as shown in Fig. 1. Rifting began in the central Atlantic Ocean between 180 and 150 Ma (Jurassic), coincident with a period of rapid apparent motion of Pangea relative to the hot spot mantle reference frame. However, the main period of breakup occurred later, between 120 and 90 Ma (Cretaceous), following an interval when Pangea was nearly stationary with respect to the mantle. The location of the present Atlantic–Africa geoid high and associated mantle plumes coincides with the Cretaceous position of Pangea; the global ring of geoid lows coincides with the subduction zones that formerly encircled Pangea and evolved into the present circum-Pacific subduction system. This led Clement Chase of the University of Arizona to suggest that the planform of deep mantle convection, as represented by long-wavelength geoid anomalies, is governed by the cooling effect of long-lived subduction zones as well as by the heating effect of stationary supercontinents. (Because of the viscosity of the lower mantle, its response time is long relative to surface plate motions, accounting for the persistence of a mantle upwelling

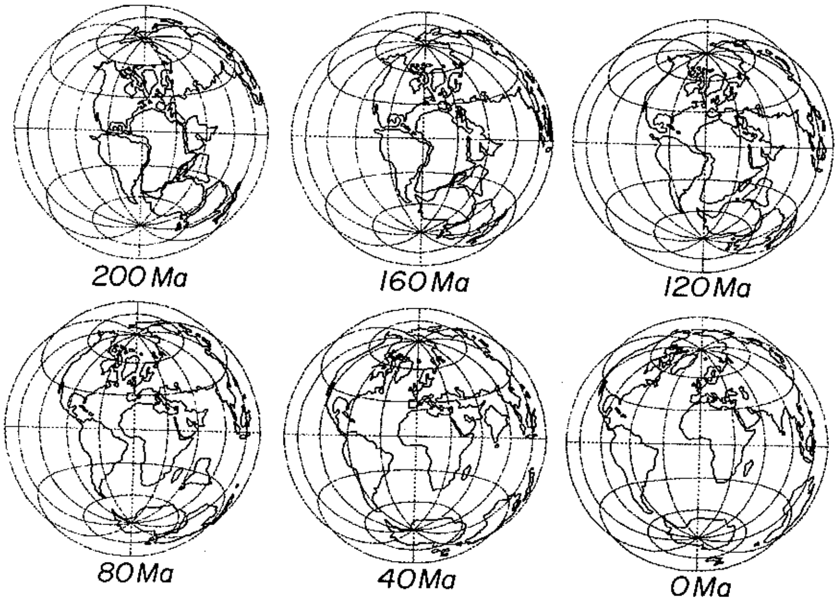

Fig. 1 Relative motions of the major continents over the past 200 m.y. Continental outlines are drawn according to modern shorelines solely for the purpose of identification.

beneath the former position of Pangea long after its dispersal.) Vast outpourings of basaltic lava occurred where continents separated above hot mantle plumes. For example, the Karoo and Parana lavas were erupted during the separation of Africa from Antarctica and South America, respectively. [*See* Continental Rifting; Mantle.]

The breakup and dispersal of Pangea was accompanied by a first-order rise in sea level and concomitant flooding of the continents, as indicated in Fig. 2. Continental flooding increased to a maximum in the late Cretaceous before falling again to the present, largely emergent state. The elevation of Pangea was supported dynamically by the hot mantle upwelling, which also resulted in isostatic uplift due to thermal expansion. Of course, the positive geoid anomaly implies that sea level would have been about 100 m higher than the global mean in the region of the supercontinent, but the epeirogenic uplift of the supercontinent would have been an order of magnitude greater. During dispersal, the continental fragments migrated toward regions of cooler downwelling mantle, causing them to sink dynamically in response to thermal convection. Furthermore, the creation of new oceanic lithosphere following breakup would have caused a rise in global, or eustatic, sea level. This is because of change in the global mean age of the oceanic lithosphere and the fact that the depth of the ocean floor increases exponentially as the lithosphere ages and cools. Today, the mean age is about 80 Ma, similar to the mean age of the oceanic lithosphere which has been subducted around the Pacific Ocean (old lithosphere has been subducted in the western Pacific but young lithosphere in the eastern Pacific). Therefore, the generation of new crust in the Atlantic and Indian oceans would have lowered the global mean age until about 80 m.y. after breakup, resulting in an upward displacement of sea level. After that time, the mean age would have increased again and sea level consequently fell. This reasoning is consistent with the timing of the observed changes in continental freeboard as depicted in Fig. 2. [*See* Oceanic Crust; Sea Level Fluctuations.]

