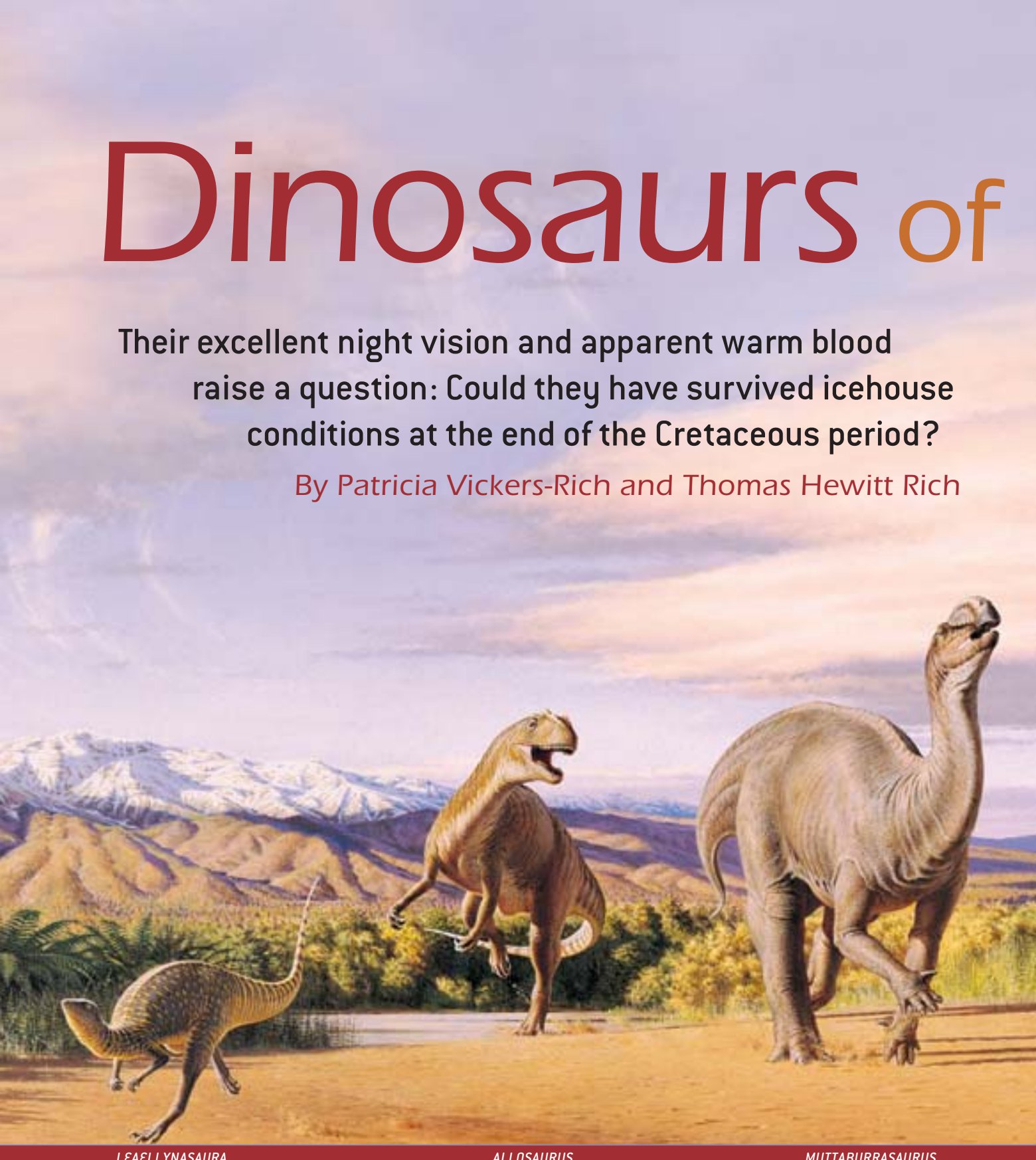
Dinosaurs of

Their excellent night vision and apparent warm blood raise a question: Could they have survived icehouse conditions at the end of the Cretaceous period?

