NATIONAL CENTER FOR CASE STUDY TEACHING IN SCIENCE

It's a Crocodile! No, a Fish! No, a Dolphin!

Interpreting Evolutionary History from Fossil Evidence

by
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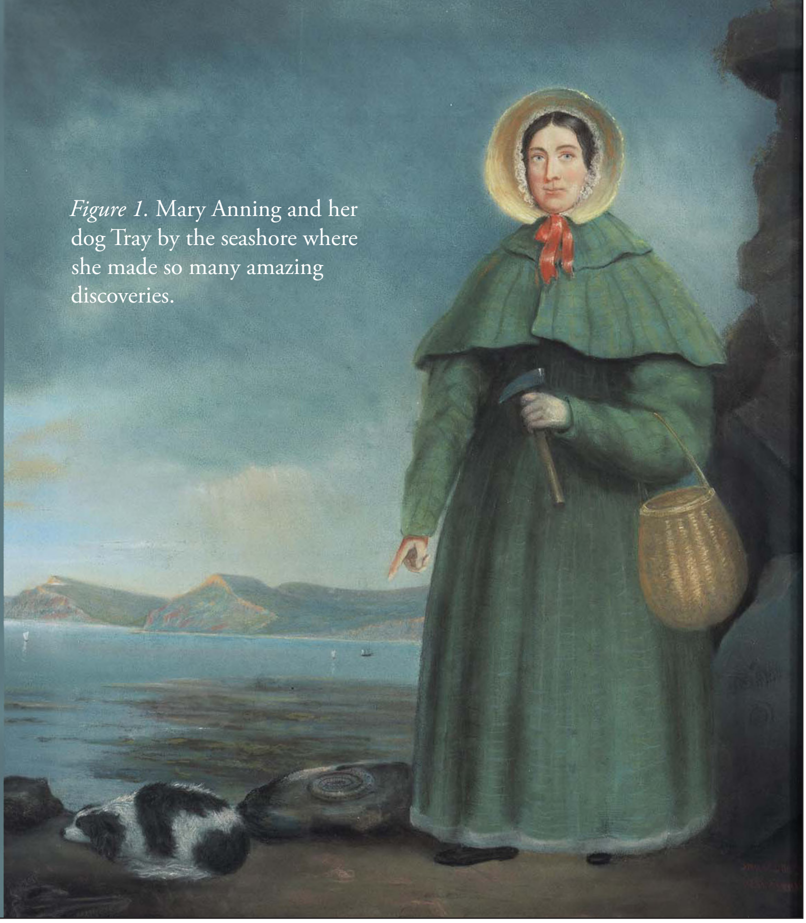


Figure 1. Mary Anning and her dog Tray by the seashore where she made so many amazing discoveries.

Part I – A Very Confusing Fossil

In 1811, a 12-year-old girl named Mary Anning (Figure 1) was the first person ever to collect a fossil like the one depicted in Figure 2 (UCMP, 2006). Her brother Joseph actually found the fossil near the family home in southwest England, but Mary did the skilled, painstaking work necessary to remove the entire specimen from the rock surrounding it.

This contribution of Mary's to paleontology was not a fluke. She discovered and excavated numerous other important fossils during her life (UCMP, 2006; BBC, 2014). Her finds were often exposed by storms that made the going treacherous. Mary's father, who taught her about fossil hunting, died in a fall the year before she found this specimen, and Mary's dog died in a later landslide that almost killed Mary too (BBC, 2014).

Mary was well known for her fossil finds during her lifetime (Lyme Regis Museum, n.d.), but she has been largely forgotten since. She was female and from the lower class, and both these factors caused scientists at that time to assume she was ignorant and unskilled. (Such prejudices unfortunately persist today.) Mary taught herself to read and write, and then learned paleontology on her own (BBC, 2014). Men to whom she sold her fossils in order to make a meager income published the findings, "often without even mentioning her name" (McGowan, 2001, p. 20). In fact drawings such as Figure 2 usually carried the signatures of men and it is their names that are better remembered.

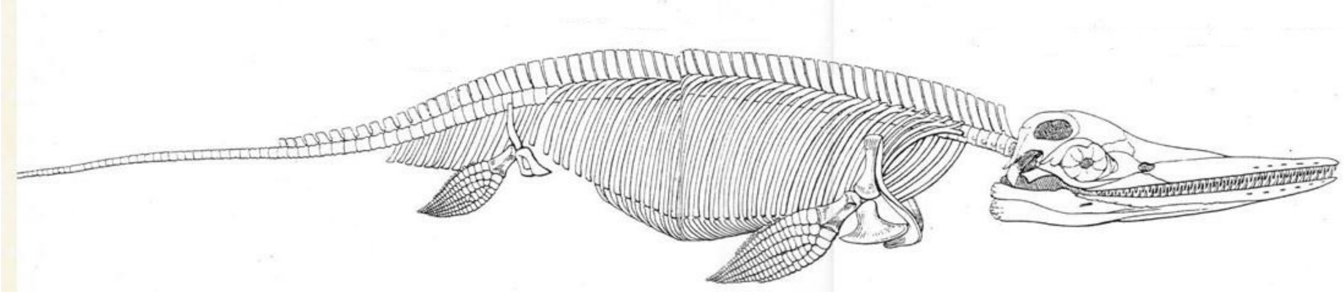


Figure 2. A drawing of the unknown fossil by Conybeare (1824). [*Note:* The crease in the center is an artifact of the scanning process where the drawing spanned the spine of the book; it does not appear in the original drawing.]

