Investigate How Whales Evolved from Living on Land to Life in the Sea

Overview

Before Your Visit: Students will discuss what makes a whale a mammal and read about the placement of whales in the Tree of Life.

During Your Visit: Students will observe features and gather evidence to support the claim that the ancestors of present-day whales lived on land.

NYS Science Core Curriculum

LE 3.1a: The basic theory of biological evolution states that the Earth's present-day species developed from earlier, distinctly different species.

After Your Visit: Students will use the evidence collected from observing fossil specimens and reading labels at the Museum to write an explanation of how whales evolved from terrestrial to aquatic animals.

Background for Educators

Recent molecular and fossil discoveries show the close relationship of whales to even-toed ungulates, the artiodactyls (i.e. cow, sheep, hippopotamus). In fact, their closest relatives are hippos. The ancestors of whales lived on land about 50 million years ago. Known collectively as Archeocetes, or ancient whales, they might have moved into water in part because of environmental factors – a hot period on Earth.

Once whales adapted to water, they diversified and came to inhabit the world's oceans. Almost 80 species of Cetaceans are alive today. Scientists study both living and fossil species, and use both anatomy and genetic evidence to understand how these intelligent mammals evolved and where they fit in the Tree of Life.

Additional information about the evolution of whales:
http://evolution.berkeley.edu/evolibrary/article/evograms_03

Before Your Visit

Activity 1: Discussion of What Makes a Whale a Mammal

Ask students to work in groups of two or three to list all basic characteristics of mammals. *(Answers may include: almost all mammals have hair; they're warm-blooded; they produce milk to nurse their young)*

If whales are mammals like us, how did they come to live in the sea? Ask students to reflect on this question and write their thoughts on the board. *(Accept all answers.)*

Introduce the reading: "Onto Land and Back: Dr. Maureen O'Leary Studies Whale Evolution". Ask students to read the first half, from "Why study whales" through "What do we know about whale ancestry" (paragraph #4). Use a text code or margin codes as a reading strategy for students to look for evidence about the nature of whale evolution. Some suggestions:

P: for Evidence from physical features or morphology
M: for Molecular or DNA evidence
?: for students' questions

Plan how your students will explore the *Whales* exhibition using the worksheets.

Distribute the worksheets to the students beforehand. You may want to review the worksheets and the map of the exhibition with them to make sure they understand what they are to do.

Activity 2: Whale Features

Explain to students that they'll be observing actual-size casts of early whale ancestors to collect data about features that changed as whales evolved. Distribute the worksheets that students will use at the Museum. Have them read the questions and supply as many answers as possible for the modern whales column. *(Some answers will be found in the exhibition.)*

During Your Visit

Whales: Giants of the Deep
4th floor, LeFrak Family Gallery (30-45 minutes)

Using the worksheet, students will observe features and gather evidence to support the claim that the ancestors of present-day whales lived on land.

Wallace Wing of Mammals and Their Extinct Relatives
4th floor (20-30 minutes)

Have students visit the fossils of sea cows (Sirenians), another group of aquatic mammals. (The display is close to the mammoths). Have students closely observe features such as hind legs, pelvic bones, front legs, tail, and head, and prompt them to notice differences and similarities with modern whales. The goal is to have students recognize that the transition from land to sea has happened independently several times in the history of mammals. (Other examples are true seals, walruses, and sea lions, which are Pinnipeds in the Order Carnivora.)

If time permits, have students visit the Cetaceans alcove in the same hall. Have students notice the age, shape of the head, and the presence or absence of teeth in the fossil specimens on display.

Back in the Classroom

Activity 1: How did the whales' physical features change over time?

Make a timeline on the board from 50 million years ago to the present, with increments of 5 million years.

Use the information gathered in the *Whales* exhibition and recorded on the worksheet to create prompts such as:

- What happened to the hind limbs of ancient whales?
- What happened to the anklebones?
- What happened to the forelimbs?

