A palaeogravity calculation based on weight and mass estimates of *Giraffatitan (=Brachiosaurus) brancai*

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Abstract

There is great interest in calculating accurate values for Earth's palaeogravity since the results have profound implications for many sciences. One fundamental technique to quantify palaeogravity is to compute weight against mass estimates of ancient animals. In this paper this technique is applied to *Giraffatitan (=Brachiosaurus) brancai* (MB.R.2181, formerly HMN S II), one of the most complete sauropod dinosaur skeletons known. The results indicate that a palaeogravity of 0.54g (5.3 m/s^2) ±20% is a reliable estimate for 152 Ma.

Key words: Palaeogravity, *Giraffatitan (=Brachiosaurus) brancai*

Introduction

Palaeogravity is the study of ancient surface gravity on the Earth.[1] There has been great interest in producing reliable estimates of palaeogravity for at least half a century. In the early 1960s Arthur Holmes and S. Warren Carey, two professors of geology, corresponded about possible methods of calculating palaeogravity based on 50 different methods, eventually concluding that none could provide the accuracy needed to be useful. Over a decade later, Carey (1975, p134) still reported that "variation of gravity acceleration *g* at the surface has not been recognised, although no critical test has yet been proposed."

Stewart (1970, 1972, 1977, 1978, 1981) studied various methods to estimate palaeogravity. Although his methods were not accurate enough to estimate palaeogravity to a high accuracy he was able to set limits to variations in surface gravity. His general conclusion was that the studies undertaken indicated that the force of surface gravity had never been significantly greater than it was now but may have been less. In contrast to these results, Hladil (1991) suggested intensive dropstone impact deformations could be caused by higher gravitational acceleration during the Ordovician.

A number of authors, Harlé (1911), Kort (1947), Pennycuick (1992, 2008, 2016), Hurrell (1994, 2011, 2012, 2014a, 2014b), Carey (2000), Mardfar (2000, 2012, 2016), Erickson (2001), Scalera (2002, 2003, 2004), Maxlow (2005, 2014), Sato *et al* (2009) and Strutinski (2012, 2016a, 2016b) have speculated that ancient life might indicate that palaeogravity was less than the present average of 1g (9.81 m/s^2).[2]

In my previous publications and presentations [Hurrell (1994, 2011, 2012, 2014b)] I proposed that a comparison of weight and mass estimates of prehistoric animals would provide reasonably accurate estimates of palaeogravity. In this paper the weight-mass method is applied to the dinosaur *Giraffatitan (=Brachiosaurus) brancai* to estimate palaeogravity when this dinosaur specimen was alive. The geologi-

[1] Palaeogravity can also be spelled paleogravity.

[2] Today's surface gravity varies over the Earth from 9.7639 m/s^2 to 9.8337 m/s^2. The average is taken as 9.81 m/s^2.

cal sequences where this specimen was found have been dated to the Late Jurassic, between the Late Kimmeridgian to the Early Tithonian. It is therefore anticipated that this specimen lived 152 million years ago.

1. The theory

It is well known that gravity can be quantified using accurate values of weight and mass. The weight of an object varies in direct relationship to gravity but the mass of the same object never varies. Any mass would be approximately one third its weight on Mars and only one sixth on the Moon. Thus any known mass can be used to calculate gravity.

An animal can be used to calculated gravity using this weight-mass method if its weight and mass are known accurately. It naturally produces a gravity of 9.81 m/s^2 (1g) for present day life on Earth.

The same weight-mass method can be used on prehistoric life to calculate palaeogravity when a particular ground-based animal was alive, since fossil skeletons of prehistoric land-based animals allow calculations of both weight and mass. The weight of a land-based animal can be calculated from the strength of its leg bones. The mass of the same land-based animal can be calculated from its body volume and tissue density. Because fossils of land-based life are known from hundreds of millions of years ago the weight-mass method can be used to quantify reasonably accurate estimates of palaeogravity at defined periods in the past.

Palaeogravity can be calculated from:

$$g_a = w_a / m$$

where g_a is palaeogravity at some predefined age, w_a is the weight at that age and m is the mass. Since mass never varies it does not need a subscript to denote its age.

2. The practice

2.1 Introduction

Although the theory is simple the practice of applying it is more challenging. Major factors to consider are the determination of accurate values of weight and mass for a particular animal.

Giraffatitan (=Brachiosaurus) brancai must be considered a particularly good choice of animal to obtain accurate values of weight and mass since it is a virtually complete skeleton and has been examined in detail over many years.

The widely held assumption that palaeogravity has never varied has produced much confusion. Weight is often reported as mass and vice versa. Various hypotheses have been proposed that distort weight and mass estimates. It is vital to identify where these hypotheses have distorted weight and mass estimates so the error can be corrected, permitting the most accurate possible values for palaeogravity to be the calculated.

