THE MICROSCOPE • Vol. 60:3, pp 123–131 (2012)

CRITICAL FOCUS

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Aquatic Dinosaurs Under the Lens

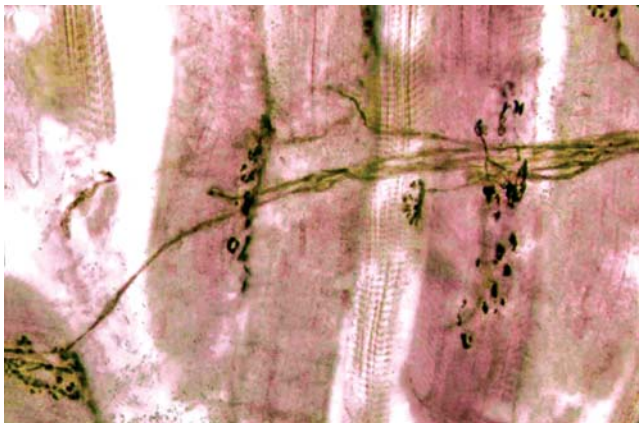
Paleontologists have long contended that dinosaurs were terrestrial species. But microscopy reveals the great truth that dinosaurs evolved in water, not on land.

Paleontologists get dinosaurs wrong. They look at them as gigantic terrestrial monsters, but there are other ways of contemplating them. I prefer to envisage them as communities of microscopic cells. This understanding of life at the cellular level leads me to one great truth: Dinosaurs must have developed in water and not on land. I am not simply suggesting that they retreated to swamps to rest; in my view, dinosaurs evolved under the constraints of an existence in shallow water and everything about them points to an aquatic habitat. They were certainly not the terrestrial monsters we see in the films and books, perpetually pounding across desert dunes with the force of a truck and the speed of a tank.

A dinosaur's cells are very much like ours; it's just that dinosaurs have more of them. For example, I know the size of a dinosaur's leukocyte and the dimensions of their muscle cells. Paleontologists don't. I am aware of these things because I can study the cells of present-day reptiles, and somatic cells alter little with time. That's why I know that a dinosaur leukocyte measured about 10 μm across — all such leukocytes are about that size. How many cells are we talking about? A water-flea contains about 1,000 cells. There are around 100 trillion (10^{14}) cells in a human being and in a 100-ton dinosaur there would have been around 130,000 trillion cells (13^{16}) total. The reign of the dinosaurs lasted for 165 million years yet, for all the research, nobody can agree how heavy they were. Some recent estimates exceed 120 tons, and there is an industry devoted to showing dinosaurs as colossal creatures, pounding about across the land and throwing up clouds of desert dust beneath their fabulous feet. Their heads are held erect, they fight and rip flesh from each other's bodies, they roar and bellow with unbridled lust and strut with pride and unassailable dominance as though they were the lords of creation.

There's something Freudian about the machismo of a monster that the paleontologists prefer to perpetuate, but to me, dinosaurs behaved more like a hippopotamus or an alligator. Paleontologists suffer from terrestrial hysteria, which is misplaced. For decades I have wanted to say that dinosaurs were aquatic, and I am glad I saved this theory for later, for it has dropped me into enough hot water to take the peel off a pepper.

The ancient Chinese imagined that dinosaur fossils were the remains of dragons, and they weren't far wrong. When dinosaurs were first studied by naturalists in Victorian England, few of those wealthy individuals dug them up, for most of them came from beachcombers like Mary Anning, a carpenter's daughter in Dorset, who made her living selling fossils to enthusiasts. She discovered plesiosaurs, and her enterprise helped to found paleontology.



The innervation of striated muscle by the motor end plates shows clearly in this detailed micrograph by microscopist Spike Walker. A dinosaur's tail was moved by voluntary muscle fibers like these. Although this preparation is of a present-day reptile, the cells do not change greatly over time.

Curiously, the word "dinosaur" came down to us not from fossil hunters, but from a microscopist, Sir Richard Owen. It was Owen who first identified the microscopic parasite *Trichinella spiralis* that lay behind the traditional religious ban on eating pork. In 1841, Owen put together two Greek words *deinos*, meaning terrifying, and *sauros*, which means lizard. And there you have a dinosaur — terrifying lizard. Good name. Everything about dinosaurs is terrifying — the size to which many could grow, their huge teeth and vicious claws, their overwhelming dominance of the world. All this fascinated paleontologists. They can attack with unbridled anger and seem fearless in their frenzied ferocity. I am speaking here of the paleontologists, not the dinosaurs.