Mary Anning's opinion on the type of animal this fossil represented has unfortunately not been preserved. But we know that scientists were quite confused by it. Some thought this type of animal was most similar to dolphins or sea lions. But,

> *"Sir Everard Home, … who first studied [the fossil], initially thought it was a new kind of crocodile. Then he thought it was a fish, … later … concluding it to be an amphibian, intermediate between salamanders and lizards" (McGowan, 2001, p. 23).*

Questions

1. Based on Conybeare's drawing and Home's description, do you think this animal walked on land, flew in the air, or swam in the sea? It does look very streamlined, with flipper-like appendages, but remember, so does *Tiktaalik*.

2. What type of animal do you think this was that could be mistaken for a crocodile, fish, marine mammal, or salamander-like creature? You might have more than one guess.

3. How could you support or refute your ideas? What further evidence do you need? What type of evidence is available from fossils, if that is all you have to go on?

Part II – The Scientific Method

A: The "Typical" Scientific Method

How might scientists like Sir Everard Home (the first person to describe one of these fossils, as confused as his interpretation was) or ordinary people like Mary Anning determine what type of animal it was? With the scientific method, of course! Textbooks and instructors often teach a "typical" scientific method, even though in practice the method varies by the scientist using it and the occasion on which it is used.

Questions

1. What are the first few steps of "the scientific method" as you have learned them?

2. What is a hypothesis and how is it typically tested?

3. What are some important characteristics of scientific experiments?

Part II – The Scientific Method

B: What If No One Was There? The Scientific Method without Experimentation

You might be thinking this is all very well and good, but Sir Everard and Ms. Anning couldn't do experiments on a fossil, or at least not manipulations of the organism that lived millions of years ago and became the fossil. Does that mean that their questions about the fossil weren't scientific or could never be answered? Of course not. Let's consider some other examples.

Questions

1. Are there instances when the scientific method is used without the possibility of conducting experiments? List as many fields of study as you can in which experimentation is difficult or impossible.

2. Science should be repeatable, even when experiments aren't possible, and use multiple sources of data. Crime scene investigation is an applied science and, as such, uses the scientific method. What types of data are available to a forensic scientist at a crime scene? Are the data used by forensic scientists "repeatable" or able to be verified by others? What does it mean for a detective to "use multiple sources of data"?

3. Think back to your suggestions in Part I about how to support or refute your ideas as to the identity of the fossil. Are there any parallels between your suggestions for determining that and what a detective does at a crime scene? List similarities and differences in the *methods* used.

4. Outline how you could try to support or refute your ideas about the fossil in Part I using the tools and methods familiar to you from forensic science. For example, a detective working a murder case would try to establish time of death. Is there an analogous piece of data that would be relevant to a paleontologist? What other types of data would be important?

Part III – More Evidence

Here you learn more information about the animal described in Part I so that you can use these data to support or refute your hypothesis (or hypotheses) about what it was.

This animal is often said to be "dolphin-like." This is largely because of its overall shape, seen again in Figure 2 repeated below. Sir Everard (quoted in Part I) thought it could be something like a salamander, probably for the same reason. As mentioned earlier, and as you probably saw, the head appears to be like that of a crocodile. On the other hand, the eyes seem huge compared to the eyes of that reptile. And what about fish? Don't this fossil's flippers and fins look similar to a fish's?

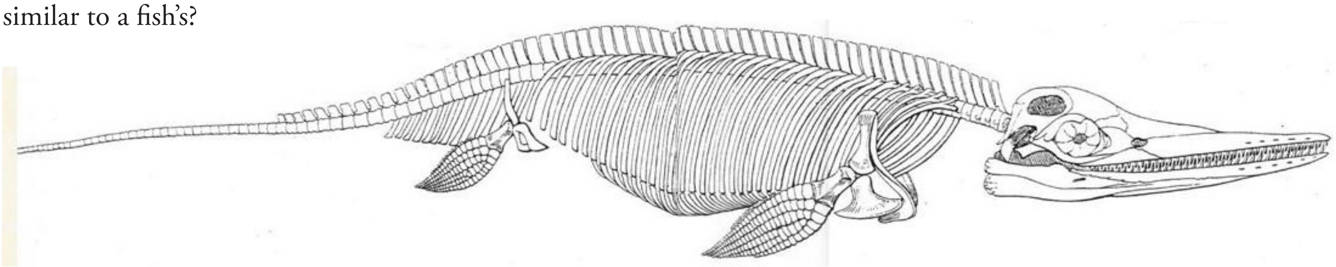


Figure 2. A drawing of the unknown fossil by Conybeare (1824).

Your task now is to determine whether this animal was a fish, amphibian, reptile, or mammal. Examine the evidence below, all describing various species of the same group. It is roughly ordered from the head to the tail of the organism.

