5 Using Fossil Evidence to Investigate Whale Evolution

INVESTIGATION • 1–2 CLASS SESSIONS

OVERVIEW

Students examine seven illustrations of fossil skeletons of modern whales and their extinct ancestors. The fossils, along with stratigraphic representations, provide evidence with which students trace the evolution of whales.

KEY CONTENT

1. Species are related by descent from common ancestors.
2. The theory of natural selection is a scientific explanation for the fossil record of ancient life forms.

KEY PROCESS SKILLS

1. Students communicate and defend a scientific argument.
2. Students develop conclusions from evidence.

MATERIALS AND ADVANCE PREPARATION

For the teacher

Transparency 5.1, "Complete Whale Fossil Chart"
Transparency 5.2, "Whale Evolutionary Tree"

For each pair of students

set of 5 Fossil Skeleton cards, B, K, M, O, and T
2 additional Fossil Skeleton cards, A and D

For each student

Student Sheet 5.1, "Whale Fossil Chart"
Student Sheet 5.2, "Whale Evolutionary Tree"
Student Sheet 3.2, "Geologic Time and Major Events," from Activity 3

Teacher's Note: *If your students completed the SEPUP* Issues and Life Science *course, they may have done an activity similar to this one. Whale evolution is an important example of macroevolution and how paleontologists study evolution with fossil evidence. If your students did that activity, have them work through this version quickly, or just review it with them to set the foundation for investigating additional examples of macroevolution in Activity 6, "Evidence from the Fossil Record."*

TEACHING SUMMARY

Getting Started

- Introduce the question of how modern whales evolved.

Doing the Activity

- Students group whale and whale ancestor skeletons according to similarities and differences.
- Students organize the skeletons into a possible evolutionary sequence.
- Students use the claims, evidence, and reasoning argumentation to determine the placement of skeletons A and D.

Follow-up

- The class discusses the placement on the tree of skeletons A and D and what the branching points on a tree show.

BACKGROUND INFORMATION

Cetacean Evolution

While many people view evolution as a progression from taxa found in the sea to land taxa, there are quite a few instances where a lineage of land taxa evolved into sea taxa. The aquatic mammals—pinnipeds (seals, sea lions, and walruses), sirenians (manatees, dugongs, and the recently extinct Stellar's sea cow), and cetaceans (whales, dolphins, and porpoises)—all have land-dwelling ancestors. In fact, the pinnipeds are not completely aquatic and provide an example of an intermediate state during the transition from land to water.

Whales, dolphins, and porpoises make up the order Cetacea, which includes 40 genera of living cetaceans and approximately 140 genera of known extinct cetacean ancestors. The cetacean evolutionary tree, shown on Transparency 5.2, "Whale Evolutionary Tree," illustrates the relationships of the various extinct whale ancestors to the whales that exist today. Many of the scientific names of whale ancestors contain the root "cet" to indicate that these animals are related to modern cetaceans.

Animals recognizable as modern whales have been swimming the earth's seas and rivers for at least 1 million years. Their mammalian characteristics (milk production, lungs, maintenance of internal body temperature, and vestigial hair) and forelimb structure have long suggested a terrestrial origin, and now DNA evidence supports the origin. In the 1990s, fossils were unearthed that allowed the whale lineage to be traced back 55 million years to ancestors that were relatively small land-dwelling mammals. The skeleton reconstructions shown on the Fossil Skeleton Cards are from ancestral whales for which the fossil evidence allows complete drawings to be made with confidence. There are numerous other partial skeletons of other whale ancestors intermediate in age to the ones appearing in this activity, but to simplify the evidence for students, only skeletons with obvious evidence of transitional features were included.

There are two suborders of modern whales: the Odontoceti, or toothed whales, and the Mysticeti, or baleen whales. Both groups are predators that feed on other animals, but they have different feeding methods and anatomies. Toothed whales eat fish, crabs, and squid, and, in the case of orcas, seals, birds, turtles, and many other aquatic animals. Baleen whales eat mostly krill. Toothed whales include porpoises, dolphins, orcas (killer whales), narwhals, and sperm whales. Baleen whales, such as humpback, gray, fin, and blue whales, have huge mouths spanned by large sieves made of keratin that strain zooplankton from the seawater. Available evidence suggests that the toothed whales and the baleen whales descended from the same group of aquatic ancestors, the dorudontids.