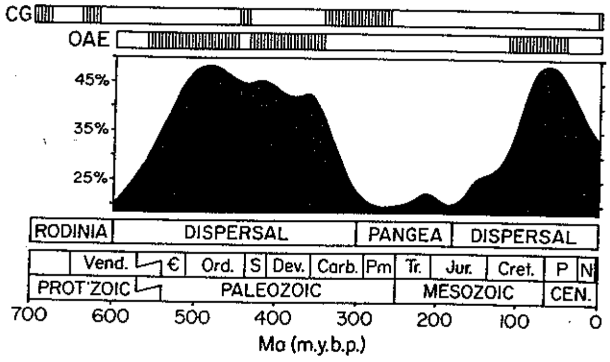

Fig. 2 Phanerozoic variation in percentage of continental area flooded, showing the correlation of relative sea level high stands with continental dispersal and relative low stands with supercontinents. Also shown are the times of continental glaciation (CG) and ocean anoxic events (OAE).

The changes in continental freeboard are correlated with profound changes in global climate. As pointed out by Alfred Fischer of Princeton University, the geologic record shows that continental glaciation occurred during low stands of sea level and continental flooding was accompanied by global warming. The reason for this is related to the fact that global climate is modulated by the "greenhouse effect" of carbon dioxide (as well as other gases) in the atmosphere. The source of atmospheric carbon dioxide is volcanic outgassing; its removal is accomplished primarily by the "weathering" of crustal silicate rocks (i.e., reaction with carbonic acid rain) to form deposits of limestone and silica. Carbon dioxide is also removed from the atmosphere through burial of organic carbon. Weathering is obviously dependent on subaerial exposure of continental crust, and organic carbon production is dependent on weathering to provide the limiting nutrient phosphorus, which is mainly derived from the mineral apatite, a ubiquitous minor constituent of silicate rocks. When continents are emergent, weathering is maximized and the atmosphere becomes depleted in carbon dioxide, causing global cooling. (Although global cooling is a prerequisite, other factors such as extensive high plateaus may be required to initiate continental glaciation.) Continental flooding minimizes weathering, allowing atmospheric carbon dioxide to increase with consequent global warming. The intense volcanism which accompanied the breakup of Pangea may also have contributed to the Cretaceous global warming by the addition of mantle-derived carbon dioxide. [*See* ATMOSPHERIC EFFECTS OF VOLCANIC ERUPTIONS; PALEOCLIMATIC EFFECTS OF CONTINENTAL COLLISION AND GLACIATION.]

The Cretaceous global warming had an important effect on ocean sediments which served to limit the buildup of carbon dioxide and therefore temperature increases. Convective circulation of ocean water is promoted by dense glacial meltwater and strong latitudinal temperature gradients. Diminished circulation due to global warming resulted in episodes of bottom-water anoxia and consequent burial of reduced, carbon-rich sediments. Figure 2 shows the antithetic relation between continental glaciation and ocean anoxic events. The massive removal of carbon from the oceans during episodes of ocean anoxia reduced the atmospheric greenhouse effect, thereby limiting further warming. This negative feedback, which operated in response to temperature increases resulting from accelerated weathering, prevented runaway warming.

