NEWS & VIEWS

PALAEONTOLOGY

Embryonic identity crisis

Philip C. J. Donoghue

The oldest known animal fossils, identified as eggs and embryos, had been expected to reveal secrets from a period of great evolutionary change. Will the latest theory about the fossils' origins confound these hopes?

The origin of animals is almost as much a mystery as the origin of life itself. An abundant fossil record extends back 542 million years to the beginning of the Cambrian period, testifying to the establishment of all of today's main groups of animals by this time. However, the degree to which animal evolutionary history extends beyond the Cambrian is a controversy rich in speculation but sparse in evidence. It is no wonder that the 1998 report of fossilized animal embryos from the Doushantuo phosphorite rocks of southern China created a stir[1]. At more than 580 million years old, these were the oldest unequivocal animal fossils, and, as embryos, they provided a glimpse of animal embryology at a time when today's main animal groups were emerging. These fossils have revealed ancient patterns of cell division and cell arrangement[2], and promised to reveal further secrets about developmental evolution at this crucial time. But this prospect may have been dashed by a study on page 198 of this issue[3] presenting a compelling reinterpretation of these fossils — not as animal embryos, but as giant bacteria*.

The fossils in question are species of *Parapandorina*, which were thought to be embryos, and *Megasphaera*, which were proposed to be fertilized eggs. Most *Parapandorina* fossils were preserved only in their very earliest stages of embryonic development, and were composed of 2, 4, 8, 16, 32 or 64 cells, with some examples having undergone further rounds of cell division — a process known in embryos as cleavage. These remarkable fossils are preserved in calcium phosphate, and are present in such abundance that they are often the main constituent of the rock. But the icing on the cake is that, in the Doushantuo rocks, quantity goes hand in hand with quality. The detail of preservation can be staggering, with features such as cell nuclei and subcellular vacuoles — membrane-bound compartments — being observed[2].

The embryos were originally identified as colonies of green algae, but were later classified as animal embryos because of their comparatively large size (typically just under a millimetre in diameter), and because the cell walls show evidence of distortion in response to the division of their neighbours, suggesting that they are not rigid, as algal cell walls would be[1,4]. More specific evolutionary relationships to sponges and arthropods have been mooted, but definitive evidence has been lacking.

*This article and the paper concerned[3] were published online on 20 December 2006.

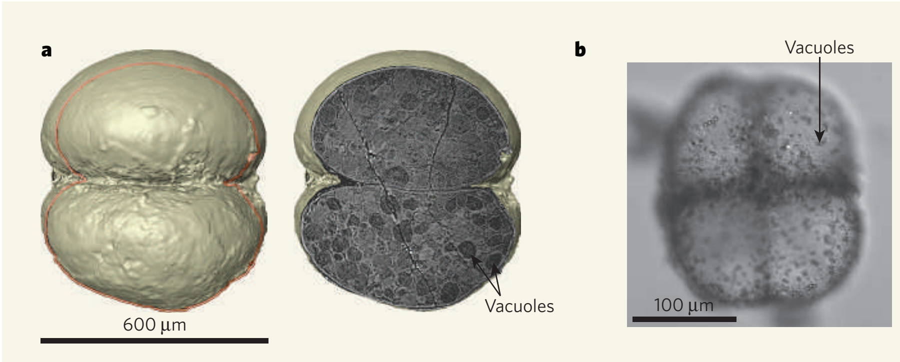

Figure 1 | Fossil embryos? a, *Parapandorina* fossils from the Doushantuo region of southern China have features akin to those of animal embryos. This image of a two-cell *Parapandorina* 'embryo' was derived using X-ray microtomography. The virtual cross-section reveals the component cells separated by walls. The cells' interiors are dominated by what seem to be membrane-bound vacuoles or yolk particles. (Images courtesy of P. C. J. Donoghue.) **b**, Bailey *et al.*[3] suggest that the fossils could be bacteria similar to *Thiomargarita* (pictured), which exhibit some of the same features as animal embryos. The bacterium shown has divided into four cells, in which the vacuoles are clearly visible. (Image from ref. 5.)