It wasn't always like this. Have you ever wondered what was the first-ever cartoon character to appear in a film? Betty Boop, perhaps, or what about Felix the Cat? No, they are creations from the 1920s and 30s. The first movie cartoon character in the world was a dinosaur from Chicago, a doe-eyed character named Gertie in a film that was released before the First World War. Gertie was a smiling, endearing sauropod who was created by Winsor McCay. He studied art in Chicago from 1899 and released his movie "Gertie the Dinosaur" at the Palace Theater on Feb. 8, 1914. That historic occasion marked the dawn of the cartoon character, and also the emergence of the dinosaur in movies.

Gertie the cartoon character had been drawn from the skeleton of a brontosaurus in the American Museum of Natural History. I have lectured to the New York Microscopical Society in that historic venue and have seen those impressive displays. That dinosaur had been discovered by Othniel Charles Marsh, professor of paleontology at Yale University, in 1879. The huge skeleton was unearthed at Como Bluff, Wyoming, and Marsh dubbed it *Brontosaurus excelsus*. This was the largest dinosaur yet discovered, though the skeleton was not complete. The feet were nowhere to be seen, part of the tail was missing, and there was no skull. Marsh took the heaviest skull and jaw bones he could find (mostly from the unrelated dinosaur *Camarasaurus*) to invent a skull that he added to the skeleton. He took the feet from other fossils excavated nearby, so that the resulting skeleton was a composite of several. It first went on display at the Peabody Museum of Natural History in Yale during 1905 and was soon the subject of controversy. Other workers insisted that the new species belonged to the genus *Apatosaurus*, and the name brontosaurus was officially abandoned many years ago.

TAIL ADJUSTMENT

A feature of all these dinosaurs is the massive tail. When the skeleton discovered by Marsh was first mounted, it had its tail resting on the floor; in the movie, the cartoon Gertie rested hers on the ground. When the replica *Diplodocus* skeleton was erected in the entrance hall of the Natural History Museum in London, its tail also lay on the floor. This soon posed a problem: Dinosaur hunters frequently found the footprints of giant dinosaurs yet none of them showed the dragging marks left by the tail. As these findings accumulated, paleontologists responded by changing the way the skeletons were displayed. London's "Dippy" had her tail raised and was shown to be held aloft, and other dinosaur skeletons around the world were similarly adjusted.

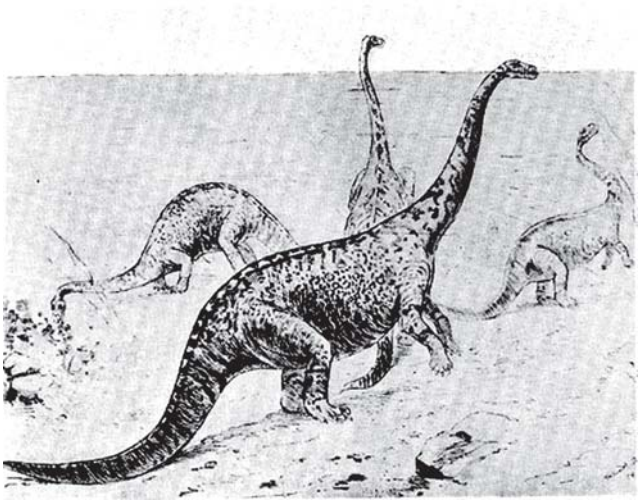
The fossil findings had a very different significance to me. I concluded that the lack of drag marks from a dinosaur's tail was because these creatures were aquatic, and their tails floated in water as swimming organs. If a dinosaur held its tail erect on dry land it would do so with voluntary muscle, comprised of bands of striated muscle fibers. Holding a heavy tail aloft consumes carbohydrate energy reserves and burns oxygen. Let us try to quantify the consequences. A human at rest typically burns about one calorie per minute. Therefore, it is simple to calculate that a body at rest consumes 60 calories per hour, or 1,440 in a 24-hour cycle. Standing consumes about 110 calories per hour; driving your car takes 120 calories; weeding the yard takes 200; dancing, 400; tennis, 500; playing squash close to 700. The more you do, the more energy

you burn. Athletes use the term VO_2 (meaning volume of gaseous oxygen per kilogram of body mass) corresponding to the oxygen consumed during one minute of activity. Thus, a man exercising in the gym consumes approximately 35 ml O_2 per kilogram of body mass per minute. Let's scale this up to a 100-ton dinosaur with a tail weighing 25 tons. Based on human measurements, waving the dinosaur's tail around could consume an extra 800 liters of oxygen each minute. No organism develops in order to waste energy in such a conspicuous fashion.

Paleontologists insist that the dinosaur tail "counterbalanced" the long neck, but this is a mistake. These are muscular extremities that consume energy to remain aloft. A herbivorous dinosaur (left) had a massive, heavy tail and an elongated neck. The present-day giraffe (right) has a similarly long neck but only a diminutive "fly-whisk" tail.