III. Dispersal of Rodinia and Assembly of Pangea

Since no oceanic crust older than about 160 Ma remains in the ocean basins, magnetic anomalies cannot be used to derive the relative motions of continents before the breakup of Pangea. Consequently, other methods must be employed. Gerard Bond and his colleagues at the Lamont–Doherty Geological Observatory of Columbia University have analyzed the subsidence history of early Paleozoic sedimentary sequences deposited near continental margins worldwide. Their work shows that virtually all of the Paleozoic sequences they studied formed by penecontemporaneous rifting and continental breakup at about 600 Ma. To many this implies the breakup of a late Proterozoic supercontinent, for which the name Rodinia has been proposed (from *rodit*, the Russian infinitive "to beget"). There is little agreement as to the configuration of the present continents within Rodinia, but paleomagnetic data suggest that many were close to the equator. They include continents which experienced extensive contemporaneous glaciation. The seeming contradiction of low-latitude glaciation may attest to the increased albedo of a globe characterized by emergent equatorial continents devoid of vascular plants (which had yet to evolve). [*See* PALEOMAGNETISM.]

Paleomagnetism provides information on the changes in paleolatitude (but not paleolongitude) and orientation of continents. Bolstered by inferences from paleoclimatology and biogeography (the distribution of climatically sensitive fossils such as coral reefs), increasingly sophisticated models for Paleozoic continental motions have been developed. In general, they imply that continents were widely dispersed in the Paleozoic until about 300 Ma (Carboniferous). During this interval, the southern, or Gondwana, continents (Africa, South America, Antarctica, India, and Australasia) remained consolidated; but Laurentia (North America, Greenland, and northwest Britain), Baltica (Baltic shield and Russian platform), Kazakhastania, Siberia, North China, South China, and various smaller microcontinents drifted separately. Between 400 and 300 Ma (Devonian–Carboniferous), all these continents converged and were fused, save for North and South China and other east Asian blocks, which joined the aggregation about 100 m.y. later (late Triassic–early Jurassic). The amalgamation produced a vast system of collisional mountain belts, among which (in order of decreasing age) are the Caledonides, Urals, Appalachians, Tien Shan, and Qinling. The resulting Pangea supercontinent (Fig. 1) consisted of a southern half, Gondwana, joined in the west to a northern half, Laurasia, separated by an eastward-opening embayment named Tethys. During the final consolidation of Pangea and persisting to the present day, continental fragments derived from Gondwana (e.g., Italy, Arabia, Iran, Afghanistan, Tibet, India, Southeast Asia, and Australasia) drifted piecemeal across Tethys and were accreted to Eurasia, producing the Mesozoic–Tertiary "Alpine" mountain belts. The generation of mountain belts by shortening and thickening of continental crust also contributed to eustatic lowering of sea level by reducing the volume of seawater displaced by continents. [*See* CONTINENTAL DEFORMATION; OROGENIC BELTS.]

Additional evidence for the breakup and dispersal of a supercontinent at about 600 Ma comes from the variation in continental freeboard during the early Paleozoic (Fig. 2), which is similar to that following the breakup of Pangea. A first-order rise in relative sea level is inferred from the observed flooding of the continents, which peaked at 510–480 Ma (late Cambrian–early Ordovician). Thereafter, sea level apparently fell to a low stand following the assembly of Pangea. Global warming, resulting from the sea level high stand, contrasted with the widespread glacial conditions associated with both the Rodinia and Pangea supercontinents.

IV. Earlier Precambrian Supercontinents

Based on worldwide compilations of radiometric ages, Precambrian crustal evolution appears to have been marked by episodes of widespread orogenic activity alternating with periods of stabilization and/or rifting. The orogenic episodes, identified by belts of crustal shortening and attendant plutonism and metamorphism, occurred at 0.8–0.6 Ga (Pan-African orogeny), 1.3–1.1 Ga (Grenvillian orogeny), 1.9–1.7 Ga (Hudsonian orogeny), 2.3–2.1 Ga (Eburnian orogeny), and 2.8–2.6 Ga (Kenoran orogeny). (Not enough is known of the worldwide crustal record prior to 3.0 Ga for relevant generalizations.) The recurrence interval of the orogenic episodes is of the same order of magnitude as that of the Phanerozoic supercontinent cycle, and their worldwide extent led Tom Worsley of Ohio University and his associates to advocate that they represent periods of rapid continental drift and aggregation of successive Precambrian supercontinents. Little is known, however, of the configurations of those supercontinents.