Teeth

Teeth can be extremely helpful in the identification of animals. The images in Figure 3 show that terrestrial mammals are known for having "heterodont" dentition (different-shaped teeth, such as pointy canines and squared-off molars) while fish and reptiles tend to have lots and lots of similar-looking teeth. Amphibian teeth are not shown in the figure, but when they have teeth, they are near the front of their upper jaw only.

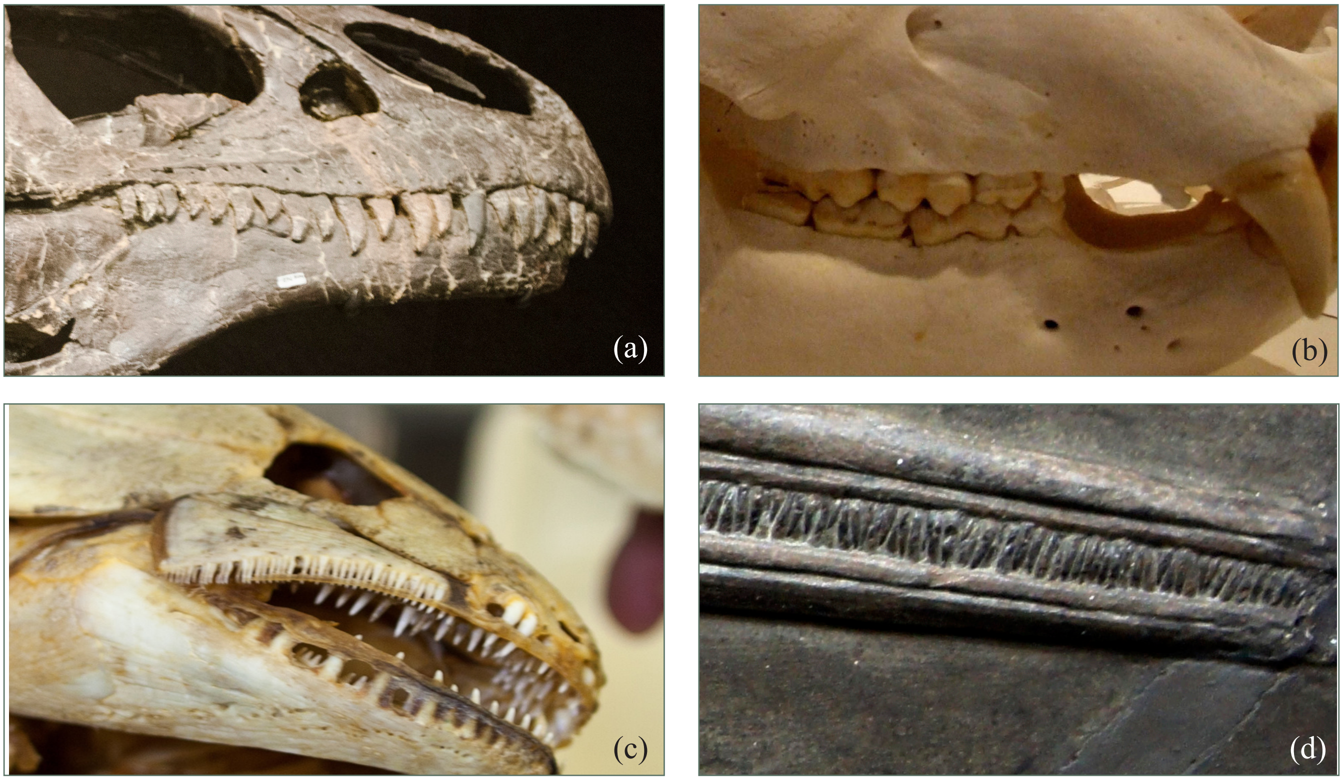


Figure 3. Dentition of various animals. (a) teeth of a reptile (Evanson), (b) teeth of a mammal (Travis), (c) teeth of a fish (Chesapeake Bay Program), (d) teeth of the fossil in question (Elmon).

Eyes

Members of this group have the largest eyes of any animal, 25 cm or more across! In Figure 4, the eye socket is outlined to make it clearer for you.

Of course, other animals have large eyes, too, as shown in Figure 5. What do the four animals with large eyes have in common, other than being swimmers?