The confusion about the large size of prehistoric life has generated many different *ad hoc* hypotheses to account for the large size of sauropod dinosaurs, including specimens such as *Giraffatitan (=Brachiosaurus) brancai*. An early popular hypothesis, widely accepted for the sauropod dinosaurs until the 1960s, proposed that they were slow and lumbering animals that supported their massive bulk with the buoyancy effect of water. Subsequent research indicated that these animals were land animals and the hypothesis was widely abandoned by the 1980s, although the problem of their large size still remained. The wide adoption of this early water supported hypothesis means that mass estimates of sauropod dinosaurs produced before the 1970s are often much larger than many present-day estimates.

Beginning in the 1980s it started to become popular to depict dinosaurs as very skinny animals compared to present-day life, partly because large mass estimates of land animals seemed incompatible with weight estimates calculated from bone strength. These sleek versions were stripped of extraneous soft tissue, reducing their mass estimate by a large amount. Many of these skinny reconstructions are still popular today.

More recently, Conway *et al* (2013) have criticised these skinny reconstructions. They argue that many of these skinny reconstructions are not accurate. While palaeontological artists have been keen to portray most dinosaurs as slim, sleek animals where every muscle can clearly be seen, no living mammal, reptile or bird has such “visible” anatomy. They argue that the use of modern “high-fidelity” musculoskeletal reconstructions indicates that these skinny “shrink-wrapped” reconstructions have gone too far. To illustrate just how unlikely some of these reconstructions are they used the same “shrink-wrapping” method on modern-day animals to produce virtually unrecognisable skinny versions of modern animals.

Another hypothesis that became popular to reduce the mass of dinosaurs was the suggestion that they contained large air sacs within their body, making them lighter than they looked from external appearances. The mass estimate of dinosaurs can be reduced by up to 20% by simply assuming that a large proportion of their body was hollow with separate air sacs. It is common to find this popular hypothesis combined with a "skinny" reconstruction to reduce the estimated mass of dinosaurs by a substantial amount.

Life today has an average tissue density of about 0.97 tonne/cu. m. This average value includes the lung volume, typically between 5 to 6 % for a range of life from small to large. The buoyancy effect of the lungs means that living animals can float in water because they are slightly less dense but a drowned animal sinks in water once the lungs are full. Since dinosaur fossils are often recovered from the bottom of ancient rivers or lakes it would indicate that their tissue density was similar to today's life when they drowned. It would therefore seem unlikely that dinosaurs contained large air sacs that reduced their mass by a substantial amount.

Other hypotheses have been proposed to explain the large size of dinosaurs: perhaps the atmosphere was less dense, or perhaps more dense, perhaps the vegetation was more appetising so they grew bigger, or perhaps the vegetation was less easy to digest so these animals had to grow bigger to process it. These types of hypotheses probably don't affect mass estimates greatly.

Some hypotheses propose that prehistoric animals were somehow better with stronger muscles and bones, perhaps with changes in atmosphere or food supply. However, all present-day life is restricted by mechanical limitations. Studies of bone, muscles and ligaments have shown that these don't vary across a vast array of animals, from small to large. It would seem highly unlikely that the mechanical limitations of prehistoric animals differed from present-day life.

By their very nature these various *ad hoc* hypotheses often only explain a limited range of animals. Since the same gigantism is observed in a wide range of life forms, spread over hundreds of millions of years, a multitude of hypotheses are required to explain the gigantism observed in all forms of life, in the same and other time periods. For example, one hypothesis may be used to explain the giant insects in the Carboniferous, another to explain the giant plants of the Carboniferous, another to explain giant dinosaurs and yet another to explain the large size of prehistoric mammals and their current size reduction to present-day forms. A multitude of hypotheses are required to explain the same phenomena.

In complete contrast to many of these multitude of hypotheses that only affect small portions of life, often in a restricted time period, the hypothesis of reduced gravity is a grand theory of all life, since it affects all life in all time periods. It replaces a multitude of *ad hoc* hypotheses with one all-encompassing hypothesis.

2.2 Introduction to Giraffatitan (=Brachiosaurus) brancai

Giraffatitan (=Brachiosaurus) brancai is one of the most complete specimens of a sauropod dinosaur, containing an estimated 90% of the skeleton. It was excavated in Tanzania by several German expeditions undertaken from 1909 to 1912. The Tanzania formation was dated at between Late Kimmeridgian to Early Tithonian, placing its absolute age as approximately 152 million years old.

The fossil skeleton was initially identified as a *Brachiosaurus* and given the species name *Brachiosaurus brancai*. The mounted reconstruction of its skeleton was housed in the Berlin Museum für Naturkunde (Berlin Museum of Natural History) and it can still be viewed there today (see figure 1). The Berlin *Brachiosaurus* was reconstructed from many specimens to form a nearly complete composite skeletal reconstruction of the animal. Since the Berlin specimen was more complete than the North American *Brachiosaurus* specimen the popular image of a *Brachiosaurus* is often based on this Berlin specimen. After decades of scientific study the Berlin *Brachiosaurus* has become the most comprehensively described of all the sauropods.