Activity 2: Reading

Have students read the second half of Dr. O'Leary's essay "Onto Land and Back," from "Drawing on all the evidence" (paragraph #5) through "Whales have more to teach us" (#8). The goal is to support students' understanding of the transition from land to an aquatic habitat. Ask students to use the text code as a reading strategy.

Activity 3: Write an Explanation Task

Using the evidence gathered from the exhibition, support the claim that whales evolved from ancestors that lived on land.

Answers may include:

The evidence is changes in the skeleton during the transition from a terrestrial to an aquatic habitat. The changes can be inferred from the fossil record. For example:

1. *the change from well-developed hind legs (Pakicetus and Ambulocetus) to reduced legs (Kutchicetus), to absence of legs (Dorudon and modern whales)*
2. *the change from well-developed front legs (Pakicetus, Ambulocetus, Kutchicetus) to paddle-like flippers (Dorudon and modern whales)*
3. *the change from pelvis bones attached to the vertebrae (Pakicetus, Ambulocetus, Kutchicetus) to pelvic bones detached from vertebrae (Dorudon and modern whales)*
4. *the change from long tail (Pakicetus, Ambulocetus, Kutchicetus) to fluke (Dorudon and modern whales)*
5. *the change from nostrils at the front of the skull (Pakicetus, Ambulocetus, Kutchicetus) to blowholes on the top of the skull (Dorudon and modern whales)*

WHALES: Giants of the Deep

Grades 9-12

Student Worksheet

Working in groups of three, assign the roles below, collect the data, and fill in the chart. Be prepared to share your findings.

______________________________ Visual Tech (this person likes to pay attention to detail and will need to closely observe the fossil skeletons)

______________________________ Information Tech (this person likes reading and finding new information)

______________________________ Artist Tech (this person likes to sketch and will draw two or more features)

QUESTIONS:	Ancient Whale				Modern Whale
	Pakicetus	***Ambulocetus***	***Kutchicetus***	***Dorodus (basilosaurids)***	
How many million years ago did they live?					
Habitat (land/water)					
Does it have hoofed-animal ankle bone? (Yes or lost)		No information	No information	No information	
Are the hind limbs (back legs) developed? (Yes, reduced, no)					
Are the forelimbs "paddle-like" flippers? (yes, no)					
Does it have a elongated whale-like head? (yes, no)					
Does it have whale-like ear bones? (yes, no)		No information	No information		
Does it use jaws to improve hearing (yes, no)	No information		No information	No information	
Does it have a fluke? (yes, no, maybe)					
Do they have blow hole/s? (yes, no)					

Student Worksheet

ANSWER KEY

Working in groups of three, assign the roles below, collect the data, and fill in the chart. Be prepared to share your findings.

________________________ Visual Tech (this person likes to pay attention to detail and will need to closely observe the fossil skeletons)

________________________ Information Tech (this person likes reading and finding new information)

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QUESTIONS:	**Ancient Whale**				**Modern Whale**
	Pakicetus	***Ambulocetus***	***Kutchicetus***	***Dorodus (basilosaurids)***	
How many million years ago did they live?	*50*	*49*	*43-46*	*37-40*	*Present*
Habitat (land/water)	*Land/water*	*Land/water*	*Water*	*Water*	*Water*
Does it have hoofed-animal ankle bone? (Yes or lost)	*Yes*	No information	No information	No information	*No; because they have no hind limbs*
Are the hind limbs (back legs) developed? (Yes, reduced, no)	*Yes*	*Yes*	*Reduced*	*Very reduced*	*No*
Are the forelimbs "paddle-like" flippers? (yes, no)	*No*	*No*	*No*	*Yes*	*Yes*
Does it have a elon-gated whale-like head? (yes, no)	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*
Does it have whale-like ear bones? (yes, no)	*Yes*	No information	No information	*Yes*	*Yes*
Does it use jaws to improve hearing (yes, no)	No information	*Yes*	No information	No information	*Yes*
Does it have a fluke? (yes, no, maybe)	*No*	*No*	*No*	*Maybe*	*Yes*
Do they have blow hole/s? (yes, no)	*No*	*No*	*No*	*Yes*	*Yes*

Reading: Onto Land and Back

Dr. Maureen O'Leary Studies Whale Evolution

This essay was developed for Week 1 of the AMNH online course Evolution, part of Seminars on Science (amnh.org/learn), a program of online graduate-level professional development courses for K-12 educators.

