Dinosaur with a Heart of Stone

Comparative anatomists since the time of Richard Owen (*1*) have observed that birds and crocodilians have a four-chambered heart and have speculated that such a heart was present in extinct archosaurs as well. Until recently, no direct evidence of the cardiovascular system had been reported in any archosaur fossil. Fisher *et al*. (*2*), however, using computerized tomography (CT) scanning, reported the discovery of a four-chambered heart with a single systemic aorta within the chest region of a dinosaur fossil dating from the Cretaceous. Even more surprising, the specimen reportedly was collected from channel sandstones of the Hell Creek Formation, a fluvial setting that rarely preserves soft tissues. Examination by one of us (Rowe) of the specimen in the North Carolina State Museum of Natural Science and examination of the CT imagery (*3*), however, lead us to conclude that the object is not a fossilized heart but an ironstone concretion. Such concretions are commonly found in Upper Cretaceous fluvial sediments of the North American western interior, often in association with dinosaur bones.

To explain preservation of the supposed heart, Fisher *et al*. (*2*) suggested that the object was saponified in anaerobic burial conditions and then permineralized by goethite as iron-bound oxygen in the muscular walls contacted groundwater during early diagenesis. Although soft tissues are occasionally preserved in stagnant anoxic environments (*4*, *5*), bacteria in the oxygenated waters of river channels rapidly degrade such tissues. Permineralization of soft organs is virtually unknown in these sedimentary environments.

Spheroidal goethite concretions, moreover, are never primary, but rather form by near-surface oxidation of siderite concretions in shale and sandstone. Siderite concretions form in the dysaerobic shallow burial zone, centimeters to decimeters below the water table, as iron-specific bacteria reduce ferric oxyhydroxides (*6*) contained in clays, detrital grains, and other riverine sources. In the absence of seawater or other sulfide-rich pore fluid, ferrous iron generated in the dysaerobic zone can combine with carbonate to form siderite. Carbonate can be generated in fluvial environments by bacterial oxidation of organic matter close to the surface or by the oxidation of slightly deeper, bacterially generated methane. Spheroidal siderite concretions apparently nucleate around concentrations of microbes and grow slowly, by diffusive supply of components (*6*). The only known instance of rapid growth is from the cathodic corrosion of iron ordnance from World War II, which generated concretions 40 cm in diameter in 50 years (*7*). Modeling suggests that it takes millions of years to form concretions the size of the hypothesized heart by diffusive processes (*8*). Siderite oxidizes quickly into goethite in oxygenated groundwater. It is unlikely, therefore, that a dinosaur heart could become fossilized in fluvial sediments before bacteria could consume it, and it is even less probable that it could be directly permineralized by goethite.

Although CT imagery of the concretion has revealed internal cavities reminiscent of the ventricular chambers of a four-chambered heart, the object exhibits none of the other anatomical structures of an actual heart. Its supposed ventricular portion engulfs the eleventh rib and lies partly outside of the thoracic cavity. The right cavity interpreted by Fisher *et al*. as a ventricle is almost completely closed; only its "interventricular" wall is penetrated, by complex fractures containing lower density materials. Their shape and position are entirely unlike the single, oval foramen of Panizzae of extant crocodilians, which affords a pulmonary shunt during prolonged periods underwater. There are no atria, coronary arteries, cardiac veins, pulmonary vessels, or vena cavae.

The structure identified as an aorta lies within the thoracic cavity, but its lumen is completely enclosed by the same concretionary mass that encloses the supposed ventricles. The lumen is irregularly shaped, with several blind diverticula protruding at the caudal end, and, unlike a true aorta, it narrows approaching the interpreted left ventricle. No carotid, subclavian, or other arteries emerge from it.

Finally, the lumen of the interpreted ventricles and aorta is entirely encapsulated, yet it is reportedly full of iron-free quartz silt. In cross section, the walls are built from concentric layers marked by different densities and fracture patterns. Behind the right femur is a second concretion preserving apparent remnants of original bedding planes. All of these features are consistent with the identification of the structure as a spheroidal concretion.

Ironstone concretions are notorious for producing suggestive and misleading shapes. A specimen from the Lower Permian of Texas, for instance, was widely accepted to be the oldest amniotic egg (*9*), until more sophisticated analyses revealed that it lacked the mineralogy and microstructure of verified amniote eggshell (*10*). The object studied by Fisher *et al*. (*2*) likewise fails both geological and anatomical tests of its unprecedented identification.

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Response: Rowe *et al*. speculate that the object that we interpreted as a heart (*1*) is an ordinary ironstone concretion. A casual inspection of its structure, however, indicates that it is a sandstone concretion, and its occurrence and our more extensive examinations support our original interpretation.

Rowe *et al*. question the preservation potential for soft tissues in the fluvial deposits of the Hell Creek Formation. Notwithstanding the implication of Rowe *et al*., however, soft tissues of dinosaurs have been reported from the Hell Creek Formation, including beaks (*2*), cartilaginous extensions of vertebral spines (*3*), and sternal ribs and costal plates (*1*). Since the publication of the Fisher *et al*. study (*1*), structures resembling blood vessels have been found preserved in sandstone closely associated with a Triceratops skull (*4*). Dinosaur "mummies" draped in skin impressions have been found in channel sandstones of the contiguous Lance Formation (*5*).

Rowe *et al*. suggest that the object we have interpreted as a heart is instead an ironstone concretion. Irregular, poorly delimited ironstone concretions containing abundant plant debris can indeed be found at a horizon several meters above the one at which the thescelosaur skeleton was found; no such concretions occur in strata adjacent to the skeleton, however. By contrast, the concretion studied by Fisher *et al*. is intimately associated with the skeleton, in a manner unlike that of any other concretion in the vicinity of the site or reported from Upper Cretaceous strata elsewhere in the western interior of North America. A rib in the front of the chest, on the undersurface of the skeleton as buried, contacts the concretion and is partly embedded in it.

Concretions often form around an organic residue (*6*), and it is logical to suspect that organic residues derived from the decaying thescelosaur constituted the nucleus of the object studied by Fisher *et al*. The configuration of the rib embedded in the concretion suggests that those residues were displaced toward the lower part of the skeleton. Another, smaller and less deeply colored concretion lying in close proximity to the pelvic area may also have formed around organic residues derived from the decaying animal. CT imaging of this concretion has not been completed, but initial inspection shows no evidence of bedding plane preservation.

CT imaging has allowed identification of structures embedded within the chest concretion that are consistent with the shape, volume, position, and orientation of the more muscular portions of a heart (ventricles and aortic arch). It is logical to suspect that the structures formed the nucleus for the peculiar concretion that surrounds them. Permineralization of the structures is not implied, because organic residues may have initiated the mineralization of cements within the concretion. Time scales of months to tens of years—not millions of years, as Rowe *et al*. maintain—are common for many types of concretions (*7*).

The concretions submitted to museum curators are usually simple shapes (they are often suspected of being fossil eggs) and are seldom subjected to CT scanning to the same extent as the concretion studied by Fisher *et al*. (*1*). No tubular structure associated with two contiguous ovoid structures has ever been reported within a concretion in such intimate association with a dinosaur skeleton before. Identification of the object as a fossil dinosaur heart need not assume structural identity with a crocodile heart or the preservation of relatively thin-walled structures. We continue to pursue our investigations of this unusual fossil.

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