The Berlin *Brachiosaurus* was initially reconstructed with somewhat sprawling upper arms. Later reconstructions corrected this so its limbs are now held more vertically. While the skeleton is a composite of different animals most of this skeleton appears to be from the same individual and it would seem that most of the limb proportions are reliable.

After many years, Gregory Paul (1988) recognised proportional differences between the North American *Brachiosaurus* and the Berlin *Brachiosaurus*, suggesting that the Berlin *Brachiosaurus* was separate from the North American species. Further scientific study by Taylor (2009) confirmed these differences, showing there were at least 26 differences between the bones of the German and American specimens. Taylor recommended that these animals should be considered genetically separate species and the new name of *Giraffatitan brancai* should be used for the Berlin *Brachiosaurus*.

Figure 1.

The specimen of *Giraffatitan (=Brachiosaurus) brancai* on display at the Berlin Museum für Naturkunde (Berlin Museum of Natural History). It was given a new scientific name in 2009 so *Brachiosaurus brancai* became *Giraffatitan brancai*. It is the tallest mounted dinosaur skeleton in the world, standing 13.27 metres tall, as the Guinness Book of Records confirms. The humerus, the upper front leg bone, is taller than an average man at 2.13 metre long. This specimen was still an adolescent when it died. One isolated fibula of another specimen was 13% larger indicating it would have grown even bigger.

2.3 Mass estimates for Giraffatitan (=Brachiosaurus) brancai

There have been many estimates of the body mass and weight of *Giraffatitan (=Brachiosaurus) brancai* and the estimated mass has varied by a very large amount. Different studies have given results from at least 28 to 78.3 metric tonne.

The early estimates of the mass often don't seem very scientific – Janensch (1938) estimated a mass of 40 tonne based on personal opinion. Despite the simplicity of this method the estimate is within the range of modern estimates.

2.3.1 Volumes of physical models

One of the first and most popular scientific methods to estimate *Giraffatitan's* mass was to make a physical scale model based on the skeleton. The volume of the model was measured, scaled up and multiplied by the presumed tissue density to give a mass estimate.

Colbert (1962) was one of the first researchers to issue a scientific report on the mass of *Giraffatitan*. Using a model as a basis for his estimate he obtained an estimate of 78.3 metric tonne. One important point to remember when looking at weight estimates of all dinosaurs is that the metric tonne, the imperial long ton and the American short ton are all slightly different. Some reports do not make it clear which unit has been used, so for example the Colbert mass estimate is reported as 78.3, 80 or 87 tons in different publications, presumably when they tried to convert between the different units of measurement. At the time the estimate was produced, the most popular theory to account for the sauropods' large size was that they lived in water, perhaps moving about the bottom of a lake. This implied that their density would be greater than water, so the value of 1.1 was used by Colbert. Taking these factors together the volume of the Colbert model would be 71.18 cu. m and the mass would be 69 tonne assuming an average tissue density of 0.97 tonne per cu. m. Mazzetta et al (2004) have highlighted proportional differences in the model that reduced the mass estimate to 63.4 tonne.

Alexander (1985) calculated the scaled-up volume of a commercially available model produced by the London Natural History Museum to be 46.6 cubic metres. Assuming a density of 1000 kg per cu. m allowed Alexander to estimate a mass of 46.6 tonnes. Later, Alexander (1989) still gave a preferred estimate of 47 tonne but also gave a minimum estimate of 32 tonne and a maximum estimate of 87 tonne. It is interesting to note that a mid-range value between the lower 32 tonne and higher 87 tonne would actually be 59.5 tonne so it is unknown why Alexander still preferred the lower 47 tonne.

Paul (1988) estimated a mass of 31.5 tonne for *Brachiosaurus* based on a physical model he constructed, presumably with an average density of 0.86 to give a volume of 36.63 m³. This volume is nearly the same as the 37 m³ that Paul (1997) gave in a later paper. This later paper also compared Paul's profiles with models from the British Museum of Natural History and the "fat" restoration of Gunga *et al* (1995), quoting volumes of 47 m³ and 74 m³ for those respective models.

Later, Paul (2010) gave an estimate of 40 tonne in his book, *Dinosaurs: A field guide*. Interestingly, this would produce a volume of 46.46 m³, very close to the volume calculated by Alexander (1985) for the Natural History Museum model. Paul (2010, p202) also provides an artistic restoration that is noticeable for its skinny legs and tail. However, as part of an appendix to the book there was a link to a spreadsheet (also available from his website) that indicates that this estimate was an average mass estimate. The data is given as "specimen (modelled 1st): kilograms: femur or other long bone length (usually decametres), HMN MB.R.2181: 31500 (neck 2800):~20.90 "XV2": ~45000:~23.50". This would seem to imply that the Berlin specimen (MB.R.2181, formerly HMN S II) was modelled with a mass of 31.5 tonne but a larger specimen (HMN XV2), with a tibia that is reported to be 13% longer, was modelled with a mass of 45 tonne. Paul (2010) estimated the density of the body as 0.85 and the neck as 0.6, so the volume of his model would be 38.42 m³.