By Patricia Vickers-Rich and Thomas Hewitt Rich



LEAELLYNASAURA *ALLOSAURUS* *MUTTABURRASAURUS*

AUSTRALIAN DINOSAURS flourished in southeastern Victoria during the Early Cretaceous, when the region lay within the Antarctic Circle. This mural depicts six species that left fossils there and a seventh—the large iguanodontid *Muttaburrasaurus*—that has been found only in Queensland,

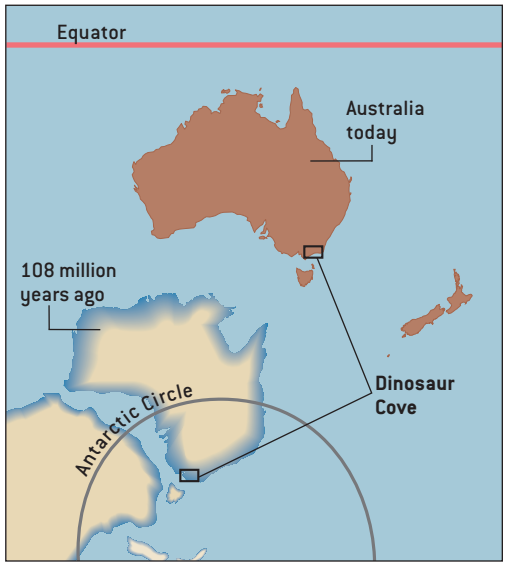
the Antarctic

IN THE EARLY CRETACEOUS PERIOD, about 100 million years ago, Australia lay alongside Antarctica, which straddled the South Pole as it does today. Australia's southeastern corner, now the state of Victoria, lay well inside the Antarctic Circle. At that time, the region hosted an assemblage of animals and plants that lived under climate conditions having no modern analogue. The average temperature appears to have ranged from frigid to low temperate. Through the long winter, the sun did not shine for weeks or months at a time.

PTEROSAUR (*flying*) ANKYLOSAUR *ATLASCOPCOSAURUS* *TIMIMUS*

far to the north. The paucity of large polar dinosaurs may reflect a real absence or merely the selective preservation of small bones.

Peter Trusler painted the mural of the creatures, which was created for an Australia Post stamp issue entitled "Australia's Dinosaur Era."



SOUTHERN SUPERCONTINENT known as Gondwana began to break up more than 100 million years ago, when a rift valley formed between what would become Australia and Antarctica (*left*). Stream channels in the valley received bones gathered by floodwaters that periodically swept these broad plains. The bones, together with clay and silt, created the fossil-bearing formations of Dinosaur Cove (*right*).

Many dinosaur lineages survived in this strange environment after they had died out in other places. At least one member of the group evolved an adaptation to the cold and to the dark that is interesting both in itself and for what it tells of the passing of a biological epoch. If global cooling indeed killed the dinosaurs, as many paleontologists have suggested, then Australia's species were the ones most likely to have survived the longest. Did their adaptations to an already marginal climate help them survive a sharp cooling trend, one that caught species living on other continents unprepared?

Although the Cretaceous fossil plants of southeastern Australia have been studied for more than a century, the animals remained mostly hidden until recently. In 1903 geologist William Hamilton Ferguson found two bones that have had a bearing on later paleontological work—the tooth of a lungfish and the claw of a carnivorous dinosaur, assigned to the theropod genus *Megalosaurus*. For the next 75 years, as no further finds joined them, these bones lay neglected in a cabinet in Museum Victoria. Then, in 1978, two graduate students at Monash University, Tim F. Flannery and John A. Long, discovered near Ferguson's original site the first specimens of a trove of dinosaur bones embedded in hard sandstones and mudstones from the Early Cretaceous.

