A Palaeogravity calculation based on weight and mass estimates of *Ankylosaurus magniventris*

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Abstract

There is great interest in calculating accurate values for Earth's palaeogravity. One fundamental technique to quantify palaeogravity is to compute weight against mass estimates of ancient animals. This technique is applied to the quadrupedal armoured dinosaur *Ankylosaurus magniventris* AMNH 5214 specimen. The results indicate a palaeogravity of 0.69g ± 20% is a reliable estimate for 67 Ma.

Key words: Palaeogravity, *Ankylosaurus magniventris*

1. Introduction to palaeogravity

A more extensive introduction to the study of palaeogravity was given in Hurrell (2018). The key points identified in that publication were:

- There has been great interest in calculating palaeogravity with a number of authors speculating that ancient life might indicate palaeogravity was less than the present average of 1g (9.81 m/s^2).[1]

- The weight-mass method was identified as one of the most accurate ways to calculate palaeogravity from ancient life. It 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.

- Accurate values of weight and mass are required to apply this technique. Weight can be determined from the strength of leg bones, and mass can be determined from model reconstructions and tissue density.

- The study of Hurrell (2018) observed that a wide divergence of mass estimates seemed to be mainly due to variation in the size estimates of the gut volume.

The specimen chosen for this study of palaeogravity was the quadrupedal armoured dinosaur *Ankylosaurus magniventris* AMNH 5214.

[1] See for example: Harlé (1911), Kort (1947), Pennycuick (1992, 2008, 2016), Hurrell (1994, 2011, 2012, 2014a, 2014b, 2018, 2019a, 2019b, 2019c, 2019d), Carey (2000), Mardfar (2000, 2012, 2016), Erickson (2001), Sato *et al* (2009), Scalera (2003a, 2003b), Strutinski (2012, 2016a, 2016b), and Maxlow (2014).

2. *Ankylosaurus magniventris*

Ankylosaurus magniventris is an iconic dinosaur species often depicted in popular media. It was the last and largest of the ankylosaurid dinosaurs, a group of tail-clubbed armoured dinosaurs that dispersed into North America from Asia during the Late Cretaceous.

It is known from relatively fragmentary remains compared with its earlier Campanian–Maastrichtian relatives *Euoplocephalus* and *Anodontosaurus*, with only a handful of specimens. *Ankylosaurus magniventris* was a bulky, broad quadruped studded with osteoderms of various shapes and sizes, and had a stiff distal tail with enlarged osteoderms enveloping the tail tip to form a formidable tail club. Horner *et al* (2011) described how it formed part of the dinosaur megafauna of the latest Cretaceous of western North America, living alongside *Tyrannosaurus*, *Triceratops*, and *Edmontosaurus*.

Carpenter (2004) identified the geological formation where it was found as the Hell Creek Formation, 61–67 metre below the Cretaceous-Palaeogene boundary, late Maastrichtian, placing its age as approximately 67 million years.

Specimen AMNH 5895, the holotype, includes a partial skull and the most complete postcranium of any of the known specimen. Other specimens fill in some of the details missing. The 1910 discovery of AMNH 5214 provided the first evidence for a tail club in Ankylosaurus, and this structure was incorporated into later depictions of *Ankylosaurus magniventris*. Arbour & Mallon (2017) recently reviewed the anatomy of this unusual ankylosaur using data from historic descriptions like Ford (2003) and Carpenter (2004) alongside newly identified material to provide the most up-to-date scientific description of this animal.

3. Mass estimates from body volumes

The mass of a dinosaur can be estimated by reconstructing a model and using the calculated volume and tissue density to work out the mass of the living animal. However, as the well-known palaeontologist Paul (1988, p134) explained: "Estimating the mass of a fossil species is not an exact science." He considered that the margin of error of an accurately restored model was probably about ± 15% even when the skeletal restoration was not missing any major sections. Certainly most estimates fall within this range with only a few outliers.