Henderson (2006) constructed models of Giraffatitan initially based on the published restorations of Paul (1987) but later modified with additional new data. This Paul-like reconstruction has perhaps the most extreme low tissue density of any model, set at 0.8 for the body and 0.3 for the neck. The quoted mass of 25.92 tonne equates to a volume of 34.1 m³.

2.3.2 Bone strength indicators

The Mazzetta *et al*. (2004) estimate is based on a "bone strength indicator" method of Christiansen (1997) that doesn't appear to fit in either the mass or weight estimates required for this exercise.

2.3.3 Three-dimensional computer models

Calculations of *Giraffatitan* based on models can obviously lead to errors since the model proportions may not be correct in relation to the skeleton. Any discrepancies ultimately depend on the accuracy of the models used. It is clear that models can lead to variable results since it ultimately relies on the artistic ability of the sculptor constructing the model.

More recent studies such as Gunga *et al* (1996, 2008) have tried to overcome the problems with physical models of *Giraffatitan* by collecting the dimensions directly from the fossil. This enables precise data about the size of the dinosaur skeleton to be input directly into a computer model.

First a precise and detailed laser scan of the skeleton is used to arrive at the size of the skeleton without any physical contact with the skeleton. Dinosaur skeletons consist of many independent bones but the position and the form can be determined accurately with the laser scanning technique. Once this data is input it can be used to develop a computer wire model consisting of the outlines of the bones. The skeleton outlines are placed in a computer model allowing a flesh layer to be added to the model so the volume of the computer model can be calculated. Dinosaur skeletons are complex objects with irregular structures but the laser scanning technology was able to achieve highly accurate results to determine the shape of the bones.

There are still possible errors with this method. The dinosaur skeleton may be incorrectly constructed, or the thickness of the flesh layer may be incorrect (the lower belly area is a particular problem because the lack of bones in this area make the volume uncertain).

Table 1.

Mass and weight estimates for the specimen of *Giraffatitan (=Brachiosaurus) brancai* on display at the Berlin Museum für Naturkunde (Berlin Museum of Natural History).

Mass and weight estimates in metric tonnes for *Giraffatitan (=Brachiosaurus) brancai*				
Mass estimates in tonne from models				
Reference	Mass	Notes	Density tonne/cu. m	Volume cu.m
Janensch (1938)	40.00	"estimated from personal opinion"	?	
Colbert (1962)	78.30	Reduced to 63.4 tonne by Mazzetta	1.10	71.18
Colbert (1962)	80.00	reported model estimate	1.10	72.73
Colbert (1962)	87.00	reported model estimate	1.10	79.09
Alexander (1985)	46.60	Natural History Museum model	1.00	46.60
Paul (1988)	31.50	"Brachiosaurus"	0.86	36.63
Alexander (1989)	32.00	Minimum estimate	1.00	32.00
Alexander (1989)	87.00	Maximum estimate	1.00	87.00
Alexander (1989)	47.00	Preferred estimate	1.00	47.00
Gunga et al. (1996)	74.40	"Fat Model"	1.00	74.40
Paul (1997)	31.50	Same as 1988 estimate	0.86	36.63
Christiansen (1997)	37.40	See also Mazzetta et al. (2004)	0.90	41.56
Henderson (1999)	25.79		?	
Seebacher (2001)	28.66		?	
Mazzetta et al. (2004)	39.50	Based on Christiansen (1997)	0.95	41.58
Henderson (2006)	25.92	Variable tissue density (0.8, 0.3)		34.10
Gunga et al. (2008)	38.00	"Skinny model"	0.80	47.50
Bates et al (2009)	23.34		?	
Paul (2010)	31.50	Variable tissue density		38.42
Sellers et al. (2011)	23.20	Using convex hull mass est.	0.80	29.00
Bates et al. (2015)	25.28	Using convex hull mass est.	0.82	30.92
See this paper	43.11	"Slim" Collect A ©2008 model	0.97	44.44
See this paper	51.81	"Robust" Papa ©2012 model	0.97	53.41
See this paper	60.00	"Robust" Papa model with extra mass	0.97	61.86
See this paper	55.00	Based on 3D computer model	0.97	56.70
"Alexander" High & Low	57.72	Average of Alexander high and low est.	0.97	59.51
"Gunga" High & Low	59.12	Average of Gunga high and low est.	0.97	60.95
Best estimate	**58.00**		0.97	59.79
Weight estimates in tonne(f) from leg stress				
Reference	Weight	Notes		
Anderson et al (1985)	31.60	Maximum estimate		
Campione at al (2010)	35.78	Estimate ranges from 26.8 to 44.7 tonne(f)		
Bone dimension	31.59	Quadrupedal calculation		
Best estimate	**31.59**			