Paleontologists say that the tail acts as a counterbalance to the neck. It seems logical: The extended neck and head at the front counterbalance the extended tail at the rear. Although the argument is seductive, it is erroneous. Counterbalancing works with girders or machines, but holding the neck and the tail above ground exerts additional burdens on a dinosaur's energy reserves. There is no need to counterbalance the extended neck, and a glance at present-day animals substantiates the point. A giraffe has a neck and head that is remarkably similar to that of an herbivorous dinosaur. And does it have a counterbalance? No — the giraffe has a diminutive fly-whisk tail.

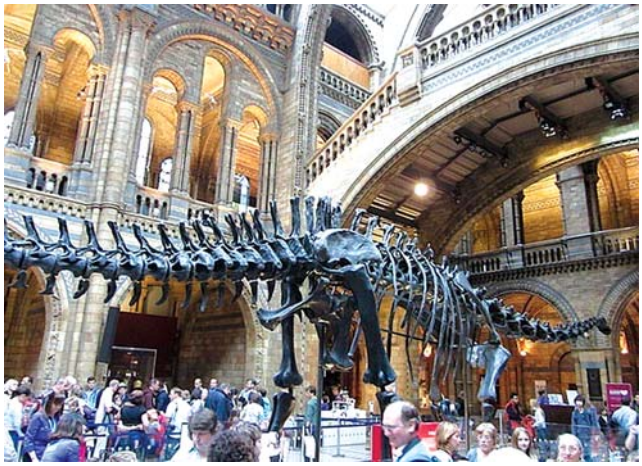
The elongated neck caught the attention of the earliest paleontologists and most concluded that these gigantic creatures were herbivores, grazing on the high branches of lofty trees. Others had a more adventurous opinion and envisaged dinosaurs walking across the bottom of ponds, using the long neck to keep their heads above water like a snorkel. Some creatures do this like the apple snail of Brazil, which has a snorkel as long as its body. Applying the idea to dinosaurs first occurred to Edward D. Cope, an American paleontologist who claimed that giant sauropods used their long necks to breathe and feed on pond weed growing deep in the water. Charles R. Knight transformed Cope's sketch of submerged sauropods into a drawing that was reproduced in *The Century*, a popular magazine in the late 1800s. These paleontologists did not realize that a dinosaur could not possibly inflate its lungs with the water pressure from above, crushing its chest at the bottom of a lake.



One Victorian paleontologist naively pictured sauropods living deep underwater and feeding on pond weed (even though water pressure would have prevented their inhaling). The idea was proposed in the U.S. by Edward Cope, and Charles R. Knight based this sketch on Cope's vision, which was first published in 1897 and reprinted in 1921.

Occasionally, terrestrial dinosaurs were conceived as wallowing in swamps, and several early artists portrayed them resting in pools. In 1897, Knight painted a study titled "Brontosaurus," which became a classic. It shows sauropods browsing in a swamp, feeding on luxuriant vegetation. Even then, his image was regarded as a curiosity, for you can look back at the encyclopedia descriptions of dinosaurs year by year, and they were always described as "land ani-

England's King Edward VII saw a picture of a *Diplodocus* skeleton excavated from the American Morrison Formation — rocks initially laid down at the bottom of water — and asked if one could be exhibited in London. This plaster cast was donated by the Scottish millionaire Andrew Carnegie, and at the unveiling ceremony in 1905, the tail is resting on the ground.



Many fossilized footprints from dinosaurs were discovered, none of them showing marks from the tail resting on the ground. In 1993, to fit this growing body of evidence, the Natural History Museum of London rebuilt their plaster skeleton to show the tail held aloft.

mals." *Life* magazine ran a feature on prehistoric life in 1953 that showed typical dinosaurs as terrestrial animals. Here, too, their artist, Rudolph F. Zallinger, portrayed one of them sitting in a swamp.

For half a century, dinosaurs were regarded as curiosities and little interest was paid to them until the 1960s, when the dinosaur industry was reborn. Models started to appear. Scientific papers on dinosaurs flourished as never before. There were exhibits in museums, new movies featuring dinosaurs, and animatronic models that went on tour. These dinosaurs were always shown as tramping about on land. To me, this didn't fit the facts.

