A prehistoric

Many dinosaurs were big – very big. So just how did they manage to support themselves and get around? Brian J Ford thinks he knows – and it could change the way we think of these marvellous prehistoric beasts for ever

◀ This interpretation of *Spinosaurus aegyptiacus*, posted on the jurassicpark forum, is a typical reconstruction of a large carnivorous dinosaur. Each limb would have had to support up to 15 tonnes. It seems incongruous on dry land

▶ In this revised image, I have shown it immersed in water to the shoulders. The tail becomes buoyant and the mass of the body is supported by the water. The loading per limb would be less than 1 tonne – and would be reduced to zero if the dinosaur floated in water like a present-day crocodile

Dinosaurs don't work. They pose a huge problem – the biggest problem that we have ever encountered on land. The immense size of the largest genera places impossible loadings on their extremities. A single limb would have to support many tonnes – this would not be compatible with the agility we associate with dinosaurs. We accept the remains of their footprints without demur, although for such gigantic creatures the imprints that we observe in rocky strata make no sense. The prints are roughly as deep in the layers of Liassic mud as ours might have been, although the high mass of an adult dinosaur would cause it to sink up to its knees. The footprints seem to be those of an altogether lighter organism.

Children were traditionally fascinated by dinosaurs, and in recent years, new dinosaur discoveries have refocused popular attention. Had you said 'raptor' to a teenager a generation ago it would have signified birds of prey; try it later and you'll find it has become a clawed and vicious creation from *Jurassic Park*.

Once we celebrated *Tyrannosaurus rex*; now youngsters are as likely to know about *Spinosaurus* and *Velociraptor*. Books on dinosaurs have flourished like never before, from the great National Geographic *Dinosaurs* to the Dorling Kindersley *Dinosaurs Eye to Eye*. Television, always eager to capitalise on any commercial trend, was soon to follow. The BBC transmitted *Walking with Dinosaurs*, and followed that with *Planet Dinosaur*. There has been an upsurge of enduring interest with the discoveries in North America by Professor Jack McIntosh and now in China by Dong Zhiming, so publishers and programme producers are sinking millions into the subject.

Animatronic dinosaurs were not just manufactured, but went on tour like rock stars. The first such exhibition was of concrete dinosaurs made by Benjamin Waterhouse in 1854 for the Crystal Palace exhibition. Waterhouse was personally instructed by Sir Richard Owen, the greatest dinosaur expert of the Victorian era. And now there are computer games like *Dino Hunt* – there is no end to the current fascination for the great dinosaurs

revolution

Yet dinosaurs make no sense. The most obvious problem to me is the sheer mass of the dinosaur and the modest plantar area of the lower limbs. Compounding this is the bipedal stance that is typical of these gigantic creatures. Today's heaviest land creatures are the elephant, the hippopotamus and rhinoceros; they sensibly spread the load across four limbs rather than two. This is an obvious evolutionary necessity. And it is worse – dinosaurs seemingly compound the problem by possessing a tail that is proportionately massive. It is not clear to me how one would calculate the expenditure of metabolic energy required to hold such a huge member horizontal and clear of the ground, but the lack of tail drag-marks associated with footprints in fossiliferous strata substantiates my view that little ground contact for the tail was normal for dinosaurs. In every reconstruction, they hold their massive tails aloft. This would have consumed a high proportion of the energy input from their diet. It runs counter to evolutionary theory.

We thus have a set of factors that makes the largest dinosaurs seem impracticable as a product of evolution. They are massive, whereas their surviving spoors suggest that they cannot have been so heavy or they would have sunk into the mud across which they walked. They also developed colossal caudal structures which, in conventional portrayals, are held aloft and do not drag on the ground. Finally, and crucial to my understanding of how dinosaurs are supposed to have functioned, they typically evolved to walk erect, thus forcing the hind limbs alone to bear the burden. An adult *T. rex* is reckoned to have had a mass of up to seven tonnes, which must have been supported by a single limb when the animal moved.