These discoveries—only an hour and a half's drive southeast of Melbourne—encouraged paleontologists to prospect other coastal sites. In 1980 we struck a rich lode in the Otway ranges, which the Victorian government, at our suggestion, has since named Dinosaur Cove. There, for a decade—with the help of Earthwatch and other volunteers, the National Geographic Society, the Australian Research Council, and Atlas Copco, a manufacturer of mining equipment—we spent three months out of every year chiseling, hammering and on occasion blasting tunnels into the fossil-bearing strata. With Dinosaur Cove worked out in 1994, effort has since been concentrated at a site about 300 kilometers east, called Flat Rocks. The rocks there are about 10 million years older than those at Dinosaur Cove.

Flat Rocks, Dinosaur Cove and other sites of similar character were formed when violent, seasonal streams swept broad floodplains of their accumulated bones and plant life, depositing this flotsam and jetsam at the bottom of shallow stream channels. These deposits appear along the southern Victorian shore because only there could gnawing waves expose the sediments laid down in the rift valley that formed when Australia and Antarctica went their separate ways, as did the other fragments of Gondwana, an ancient supercontinent [*see illustration above*]. Only two fossil sites from the same period have been found inland, one in sediments laid down under far quieter conditions at the bottom of an ancient lake. This inland site has therefore yielded some uncommonly well preserved specimens.

It must be noted that southeastern

THE AUTHORS

PATRICIA VICKERS-RICH and *THOMAS HEWITT RICH* collaborate on the study of fossils. Vickers-Rich holds a personal chair in paleontology at Monash University in Melbourne, Australia. She is interested in reconstructing ancient environments, especially those without modern analogues, and in analyzing rapid biotic change. Rich is curator of vertebrate paleontology at Museum Victoria in Melbourne. He conducts research on the evolutionary patterns of Mesozoic vertebrates, specializing in primitive mammals and ornithischian dinosaurs. The Riches received undergraduate degrees in paleontology from the University of California, Berkeley, and doctorates in geology from Columbia University. They live near Melbourne and have two children.

PETER TRUSLER, OCTOBER 1993 (*preceding pages*); JOHNNY JOHNSON (*top left*); FRANK COFFA (*top right*)

Updated from the July 1993 issue

Australia's dinosaurs are known from a mere 8,000 individual bones and two partial skeletons. Only a few hundred of the bones can be assigned to a given species or genus. What they lack in number, however, they make up for in scientific interest.

All efforts at interpretation revolve around the estimation of temperature, for which three methods have been tried. Robert T. Gregory of Southern Methodist University and his associates infer Australian paleoclimate from the ratio of oxygen 18 to oxygen 16 trapped in concretions in ancient rocks. They find that mean annual temperatures probably approached zero degrees Celsius but might have reached as high as eight degrees C. Such values occur today in Hudson Bay, Saskatchewan (zero degrees C), and in Minneapolis and Toronto (eight degrees C).

Work by Andrew Constantine of Origin Energy on structures preserved in the rocks in which the dinosaur bones are buried reveals evidence for the former existence of permafrost and ice wedging as well as patterned ground and hummocky ground. Such features are formed today in regions with mean annual temperatures of three degrees C below zero to three degrees C above zero. These structures are not as commonly encountered as the concretions, yet they are most obvious only three meters stratigraphically below the Flat Rocks locality where dinosaurs, mammals and associated fauna have been found. Evidence for the occurrence of permafrost had never before been reported in association with dinosaurs.

Robert A. Spicer of the Open University in the U.K. and Judith Totman Parrish of the University of Idaho instead deduce temperature from the structure of ancient plants, arriving at the somewhat higher mean annual temperature of 10 degrees C. Their research with colleagues has demonstrated that polar Australia supported conifers, ginkgoes, ferns, cycads, bryophytes and horsetails but only a few angiosperms, or flowering plants, identifiable by a sprinkling of pollen. The angiosperms were then just beginning to spread into new niches. Perhaps they got their start by exploiting weedy ecological systems in the rift valleys that formed as the supercontinent split apart.