The shift in habitat from land to shallow water to open ocean involved many adaptations, which occurred in large part over the 20 million years between about 55 and 35 million years ago. Note that because of the incompleteness of the fossil record, the exact time these adaptations evolved cannot be pinpointed. Similarly, the branch points indicated on Transparency 5.2, "Whale Evolutionary Tree," are only approximate inferences. These adaptations included a shift of the nostrils backward and upward on the skull associated with the lengthening of the jaws, appearance of coverings for the nostrils, streamlining of the body shape, reduction and loss of the hind limbs, transformation of the forelimbs into flippers, addition of tail flukes, modification of ears and eyes, loss of most hair, and the thickening of body fat to form a layer of insulating blubber. In general, the features of a fossil that most clearly show whether an ancestor of an aquatic mammal lived on land or in the water are those skeletal features related to breathing, hearing, and locomotion.

Modern whales have no external hind limb. Some have no pelvic or hind limb bones at all, and others have very small ones that are disconnected from the rest of the skeleton and are vestigial (except as attachment points of genital muscles). On the other hand, whale forelimbs have large, flattened out, paddle-like bones, modified for use as flippers. Whales also have adaptations to their ears for underwater hearing, and a blowhole on the top of the head instead of a nose between their eyes and mouth.

Ancestors of Modern Whales

The descent of modern whales is, so far, traced to a now-extinct group called dorudontids, with diversifying forms seen among modern cetaceans evolving during the past 35 million years. Dorudontids were about 6 m (20 ft) long and proportionally more like dolphins than whales. They had a long snout with many sharp, triangular teeth, and their forelimbs were small, flattened flippers. The rear limbs were only about 10 cm (4 in) long. They may have spent some of their time on land, perhaps for mating. Dorudontids lived during the same time period as the basilosaurids (between about 41 and 35 million years ago), and those two groups share a common ancestor, one of the protocetids.

Basilosaurids probably inhabited all oceans of the world. These enormous animals—possibly up to 25 m (80 feet) long—had snake-like bodies with very small hind legs and a pelvis, resembling mythical sea serpents more than modern whales. Their long jaws (approximately 1.5 m or 5 ft) contained cone-shaped teeth in the front, which caught and held prey, and triangular-shaped teeth in the rear of the mouth for slicing prey. Basilosaurids most likely ate fish, squid, and their own smaller cousins, the dorudontids. Basilosaurids appear to have left no descendants.

Dorudontids and basilosaurids were descendants of the small, seal-like protocetids. While no complete protocetid skeletons have yet been found, they appear to have been a widespread group, evolved to a mostly aquatic existence. These creatures had small yet well-developed forelimbs and hind limbs, which may have allowed them to waddle on land. However, they also had a detached pelvis (poorly suited to supporting the body's weight on land), powerful tails, and an inner ear adapted for underwater hearing. Protocetids were probably quick and agile hunters who preyed on smaller sea creatures. Some species had nostrils above the eyes, but none had the blowhole characteristic of modern whales.

Ambulocetids, the ancestors of protocetids, had large hind limbs and probably filled an ecological niche similar to that of modern crocodiles, which they may have resembled in form. Their fossilized skeletons have been found only in rocks of the Indian subcontinent that were formed in near-shore environments. Ambulocetids could move both on land and in water. The pelvis, like that of modern land-dwelling mammals, was fused to the backbone. They probably ambushed their prey in shallow, near-shore waters, attacking with their strong jaws and large teeth. The *Ambulocetus natans* (meaning "walking whale that swims") was about the size of a sea lion—3 m (10 ft) long and about 300 kg (650 lbs)—and probably swam similarly to a modern otter, using large hind limbs as paddles. Ambulocetids fossil representatives are about 49-million-years old.

Remingtonocetids, an odd group of animals that lived at about the same time as ambulocetids, appear to have left no descendants. Similar to ambulocetids in their large hind limbs, they differ in having smaller eyes, long and slender snouts, and widely separated ears. The ears might have been adaptations for enhanced hearing to locate prey.

Ambulocetids and remingtonocetids appear to be descendants of the earliest known whale ancestors, the pakicetids, fossils of which first appear in rocks found in Pakistan and formed around 55 million years ago. Although thought to have spent considerable time in the water, pakicetids had four fully developed legs to support their weight on land, as well as nostrils and ears typical of land mammals. Their skeletons are very similar to those of an extinct group of land mammals called mesonychids, which are thought to be a sister group to the ancestor of whales. Fossil evidence suggests that whale ancestors of that time were most likely members of a larger, less well-defined group of hoofed land mammals called paraxonians.

Claims, Evidence, and Reasoning

The claims, evidence, and reasoning approach to scientific argumentation used in this activity is based on the argumentation model first developed by Stephen Toulmin, and adapted by researchers investigating argumentation in the context of inquiry-science classrooms (see for example McNeill et al., 2006 below).