FOSSILIZED EVIDENCE

During those earlier eras when dinosaurs flourished, the earth was very different to what we see today. There were few mountain ranges. Today's highest peaks are in the Himalayas, a mountain system that resulted from the cataclysmic collision between the Indian tectonic plate and the Asian plate. These peaks were non-existent when the dinosaurs lived, and even by the time the dinosaurs died out, India was still as far from Asia as Britain is now from America. The world's water lay in vast shallow lakes. We can see the evidence today. Across the coast of South Wales are huge layers of limestone lias, narrow rocky strata that were once the muddy beds of lakes. Along the coast of Dorset, England (where Mary Anning picked her living) are lengthy stretches of cliffs showing where shallow lakes once lay. Much of northern France is the same and in America, most of the dinosaur fossils have been found in the strata of the Morrison Formation, which extends from Canada right down to New Mexico, and from Idaho across into Nebraska. These are all mudstones, siltstones, sandstone or limestone — deposits from shallow lakes. All these strata bear fossilized remains of creatures (like dinosaurs) that lived in water.

Around 1972, I saw a dinosaur exhibit in a museum display case. They were all shown with their tails held out astern, supporting them aloft like trailing banners, and I shuddered to think of the metabolic burden that imposed. I showed visitors how the scene made far more sense if you kept your eye level with the models, and then imagined the glass case to be half-filled with water. The dinosaurs' tails were then floating and all seemed much more feasible. Several times I was encouraged to publish the idea, but I knew it would embroil me in controversy and it went into a file. I'd write about it in my seventies, I said, and now's the time. The closest I came was an account in my book *Microbe Power*, published in 1976 (Stein & Day, New York). In the book, I wrote:

"We have had those ages of vast shallow seas, where microbes built up the immense beds of chalk, limestone, and diatomite we see today. We have seen ages of gigantic plants. Did they perhaps flourish because levels of carbon dioxide were higher then, as a result of the previous eons of volcanic activity? This would have meant that temperatures were higher, too,

and this in turn would have triggered off widespread plant growth which would have greatly increased the amounts of oxygen in the atmosphere. I suppose that could have been a factor in the development of the giant reptiles that followed."

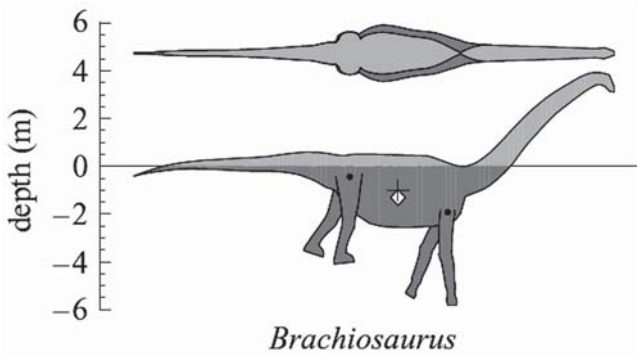
So I had "vast shallow seas" and "development of giant reptiles" in the same paragraph, but I did not risk putting them in the same sentence! We knew that dinosaurs could survive on land — they were egg-laying reptiles and many of them made ordered nests. I can show you eels that can cross meadows and crabs that live on dry land, but none of this prevents their being primarily aquatic. You can find my footprints across tropical deserts and in the polar regions, but it does not mean that I lived there.

Reconstructions of *Tyrannosaurus rex* make far more sense to me if the creatures were immersed in water and fossils of the long-necked herbivores (like *Diplodocus*) are a feature of strata that once was silt at the bottom of shallow lakes. Dinosaurs walking across muddy terrain would sink in deep, and the shallow footprints we see so abundantly are only feasible if their body mass was supported by water. Some genera have longer forelimbs than hindlimbs, and fossil trackways have been discovered in which only the front feet had left impressions. Clearly, the water was just a little too deep for the hindlimbs to reach down to the mud. The evidence fitted my theory perfectly.

It has been shown many dinosaurs had evolved air sacs within their bones — an adaptation that paleontologists mused would reduce their body weight. This is illogical. Air sacs have only a small proportionate effect on body mass and are only likely to be evolved in aquatic life forms where buoyancy is crucial. One paper published by the Royal Society had crude diagrams showing that dinosaurs would tip over if placed in water, because of a mismatch between the center of gravity and their center of buoyancy. This occurs because these crucial centers were decided upon by the speculating author, of course, for they are not known points. If you made subtle corrections then the dinosaur was as stable as a galleon. Evolution does not generate animals that are life-threateningly unstable.

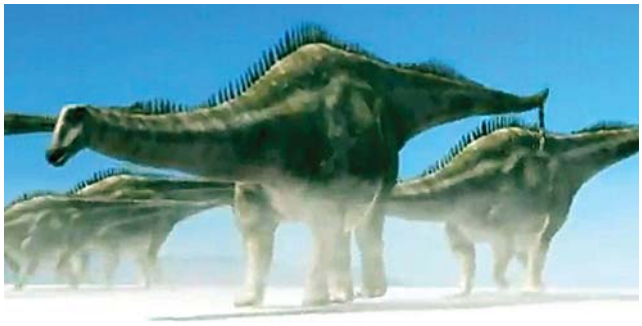
COLD-BLOODED CREATURES?