Dr. Maureen O'Leary is an assistant professor in Stony Brook University's Department of Anatomical Sciences

1. Why study whales?
Consider these enormous, intelligent animals. They're mammals, but they abandoned dry land over 50 million years ago to recolonize the sea. And they look nothing like the land ancestors they left behind. "They've lost their hair, they've lost their hind limbs completely, and their forelimbs have been transformed into flipper-like structures that look more on the surface like a fish's fin than a forelimb," points out Dr. Maureen O'Leary, a professor of anatomical sciences at Stony Brook University on New York's Long Island. Since paleontologists such as O'Leary have discovered through their research that whales started out as dog- or pig-like animals, they can investigate how this extraordinary transition occurred step-by-step over time. "It's really exciting to study a group of animals that encapsulates so much change, because it's possible to see how evolution has modified organisms in very peculiar ways, and how much they've changed," she points out.

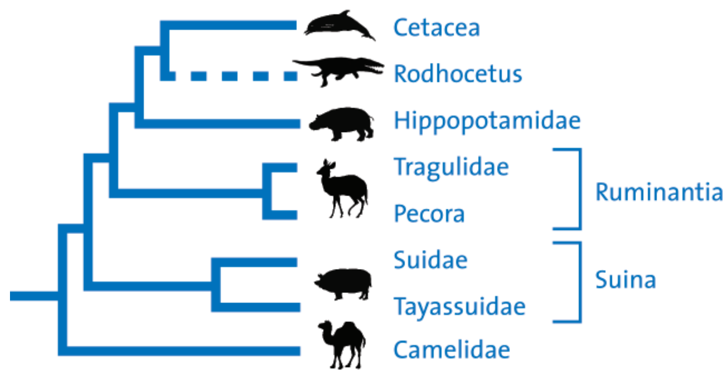
2. Fossils and DNA: two kinds of data that determine relatedness
Studying whales also happens to be something of a scientific hot potato. It's at the front lines of a debate about the tools that modern evolutionary biologists use to study the history of life. Biologists used to rely entirely on morphology—the physical features of organisms like the shapes of bones or muscles, or the presence of fins or fur—to figure out the relationships among organisms (their phylogeny, a family tree of species). Comparing similarities and differences among both living and extinct organisms enabled these morphologists to classify them into species, and to construct evolutionary trees. Then, in the 1980s, the widespread use of new tools developed by molecular biologists made it possible to study and sequence the genetic makeup of different organisms. Molecular biologists could now use DNA and other molecules to compare the genomes, or complete sets of genes, of different organisms to unravel their evolutionary histories. The more the genomes overlap, the more closely related the organisms. The availability of these two sets of information—morphological data from extinct and living organisms, and molecular data from living ones—has upset a few apple carts, because the two types of data do not always provide the same result.

3. How do scientists construct the Tree of Life?
"The best way for scientists to establish relatedness is to use modern phylogenetic methods," says O'Leary. Phylogenetics is the study of evolutionary relatedness among species. This research involves choosing at least three species and identifying heritable features, or characters, to compare across them. For morphologists, these features consist of specific physical characteristics; for molecular biologists, they consist of nucleotide sequences in the DNA of an organism. Both approaches rely on the same computer algorithms to analyze the distribution of those features.

Reading Continued

4. What do we know about whale ancestry?

Whales, dolphins, and porpoises have long been recognized as being more closely related to each other than to other mammals, and so they are united in the group Cetacea. Cetaceans are related to Artiodactyla, a group of mammals that consists of camels, deer, pigs, hippopotamuses, and their living and fossil relatives. These animals typically have an even number of digits on their hands and feet: two or four, unlike the five that humans have. Early fossil whales also had even-numbered digits on their feet, which is one of many features that suggest a relationship to Artiodactyla on the Tree of Life.