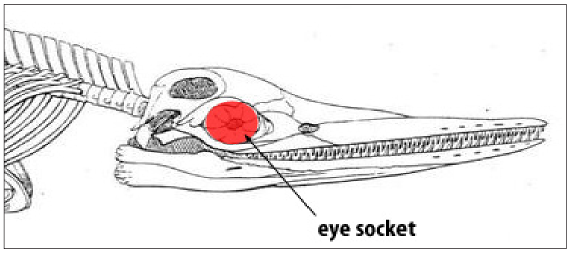
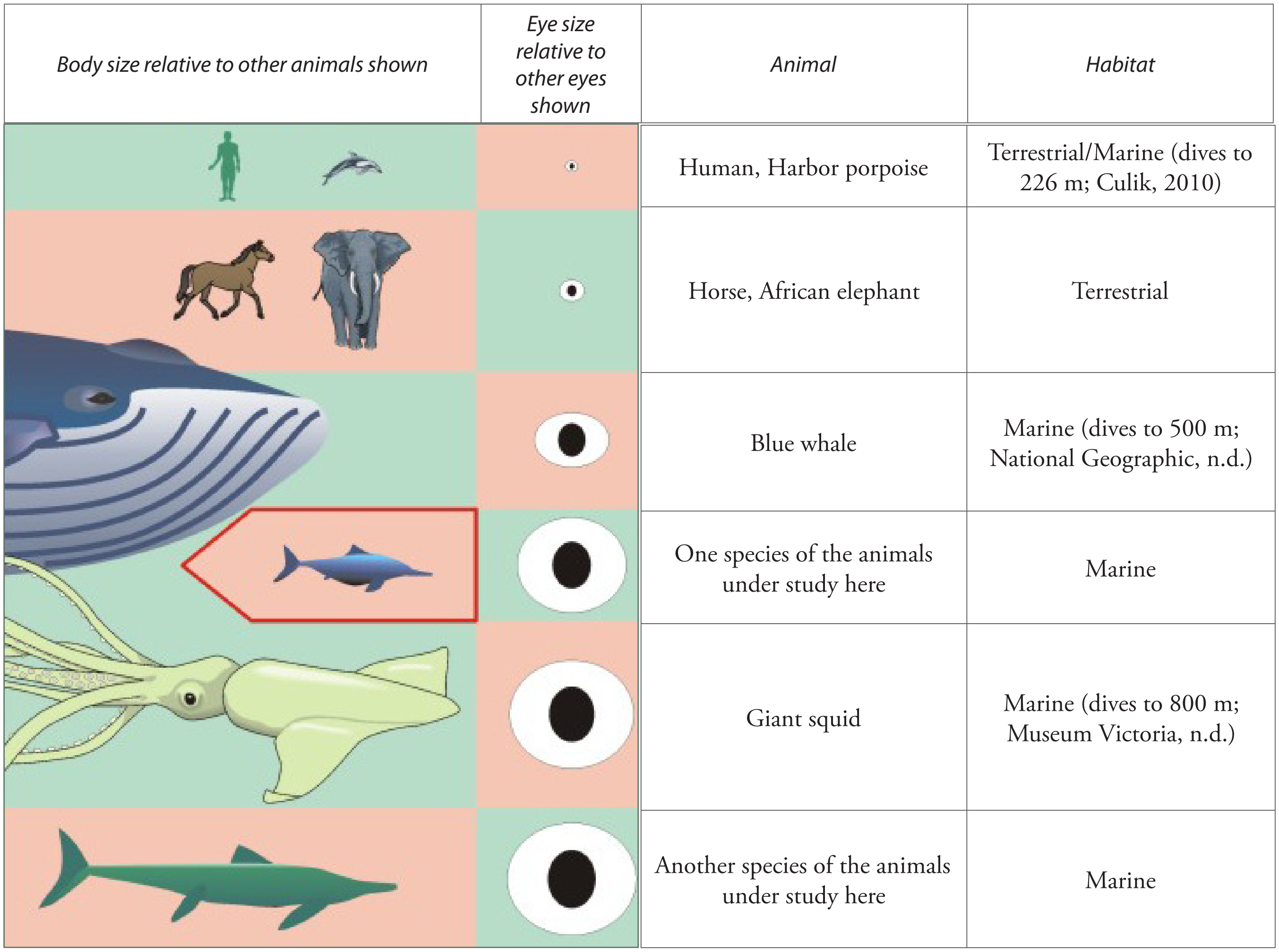


Figure 4. A portion of Figure 2, with the eye highlighted for easy reference. Other openings in the skull are temporal fenestrae (explained later).



Animal	*Habitat*
Human, Harbor porpoise	Terrestrial/Marine (dives to 226 m; Culik, 2010)
Horse, African elephant	Terrestrial
Blue whale	Marine (dives to 500 m; National Geographic, n.d.)
One species of the animals under study here	Marine
Giant squid	Marine (dives to 800 m; Museum Victoria, n.d.)
Another species of the animals under study here	Marine

Figure 5. Eye sizes of various animals (modified from Motani, 2000a).

Temporal Fenestrae

Amniotes (vertebrates whose embryos are contained in an amniotic sac, like reptiles, birds and mammals) are classified by the number and position of their temporal fenestrae. These are large openings in the skull posterior to the eye sockets that may function in elongation and expansion of chewing muscles (Tree of Life Web Project, 1996). There are three to four different patterns of temporal fenestrae and the names of the groups of animals with which these patterns are associated are shown in Figure 6.