The scientists hoped to undertake further work to improve the accuracy of the result. Skeletons of known animals were scanned as a check of the accuracy of the technique. Two models were used for this check: a rhinoceros and an elephant. The volume and mass of the model produced from the skeleton of the elephant was compared with the known living weight to delineate the accuracy of the method. This data on living animals provides a reference for modelling all animals including dinosaur skeletons since they were measured and modelled in exactly the same way as the dinosaur skeletons. The volume computed and the mass could then be compared with the known weight of the elephant. The shape and volume of the elephant model was used to calculate the estimated mass of the animal and this was then compared with the known mass of the animal to check the accuracy of the method. The degree of error, which includes the possible error of the computer modelling, amounted to 16% of the known mass. The authors thought this seemed to be a reasonable margin for the possible deviation from the true mass. A number of dinosaurs have now been scanned from Germany, France, Switzerland and China.

Interestingly, the work of Gunga and his colleagues has still provided two widely different results for the weight of *Giraffatitan*, one of 74.4 metric tonne for a "well built" computer model in Gunga *et al* (1995), and another of 38.0 metric tonnes for a "skinny" model in Gunga *et al* (2008). The weight of the "skinny" model has also been further reduced by assuming that the tissue density was only 0.8 instead of the 1.0 assumed for the "well built" computer model. The volume of the "skinny" model was 47.5 cu. m.

One of the main influences for reducing the mass estimate of the "well built" reconstruction was highlighted in the paper, *Gravitational tolerance and size of Brachiosaurus brancai*, by Günther *et al* (2002). The authors recognised there remained "an unsolved contradiction between the theoretical assumptions" of gravity and the largest fully terrestrial animal. The previous estimate of 74.4 tonne by Gunga *et al* (1996) was too large to exist in a 1g environment.

2.3.4 Three-dimensional (3D) Mathematical Slicing

Henderson (1999) used a mathematical slicing technique to estimate the mass of extinct animals. This is a simple method to easily estimate a mass from drawings instead of a model. The mass estimate for *Giraffatitan* is 23,337 kg using an assumed density of 0.8 kg per litre.

2.3.5 Minimum Convex Hull techniques

One interesting new method is to calculate the "minimum convex hull" volume of a skeleton and then apply a known relationship between the "minimum convex hull" volume and body mass to estimate the body mass. Since the technique effectively removes any human intervention it was hoped it would produce more accurate and repeatable results. The technique has been used to estimate the body mass of a number of dinosaurs.

The method was developed by Bates *et al* (2009) based on generating a "minimum convex hull" from a scan of a mounted skeleton. Using laser-scanning equipment they first generated a three-dimensional computer model of the skeleton. Then the computer program Matlab was used to calculate the enclosed volume of each element of the skeleton and the total of these volumes was taken as the "minimum convex hull". They tested this method first on mounted skeleton reconstructions of some large bodied mammals and found that it underestimated body mass by 21 per cent. Assuming that this was also true for dinosaurs they predicted that the weight of *Giraffatitan* would be 23,200 kg assuming an average tissue density of 0.8.

A refined version of this minimum hull technique was developed by Bates *et al* (2015) using a new algorithm to estimate the volumetric mass. This new technique has produced a mass estimate of 25,282 kg assuming a tissue density of 0.817 for *Giraffatitan*. However, a mass of 25.3 tonne is much lower than even the skinniest scale models, so it is difficult to see how such a low mass could be achieved without completely emaciating the animal. Possibly the obvious differences in body shapes between dinosaurs and mammals are distorting the results.

2.3.6 Further mass estimates

Three further models were used to produce additional mass estimates as part of this study.

The volume mass estimate based on two commercially available physical models was calculated using the volume mass estimate apparatus described by Alexander (1989 p19-20).

The volume of a "*Brachiosaurus*" model by CollectA ©2008 was measured to produce a scaled volume of 44.44 cu. m for what appears to be a slim reconstruction (see figure 2). Although this model was called a *Brachiosaurus* it was proportionally similar to the *Giraffatitan* skeleton when scaled to 1/80 full size. A tissue density of 0.97 predicts an animal mass of 43.11 tonne.

The volume of a "*Brachiosaurus*" model by Papa ©2012 was measured to produce a scaled volume of 53.41 cu. m for what appears to be a robust reconstruction (see figure 3). Although this model was called a *Brachiosaurus* it was proportionally similar to the *Giraffatitan* skeleton when scaled to 1/40 full size. A tissue density of 0.97 predicts an animal mass of 51.81 tonne. Interestingly, although this reconstruction is robust in comparison to other reconstructions the animal is still thin enough for the ribs to be clearly visible. It was found that additional mass could easily be added around the visible rib area to increase the total scaled mass to 60 tonne.