Spicer and Parrish noticed that evergreens, which provided forage in all seasons, had thick cuticles and other structural features that indicate adaptation to cold or dryness (perhaps brought on by winter freezing). Deciduous plants offer another climatic clue: they seem to have lost all their leaves at once. These mass falls may have been triggered by darkness or cold. Drought, however, probably did not serve as a constant cue—the sedimentary record and the abundance of ferns and bryophytes argue for conditions that were moist in all seasons except perhaps winter.

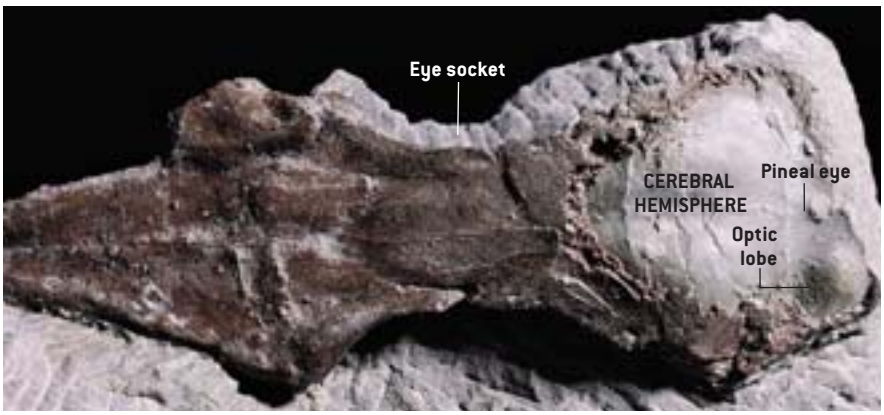
Surviving the Cold

IF THE HIGHER ESTIMATE of mean temperature is correct, Australia was both temperate and subject to a period of continuous darkness every year—a combination with absolutely no modern counterpart. The winter night lasted between six weeks and four and a half months, depending on the true paleolatitude. Because the lower extreme of temperature would then have fallen well below the mean, most of the vertebrates preserved as fossils must have lived quite close to their thermal limits. Some, such as lungfish, cannot now breed in waters colder than 10 degrees C.

If, on the other hand, the lower mean temperature is correct, it becomes more than a typical scientific challenge to understand how this paleocommunity functioned at all. Before seriously attacking this problem, scientists will first have to demonstrate that it exists. To refine the estimate of the average annual temperature, a multidisciplinary team is comparing floral, geochemical and other forms of evidence.

Nothing in this fauna is quite so peculiar to the region as the koala is today, for although the species and genera were local, they belonged to cosmopolitan families. Yet their adaptations are striking, as is the fact that some survived beyond the time of demise for their families elsewhere.

Among such anachronisms—or relicts—are the labyrinthodont amphibians, ancestors of modern amphibians



ACUTE NIGHT VISION is suggested by the eyes and brain of *Leaellynasaura amicagraphica,* a hypsilophodontid shown here at life size (*top*). The large eyes were common to all hypsilophodontids and may have helped the group dominate an environment marked by seasonal darkness. This hypothesis may also explain the huge optic lobes, of which the left one can be seen at the rear of this natural brain cast (*bottom, enlarged*), formed when silt solidified in the skull.

PATRICIA J. WYNNE (*top*); STEVE MORTON *Monash University* (*bottom*)

WHEN ALIVE during the Cretaceous, *Ausktribosphenos* from southeastern Australia may have resembled this modern-day spineless hedgehog from China. The jaw, superimposed on a sketch of the hedgehog, shows what is known of the fossil.

and reptiles. Most paleontologists had thought this group went extinct by the Jurassic, some 160 million years ago. In the past 25 years, however, Michael Cleeland and Lesley Kool of Monash University found three jaws from this group in Victorian sediments dating from the Early Cretaceous. Two of the jaws were unmistakable, because their teeth had the labyrinthine infolding of the enamel that gives this group its name. At least one large species of labyrinthodonts lived in polar Australia 115 million years ago, several million years after the group had died out elsewhere.