We may find substantiation of my views on the role of evolutionary pressures in the development of load-bearing anatomy by looking at today's largest land animals. The elephant and, to a lesser extent, the hippopotamus conform exactly to the argument I propose. Their great mass is supported by four legs rather than two. They have tiny tails that impose no metabolic burden. Crucially, the trunk of an elephant is an additional member whose weight has to be supported and you could analogise the elephant's trunk to the tail of a dinosaur – yet it normally hangs downward and consumes little metabolic energy for support. Indeed, the hippopotamus and (to a lesser extent) the elephant find one practical answer to supporting their body mass, for they often resort to partial immersion in lakes or rivers where the displacement of water can help to reduce the load on their limbs. The hippo is now categorised as a semi-aquatic mammal.

Although both of these creatures have diminutive tails, there are other large animals that are equipped with examples of dinosaur-like proportions – present-day reptiles. Monitor lizards, culminating in the Komodo dragon (*Varanus komodoensis*) have substantial tails though even the largest is far smaller than a dinosaur's. Dinosaur footprints are those of a walking creature and there is no sign of the tail touching the earth. I have observed monitor lizards in Borneo, Central America and elsewhere and they do not always hold the tail free from the ground. The trail of the Komodo dragon is characterised by a deep groove left by the tail dragging along the ground. Crocodilians, notably the salt-water crocodile (*Crocodylus porosus*) can weigh up to one tonne and possess truly gigantic tail structures which can be up to one-third of the body mass. These tails also drag along the ground, for they are too massive to be held aloft. A few weeks ago I was observing crocodiles in Costa Rica; the spoors that the animals leave behind them feature the clear signs of this great caudal mass dragging along the ground.

Crocodiles are the only present-day creatures that compare with dinosaurs and for most of their lives, apart from times when they haul themselves out onto the bank, they inhabit an aquatic environment. It is the displaced water that bears the weight of the tail, for this is the organ which primarily helps the animal to swim. This, I postulate, provides the answer to the paradox of the ungainly gigantic dinosaurs – the only reasonable solution to the problems that they otherwise pose. I am now certain that the dinosaurs were primarily aquatic creatures.

Let us see how the physics stacks up. An African elephant weighs around eight tonnes. It keeps three feet on the ground when walking; so each limb must support some 2.6 tonnes. Of the rhinoceros species, *Ceratotherium simum* is the largest and weighs up to 4.5 tonnes. Each limb thus has to support 1.5 tonnes. The adult hippopotamus (*Hippopotamus amphibious*) weighs some seven tonnes and thus each limb comfortably supports a weight up to 2.3 tonnes.

The effects of immersion in water are dramatic. Animal tissues, being predominately composed of water, may be regarded as of neutral density for this discussion and a large mammal that is 90% below the water level will exert proportionately reduced loading on the limbs – from about eight tonnes to 800 kg for the elephant, from seven tonnes down to 700 kg for the hippo. Similarly, a large crocodile that is scarcely able to stand on its own feet on land becomes effectively weightless in water. In the real world, a crocodile is most typically observed with only the top of the head exposed. In terms of metabolic efficiency, walking on land for a crocodilian can be seen as a costly indulgence.

We now turn to dinosaurs. Volumetric analysis of scale models provides a helpful indication of the effects of an aquatic habitat on the physics of a large extinct reptile like *T. rex*. The mass of an adult is believed to be as much as much as seven tonnes. I find that the head and shoulders occupy roughly 15% of the volume of the entire animal. Partial immersion in the aquatic surroundings that I now postulate sets the figures into an interesting context; the loading per limb is reduced to 1050 kg in total, or 525 kg per limb when standing. The largest dinosaur yet discovered, *Bruhathkayosaurus*, was a quadruped weighing some 120 tonnes. Each limb must have supported 60 tonnes when standing, 80 tonnes when walking. Yet this creature, if immersed in water so that only its head and neck are exposed, would have exerted less than five tonnes per limb when standing on all fours, rising to 6.6 tonnes when walking.

The anatomical adaptations we see in these species are consonant with that I propose: they have a large and bulky body with a huge and muscular tail. The mass of the abdomen is immaterial when it is customarily submerged, whereas the nature of the tail fits well with its use as a powerful organ of propulsion and steering for a swimming dinosaur.