My concept also solves an enduring controversy: Were dinosaurs endothermic or ectothermic (warm or cold blooded)? In favor of the warm blooded theory is the finding that there was high vascularity in dinosaur bones. This suggests that their metabolism was active and their body temperature was high. On the other hand, biologists know of no reptile that evolved a mechanism to maintain body temperature. Paleontologists have insisted that dinosaurs were cold blooded and had a fluctuating inner temperature like that of other present-day reptiles. In support, they show that dinosaur bones exhibit concentric zones of faster and slower development known as lines of arrested growth (LAGs). These are analogous to the annual rings in a tree trunk, paleontologists say, showing that the dinosaur bones responded to outside temperatures. This single argument convinced paleontologists that dinosaurs were ectotherms.



Many large dinosaurs are known to have developed air spaces within some of their bones, a likely indication of an aquatic habitat. In a 2004 paper published in *Proceedings of the Royal Society* (Biological Sciences), Donald M. Henderson included rough diagrams that attempted to show that a *Brachiosaurus* would tip over if partially immersed in water.

Paleontologists are wrong here, too. All animals, including present-day mammals, have bones that feature these LAGs, and it does not matter whether they are cold or warm blooded. The first extensive study appeared in June 2012, just before I gave my presentation on cells and dinosaurs at Inter/Micro in Chicago. In my view, aquatic dinosaurs developed as ectotherms — and their vast size and aqueous habitat gave them a constant body temperature that was the same as that of the water. The term *gigantothermy* was once coined for the maintaining of a relatively constant body temperature by large creatures (like a giant leatherback, which can weigh a ton). If dinosaurs used a combination of gigantothermy and immersion in warm water then the problem is solved. According to calculations of the prevailing conditions in lakes and the oceans at that time, the temperature could have been about 37 °C (or 99 °F). It all fits my concept perfectly. As the climate changed, we can immediately see why dinosaurs adapted by developing feathers. This would



BBC

BBC artists created this digital image of a *Diplodocus* herd for the "Walking with Dinosaurs" program. All that is missing is the water. Holding the tail aloft could consume hundreds of liters of oxygen per minute, and evolution is not so wasteful. The commentary confirms that they had walked across the bed of "an ancient sea."

have been important for thermal insulation. If I'm right, the subsequent adaptation of feathers for flight would have been a secondary process.

Many reconstructions show dinosaurs near water. There is an extraordinary sequence in the BBC documentary "Walking with Dinosaurs," where we see the digital reconstruction of a dried lake bed. The majestic commentary describes the crusted surface, "formed by the retreat of an ancient sea." From time to time, the voice intones, the arid plain was invaded "by herds of dinosaurs." A great group of *Diplodocus*, waving massive tails aloft in the arid air, plods painfully across the blistering desert. Paleontologists had the right facts — the shallow sea, the remains of dinosaurs — but not in the correct order. I believe that the dinosaurs had been around when the water was still there. That is why their skeletons had been found in alluvial deposits. I hope that microscopists will look more closely at the rocks in which dinosaur fossils have been found and identify the diatoms and coccoliths that might be seen.

Let me offer just one example of how the latest research supports my case by considering one giant dinosaur, *Spinosaurus*, in more detail. This is a huge predator measuring about 15 meters (50 feet) long and weighing 20 tons with a long snout, a large dorsal fin and an impressive array of sharp, pointed teeth. This dinosaur's anatomy has always suggested to me that *Spinosaurus* was aquatic, for it had raised nares (like the nostrils of a crocodile) so it was obviously adapted to cruise across a lake or shallow sea. Three scientists at the Ospedale Maggiore di Milano in Italy examined the snout of a fossilized spinosaur with a Siemens CAT scanner and announced their research at the International Congress on North African Vertebrate Paleontology in May 2009. They concluded that the sense organs around the snout of *Spinosaurus* would indeed have been like those of present-day crocodiles and, in the words of the scientists, could have given the mouth, "when positioned on the air-water interface, an unexpected tactile function, useful to catch swimming preys [sic] without relying on sight." This all fitted my model precisely.

The next paper concerned the teeth of these dinosaurs, published in 2010 in *Geology* magazine. A French team took samples from fossils found in North Africa and carried out an analysis of oxygen isotope ratios, which they compared with results obtained from samples of turtles and crocodilians. They found the fossil dinosaurs had much in common with today's aquatic reptiles. For me, that was the final nail in the coffin of the terrestrial model. All this new scientific evidence was consistent with my view that this dinosaur was aquatic. Fish scales had even been found in the stomach. There was finally the morphology of the beast. *Spinosaurus* was characterized by a conspicuous fin running down its back. Paleontologists insisted on calling it a "hump," but it was in every sense a dorsal fin. This is a feature of animals ranging from sailfish to the greater crested newt, which all evolved in water.