A *Giraffatitan* 3D CAD model was constructed based on the skeleton at the Berlin Natural History Museum (see figure 4). This 3D model was produced using the free modelling software Autodesk 123. The object was to produce a model that was neither skinny nor fat, but an average size. The tail is held erect, as depicted on most modern restorations, and the animal is frozen in the dynamic act of walking. The neck has always been reconstructed as erect on the Berlin specimen. An early reconstruction produced a height of 12.7 metres while the most recent reconstruction has a height of 13.27 metres. This 3D model is reconstructed with an erect neck that is 13.27 metres high. The computer program allowed a direct calculation of the volume of this model at 56.7 m^3. A tissue density of 0.97 predicts an animal mass of approximately 55 tonne.

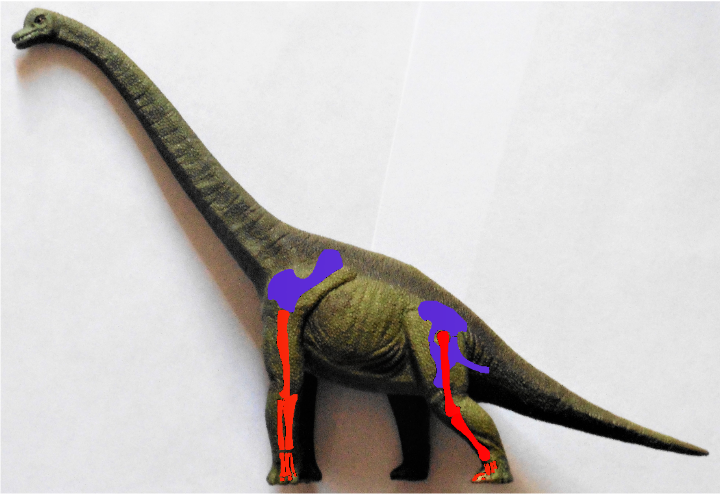


Figure 2.

The *Brachiosaurus* CollectA ©2008 model. This model scales at 1/80. The estimated mass based on this model was 43.11 tonne.

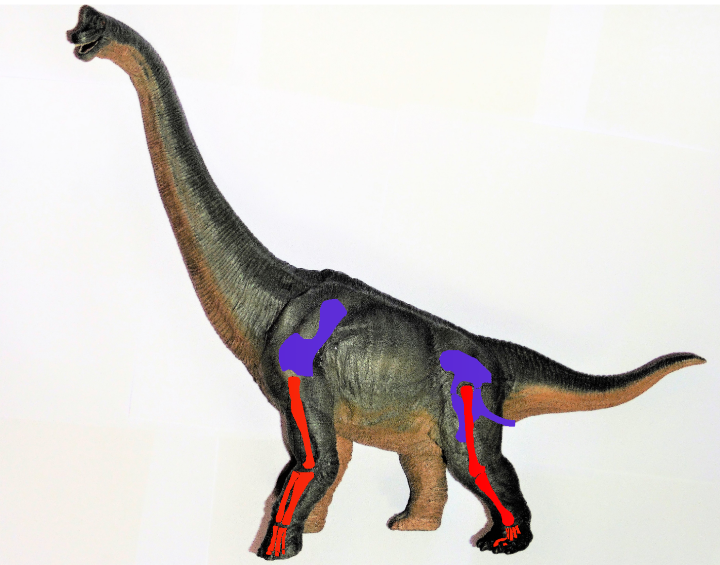
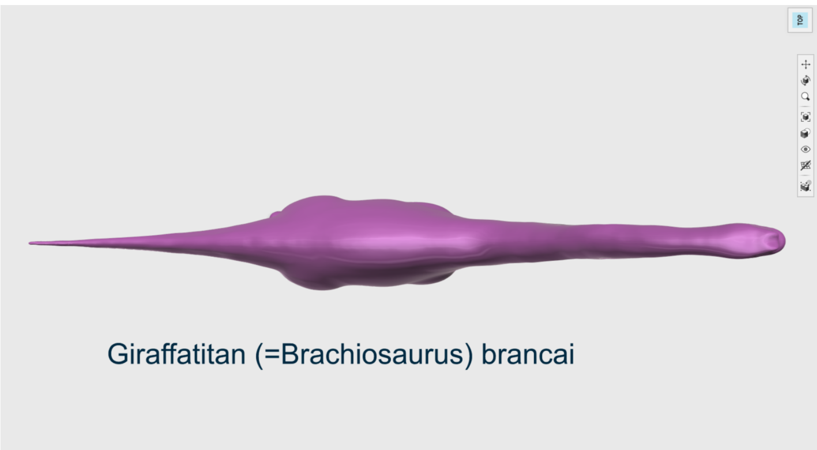


Figure 3.

