PERSPECTIVES: PALEOCLIMATE

Tropical Paradise at the Cretaceous Poles?

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One can imagine the shock that went through the scientific community a century ago when Captain Larsen and his whaling crew discovered fossil wood in the northern Antarctic Peninsula. This barren landscape is the most formidable place on the planet, inhabited only by moss and lichens. But Captain Larsen's surprising discovery meant that the polar climate had been warmer in the past, and it triggered the quest for an explanation. In the years that followed, leaf fossils, mosasaurs, pleisiosaurs, dinosaurs, marsupials, and diverse assemblages of mollusks added to a growing body of evidence that polar temperatures in the deep past were warm and the equator-to-pole thermal gradient was low. As reported on page 2241 of this issue, Tarduno *et al.* (*1*) have now added champsosaurs (see figure at right) to the list of organisms once thought to be restricted to lower latitudes.

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Previous discoveries of terrestrial vertebrates at high latitudes included only dinosaurs and turtles. But their paleoclimatic importance is limited because it is not known whether dinosaurs were cold-blooded (ectotherms) or warm-blooded (endotherms) (*2*) and turtles are known to survive subfreezing conditions by hibernating in well-protected burrows. However, the discovery of champsosaurs is important, as their occurrence on Axel Heiberg Island (72°N) is in stark contrast to the tropical to subtropical distribution of their nearest living relatives, the crocodiles. Although uncertainties remain regarding the strict relationship between crocodiles and champsosaurs, it is known that champsosaurs were ectotherms, their distribution in the fossil record and their body size were similar to those of crocodiles, and they were adapted for a mostly aquatic life. It is therefore likely that champsosaurs could not have tolerated prolonged exposure to subfreezing conditions. Their survival required that the temperature of the water in which they lived never fell below freezing so that air holes would remain available for breathing. Further, the critical minimum body temperature below which modern ectotherms of their size die is known to be 5°C (*3*).

Champsosaur, freshwater fish eater.

The high-latitude paleobotanical record also provides convincing evidence of polar warmth during the Cretaceous. The occurrence of deciduous trees as far north as 82°N during the middle Cretaceous indicates that permafrost was absent, and the abrupt cessation of cell growth in their tree rings reveals that winter darkness was the seasonal growth-limiting factor rather than cold temperatures (*4*). A more quantitative measure of terrestrial climate stems from the temperature-controlled size and shape relationships among modern leaf assemblages. This "leaf physiognomic" approach to paleotemperature reconstruction has been applied mostly to latest Cretaceous and Tertiary floras with internally and externally consistent results. Its reliability is less certain, however, when used for mid-Cretaceous plant assemblages, because this was a time of evolutionary innovation and radiation among the angiosperms. Using the leaf physiognomy method, Herman and Spicer (*5*) estimate that the mean temperature of the warmest summer month in the Arctic during the Turonian and Coniacian ranged between 18° and 20°C, whereas the coldest winter month ranged from −4° to 0°C during the Turonian and 0° to 4°C during the Coniacian (see figure on next page). Mean annual temperatures estimated from the Alaskan North Slope with this method yield similarly mild temperatures.

The case for extreme high-latitude warmth during the middle Cretaceous has recently been strengthened by oxygen isotope paleotemperature estimates from extraordinarily well-preserved foraminifera from the circum-Antarctic region (see figure on next page). An Aptian-Maastrichtian record from a deep-sea site in the southern South Atlantic [Deep Sea Drilling Project (DSDP) Site 511, Falkland Plateau] reveals that the entire water column warmed abruptly during the early Turonian, with deep waters (~1000-m paleodepth) reaching 18°C and surface waters reaching over 30°C at a site located at 59°S paleolatitude (*6*). The high-latitude ocean remained very warm from the Turonian through earliest Campanian, with surface waters varying between 20° and 27°C and deep waters varying between 14° and 16°C. This period of sustained warmth was followed by long-term cooling through the Maastrichtian, which yields the lowest temperatures of the Cretaceous (*7*).

Although tropical surface-water temperatures near the Antarctic Circle seem hard to believe for any period of Earth history, there are many reasons to trust the Site 511 data. First, the exquisite preservation of the shells analyzed indicates that there have been no secondary changes in their original isotopic values. Second, the site was located in the open ocean away from the influence of continental runoff, so riverine waters enriched in the light oxygen isotope (^{16}O) cannot explain the highly negative oxygen isotope ratios of foraminifera from Site 511 (a decrease in $^{18}O/^{16}O$ ratios indicates carbonate precipitation under warmer conditions unless the oxygen isotopic composition of seawater is changed because of an unusual amount of evaporation, precipitation, or in-