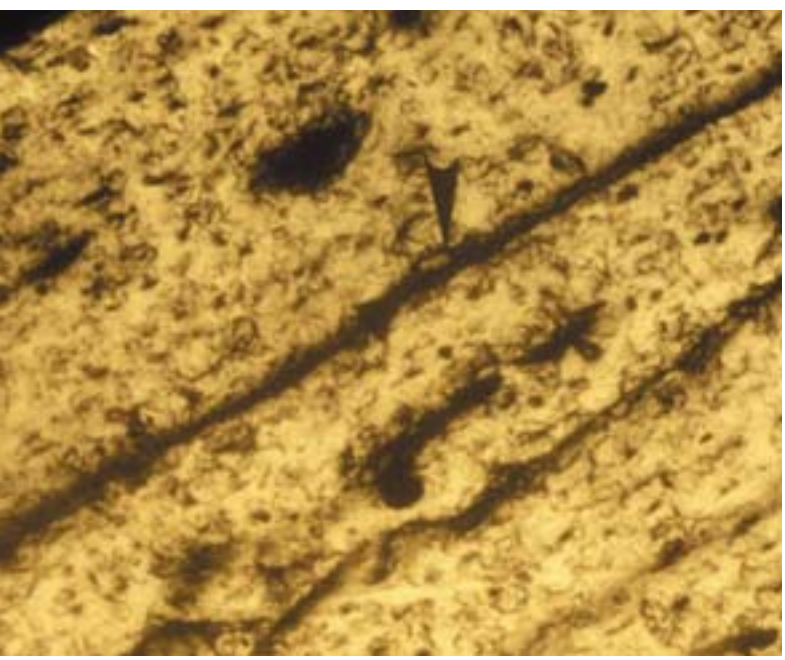
How did they survive? We suspect that the cool weather preserved the animals from competition with crocodiles, which were probably poorly adapted to the conditions prevailing in southeastern Australia until the onset of climatic warming during the last five million years of the Early Cretaceous. The hypothesis rests on the fact that contemporary crocodilians now live in waters no colder than 10 degrees C, whereas some modern frogs and salamanders can be active in meltwater from snow.

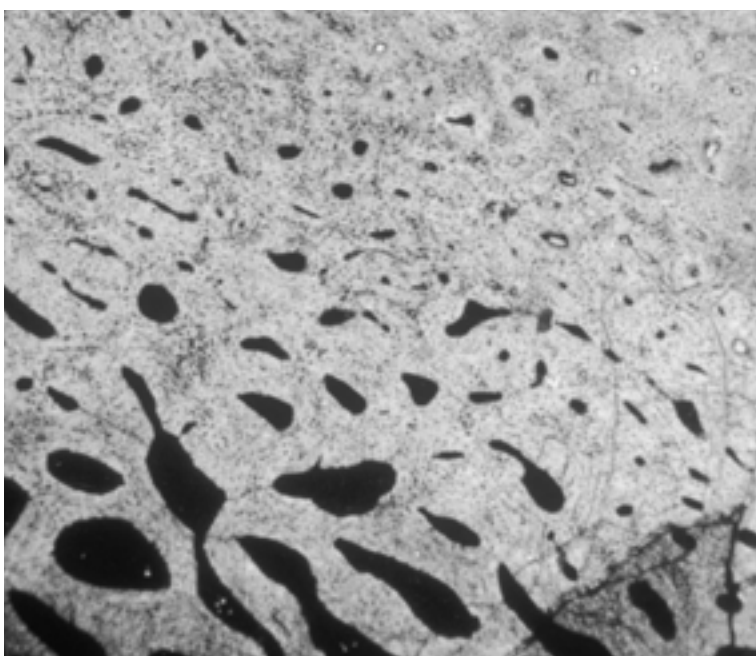
Another late survivor was a close relative of the familiar *Allosaurus*, a carnivorous theropod. Elsewhere in the world this animal ranged up to five meters in height, but the southeastern Australian specimen stood no more than two meters high—hardly taller than a human. This "pygmy," presumably a juvenile, is the latest-surviving allosaur that has yet been found. It remains unclear whether this species also owed its longevity to some niche that cold climate may have carved out for it. The discovery of juvenile forms (but no eggshells so far) does suggest that these dinosaurs were not just casual visitors but lived near the pole for much of the year, using the area as a nursery during the period of maximum sunlight.