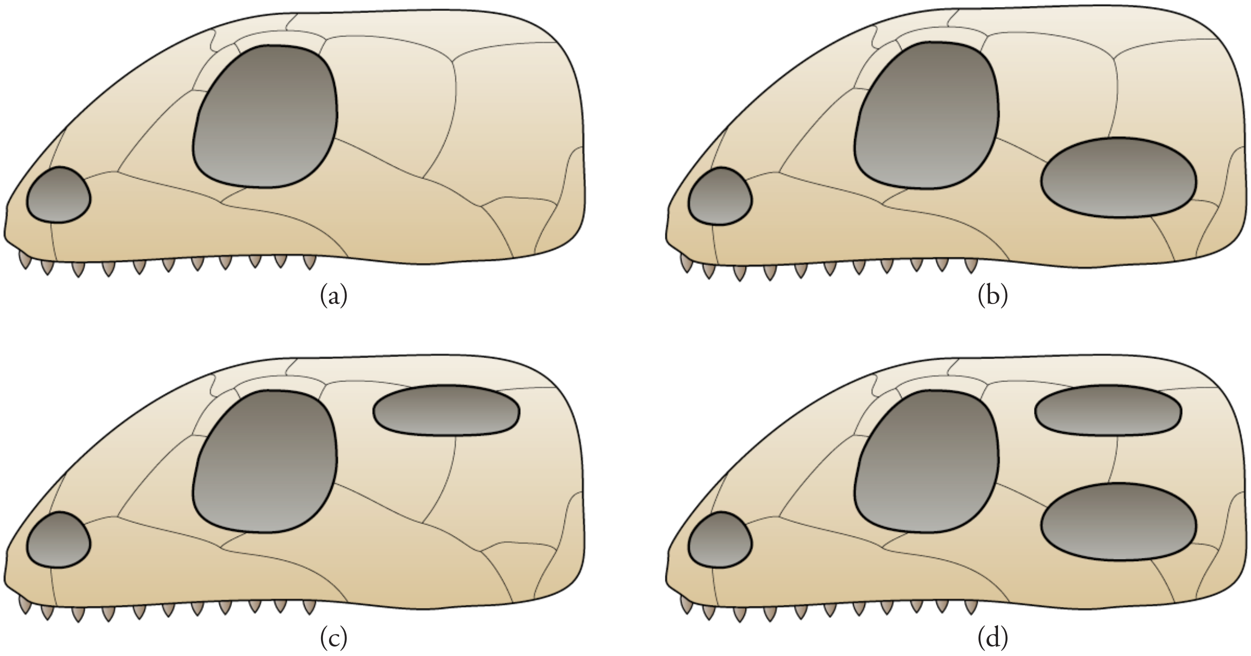


Figure 6. Temporal fenestrae of amniotes. (a) Anapsida (no temporal fenestrae—the opening you see is the eye socket); turtles. (b) Synapsida (one large temporal fenestra); mammals. (c) Euryapsida (one smaller, higher temporal fenestra); extinct marine reptiles called ichthyosaurs, plesiosaurs, nothosaurs, and placodonts. (d) Diapsida (two temporal fenestrae); many reptiles including dinosaurs and birds.

Gills

The fossil specimen does not seem to have gills, so either those structures did not fossilize well, or we can rule out the animal being a fish.

Flippers

What about the flippers? They contain the exact same pattern of bones as humans and other terrestrial vertebrates (see Figure 7). This pattern is sometimes described as "one, two, many" (referring to the humerus, radius + ulna, carpals + phalanges). How do you think this fossil's appendages compare to fish fins?

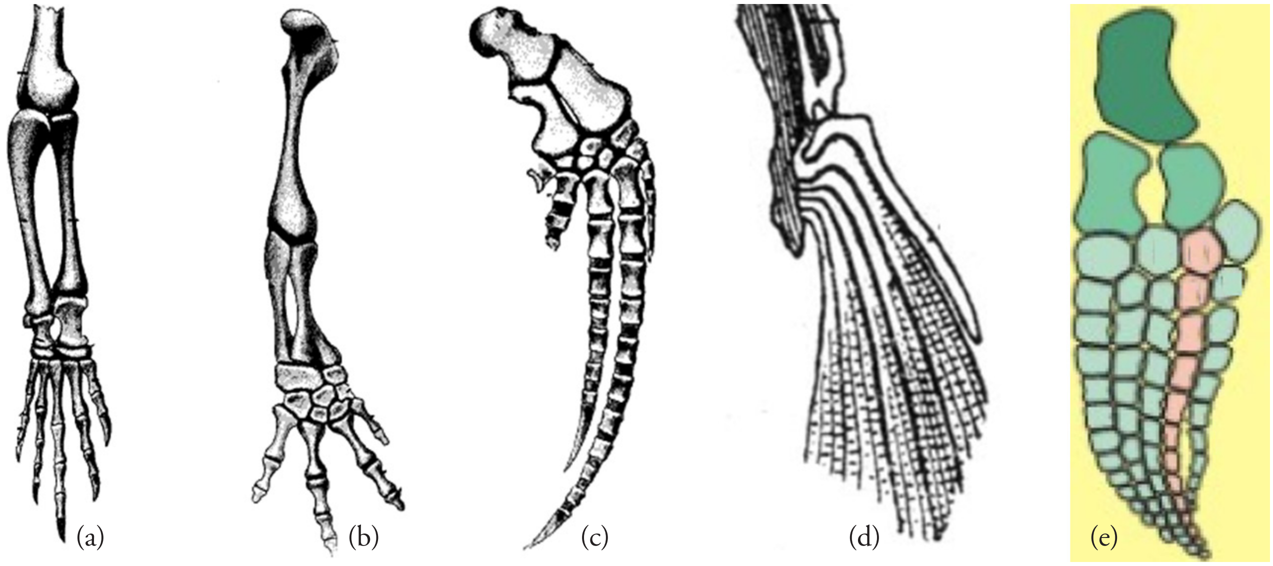


Figure 7. Forelimb anatomy of different specimens: (a) forelimb skeleton of a crocodile, (b) forelimb skeleton of a salamander, (c) flipper skeleton of a whale, (d) fin skeleton of a fish, and (e) flipper skeleton of the fossil in question.