Bailey *et al.*[3] now show that, although *Parapandorina* and *Megasphaera* may not be algae, the features thought to be indicative of animal embryos could just as readily be those of bacteria. This is based on comparisons with *Thiomargarita* — giant sulphur bacteria that live in seafloor sediments along the Namibian coast and in the Gulf of Mexico. For instance, the pattern of cell division in *Parapandorina* is conventionally interpreted as cleavage. But this pattern is also seen in *Thiomargarita*, where it represents successive rounds of cell division. This results in clusters of two, four and eight cells[5] with geometries identical to those of *Parapandorina*[3]. *Thiomargarita* is also as large as the Doushantuo fossils, and, like *Parapandorina*[2], its cells are densely vacuolated[5,6] (Fig. 1).

Intriguingly, *Thiomargarita* is capable of controlling phosphate mineral precipitation[6], so Bailey and colleagues' theory[3] provides an obvious source for the phosphate that is so abundant in the Doushantuo Formation and that preserves the fossils themselves. Together with evidence that *Thiomargarita* rarely progresses beyond a few rounds of cell division, this goes a long way to explain why fossils with few cells are so abundant in the Doushantuo phosphorites, and why adult specimens grown from the 'embryos' are apparently absent. Such issues are difficult to explain with the animal-embryo interpretation.

But equally niggling problems remain with the bacterial explanation of *Parapandorina* and *Megasphaera*. *Thiomargarita* has not been shown to undergo more than three rounds of cell division, whereas specimens of *Parapandorina* can be composed of more than a hundred cells[2], suggesting at least seven cleavage events. Furthermore, cells of *Parapandorina* and *Megasphaera* cluster together in an enveloping membrane[4]; although cells of some species of *Thiomargarita* also cluster in a sheath, the species that best simulates the early cleavage stages of animals does not[5]. And although densely packed vacuoles are a feature of the Doushantuo fossils and the sulphur bacteria, in *Parapandorina* they are present throughout the cells[2], whereas in *Thiomargarita* a dense layer of vacuoles is restricted to a thin cytoplasm surrounding one large, central vacuole[5,6]. Finally, bacteria don't possess cell nuclei, so the observation of preserved nuclei in *Parapandorina* is hardly compatible with Bailey and colleagues' proposal.

No matter. Such quibbles do not diminish the central message of the authors' report, which is that, like all other theories about Precambrian animals, the classification of these fossils is far from resolved, even at the kingdom level. More data and critical analysis of the Doushantuo biota are required, such as that already provided by X-ray microtomography[2,7]. Only then can we assess whether any of its fossils address such overarching questions as the timing and embryological basis of animal origins. ■

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PARTICLE PHYSICS

Hard-core revelations

Frank Wilczek

Our description of how the atomic nucleus holds together has up to now been entirely empirical. Arduous calculations starting from the theory of the strong nuclear force provide a new way into matter's hard core.

Our quest to understand the force that holds atomic nuclei together has turned out to be a glorious adventure. Along the way we have found quarks, the coloured gluons that mediate the strong nuclear force, and a wonderful theory — quantum chromodynamics, or QCD. This theory has guided experimental research at the high-energy frontier, inspired dreams of 'unified field theories' that would embrace all nature's forces, and allowed theoretical physics to penetrate into the cosmology of the early Universe. In all this, the original problem of understanding nuclear forces has rather fallen by the wayside. That changes with what may come to be seen as a landmark paper by Ishii, Aoki and Hatsuda that has recently appeared on the arXiv preprint server[1].

Ironically, from the perspective of QCD, the foundations of nuclear physics appear distinctly unsound. Famously, nuclear physics is best understood by modelling atomic nuclei as assemblages of protons and neutrons moving at much less than the speed of light. Yet QCD tells us that protons and neutrons are themselves built from quarks and gluons that move at very nearly the speed of light. These more basic particles carry colour charges, leading to the additional requirement that they be confined within 'bags' whose contents are overall colour-neutral. So far, so good: we understand, at least roughly, how an unbalanced colour charge produces a growing cloud of virtual particles (the process known as vacuum polarization), which has to be neutralized. The neutral cluster holds together as a unit, like marbles in a bag.