Unlike the allosaurs, many dinosaurs of Australia were not the last in their lineage; some may have been the first. At least two and perhaps as many as four families of dinosaurs have been recognized that include forms which are either the oldest or among the oldest of their kind. For instance, the ornithomimosaurs, carnivores of ostrichlike size and appearance, are manifestly primitive and among the oldest within this group. The elongated, slender hind limbs of the Australian species made them the gazelles of the dinosaur world, able to escape from predators and to run down prey. The ornithomimosaurs probably originated in Gondwana and spread northward to join the later Cretaceous faunas of North America and Eurasia, where they enjoyed wide success.

Two very small theropods remain unidentified, but one seems to resemble

DRAGA GELT *Monash University* (*top*); ANUSUYA CHINSAMY *South African Museum, Cape Town* (*bottom*)





TRANSVERSE SECTION of the femora from the ornithomimosaur *Timimus hermani* (*left*) shows prominent lines of arrested growth (*arrow*), indicating severe slowing of metabolism during prolonged winter night. But in a similar section from the hypsilophodontid *L. amicagraphica* (*right*) from Dinosaur Cove, such lines are absent, meaning the polar creature remained active during the dark season.

an egg-eating oviraptosaur, known until now exclusively from the younger Cretaceous rocks of North America and Asia. These groups may also have an origin in Gondwana.

Yet another dinosaur group that has recently been identified belongs to the neoceratopsians, or horned dinosaurs. Identification is tentative, because it is based on just two ulnae (part of the lower arm), but the similarity to *Leptoceratops,* a browser the size of a sheep, is uncanny. Previously, all neoceratopsian records dated from the Late Cretaceous and, with the exception of a few bones from Argentina, came from the Northern Hemisphere. Recent reports indicate the existence of Early Cretaceous neoceratopsians in Utah and China. This dinosaur family may also have arisen in the southern supercontinent.

In addition to dinosaurs, the region provides evidence for mammals that appear to be among the earliest members of their groups. The minuscule *Ausktribosphenos* resembles the living spineless hedgehog *Neotetracus*. This animal may have been a placental. If so, it is as old as the oldest placentals reported from the Northern Hemisphere and twice the age of the oldest marsupial yet found in Australia. This age is surprising because the domination of Australia by marsupials is typically explained as the result of land-dwelling placentals reaching the continent long after the marsupials.

Another mammalian group, whose presence is no surprise, is the monotremes. An isolated limb bone of one of them has a structure suggestive of a more upright stance than either the echidna or the platypus. A second species is by far the smallest monotreme, weighing only 1 percent as much as any other living or fossil member of the group.

The Australian Early Cretaceous also reshaped forms that continued to flourish in other regions. By far the most successful such group consisted of the hypsilophodontid dinosaurs. These animals, most of them hardly larger than a chicken, were bipeds built for speed, with large hind legs, small but well-developed hands, substantial tails and—for the most part—herbivorous habits. They thus resembled wallabies in both shape and ecological role.