Whale Ancestry

The current understanding of molecular biologists,shown in the cladogram, proposes that whales are closely related to hippos and dolphins. © AMNH

As molecular biologists started investigating whale ancestry, they began to find DNA evidence that cetaceans were contained within Artiodactyla, rather than as a sister group to it. This means that the closest relative of whales is a specific artiodactylan—a hippopotamus—rather than Artiodactyla as a whole. In other words, hippos are more closely related to whales than either is to other artiodactylans such as pigs. By the early 90s, molecular biologists were finding more confirmation of this hypothesis while, to their great consternation, paleontologists (or morphologists), were not.

"Not only were scientific ideas changing, but scientific methods as well," O'Leary comments. Skeptical about the value of applying molecular technology to evolutionary questions, some paleontologists were reluctant to believe the molecular evidence. Part of the reason was because the anklebone in artiodactyls is distinctively shaped like a pulley on both ends, and paleontologists have long considered this to be the basis for classifying a mammal as an artiodactylan. "The belief that an organism had to have this ankle to be an artiodactylan was quite ingrained, and many paleontologists were unwilling to consider relationships supported by the molecular evidence until such a fossil was found," O'Leary explains.

5. Drawing on all the evidence

O'Leary wasn't happy about that. "The concept of having a 'Rosetta stone' character runs contrary to modern phylogenetic methods," she points out. "Paleontologists shouldn't give more weight to particular characters, nor should they assume that certain characters, like a distinctive ankle, cannot reverse. Instead, they should let the data reveal which characters ultimately inform us about phylogeny." She also thought it important to confront the fact that the fossil record contradicted the molecular data. "We can't solve scientific problems by getting rid of evidence," she maintains. "Phylogenetics forces us to back away from assumptions and look at things more baldly, to compare all the data."

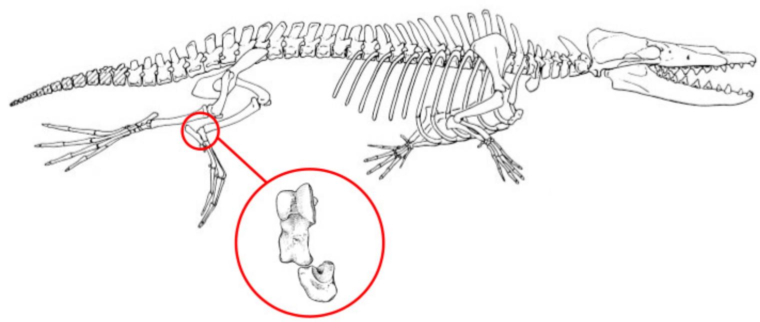
There may be good and interesting reasons why fossils and molecules sometimes appear to diverge. Over 99 percent of the organisms that ever lived are extinct, a fact that should give us pause, as O'Leary points out, because living things are just a snapshot of life on Earth. "We don't have fossils of

Reading Continued

all of that 99 percent either, but we do have a lot of fossils, and they do tell us a lot of the actual history. Reconstructing the history of life using less than 1 percent of the available data from living things alone may lead us astray."

6. A fossil find resolves a dispute—but leaves other questions unanswered

Both the fossil and the molecular record have their advantages and disadvantages, but each records the same story. Since the late 1970s, University of Michigan professor Philip D. Gingerich has been searching for evidence that would resolve the whale-evolution debate. Backbones were abundant, but hands and feet missing. Finally, in Pakistan in 2000, Gingerich discovered the 47-million-year-old fossil whales Artiocetus and Rodhocetus, the latter with a fully developed hind limb and both with ankles very much like the artiodactyls', down to the double pulley. "That's gone a long way to convincing many paleontologists that whales and artiodactyls are close relatives. It just took us a while to find the fossil," says O'Leary.