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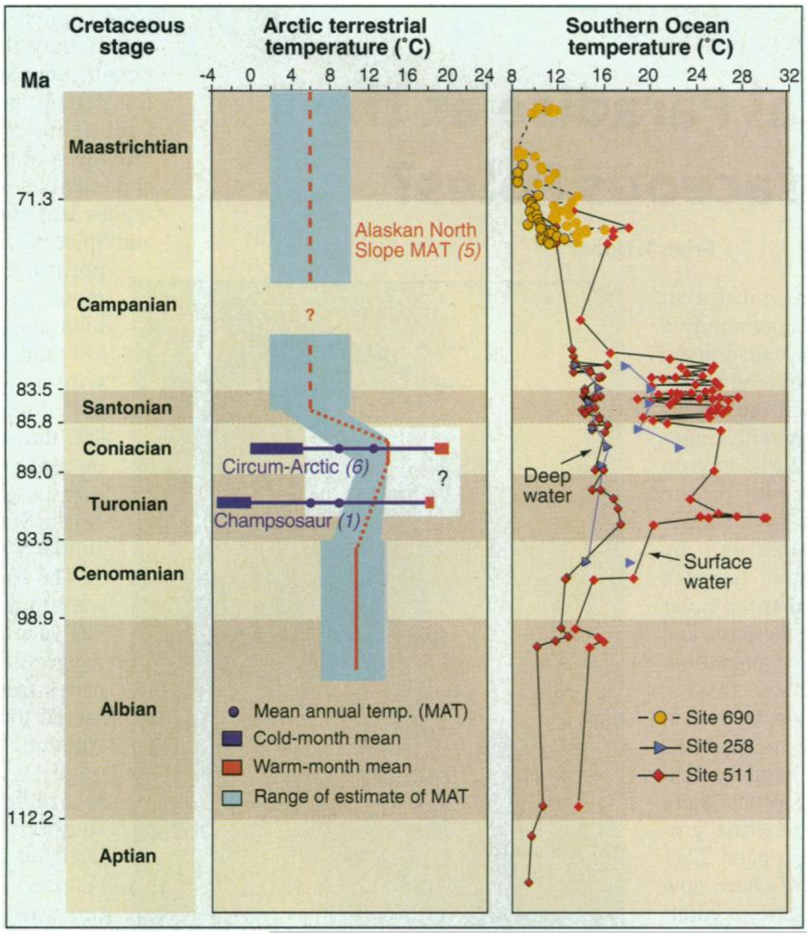
fluence by continental runoff). Third, even if the estimates of surface water temperatures are inaccurate because of uncertainties about how much latitudinal changes in salinity affected the $^{18}O/^{16}O$ ratios in the upper water column during the Cretaceous, we are still left with the problem that ocean water at 1000-m depth was over 18°C warmer than today at the same latitude. And finally, oxygen isotope measurements of planktic and benthic foraminifera from other deep-sea sites are yielding results that are consistent with those from Site 511. This has been found for a site in the southern Indian Ocean (DSDP Site 258; 57°S), which yields surface water paleotemperatures that range between 20° and 24°C and deep waters that range between 14° and 16°C (*6*). And, most recently, a new benthic oxygen isotope curve generated from a deep-sea site in the subtropical western North Atlantic reveals a pattern similar to Site 511, with an abrupt warming in the early Turonian (with deep waters reaching 18°C), long-term warmth in deep waters lasting from the Turonian through Santonian, and long-term cooling through the Maastrichtian (*8*).



Polar heat wave. Arctic (**left**) and Southern Ocean (**right**) temperatures over the past 112 million years based on leaf physiognomy analyses of Arctic plant assemblages and oxygen isotope analysis of planktic and benthic foraminifera from Southern Ocean deep-sea sites. Isotopic paleotemperatures were calculated with the paleotemperatures equation of Anderson and Arthur (*12*), assuming a mean oceanic $\delta^{18}O$ value of -1.2 per mil. Standard mean ocean water for an ice-free Earth (*13*). Surface-water paleotemperature estimates incorporate the latitudinal salinity correction of Zachos *et al.* (*13*). Lower and upper (? = uncertain) paleotemperature implications of champsosaur discovery by Tarduno *et al.* (*1*) are also shown.

So why was the Cretaceous climate so warm? The different land-sea configurations provide a partial explanation. In the middle Cretaceous, sea level was higher than at any other time during the past 250 million years. The greater proportion of continental surface covered by seawater resulted in reduced seasonal variations in temperature because of the lower surface albedo and greater thermal capacity of water. Seaways covering the Arctic, West Antarctica, and parts of East Antarctica also provided a means for heat transport to both poles throughout the year. With Australia against Antarctica and the Drake Passage closed, ocean surface currents sourced in the tropics reached further poleward than they do today, providing an additional moderating effect on Antarctic climate.

However, computer simulations of Cretaceous climate indicate that radiative warming caused by increased greenhouse gas concentrations (principally CO_2) were more important than paleogeography in explaining Cretaceous global warmth (*9*). Estimates of Cretaceous pCO_2 generally range from four to eight times preindustrial values (*10*), and some intervals, such as the Turonian-Coniacian (*1*), may have exceeded this amount severalfold (perhaps explaining the warming spike observed for that time). Climate models have revealed, however, that although CO_2-induced warming can approximate globally averaged temperatures for the Cretaceous, the models predict steeper latitudinal temperature gradients (both warmer tropics and colder poles) than geologic data seem to allow. This has led some to suggest that the oceans played a greater role in transporting heat from the tropics to the poles than they do today, particularly through sinking of dense, saline waters formed in restricted low-latitude basins (*9*). However, Sloan *et al.* (*11*) calculated that doubling the ocean heat transport to balance the energy budget for the warm climate of the early Eocene would require a mechanistically prohibitive poleward flow of warm, saline water masses. These authors concluded that either the oceanic processes of a greenhouse world were very different from those of the present or some other mechanisms must be used to explain the low equator-to-pole temperature differences.

The new lines of evidence for extreme warmth at polar latitudes during the middle Cretaceous reveal that some basic processes of atmospheric and oceanic circulation are not adequately simulated in computer climate models. Increasing sophistication of climate models by coupling atmospheric and oceanic simulations and incorporating such features as cloud and vegetation cover will help to narrow this gap. The most important clues to how the Earth System operated in a greenhouse world are recorded in an imperfect geologic record, but discoveries like those of Tarduno *et al.* (*1*) force refinements in hypotheses of greenhouse climate dynamics.

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