The family Hypsilophodontidae was common throughout the world from the Middle Jurassic to Late Cretaceous times, but its prominence reaches an absolute and relative peak in the Victorian sediments. Not only do hypsilophodontids constitute most of the dinosaur remains, they are also represented by four to five genera, depending on the taxonomic criteria one uses, and five to six species. Other areas, some much more richly endowed with dinosaur species, never harbored more than three kinds of hypsilophodontids at a time. Something clearly favored the diversification of this group in polar Australia.

These animals, so SUPERBLY ADAPTED to the cold and dark, could not have been driven to extinction BY AN ARTIFICIAL WINTER.

Big-Eyed Foragers

A PARTICULARLY intriguing adaptation of at least one species of polar hypsilophodontid is suggested by the magnificently preserved brain cast of *Leaellynasaura amicagraphica* (named after our daughter, along with friends of the Museum of Victoria and the National Geographic Society). The brain, unusually large for a dinosaur of this size, bears the marks of optic lobes the relative size of which is easily the greatest ever documented in a hypsilophodontid.

How is one to interpret these enlarged lobes? We hypothesize that they enhanced the animals' ability to see in the dark, enabling them to forage effectively during the long winter months. There would have been no lack of food then, for those capable of seeing it: the herbivores could have lived off evergreens and deciduous leaf mats, and the carnivores could have hunted the herbivores.

This hypothesis also explains why this group came to dominate the polar environment in the first place. Hypsilophodontids everywhere in the world had large eyes and, presumably, acute vision. That trait could have given them their foothold in polar Australia. Once established in this "protected" environment, the hypsilophodontids could have competed with one another to produce the observed diversity of genera and species, perhaps all sharing hypertrophied optic lobes.

If the animals foraged at night, they must have been active at freezing or subfreezing temperatures. This feat goes far beyond the cold tolerance of any modern reptile, even the New Zealand tuatara, *Sphenodon punctatus,* which can remain active at five degrees C provided it can sun itself. *Leaellynasaura* could have survived solely by maintaining a constant body temperature, eating frequently, as birds do in wintertime.

More evidence that the hypsilophodontids remained active during the prolonged winter night is found in the microscopic structure of their bones, deciphered by Anusuya Chinsamy-Turan of the South African Museum. So-called lines of arrested growth form when terrestrial vertebrates markedly slow down or cease their growth. The markings appear as dark lines of dense bone against a background of lighter bone. The lines can be laid during a period of lack of food or water or when an animal estivates or hibernates. The hypsilophodontids from polar southeastern Australia, as well as from elsewhere, all lack such lines, unlike the majority of dinosaurs. So

they seem to have maintained relatively uniform metabolic activity year round.

Pterosaurs—the flying reptiles—and the heavily armored ankylosaurs also appear in the Gondwana fossil record, but the remains are so fragmented that they tell us little about the animals' lives. Much can be gleaned from one handful of teeth, however, for they come from plesiosaurs. These long-necked reptiles, not themselves dinosaurs, generally paddled the seas, but here they inhabited fresh water in the ancient valley between Australia and Antarctica. They thus recall the Ganges River dolphin, one of the few cetaceans that live in fresh water.

The sauropods are one of the few major dinosaur groups that are absent. These giants, familiar from the example of *Apatosaurus* (or *Brontosaurus*, as it is more popularly known), lived at that time in Australia's lower latitudes. Not one, however, has been found farther south nor, indeed, in any of the nine Cretaceous polar dinosaur sites so far identified in both hemispheres. The only polar sauropod yet discovered is the much older (Early Jurassic) *Rhoetosaurus* from northeastern Australia.

The apparent restriction of these large dinosaurs to lower latitudes in the Cretaceous of Australia may be real or merely an artifact of sampling. We worry about this question because the floodwaters that broke out of rain-swollen rivers would have collected small and medium-size bones but left large ones. The body of a sauropod would have stayed put rather than floating to a place where many specimens were concentrated in the small flood channels, which were no more than five to 10 meters in width and 20 to 30 centimeters in depth.