COMPUTER-GENERATED INNACCURACY

Research was accumulating at such a rate that television producers were churning out documentaries, and at times it was hard to find a channel that wasn't highlighting the era of great dinosaurs. Many of the programs were superficial, but then came news that the definitive series was in production. The researchers were searching worldwide for the very latest discoveries, and the international community of paleontologists gave advice to ensure that the details were correct and that the programs were up-to-date. The most advanced computer-generated imagery (CGI) was harnessed so that viewers were assured of the most accurate and vivid portrayal of dinosaurs ever screened. This was the "Planet Dinosaur" series first released in 2011 and now reissued in 3-D.

The moment the programs started, I was disillusioned. First, they were narrated by John Hurt, the movie actor who became globally renowned for his portrayal of Joseph Merrick in the 1980 film "The Elephant Man." Hurt is terrific — he has a Golden Globe to his credit — but why do producers chose actors to narrate science documentaries? Nobody books Johnny Depp to explain the latest developments in Syria, or

Meryl Streep to account for the problems with the banks. It's a curious modern phenomenon that patronizes the audience for science programs, and it is one that should be abandoned.

I eagerly awaited the episode featuring *Spinosaurus*. The script began with many of the right facts — they mentioned the sensory organs on the dinosaur's snout, though there was no reference to the crucial isotope results — and Hurt intoned them all with perfect precision, even though it was obvious that he hadn't the slightest idea what he was talking about. Then came the producer's reconstruction of the mighty *Spinosaurus* hunting for food. I was dumbstruck. Their CGI version was pictured balancing on the banks of a brook with the tip of its snout held above the water ready to snap at a passing fish. The script emphasized that the dinosaurs visited the shore to feed, but they definitely didn't live in water.

Immediately, I began to revise my notes and compile a paper. At the time I was on a speaking trip and I used every minute of spare time to compile two accounts. One of them ran to 800 words, the other was 2,000 words longer. Knowing how rationed science journals are for space, I contacted Phil Prime, the editor of *Laboratory News* in London, and offered him the 800-word article. Phil was fascinated by the subject and said they would be delighted to publish it and to do a first-rate design for the pages. His only problem was the length of the article. "Could you let me have a longer version?" he asked. "At least 2,500 words? Plus, some vivid illustrations?" Purely by chance, I had the very manuscript ready and waiting.

This was the perfect opportunity to study how a heretical theory would be received so I did not set the concept into an historical context, but simply launched it cold. The article appeared on April 3, 2012, and there was a flurry of interest shown by the international media. Newspapers and broadcasters around the world bombarded us with inquiries and published excited reports. I felt certain that this would trigger a debate — and probably bring other "aquaticists" to join it. Not at all.

BBC

Spinosaurus was a 10-ton dinosaur with a dorsal fin. It ate fish, and recent research suggests that it possessed sense organs around its snout for finding prey under water. The only sensible conclusion is that this dinosaur was aquatic. The BBC reconstruction for its "Planet Dinosaur" program showed the accepted view — a terrestrial monster that just paddled in water.

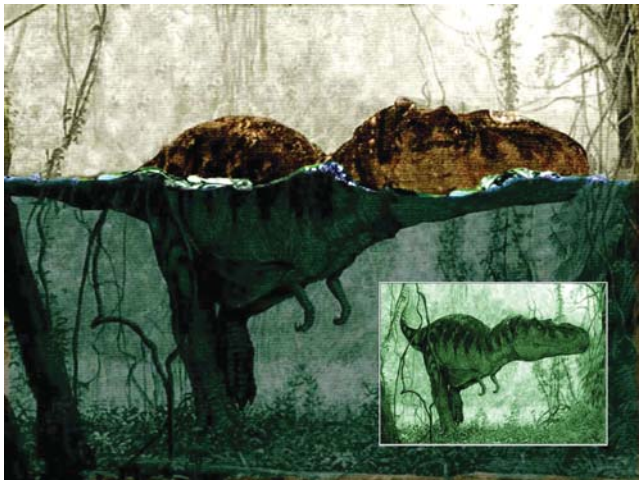
IN THE TEETH OF OPPOSITION

From all sides I was assailed by paleontologists who insisted that my views were pernicious, distorted, ignorant, unrealistic and obtuse. Many objected to a BBC interview about my theory. It ended by pointing out that Galileo had similarly volunteered an unacceptable view in the teeth of opposition. Galileo was persecuted because of his claim — originally published by Copernicus a generation earlier — that the earth orbited around the sun. The opinion of the time was firmly that the world was the center of the universe, so the religious authorities demanded that Galileo should recant. They produced no evidence that he was wrong, just forced him to withdraw his remarks. The legend persists that, as he left their court, Galileo muttered in defiance, "*eppur si muove"* (it still moves). Those were the words with which the BBC's science correspondent Tom Fielden ended his report on my theory. The comparison was invidious, and when I was in Florence, Italy, a few days after the broadcast, I went to the Galileo museum and personally apologized to the effigy of that great pioneer.