Fins, Limbs, and Tails

While you're thinking about flippers, consider the numbers of flippers (or limbs or fins) these various animals have. Figure 8 shows that sharks have forefins and hindfins, as do the fossil specimens you are studying, while dolphins do not. However, if you examine the internal anatomy of these creatures, you see a slightly different pattern. The hindfins of fish are not attached to the vertebral column as there is no pelvis. Dolphins, on the other hand, have the remnants of a pelvis and femur, helping demonstrate their terrestrial ancestry. Crocodiles and salamanders (aquatic or not) have forelimbs and hindlimbs. As you saw in Figure 2, our fossils possess forefins and hindfins attached to scapulae and a pelvis, respectively.

The particular specimen pictured in Part I does not have a dorsal fin, but many of the species in this group do. They also have vertically-oriented tails like fish do. Dolphins' tails are horizontal.

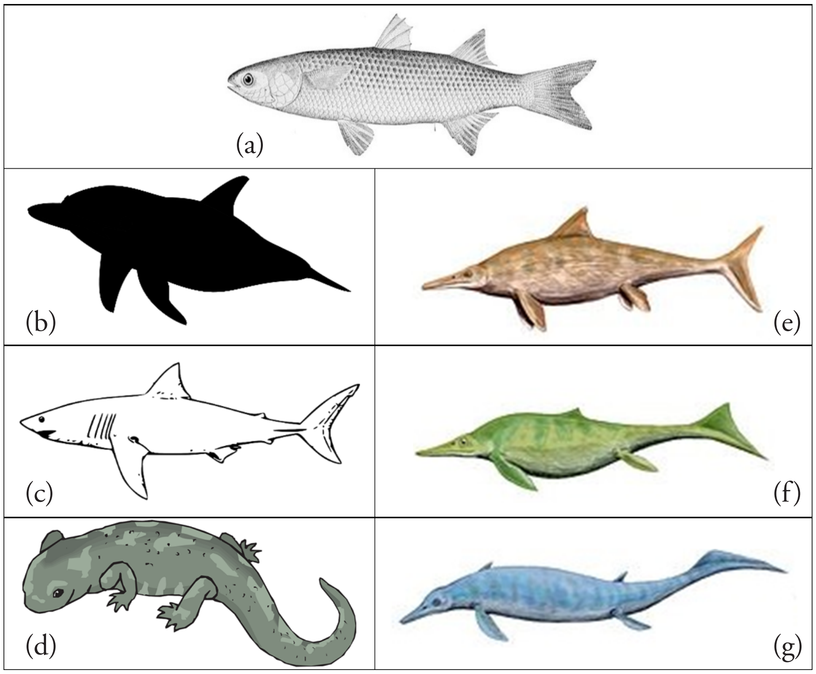


Figure 8. Body shapes of: (a) flathead mullet/bony fish, (b) dolphin, (c) shark/cartilaginous fish, and (d) salamander; (e), (f), and (g) are various shapes of the animal in question.

Diet

It also might help you to know that lots of fossils of this group have been found with squid in their stomachs. Calamari, anyone? They also ate fish.

Reproduction

The fossil shown in Figure 9 is of an animal giving birth to live young. It's a little difficult to see, but the mother's vertebral column stretches across the middle of the image, and the head of one of the babies (there are actually three!) is clear below that.

Figure 9. A fossil of the animal in question giving birth to live young (from Motani et al., 2014).

Body Temperature

A last piece of evidence that you might consider is that, based on the ratio of $^{18}O/^{16}O$ in the fossils, these animals were *endothermic* ("warm-blooded") (Centre National de la Recherché Scientifique, 2010).

Questions

1. Do you still agree with your answers to questions 1 and 2 in Part I? Explain what kind of animal (mammal, reptile, or fish) you think these fossils are and why.

2. If someone were to argue that certain pieces of evidence conflict with each other, can this be explained by convergent evolution (unrelated organisms becoming more similar through adapting to similar environmental pressures, like sharks [fish] and dolphins [mammals] both evolving a streamlined body shape)?

Part IV – The Ichthyosaur

The organisms described in Parts I and III were from the Ichthyopterygia, commonly known as ichthyosaurs. Even this name does not quite tell you what the fossil is, since it means "fish lizard," but these were indeed marine reptiles.

Ichthyosaurs originated 230 million years ago (Motani, 2000). At one time, there were dozens of species of these animals (Maisch, 2010), all of which lived exclusively in the ocean. Ichthyosaurs ranged in size from about 40 cm to a huge 20 m (Dell'Amore, 2014; Motani et al., 2015).