Yet we suspect there was an underlying tendency toward small body size in these polar environs. None of the hypsilophodontids, it must be remembered, stood taller than a human, and most were barely knee-high. The dwarf allosaurid matches the smallest we have examined in the North American collections. The

BONE TURNS TO STONE: *Leaellynasaura* as it might have appeared in the process of becoming a fossil. A bone assemblage from an individual could have fossilized in this way only if the stream channel was choked off, forming an oxbow or billabong.

PETER TRUSLER, COURTESY OF *WILDLIFE OF GONDWANA*, © REED BOOKS INTERNATIONAL, 1993

HARD ROCK made hard work for these volunteer paleontologists at Dinosaur Cove in Australia. Full-scale mining techniques (*left*) and rock saws (*right*) are used to extract fossil-bearing slabs, which tend to fracture along the planes containing the largest treasures.

ornithomimosaur is equally unprepossessing, and the protoceratopsid and the ankylosaur are each no bigger than a sheep. A single fragment of a claw constitutes our sole record of a large dinosaur—a carnivore, apparently similar to *Baryonyx* of England—which may have measured up to eight meters in length.

This pattern contradicts the classic scaling laws formulated by Carl Bergmann and Joel Allen in the 19th century. According to these laws, animals in a given lineage tend to become larger and more compact as the average temperature of their environment falls. This trend is exemplified by the comparison of mountain lions in Canada with pumas of Central America and of human populations in the subarctic and tropical zones.

Other factors also determine body dimensions, especially the size of the territory in which a population lives. Individuals found on islands are often smaller than their mainland counterparts. For example, there were dwarf elephants on the ancient Mediterranean islands, and pygmy mammoths were recently found in 4,000-year-old sediments on islands off the north coast of Siberia. Dwarfism may be a response to selective pressure to increase the number of individuals so as to ensure a gene pool diverse enough for the species to survive in a restricted area. This effect has also been observed on peninsulas—and ancient southeast Australia was a peninsula of the Gondwana landmass.

The dinosaurs on that peninsula were trapped virtually at the ends of the earth. Their direct path north was blocked by a vast inland sea, which they could have passed only by going hundreds of kilometers to the west before wheeling about to the north. At the end of such labors, they would have been able to catch, at most, an hour of sun a day in winter. Migration would have made little sense for such small animals.

Less formidable barriers sealed in the dinosaurs of the one other polar site that has yielded large quantities of fossils: the North Slope of Alaska. The dinosaurs there had a clear north-south corridor along which they could migrate with ease. It is significant that those dinosaurs were big—at least equal in size to caribou, wildebeest and other modern animals that migrate.

Safe Haven in Gondwana

ONE MUST QUESTION whether animals so superbly adapted to the cold and the dark could have been driven to extinction by an artificial winter, such as is supposed to have followed a cataclysmic event at the boundary between the Cretaceous and Tertiary formations. It is proposed that the cataclysm, perhaps a collision with a comet or asteroid or a series of volcanic eruptions, suffused the atmosphere with a blanket of dust, excluding sunlight and freezing or starving most animals to death.

We suspect, however, that no such artificial winter could have killed the dinosaurs unless it lasted for a long time, certainly more than a few months. Otherwise at least a few of the polar dinosaurs would have survived the cataclysm. Of course, it is possible that a different development had already ended the reign of southern Australia's dinosaurs by the end of the Cretaceous.

English writer Arthur Conan Doyle once dreamed of a plateau in South America that time forgot, where dinosaurs continued to reign. Reports in the early 1990s that dwarf mammoths survived to early historical times, on islands off the coast of Siberia, give force to such speculation. If dinosaurs found a similar haven in which they outlived the rest of their kind, then we think polar Gondwana, including southeastern Australia, is a likely place to look. SA

MORE TO EXPLORE

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PETER MENZEL, COURTESY OF NATIONAL GEOGRAPHIC SOCIETY (*left*); FRANK COFFA (*right*)