The *Brachiosaurus* Papa ©2012 model. This model scales at 1/40. The estimated mass based on this model was 51.81 tonne. Note that although this reconstruction is considered robust in comparison to other reconstructions the animal is still thin enough for the ribs to be clearly visible. Additional mass was easily added around the visible rib area to increase the total scaled mass to 60 tonne.

Figure 4.

A 3D reconstruction of *Giraffatitan (=Brachiosaurus) brancai* based on the skeleton mounted and exhibited at the Berlin Museum für Naturkunde (Museum of Natural History). The estimated mass based on this model was 55 tonne. A video and 3D model of the *Giraffatitan* in object format is available [here]



2.3.7 A review of various mass estimates

It would be natural to wonder how many of the scientific mass estimates of *Giraffatitan* could vary so widely from each other. However, it is clear that many results have been greatly influenced by the confusion about palaeogravity. One noticeable trait in some scientific papers is that they tend to reference other scientific studies that agree with their results whilst ignoring any results that differ, allowing each paper to claim that it is the most accurate and up-to-date mass estimate produced to date. This allows many wildly optimistic claims for the accuracy of the mass estimates. A wider review often illustrates that some of the results are in total disagreement with some previous estimates.

Using commercially available scale models clearly illustrates that a 47 tonne *Giraffatitan* is a slim animal. The mass of 46.6 metric tonne calculated by Alexander (1985) using a Natural History Museum model would seem to indicate that this was also a "slim" model. Paul (2010) produced mass estimates of 31.5 tonne with a combination of a "skinny" model and a reduced tissue density.

The mass estimate derived from "slim" and "skinny" models rules out many of the lower estimates not based on physical models. The convex hull technique of Sellers *et al* (2012) estimated a mass of 23.2 tonne and Bates *et al* (2015) estimated 25.28 tonne. The more recent mass estimate of Bates *et al* (2015) is 60% less than the "slim" model reconstructed by Gunga *et al* (2008) and still less than the "skinny" model produced by Paul (2010), so it is difficult to see how extra mass might be removed from these already "skinny" models.

The assumed tissue density of *Giraffatitan* also varies widely between 0.8 – 1 tonne per cu. m in many modern mass estimates. These estimates allow the sauropod to simply lose 20% of its mass by assuming a different density. Correcting this wide variation to a constant density removes some of the variation.

The mass of present-day wild animals often varies by up to 30% between periods of feast and famine. Consider how much our own weight would vary if we were young, fit and well fed and then lost much of this bulk through starvation; this may have befallen *Giraffatitan*. Defining this maximum possible mass range and then taking the average of these two limits should provide the "best estimate" of mass. So what is a real optimal mass estimate based on the volume method? Correcting the density variation to a constant 0.97 tonne per cu. m., the maximum and minimum estimates of Alexander (1989), with his estimates ranging from 87 to 32 tonne, is actually a range of 84.39 to 31.04 tonne, giving an average mass of 57.72 tonne. The two estimates of Gunga *et al* (1995, 2008), with their estimates ranging from 74.4 to 38 tonne for "fat" and "skinny" models, is actually a range of 72.17 to 46.07 tonne, giving an average mass of 59.12 tonne. These figures begin to seem reasonable if we consider that the "fat" and "skinny" limits are the very extreme of what *Giraffatitan* might have weighed.

The mass estimates produced from commercially available models are particularly interesting. Although the use of these models seems to have been widely ignored by the scientific community [apart from Alexander (1985)] they do seem to provide an easy and accurate method of estimating the mass of *Giraffatitan*. The models need to be reasonably realistic representations but this can easily be verified by checking the dimensions and proportions of the model against published measurements taken from the fossil skeleton. With the two models used in this study, one could clearly be seen to be a "slim" reconstruction, whilst the other was a more "robust" reconstruction. Both mass estimates agreed with the more realistic mass estimates published in the scientific press. It would therefore appear that this relatively simple method could be used to estimate the mass of all well-known dinosaurs with an acceptable level of accuracy. However, it was noted that even the "robust" reconstruction appeared to be influenced by the preference for slim reconstructs so the ribs were clearly visible. Additional mass was easily added to increase its scaled mass to 60 tonne.

Taking all these estimates together, I consider the "best" mass estimate for this specimen of *Giraffatitan* is approximately 58 tonne, assuming the animal was neither skinny nor fat.

3. Weight estimates

The weight of *Giraffatitan* can be directly calculated from the strength of its leg bones. The standard metric unit for weight is newton but the incorrect unit of kg or tonne has been widely used in most previous studies. I have highlighted it is really a force by denoting weight as either kg(f) or tonne(f). A kg(f) force would be multiplied by 9.81 to convert it to the standard metric unit of newton.