This comparison caught the attention of the paleontologists at the University of Bristol, England. They drew up a petition which was signed by 20 paleontologists from all around the world. There was no evidence in the petition about why my views might be wrong. All they wanted was for the BBC to retract:

"[The BBC] gave air-time to this speculation, even comparing Ford with Galileo … which lent it a credibility that it has not earned, introduced a time-wasting controversy where there is not a controversy, misled the public, and maybe most importantly, compromised its own credibility as a trusted source of

This image of *Edmontosaurus* by an unnamed artist is typical of those endorsed by current theories. Its duck bill and watery habitat substantiate my view that it evolved for an aquatic environment, yet it is routinely pictured gamboling across the beach. This dinosaur weighed as much as an elephant, and such terrestrial skipping cannot have been its normal behavior.



The best-known dinosaur *Tyrannosaurus rex* has been expertly portrayed on land by paleontologists (inset). But everything about its morphology fits my theories, so I have added the water level where I believe it was. This is the new view of *T. rex:* A scavenging crocodilian that cruised through the shallow lakes.

science reporting."

The petition concluded with these significant words:

"To mitigate this damage, we recommend and request that you broadcast a formal retraction."

And there you have it — the demand to recant. The BBC replied:

"You were unhappy with the report by Tom Feilden on a theory proposed by Professor Brian Ford regarding how dinosaurs lived. I note you believe the report gave credibility to this theory, and compared the professor with Galileo. The item was a lighthearted feature looking at an outlandish new idea about the dinosaurs and which was clearly signposted as such … the reference to Galileo was simply an aside about the importance of dissent in science [suggesting that] Brian Ford was unlikely to be put off by the condemnation of the established experts."

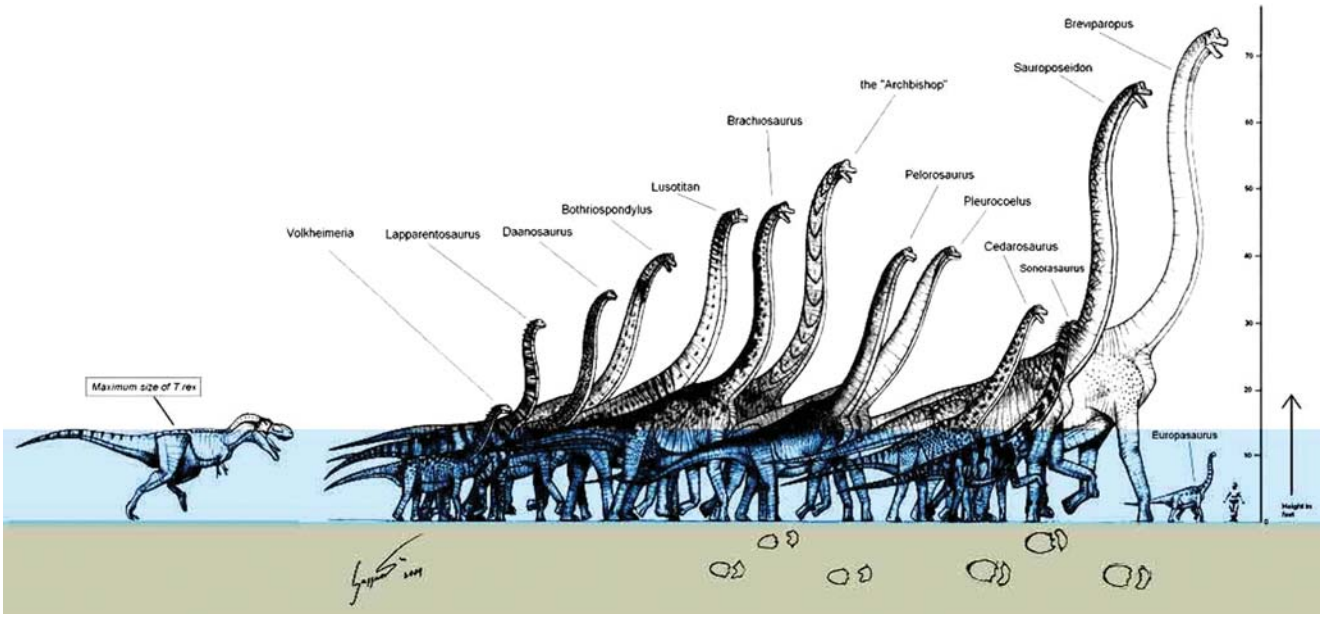
The same Bristol University was responsible for one of the most implausible of all dinosaur reconstructions. They created a picture of *Edmontosaurus regalis*, a dinosaur some 13 meters (40 feet) long and weighing four tons. Like all other paleontologists, they insisted it was terrestrial. I disagree. Its duck bill should indicate that this is an aquatic species, as are all other creatures with this feature (from ducks to the duck-billed platypus). The image of *Edmontosaurus* published by Bristol University shows an adult skipping like a gazelle across the shore. I have news for Bristol: Those dinosaurs weighed as much as an elephant. Whatever elephants do, they don't skip. Their dinosaur belonged not on the shore but in the water.