The extinction of the ichthyosaurs, long before the dinosaurs, is now known to have been related to climate change (Fischer et al., 2016). About 90 million years ago, the earth underwent dramatic alterations, including loss of polar ice, markedly increased sea levels, and higher sea temperatures (the last determined in part by those $^{18}O/^{16}O$ ratios discussed before). While these changes may not have directly led to the extinction of the ichthyosaurs, they likely caused fluctuations in the availability of ichthyosaur prey, and that, in combination with ichthyosaur's slow evolutionary rates, caused them to go extinct (Fischer et al., 2016; University of Oxford, 2016). This is yet another example of the amazing level of detail we can gain from fossil evidence!

For further information, you might want to check out the ichthyosaur animations shown at: **http://ngm.nationalgeographic.com/2005/12/sea-monsters/sea-monsters-interactive** (this requires Flash). The third and fourth animals profiled are types of ichthyosaurs. And in case you're wondering, the marine predator in 2015's *Jurassic World* is a mosasaur, another group of marine reptiles that came into their own after the extinction of ichthyosaurs (Ohlheiser, 2014).

Part V – Hypothesis and Theory

A hypothesis is a tentative explanation based on some knowledge of the world (prior observations), but not confirmed by repeated observations or experiments. A theory is a body of knowledge based on multiple tests of a series of related hypotheses. Theories have explanatory power; in other words, they help us understand why things are the way they are. For example, the theory of evolution helps us make sense of the fact that all living organisms use DNA and all vertebrate forelimbs follow the "one, two, many" pattern; this is because all organism have a common ancestor that used that genetic material and all vertebrates have a common ancestor with that configuration of bones. Furthermore, theories should have predictive power such that we can use them to extrapolate the existence of unknowns from what we already understand. Examples include the prediction that whales and snakes descended from four-legged terrestrial ancestors because they have vestigial femurs, and the expectation that antibiotic and herbicide resistance will continue to increase as organisms evolve in response to the chemicals. For these reasons, theories should be used in formulating new hypotheses. Well-known theories include the theory of gravity, cell theory, and the theory of evolution.

Questions

1. Given what you know, hypothesize what kind of animal might have been the most recent ancestor of the Ichthyopterygia (the whole group of ichthyosaurs). In other words, what kind of animal that was not an ichthyosaur might have given rise to this group? Would it have been a terrestrial reptile? A fish? Or something else? It may help to think back to *Tiktaalik* again: it was one of the earliest animals with tetrapod characters, and could have been the most recent ancestor of all tetrapods. Explain your answer.

2. Assume for a moment that the ancestor of the ichthyosaurs was a terrestrial reptile. Give an example of a *hypothesis* you could make, based on the *theory* of evolution, about the animals that occurred on the phylogenetic tree between these terrestrial reptile ancestors and the ichthyosaurs (marine reptiles). Remember, we call these sorts of organisms transitional forms.

3. What would it mean to the theory of evolution if the types of transitional forms you hypothesized in your answer to question 2 above were never found? What would it mean if a very different type of animal, like a mammal or a fish, were found to have lived then?

4. Based on the origin of ichthyosaurs about 230 million years ago, predict when the transitional form you described in your answer to question 2 above would have lived. Since evolution is not a linear but a branching process, there could have been considerable overlap of earlier-evolved and later-evolved forms, so this question cannot have a clear-cut answer, but you can speculate.

Part VI – Scientists' Hypotheses

Biologists wanted to put the ichthyosaurs into a larger phylogenetic tree consistent with all the observations made about them and the theory of evolution. They suggested that the ancestors of ichthyosaurs were terrestrial reptiles, based on the fact that ichthyosaurs have two pairs of limbs modified into flippers, no gills, and (something not mentioned previously) skull characteristics typical of reptiles. Even the fact that the offspring were born head-first is indicative of terrestrial origins, since air-breathing marine mammals and later-evolved ichthyosaurs have adapted over time to be born tail-first rather than take in a lung-full of water before they are completely out of the birth canal (Motani et al., 2014).

Scientists then used the predictive power of the theory of evolution to suggest that transitional forms between ichthyosaurs and their terrestrial ancestors would be amphibious (able to move both in water and on land; note that this is not the same thing as being a member of the Class Amphibia, like a salamander). It was expected that these amphibious ichthyosaurs would have lived on earth shortly before 250 mya, and since scientists know where they can find exposed rocks of that age, they searched there for transitional forms.

Figure 10. Cartorhynchus lenticarpus fossil. Reprinted by permission from Macmillan Publishers Ltd: *Nature*, (Motani et al., 2015), copyright 2015.

In 2014, Motani et al. (2015) discovered the fossil of an amphibious animal in 248-million-year-old rocks in China (see Figure 10). They called it *Cartorhynchus lenticarpus* (meaning "short snout, flexible wrists"). It is classified as an ichthyosaur because of the shapes of its vertebrae and the bones of its limbs. However, it shows characteristics of both its terrestrial ancestors and its future fully marine descendants. Its shortened nose and trunk are typical of its terrestrial ancestors (and modern terrestrial reptiles) and suggest it was a suction-feeder, like some later ichthyosaurs. Although its forelimbs took the form of flippers, they were quite long, with flexible wrists. Shorter, more rigid flippers are better for swimming, so *Cartorhynchus* probably used its flippers to prop itself up and move on land as well. It also had thicker bones than its ancestors, probably to help it fight waves in coastal areas (Dell'Amore, 2014). Overall, however, this is the smallest ichthyosaur-like animal ever discovered, with full body length estimated at 40 cm (based on the specimen length of 21.4 cm; Motani et al., 2015). Interestingly, its eyes are more in keeping with the size of terrestrial vertebrates than deep divers.