Anderson *et al* (1985) studied the bones of a range of mammals to see if there were any rules that would allow them to estimate the weight of an animal from just its leg bones. This would be very useful for extinct animals such as dinosaurs.

The Anderson team chose to study the major leg bones which are often well preserved in otherwise incomplete fossils. A good indication of the weight of present-day animals is the circumference of the upper leg bones – the humerus and the femur. The bones were measured where they were the thinnest, and so the weakest, usually about half way along the length of the bones. These two circumferences were then added together to give the total circumference.

The Anderson team used statistical analysis to define the equation:

$$w = 0.000084.c^{2.73}$$

where w = body weight in kg(f), and c = total of humerus and femur circumference in mm.

This equation can be used to estimate the body weight of a quadrupedal animal from just the humerus and femur bones. As previously discussed in Hurrell (2012), checking the accuracy of the data showed that virtually all the weight estimates from bone dimensions were within an error band of ±30% with many much closer than this.

One use of these equations would be to calculate the weight of extinct animals and the Anderson team applied their equations to a number of dinosaurs. Most dinosaurs should have been close to the best fit line, and certainly within ±30%, but the calculated results indicated dinosaurs that were much lighter than anyone had ever thought possible.

The even weight distribution between the humerus and femur bones indicates *Giraffatitan* was quadrupedal. The circumferences of the humerus and femur of *Giraffatitan* are 654 and 730 mm, giving a total of 1,384 mm. The equation based on the strength of *Giraffatitan* leg bones predicts that its weight would be 31.59 tonne(f).

Since the bone results were first published in 1985 the mass of dinosaurs based on volume methods has been reduced to try to agree with these super-lightweight estimates for dinosaurs. Since the two methods give very different results some palaeontologists advised abandoning the use of the formula based on leg bones entirely, since they cannot get dinosaurs' mass small enough to agree with the bone weight calculations. The differences are so great for large bipeds that Hutchinson *et al* (2007) concluded that: "...it is almost certain that these scaling equations greatly underestimate dinosaur body masses... Hence, we recommend abandonment of their usage for large dinosaurs."

These types of criticisms encouraged Campione *et al* (2012) to slightly modify the original Anderson *et al* (1985) formula to produce increased weight estimates for larger dinosaurs (35.78 tonne(f) for *Giraffatitan),* more in line with the volume mass estimates.

The original Anderson *et al* (1985) formula was chosen to calculate the weight estimate of 31.59 tonne(f) in this study.

4. Palaeogravity estimates

The bone dimension equation predicts the legs of *Giraffatitan* evolved to carry an animal that weighed 31.59 metric tonne(f), yet the volume method predicts this specimen's mass was 58 metric tonne. These two methods can be compared to calculate gravity approximately 152 million years ago.

Palaeogravity at 152 million years:

$$g_{152} = w_{152} / m$$

$$= 31.59 / 58$$

$$= 0.54g$$

Gravitational acceleration is calculated as 54% (5.3 m/s^2) of our present surface gravity (9.81 m/s^2) 152 million years ago based on this specimen of *Giraffatitan*.

5. Accuracy

In theory palaeogravity estimates using this weight-mass technique should provide one of the best palaeogravity estimates possible. However, the accuracy of these results clearly depends on the precision of the weight and mass estimates. As previously discussed in Hurrell (2012), typical variations would indicate that the results are only likely to be within the range of ±15% even for highly preserved specimens.

Palaeogravity estimates rely on producing accurate estimates of weight from bone dimensions and mass estimates based on the volume of accurate models. The diverse mass estimates produced by a number of studies clearly show many mass estimates for *Giraffatitan* are not constrained to a high level of accuracy. This is disappointing since this specimen is one of the most complete sauropod dinosaurs and the most heavily studied. Nonetheless, since this specimen is relatively well preserved, it is considered that this result will be accurate to within ±20%.

New techniques for predicting body mass currently being developed may be subject to less variability. One novel method of predicting mass, used by Witton (2008) for pterosaurs, relies on the relationship between skeletal mass and total mass. Scans of bone skeletons allow them to be digitised and their volume calculated. A comparison with modern animals then allows their skeletal mass and total body mass to be calculated. Possible problems with this method have been highlighted by Martin and Palmer (2014), who noted that the estimates of bone thickness used in the original calculation may have been too low. Clearly further work is required with this new technique. However, at the present time Witton (2018) reports that this technique has never been applied to sauropod skeletons in any case.

It was observed during this study that the wide divergence in mass estimates for *Giraffatitan* seems to be mainly due to variations in the size estimates of the gut, the legs and tail. The gut volume should be relatively large to process the vegetable matter but this fact is often ignored to produce low mass estimates. In view of this observation, further work to obtain better palaeogravity estimates might be obtained from studying carnivore theropod dinosaurs which cannot be subject to such a high degree of subjectivity.

6. Suggested Citing Format

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7. Publication History

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