Abundant fossils of *Edmontosaurus* have been found in the Horseshoe Canyon Formation in Alberta, Canada, which is made up of rocks that were once the bed of the Western Interior Seaway, an initially shallow sea that covered much of the United States for most of the Cretaceous era. Duck billed? Shallow sea? Can you see why an aquatic dinosaur seems to me the obvious reality?

Paleontologists' blogs poured scorn on my ideas and there were many abusive messages on Twitter. Detractors insisted that dinosaurs would have needed webbed feet were they aquatic — heedless of the fact that crocodiles do not have webbed feet. One dismissed the use of volumetric analysis, saying that I had merely "dunked models in water." That disparaging term does, indeed, describe volumetric analysis — though he spelled it "volumentric analysls" which did not inspire confidence. We used the technique to good effect, and what's more, we spelled it right.

MORPHOLOGY MATTERS

Nobody produced any evidence that disproved my theory. We all knew that dinosaurs could exist on land — there had never been any mystery about that. But I had assembled evidence to suggest that they



This "dinosaur parade" is based on a drawing by paleoartist Nima from Dinosaur Central (www.dinosaurcentral.com/panoplies.php). It shows how this varied group had limbs of similar length, no matter how massive the body. I envisage the necks as resting in water for much of the time. Terrestrial animals reaching for leaves evolved longer legs; these dinosaurs show an adaptation for wading in lakes.

evolved in water — and nobody produced any evidence to disprove that view. Scorn was poured on my concept of *Tyrannosaurus rex* as an aquatic dinosaur. Yet the most exquisite reconstructions made it look exactly like an aquatic creature, a super-crocodile. I could see it gliding through shallow lakes, scavenging on dead and dying herbivores and sometimes using its massive hindlimbs to leap upon unsuspecting prey with its sharp teeth and gaping jaws. The forelimbs of *T. rex* have become so rudimentary as to be functionally useless, which was to me a clear sign of their redundancy in an aquatic environment. One person who wrote to offer a function for these dwarf forelimbs was Rob Reyes, a central heating engineer in Los Angeles. Reyes proposed that the small front legs acted as a vacuum breaker, should *Tyrannosaurus* have been resting in a mud bank and become embedded. Like the few others who spoke in favor of my views, Reyes is not a professional paleontologist.

Morphology, as we saw, was important in my redrawing of *Spinosaurus*, and it is the morphology of the dinosaurs that provides another tranche of evidence in my favor. Giant dinosaurs all have legs about the same length — between 10 and 15 feet (3 to 4.5 meters). In animals, the length of leg varies with the overall height of the species. Longest neck? Giraffe. Longest legs? Giraffe. Groups of animals — deer, for example, or lizards — show a variety of limb length, with the larger species evolving the longer limbs. That isn't an absolute rule but a guiding principle of morphology. Uniquely, it does not apply to the great dinosaurs. If their necks had evolved to reach high plants and they were terrestrial species, then their legs would similarly have lengthened. The fact that they didn't is predicated upon their evolution for life in shallow water. Deeper seas were inhabited by swimming species (spinosaurs and plesiosaurs among them). The aquatic environment is the only sensible explanation of this curious consistency.

I am certain that all those dinosaur books on your shelves at home, every TV program on a DVD lining your study, each account of dinosaurs in every encyclopedia, is wrong. The study of cells made me realize how misleading is the current convention — and the adventure of publishing this heresy has been one of the most illuminating experiences of my life in science. Paleontologists always insist that their dinosaurs evolved to be terrestrial. Having reviewed the evidence, I am certain that they are misguided. Dinosaurs were creatures of lakes and vast, shallow seas.

But in paleontology, like so many areas of science, reputations rest on religious adherence to convention, and you challenge fashionable faith at your peril. The facts don't matter as much as preserving the comfortable security of the status quo. Galileo found that out to his cost, and the lesson he learned is with us today.