The diminished forelimbs are equally well accounted for by this view. In land animals, like the elephant, hippo and rhinoceros, each of the four limbs is load-bearing and evolutionary pressure has been against the reduction in size that we observe in flesh-eating dinosaurs like *Tyrannosaurus*. If the large dinosaurs are conceived as primarily aquatic, however, then the specialisation of the forelimbs would be towards manipulative dexterity. The fact that the limbs became foreshortened is entirely reasonable: animals like to inspect their food as they eat, and holding it closer to the face is normal behaviour. Conventionally conceived, the small forelimbs of *T. rex* make no sense – however, if we envision the animal as an aquatic carnivorous species, this adaptation becomes entirely reasonable.

Long-necked genera such as the *Brachiosaurs* and the more recently-investigated *Bruhathkayosaurus* were herbivorous, and their evolution- ▶

THE AUTHOR

Professor Brian J Ford

▼The physics of the *brachiosaurs* makes far more sense in an aquatic setting. This reconstruction by Richard Hubbert fits the current proposals well, though one hopes that readers will turn a blind eye to the angiosperms in this view

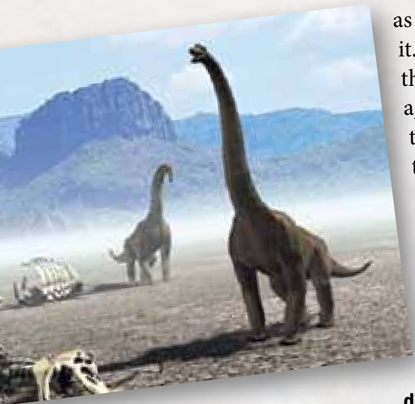
◀Current interpretations of *Spinosaurus* confirm it lived near water, plunging in its head to find food. In my view it was an aquatic dinosaur and lived largely immersed in water where its fish diet was abundantly available ary constraints were different. Since plants do not move away when attempts are made to prey upon them, and because leaves would have been eaten en masse and not painstakingly pulled apart prior to consumption, there is less evolutionary impetus towards increased manipulative facility for the forelimbs. Our modelling suggests that a 40 tonne *Brachiosaur* could have weighed a mere 3-4 tonnes above the level of the shoulder. The body mass in water is of near-neutral buoyancy and can thus be provisionally discounted, so this reduced mass is all that has to be borne by the limbs. Had only two supporting limbs evolved, as in the case of the carnivorous genera we have already considered, this loading on the limbs would have been as little as one tonne per limb – very similar to that of a present-day elephant. The mass of the elongated neck, necessarily evolved for an animal specialised for grazing on the foliage of tall trees, would have impelled these genera to evolve towards a four-footed stance. Only through this means could the load factor on the individual limbs remain within the constraints that can be calculated for the other heavy animals we have examined.

This concept offers an interesting revision of the many artists' impressions of large dinosaurs with which we are familiar. The image below shows *Brachiosaurs* abandoned in the middle of a vast and arid plain. They are depicted standing on dried, cracked mud in a desert wilderness. Now apply the view I here advance – envision the scene instead as a shallow lake in which the water supports the weight of the animals. The mud eventually formed the layers of Liassic limestone, in which state it is certainly dry; but at the time it was, in my view, mud at the bottom of interminable shallow lakes. With water flooding the scene in your mind's eye the picture suddenly makes sense; the scene as originally depicted now seems unrealistic and impracticable.

We have been calculating the likely loading upon dinosaur limbs with and without water and in each case the realities revealed by physics become far more plausible when the bulk of the animal is supported by the buoyancy of partial immersion. My colleague Richard Hubbert has used his skills as a graphic artist to provide 'before' and 'after' views that set my proposals in context. The scene is far less incongruous when the dinosaurs are half-submerged. Set in this new context, they suddenly make sense.

This revised hypothesis rationalises the paradoxically shallow nature of their footprints in soft mud. Investigations have modelled the consistency of mud in which such shallow footprints could have been impressed, and force us to conclude that closely limited constraints must have applied: the mud needed to be exactly of the right consistency for the footprints to form successfully. It has regularly been concluded that normal alluvial mud would have been so soft that large dinosaurs would sink in deeply and become trapped. In fact, there are widespread dinosaur footprints from large and small species and this variety of depth of impression is not seen. These considerations perfectly fit the concept of a dinosaur that is buoyant in water.

