

Why Earth became so hot 50 million years ago and why it then cooled

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In this issue of PNAS, Kent and Muttoni (1) offer an explanation of why Earth, after being hot 50 million years ago, cooled dramatically, changing its climatic state. What were these states, and how did they come to be recognized?

Climate States

In the early 20th century, Vladimir Köppen (2) classified present climate into five main types based on the idea that native vegetation is its best expression. There is an overall latitudinal zonation reflecting the gradient in mean temperature from pole to equator, with lateral variations arising from variability in rainfall and continentality. To determine the past distribution of climate zones, he, in collaboration with his son-in-law Alfred Wegener (2), compiled occurrences of climate sensitive deposits and fossils and plotted them on Wegener's newly minted continental drift maps back to the Devonian (350 Ma). Assuming that Köppen's present-climate model always applied, they constructed poles and parallels of geographic latitude (2). But their maps contained certain inconsistencies and failed to explain certain phenomena, not because there were gross errors in the data, but because climate zones were not always the same as at present.

Inconsistencies became increasingly evident as Early Cenozoic and especially Eocene floras of "tropical" aspect were found in northern Europe and Greenland, and floras of temperate aspect were found in the Canadian arctic islands, much farther north than would be expected. As global mapping proceeded, evidence accumulated of extensive glaciation at sea level in the later Paleozoic (320–250 Ma) and later Cenozoic, but none that survived detailed scrutiny, in the Early and mid-Paleozoic (540–320 Ma) or Mesozoic and Early Cenozoic (250–33 Ma). For most of the Phanerozoic, Earth had no large low-altitude glaciers. These developments led, in the 1930s, to the realization that Earth had two climatic states or regimes, which Brooks (3) called simply "nonglacial" and "glacial." Subsequently it has been shown that the latter can be divided into "polar-glacial" and "pan-glacial" according to whether low-altitude glaciers were confined to higher latitudes or distrib-

uted in all latitudes as they likely were during the latest Proterozoic (≈ 550 Ma).

I am glad that Kent and Muttoni (1) have adopted Brooks' simple and appropriate names. The names now commonly used for these three climate states are "greenhouse," "icehouse," and "snowball," respectively, all of which were poorly conceived. Greenhouse presupposes its cause is known; an icehouse is a shed filled with straw or sawdust for summer storage of ice, hardly evocative of Earth's present climate; and a snowball is snow, not ice, which is the critical factor (although an

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early cover of snow may have been needed to increase albedo and induce pan-glaciation, but this, too, would appeal to an hypothetical cause).

Equatorial Convergence Theory

According to Kent and Muttoni, the central act is the transfer of India across the equator from Gondwana to Asia (figure 3 in ref. 1) during the Mesozoic/Early Cenozoic nonglacial regime. Ahead of India as it moved north was the oceanic crust of Tethys, which, as it traversed the equator, became progressively loaded with carbonate-rich sediments. These sediments were then consumed in subduction zones at the Asian margin, and decarbonated, and CO₂ was released into the atmosphere. Changes in production and consumption rates of ocean crust are usually invoked to explain changes in CO₂ outgassing, but Kent and Muttoni argue that rates could have remained essentially constant because it is the composition of sediments being subducted that likely governs how much CO₂ becomes available, in this case the equatorially-situated, carbonate-loaded Tethyan crust. Tellingly, at present, under a polar glacial regime, very little equatorial carbonate

is apparently being subducted. Eruption of the huge Deccan Traps at 65 Ma produces a transient addition of CO₂. Tethyan subduction and outgassing ceased at 50 Ma, and, most importantly, was followed by withdrawal of CO₂ from the atmosphere through the intense weathering of the Deccan Traps as they drifted into the tropical humid belt, and also, for good measure, by the weathering of the newly extruded Ethiopian Traps. In the collision zone there was strong uplift, which attracted heavy rainfall, causing massive erosion and weathering and further draw-down of CO₂. By the early Oligocene (33 Ma), the decline in Earth's mean temperature over the Middle and Late Eocene triggers the first limited Antarctic glaciation, which expands as albedo intensifies, progressively evolving to the bipolar glaciations of the Pleistocene. This is Kent and Muttoni's scheme.

Their case rests on temporal correlations between tectonic and climatic phenomena. Particularly impressive is the correlation at 50 Ma of the Indian-Asian collision and the consequent shutdown of what they call the "carbon factory" during the climate optimum, which is immediately followed by the temperature decline of the Middle and Late Eocene and the transition to a glacial state. Correlations do not necessarily imply causation, but they are strongly suggestive when linked in the manner that Kent and Muttoni (1) do.

Biogeographic Applications

Kent and Muttoni's article (1) promises to assist our understanding of the causes of important biogeographic phenomena, for example, the disjunctive floras of eastern Asia and eastern North America (a long-standing problem). Now very widely separated, they share a common Early Cenozoic ancestry. Within genera (e.g., *Magnolia* or *Cotinus*, the smoke bush) species from China and the Carolinas will freely interbreed if afforded proximity in the garden. The disjunctive

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See companion article on page 16065.

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Permian *Glossoteris* flora of the now widely separated southern continents are brought together and explained by the theory of continental drift. Drift, however, failed to bring the floras of eastern Asia and eastern North America together, and it is now clear that gross climate change not drift is the cause of their present isolation. During the early Cenozoic, when temperate climates extended into polar regions, these “old”

floras, which did not then have to overcome the barriers of a wide Atlantic or polar ice, spread across North America and Eurasia. Likely facilitated by the then short and emergent Thulean land bridge (the precursor of the present Iceland Faroes Ridge) there seems to have been a free two-way exchange of biota between east Asia and North America, for example, the migration from America to China of magnolias (4) and of

monkeys from China to America (5). At first these migrations were facilitated under the Early Cenozoic nonglacial regime, and then were progressively curtailed and finally prohibited as the present polar-glacial regime became established in the later-Cenozoic. The theory of Kent and Muttoni (1) implies that the northward drive of India and its collision with Asia was the engine behind this climate-controlled evolution.

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