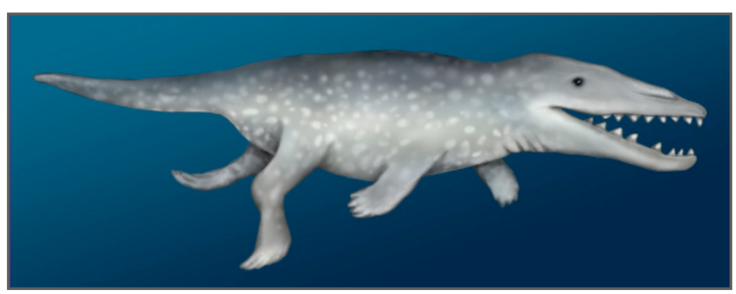


Whales With Ankles?
An illustration of an articulated skeleton of *Rodhocetus* and of the ankle bone (red), hand (green), and foot (blue) of Artiocetus.
© Philip Gingerich, illustrations by Doug Boyer and Bonnie Miljour.

Combined analyses of molecules and anatomical information produce phylogenetic trees that indicate that whales, fossil and living, are artiodactyls because they're consistent with trees based on molecular data alone. So scientists have now replaced the term Artiodactyla with the term Cetartiodactyla to describe the common ancestor of whales and artiodactylans. Still a mystery is the fact that the newly discovered ankle does nothing to reinforce whales' link to hippos. "It fits the artiodactyl group, but there's nothing that makes it hippo-like as opposed to pig-like or camel-like," O'Leary elaborates.

7. Looking for more "walking whales"

Further finds may fill in the puzzle. Recent excavations of intermediate fossils (between terrestrial and marine life forms) in India, Pakistan, and Egypt have sparked increasing interest in whale paleontology. "For example, they've found an animal not much bigger than large dog called Ambulocetus—that's Latin for 'walking' plus 'whale'—with large legs that look like they could support its weight on land. Someone without knowledge of its evolutionary history might say it looks like a crocodile or a dog, but we can tie it to whales phylogenetically because of certain features of the teeth and ear region," O'Leary recounts.



Walking Whale
A reconstruction of *Rodhocetus* with fully developed hind limbs and ankles.
Courtesy of Luci Betti-Nash

Reading Continued

O'Leary works mostly in the Republic of Mali in West Africa. The northern part of Mali is part of the Sahara Desert, but Mali was once inundated by a shallow sea that ran north to south and cut North Africa in two halves. "This means that there are now exposed fossils and rocks of marine life from about 55 million years ago, early in placental mammal evolution, in the early part of what we call the Tertiary period. It's my hope that we will ultimately find whale fossils in this area, the way paleontologists have elsewhere in Africa," she says.

8. Whales have more to teach us
Why did a group of terrestrial mammals abandon life on land for life in the sea? The answer, as scientists piece it together, has much to tell us about the pattern and process behind a major evolutionary transition. "If you can reliably, in an evidence-based fashion, place whales within the context of mammals like sheep and hippos, it's hard not to step back and say, 'Wow, it's amazing that evolution is capable of transforming an organism that much over 50 million years or less,'" O'Leary points out. "You're looking in the broadest sense at change through time, and in those terms, whales are where it's at."

RELATED LINKS

Nature: Walking with Whales
A summary of the fossil evidence that helps fill in the gaps in understanding whale evolution.
usca.edu/biogeo/studentinfo/Muizon2001.pdf

Berkeley: Introduction to Cetaceans
A brief article about whales and dolphins and their developmental history.
ucmp.berkeley.edu/mammal/cetacea/cetacean.html

Stony Brook: Vertebrate Fossil Laboratory
Get an inside view of Dr. O'Leary's research at Stony Brook University.
hsc.stonybrook.edu/som/fossil_lab/

Discovery: Walking with Prehistoric Beasts
Explore some of the ancestors to several modern species, including Basilosaurus and Ambulocetus, both closely related to whales.
dsc.discovery.com/convergence/beasts/beasts.html