The bulk of the massively muscular tails would have been impractical as depicted in the conventional graphic images. The abundant footprint fossils do not show tail dragging, and adding water to the artist's impressions makes additional sense from this point of view. There has also been controversy over whether dinosaurs were poikilothermic (their body temperature equilibrating with the environment) or homoeothermic (controlling their temperature through their metabolism). Some research leads to the conclusion that large dinosaurs had a constant body temperature – but this does not mean they were homoeothermic, as current opinions would have it. As primarily aquatic creatures, they would have been buffered against rapid thermal change and their bodies would be close to the temperature of their watery environment. Thus, dinosaurs could have had a steady internal temperature without any need for its metabolic regulation.



◀ **Conventional images of large dinosaurs like this *Brachiosaurus* in an arid desert (from the ProGenesis web site) exemplify the paradox. I contend that the dinosaurs were supported by a watery environment and the mud on which they lived was the lake bed**

▲ **Brian J Ford used volumetric analysis of scale models, and measurements from surviving skeletons at Cambridge and London, to investigate the loadings on the limbs of dinosaurs on land and in an aquatic environment**

▲ **Research on fossilised footprints at the University of Manchester concludes that large dinosaurs would have become stuck in deep mud and die. The tracks are easier to explain if the animals were partially buoyant in an aquatic environment**

The mean water temperature during this era adds a final substantiation – it was 37°C, the present-day metabolic temperature of the homoeothermic human species.

Current scientific research also fits my proposals perfectly. *Spinosaurus* was a 15 tonne dinosaur with a large sail-line fin running along its back. If it was aquatic, as I propose, then the fin would have acted as a thermoregulator if heat from the surroundings needed to be shed. Investigations of *Spinosaurus* in Milan in 2009 subjected the snout to x-ray computed tomography and found that the dinosaur may have been equipped with pressure sensors like those found in crocodilians. The researchers conclude that the dinosaur would have been able to dip its head into water, and use these sensors to catch swimming prey that would otherwise be invisible. A recent BBC television reconstruction shows *Spinosaurus* wading along and dipping its head into a stream to catch fish, in exactly this way. Clearly, it makes more sense if the dinosaurs were aquatic, and scooped up fish as they swam.

Next, in 2010, an international group based in China analysed the composition of isotopes of the oxygen in the phosphatic remains of *Spinosaurus* and found the ratios to be close to those seen in present-day crocodiles and turtles, which leads to the inevitable conclusion that they might not have been land-dwelling dinosaurs at all, but could have been semi-aquatic. I take it further still – they, and all gigantic dinosaurs, evolved to live their lives supported by the buoyancy of water.

Dinosaurs were not the lumbering monsters, teetering about on an arid landscape and burning huge amounts of metabolic energy to support both their bodies and their tails. They evolved when the world was largely covered in vast shallow lakes, the remains of which have come down to us as layered Liassic limestone. They used the water to support their mass, buoy up their tails, regulate their temperature and provide a habitat for their food. That chase of a car by *T. rex* in *Jurassic Park* is a result of that popular myth of the terrestrial monster. Without a watery environment dinosaurs do not make sense.

This may also provide a reason for their extinction. The era following the age of the dinosaurs was the period when the continents drifted towards their current positions. Mountain building was active; the vast shallow lakes were at an end and the dinosaurs' aquatic environment disappeared. The era of the Cenozoic that followed was also a time of cooler climates, which weighed against large reptiles without an aquatic thermal buffer in which to survive. During the Cretaceous era when the largest dinosaurs flourished, oxygen levels were at an all-time high of more than 30%. The enormous plants of the time would have favoured the production of atmospheric oxygen, and this would have favoured the metabolism of gigantic creatures. But during the following millennia, oxygen levels dropped to half this level. The survival of giant animals would have immediately been compromised.

There are many controversies that remain, yet most of the paradoxes that surround the study of the dinosaurs are resolved by making this change in concept. Dinosaurs look more convincing in water, and the physics stands up more soundly. All the while we were speculating in science on those remarkable creatures, this single, crucial factor eluded palaeontologists: dinosaurs were aquatic. **LN**