Between the orogenic episodes, times of inferred supercontinents were characterized by terrestrial sedimentation, intraplate magmatism, and rifting. The magmatism involved melts derived from both the crust (rhyolite ash flows and related potassic granites) and the mantle (alkaline complexes, flood basalts, and related dike swarms). The overall character of the magmatism is most like that associated with the late stages of Pangea and its initial fragmentation. The existence of precisely coeval dike swarms on different continents is best explained as a consequence of rifting of formerly contiguous continents. Magmatism during the interorogenic interval from 1.7 to 1.3 Ga was particularly intense, perhaps because its relatively long duration allowed more time for heat buildup beneath the supercontinent. Crustal melting was more prevalent in areas of crust younger than 2.0 Ga, an observation consistent with evidence (from seismic velocities and mantle samples brought up in diamond-bearing pipes) that crust older than about 2.0 Ga is protected by deep roots of refractory mantle lithosphere.

Paleomagnetic and paleoclimatic data provide means of testing the concept of recurrent Precambrian supercontinents. Paleopoles for North American rocks indicate large variations and (with less certainty) rapid changes in paleolatitude during the Hudsonian and Grenvillian orogenic episodes. In contrast, a persistent low-latitude position prevailed between the orogenic episodes. This accords with the position of Pangea, which straddled the equator, in contrast to the rapid latitudinal drift of continents during episodes of Phanerozoic continental dispersal. Paleoclimatic data provide some support but also raise problems. The evidence of widespread glaciation at 2.5–2.3 Ga is consistent with the existence of an emergent supercontinent in the interval between the Kenoran and Eburnian orogenies. However, there is no evidence of glaciation in the interval between the Hudsonian and Grenvillian orogenies. The youngest Precambrian glaciations are not precisely dated but their age is estimated to be 0.75–0.65 Ga, contemporaneous with the Pan-African orogeny. This brings into focus the problem that Rodinia can never have incorporated all the continents simultaneously, as the aggregation of Gondwana (0.8–0.5 Ga) overlaps in time with the fragmentation of the northern continents.

V. Mechanics of the Supercontinent Cycle

Michael Gurnis of the University of Michigan has carried out time-dependent numerical simulations, depicted in Fig. 3, which support the concept of a dynamic feedback between the motions of continental plates and mantle convection. The long-term insulating effect of a stationary supercontinent induces a convective mantle upwelling. (The continent must be sufficiently large to prevent the underlying mantle from being cooled by subduction zones at its periphery.) The upwelling elevates the supercontinent, increasing its gravitational potential, and thermally reduces its torsional rigidity. Tensional stress is amplified by subduction zone "rollback" (caused by sinking of old oceanic plates), which may be enhanced by a "ballooning" effect of the upwelling mantle seeking to escape from beneath the supercontinent. Diverging mantle flow may also assist continental dispersal through shear tractions imposed on the continental roots. In the numerical simulations, the continental fragments drift rapidly toward mantle downwellings, where they reaggregate to form a new supercontinent. The period of drift and reaggregation is accompanied by continental subsidence and flooding as the fragments move from regions of hotter to cooler mantle. (Gerard Bond and co-workers have presented stratigraphic evidence for continentwide subsidence at the time of aggregation of Pangea, and the existence of large 1.7-Ga cratonic basins on several continents is consistent with the aggregation of a supercontinent during the Hudsonian orogeny.) The