The authors proposed that the reason *Cartorhynchus* and its descendants adapted to marine life was because of predation pressure and competition for food on land. There might also have been climatic or geographic factors that caused the animals to take to the ocean. This area of China was, at the time, a tropical chain of islands.

Questions

1. Describe the steps of the scientific method as demonstrated by scientists involved in research on ichthyosaurs. You may write this out in words or use a flow chart. Make sure you discuss/show how hypotheses are refuted when experimentation is not possible.
2. What are the advantages and disadvantages when science occurs via experimentation versus observation?
3. Anti-evolutionists sometimes criticize evolution as "just a theory." Explain why this is based on a fundamental misunderstanding of scientific terminology. How did the theory of evolution provide a framework for predictions that led to the discovery of *Cartorhynchus*?
4. Another common critique of evolution is that it is "a belief system just like religion" because no one was present to observe evolutionary history and scientists therefore take these matters on faith, just as religious views are based on faith. Explain why this critique is based on a fundamental misunderstanding of the scientific method and how this method invites self-correction.

Image Credits

Figure 1: Painting of Mary Anning by B. J. Donne, 1847, made after her death, at the Geological Society/NHMPL, based on a portrait from 1842. p.d.
Source: https://commons.wikimedia.org/wiki/File:Mary_Anning_by_B._J._Donne.jpg.

Figure 2: Diagram of the skeletal anatomy of *Ichthyosaur communis*, 1824, by William Conybeare, p.d.
Source: https://commons.wikimedia.org/wiki/File:Conybeare_Ichthyosaur_1824.jpg.

Figure 3: (a) Photo of *Allosaurus fragilis* skull by Tim Evanson, flipped and cropped, CC BY-SA 2.0.
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(b) Photo of bear skull by Travis, cropped, CC BY-NC 2.0.
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(c) Photo of fish skull by Chesapeake Bay Program, cropped, CC BY-NC 2.0.
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(d) Photo of *Stenopterygius quadriscissus*v fossil by Peter Eimon, cropped, CC BY-NC-SA 2.0.
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Figure 4: Modification of Conybeare drawing; see *Figure 2*.

Figure 5: Comparison of eye sizes of various animals by Ryosuke Motani, used with permission.
Source: http://www.ucmp.berkeley.edu/people/motani/ichthyo/eyes.html.

Figure 6: Drawings of temporal fenestrae in skulls of amniotes by Preto(m), CC BY-SA 3.0.
Sources:
(a) Anapsida: https://commons.wikimedia.org/wiki/File:Skull_anapsida.png
(b) Synapsida: https://commons.wikimedia.org/wiki/File:Skull_synapsida.png
(c) Euryapsida: https://commons.wikimedia.org/wiki/File:Skull_euryapsida.png
(d) Diapsida: https://commons.wikimedia.org/wiki/File:Skull_diapsida.png

Figure 7: Comparison of forelimb anatomy.
(a), (b), and (c): Drawings by Wilhelm Leche, 1909, p.d.
Source: https://commons.wikimedia.org/wiki/File:Arm_skeleton_comparative_NF_0102.5-2.png
(d): Drawing of fish skeleton by Hubert Ludwig, 1891, cropped, p.d.
Source: https://commons.wikimedia.org/wiki/File:Fischskelett-drawing.jpg
(e): Drawing of *Mixosaurus* forelimb by Ryosuke Motani, cropped, used with permission.
Source: http://www.ucmp.berkeley.edu/people/motani/ichthyo/forefin.html

Figure 8: Drawings of body shapes.
(a): Fish by George Brown Goode, 1887, p.d.
Source: https://commons.wikimedia.org/wiki/File:Mugil_cephalus.jpg
(b): Dolphin by Clker-Free-Vector-Images, p.d.
Source: https://pixabay.com/en/dolphin-sea-mammals-swim-silhouette-306319/
(c): Shark by Clker-Free-Vector-Images, p.d.
Source: https://pixabay.com/en/shark-fish-great-white-shark-30367/
(d): Salamander by Clker-Free-Vector-Images, p.d.
Source: https://pixabay.com/en/green-big-salamander-tail-reptile-46180/
(e), (f), and (g): Various ichthyosaurs by Nobu Tamura, CC BY 3.0.
Source: https://commons.wikimedia.org/wiki/File:Ichthyosaurios5.jpg

Figure 9: Photo of maternal specimen fossil by R. Motani et al., 2014, Figure 2 cropped, CC BY 4.0.
Source: http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0088640

Figure 10: Photo of *Cartorhynchus lenticarpus* fossil by R. Motani/UC Davis, used with permission.
Source: Motani et al., 2015, http://www.nature.com/nature/journal/v517/n7535/full/nature13866.html

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