For the purposes of this palaeogravity calculation we need to specify an optimal mass estimate, or a "best guess", for the specimen. A key aspect of picking an optimal mass estimate from the range of possible options is to understand why mass estimates vary. These are the key factors to consider:

- Unfortunately there is still a great deal of confusion between weight and mass and this has resulted in some palaeontologists trying to produce low mass estimates to conform to weight. Paul (1988, p130) for example explains how he used weight calculated from bone dimensions "to expose implausibly high mass estimates … so a higher mass estimate should be examined critically." All this general confusion between weight and mass has undoubtedly reduced many mass estimates to unreasonably low values.

Figure 1.

The recent PNSO *Ankylosaurus* model discussed in the text. It appears to be a high-quality dinosaur sculpture providing an accurate rendition of the latest research.

- Conway *et al* (2013) have recently criticised "shrink-wrapped" reconstructions, arguing that many of these skinny reconstructions cannot be accurate. They note that 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.

- Some palaeontologists have decided to completely ignore weight estimates from bone dimensions. The differences between weight and mass estimates 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." This would indicate that the mass estimates of palaeontologists following this line of reasoning will not be influenced by the general confusion between weight and mass.

It is therefore expected that mass estimates that use "shrink-wrapped" reconstructions will be in the lowest range possible, providing a very useful indication of the minimum mass possible, but probably lower than reality. Palaeontologists who have decided to disregard weight estimates from bone dimensions will be more likely to provide the best mass estimates.

Many reconstructions assume the average tissue density of dinosaurs was in the 0.8 to 1 tonne cu.m^{-1} range and this obviously affects the mass estimates by a large amount. There clearly isn't any generally consensus on one consistent value since different densities are used even within the same study - Hutchinson *et al* (2011) for example used 0.807, 0.85, 0.87 and 0.985 tonne cu.m^{-1} for different specimens of *Tyrannosaurus rex*. Life today has an average tissue density of about 0.97 tonne cu.m^{-1}. This average value includes the lung volume, typically between 5 to 6 % of body mass for a range of life from small to large. It would seem unlikely that dinosaurs would need lungs that were nearly twice the size of present-day life, so estimates of 10% allowances for lungs seem excessive. Even if we assume that lung volume is 10% instead of a more typical 6% maximum, the average tissue density would only be 0.93 tonne cu.m^{-1}. Similar reasoning implies that the tissue density excluding the lungs is 1.03 tonne cu.m^{-1}, not the 1 tonne cu.m^{-1} often assumed for these calculations. Many studies also assume that there were additional isolated air-sacs within dinosaur bodies to reduce their mass. However, the buoyancy effect of the lungs means that living animals can float in water because they are slightly less dense while 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 any isolated air-sacs that reduced their mass by a substantial amount. Armoured dinosaurs were also covered in large bony structures that may well have increased their average tissue density. Accordingly, the average tissue density has been set at 0.97 tonne cu.m^{-1} for this armoured dinosaur specimen.

Seebacher (2001) estimated a mass of approximately 1.7 tonne using his polynomial technique. This seems excessively small for such a large animal and is probably low because the *Ankylosaurus* legs are so short compared to other dinosaurs.

Paul (1997), presumably using the smaller and more complete AMNH 5214 as reference, placed the animal at approximately 6 tonne. Later, Paul (2010, 2016a) gave a mass of 6 tonne for an unidentified specimen of *Ankylosaurus* with a total length of 7 metres. In his Dinosaur Mass Tables Paul (2016b) identified the AMNH 5214 specimen and estimated a mass of 3.9 tonne with a length of 6.7 metres.

Carpenter (2004) provided a skeletal reconstruction and a life restoration of *Ankylosaurus*. He estimated the smallest specimen, AMNH 5214, as about 5.4 m long and about 1.4 m tall at the hips. No mass estimate was provided.