But why don't the separate proton and neutron bags in a complex nucleus merge into one common bag? On the face of it, the one-bag arrangement has a lot going for it. It would allow quarks and gluons free access to a larger

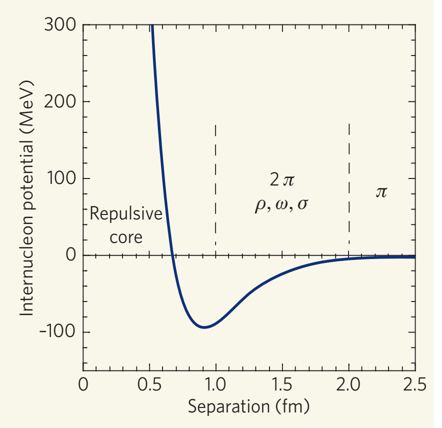

Figure 1 | The nucleon–nucleon potential. At distances of a few fermi, the force between two nucleons is weakly attractive, indicated by a negative potential. According to Hideki Yukawa's model[2], this force is mediated by the exchange of particles known as mesons. The π-meson, or pion, the lightest of the mesons, accounts for the attractive force at the largest distances where it is felt, whereas heavier mesons (ρ, ω, σ) take over closer in. The picture changes abruptly, however, below a separation of just under 1 fermi. Here the force becomes strongly repulsive, preventing nucleons merging. Ishii *et al.*[1] provide the first theoretical calculations from quantum chromodynamics, the theory of the strong force, that reproduce the empirical form of this potential.

region of space, and so save on the energetic cost of localizing their quantum-mechanical wavefunctions. But in such a merger, protons and neutrons would lose their individual identities, and our traditional, quite successful model of atomic nuclei would crumble. What prevents that calamity?

We gain insight into this question by approaching it from the bottom up. Assuming that nucleons (protons and neutrons) are the appropriate starting point, what properties lead them to bind into atomic nuclei but to shun more intimate mergers? At an empirical level, the answer has been known for decades. The strong (that is, non-electromagnetic) internucleon force becomes significant at distances below a few fermi (1 fermi is 10^{-13} centimetres). It remains attractive down to about one fermi, but, at shorter distances, very strong repulsion abruptly sets in (Fig. 1). In atomic nuclei, nucleons arrange themselves close enough to take advantage of the attraction, but they stay away from the notorious hard core. In particular, they do not merge.

This empirical 'answer' serves only to frame more questions. Does the fundamental theory produce a force like that? If so, why? As originally proposed by Hideki Yukawa[2], the longest-range part of the strong internucleon force can be attributed to exchange of the lightest strongly interacting particles, known as π-mesons or pions. At shorter distances, exchanges of heavier mesons become important. As we approach hard-core distances, however, this meson-exchange picture becomes both unwieldy and dubious as the number of relevant mesons grows and their internal structure becomes resolved. Thus the existence of the hard core, which is absolutely crucial to the structure of matter as we know it, appears as a brute fact, opaque to theoretical analysis.

In principle, the equations of QCD contain all the physics of strong internucleon forces. But in practice, it is extremely difficult to solve the equations and calculate those forces. Ishii and colleagues' breakthrough calculation[1] required sophisticated algorithms, running on the biggest and fastest massively parallel computers currently available.

Why are the calculations so difficult? The main reason is simply that nucleons are complicated objects. It is often said that protons (and neutrons) are made from three quarks. That statement contains a kernel of truth, but it is a gross oversimplification. The kernel of truth is that a proton has the same conserved quantum numbers — charge and spin — as three quarks: two up (u) quarks and one down (d) quark, uud. Because these conserved quantities match, you can produce a proton by introducing three quarks and letting them settle down into a stable state of low energy.

In the process of settling down, however, the bare quarks dress themselves with a host of additional gluons and quark–antiquark pairs. Thus the wavefunction for a proton contains components with different numbers of gluons and quark–antiquark pairs, in addition to the basic three 'valence' quarks. To do that wavefunction justice, many different components must be sampled, and within each component the spatial distribution of its constituent quarks, antiquarks and gluons must be computed. The quantum-mechanical proton can contain all those configurations simultaneously. Existing