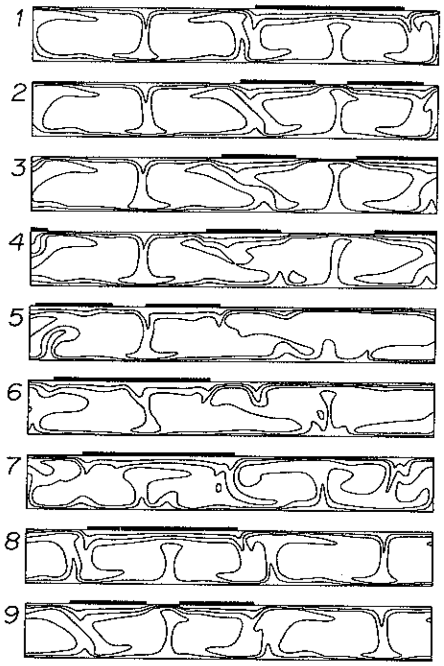

Fig. 3 Numerical simulation by Michael Gurnis, depicting the dynamic interaction of continental plates (black bars) and mantle convection indicated by isotherms. Upwellings are portrayed by upward deflections of deeper hotter isotherms, downwellings by downward deflections of shallower cooler isotherms. The depth of the box represents the entire mantle (2900 km) but the thicknesses of continental plates are not drawn to scale. Panels 1–9 show evolution over approximately 500 m.y.

overall cycle is completed as the mantle downwelling is slowly transformed into an upwelling because of the insulating effect of the reaggregated supercontinent. The time scale for the simulated cycle is on the order of 500 m.y., consistent with the geological record.

The principal inadequacy of the numerical simulations is that they do not incorporate the effects of oceanic plates and subduction zones, which evidently exert a major influence on plate motions (in the hot spot reference frame, rapidly moving plates are connected with and directed toward subduction zones). Nevertheless, it is evident from plate motions over the last 100 m.y. that a future supercontinent is gathering around Eurasia, which is located in a geoid low indicative of mantle downwelling. Interestingly, the principal geoid lows are centered near the poles, whereas the antipodal geoid highs are located on the equator. The reason for this is that the excess masses associated with the geoid highs are stabilized in the equatorial plane to conserve angular momentum. Accordingly, if supercontinents aggregate at mantle downwellings located at high latitudes, the mantle upwellings they subsequently engender would be rotationally unstable. Restoration of such upwellings to the equatorial plane might be brought about by "true polar wander," which should be correlated with times of supercontinent amalgamation. If the Pacific Ocean continues to close (as seems likely if South America follows North America in overriding the East Pacific spreading ridge), then the American continents will finally join the future supercontinent about 100 m.y. from now.

Bibliography

Anderson, D. L. (1982). Hotspots, polar wander, Mesozoic convection and the geoid. *Nature (London)* **297,** 391–393.

Bambach, R. K., Scotese, C. R., and Ziegler, A. M. (1980). Before Pangea: the geographies of the Paleozoic world. *Am. Sci.* **68** (January–February), 26–38.

Fischer, A. G. (1984). The two Phanerozoic supercycles. *In* "Catastrophes and Earth History." (W. A. Berggren and J. A. Van Couvering, eds.), pp. 129–150. Princeton Univ. Press, Princeton, New Jersey.

Gurnis, M. (1991). Continental flooding and mantle–lithosphere dynamics. *In* "Glacial Isostasies, Sea-Level and Mantle Rheology" (R. Sabadini and K. Lambeck, eds.). Kluwer Academic Publishers, Dordrecht (in press).

Nance, R. D., Worsley, T. R., and Moody, J. B. (1988). The supercontinent cycle. *Sci. Am.* **256** (July), 72–79.

Smith, A. G., Hurley, A. M., and Briden, J. C. (1981). "Phanerozoic Paleocontinental World Maps," p. 98. Cambridge Univ. Press, London.

Worsley, T. R., Nance, R. D., and Moody, J. B. (1986). Tectonic cycles and the history of the earth's biogeochemical and paleoceanographic record. *Paleoceanogr.* **1,** 233–263.

Glossary

Continental freeboard Proportion of continental surface area (alternatively, mean continental elevation) above sea level.

Epeirogenic uplift Vertical motion of a continent independent of the effects of horizontal tectonic shortening or stretching.

Geoid Reference surface of gravity equipotential (everywhere perpendicular to the plumb line) that defines sea level.

Hot spot reference frame Reference frame for plate motions based on surface expression of mantle plumes believed to be approximately fixed relative to the bulk mantle.

Intraplate magmatism Magmatism occurring away from