In their recent scientific review, Arbour & Mallon (2017) attempted an estimate of the length of AMNH 5214 by drawing the lengths of various preserved elements to scale. Using measurements of the preserved skull and vertebrae of AMNH 5895 and the skull and tail club in AMNH 5214, estimating the length of the pelvis based on AMNH 5409 and conservatively estimating the gaps between vertebrae and missing cervical and caudal vertebrae, they calculated the total body length was between 6.02-7.95 metres. This would make the most likely estimate approximately 6.985 metre for AMNH 5214. They thought the largest *Ankylosaurus* would be unlikely to reach a body length of nearly 10 metres as sometimes suggested, but a length of up to 8 metres is probably within reason. It is interesting to note that the Arbour & Mallon (2017) restoration is bulkier than previous restorations (this can clearly be seen in the Arbour & Mallon (2017) figure 9).

Until recently the latest look for this popular armoured dinosaur was based on work by Carpenter (2004). Both the older Carnegie model and the more recent Safari *Ankylosaurus* followed this reconstruction. A recent PNSO *Ankylosaurus* model follows the latest scientific description of Arbour & Mallon (2017) and appears to be a high-quality dinosaur sculpture providing an accurate rendition of the latest research. One of the main differences is the armour placement but this shouldn't affect the mass estimates unduly. Using the basic technique outlined in Alexander (1989) the model volume was used to determine the living mass of the animal. When scaled to 6.985 metre long, the PNSO *Ankylosaurus* model indicated the living mass of the full size AMNH 5214 specimen would be 6.49 tonne assuming a density of 0.97 tonne cu.m tonne.

Previous mass estimates have probably been low because the animal was considered to be less bulky than the latest scientific restoration. The mass estimate obtained from the scientifically accurate PNSO model was taken as the most likely mass and rounded up to 6.5 tonne.

4. Weight from bone dimensions

The weight of the *Ankylosaurus magniventris* specimen 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 for a quadrupedal animal:

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

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 femur bones. 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

Mass and weight estimates in tonne for *Ankylosaurus magniventris* AMNH 5214				
Mass from models tonne				
Reference	Mass	Notes	Density tonne/cu.m	Volume cu.m
Paul (1997)	6.00	?		
Seebacher (2001)	1.72	?		
Carpenter (2004)		No mass estimate. 5.4 m long 1.4 m tall		
Paul (2010, 2016)	6.00	Unidentified specimen. Length 7 m.	0.86	6.97
Paul (2016)	3.90	Specimen identified. Length 6.70 m.	0.86	4.53
Arbour & Mallon (2017)	NA	Weight only. Total body length 6.02-7.95 (6.985)		
Model	6.49	PNSO model. Length 6.985 m.	0.97	6.69
Best estimate	**6.50**		0.97	6.70
Weight from leg bone dimensions tonne(f)				
Reference	Weight	Notes		
Bone dimensions	4.50	Quadrupedal formula		
Arbour & Mallon (2017)	4.78	Using Campione (2016) calculation for quadrupedal		
Best estimate	**4.50**			
Within ±	20%			
Best gravity estimate	**0.69**			
Average Age	**67**			

Table 1.

Mass and weight estimates in tonne for the *Ankylosaurus magniventris* AMNH 5214 specimen.

calculated results indicated dinosaurs that were much lighter than anyone had ever thought possible.

Since the bone results were published in 1985 the mass of dinosaurs based on volume methods have been reduced to try to agree with these super-light-weight estimates for dinosaurs. Since the two methods give very different results some palaeontologists, as noted previously for Hutchinson *et al* (2007), 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. 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 more in line with the volume mass estimates.

Arbour & Mallon (2017) used the Campione & Evans (2012) scaling equation to estimate the weight of AMNH 5214 as 4.78 ± 1.22 tonne.

The Anderson *et al* (1985) quadrupedal equation gives a slightly lower weight estimate of 4.5 tonne and it was this result that was used to calculate palaeogravity.

5. Palaeogravity

Palaeogravity was calculated using the standard formula previously described:

$$g_{67} = w_{67} / m$$

Palaeogravity for the *Ankylosaurus magniventris* AMNH 5214 specimen was estimated as 0.69g at approximately 67 million years ago.

6. Accuracy

The *Ankylosaurus magniventris* AMNH 5214 specimen was placed within a ± 20% accuracy band for palaeogravity estimates.

7. Suggested Citing Format

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8. Publication History

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