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GETTING STARTED

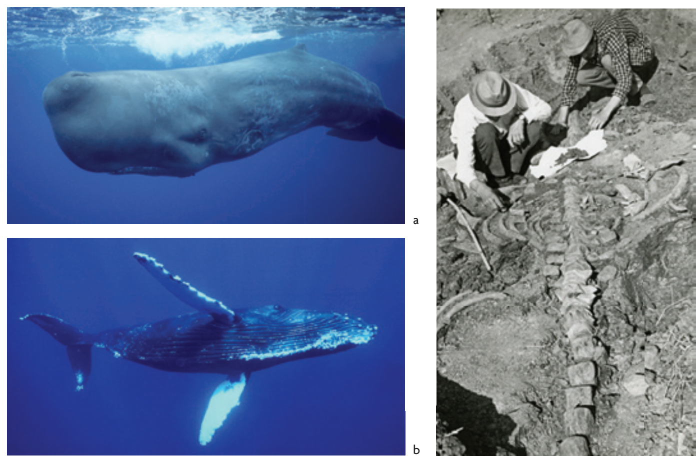
1 Begin by writing the words fish and mammals on the board. Ask students what characteristics individuals in each group have. Write those on the board. Likely responses for fish will include cold-bloodedness, gills, and fins. Likely responses for mammals will include "warm-bloodedness," milk production and nursing of their young, and lungs. If students bring up that fish reproduce with eggs, tell them that all fish come from eggs, but that in some fish the eggs hatch internally and in others the eggs hatch externally. Ask students which group they think whales belong in. Most students will know that whales are mammals. If not, explain that whales maintain a constant internal body temperature, produce milk, nurse their young, have lungs, and are classified as mammals. Tell students that in this activity they will examine fossil evidence to investigate part of the evolutionary history of whales, much as paleontologists have done, to understand how whales evolved as mammals that live in water.

5 Using Fossil Evidence to Investigate Whale Evolution

1 Living organisms sometimes leave behind physical evidence of themselves in rock, ice, tar, amber, or volcanic ash when they die. When this evidence is preserved over geologic time, it creates a **fossil.** In this activity you will use fossil evidence to investigate the evolution of whales.

Challenge

▶ How does fossil evidence determine the relationships of whale ancestors and their descendents?



a b c

Modern whales include the toothed whales, and the baleen whales. The sperm whale (a) is a toothed whale, and the humpback (b) is a baleen. This whale fossil (c), found in the northern Caucasus, Russia, dates from approximately 10 million years ago.

443

DOING THE ACTIVITY

2 Pass out sets of five Fossil Skeleton Cards, M, K, T, B, O, to each pair of students. Note that this Step is initially open-ended and that there is no single "right" answer based on the information so far. Further evidence will be made available when students reach Procedure Step 9.

Students are asked to group the skeletons into two groups of two and three skeletons. The group containing Skeleton M should be referred to as Group 1; this allows students to compare data tables easily. Most students will place M, K, and T in one group and B and O in the other.

3 If students need help distinguishing characteristics within groups and between groups, review with them an example using apples and oranges. Ask students what are the similarities between different types of apples and between different types of oranges. Then ask what are the similarities between apples and oranges.

A sample chart and Venn diagram for Steps 2 and 5 are shown below.

MATERIALS

FOR EACH PAIR OF STUDENTS

set of 5 Fossil Skeleton cards, B, K, M, O, and T

2 additional Fossil Skeleton cards, A and D

FOR EACH STUDENT

Student Sheet 5.1, "Whale Fossil Chart"

Student Sheet 5.2, "Whale Evolutionary Tree"

Student Sheet 3.2, "Geologic Time and Major Events," from Activity 3

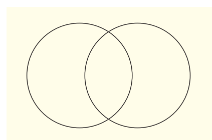
Procedure

2

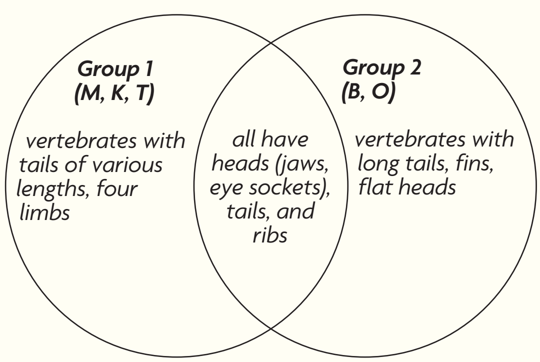
1. Compare the first set of five skeleton cards B, K, M, O, and T. With your partner, based on similarities you observe, group the skeletons into two sets, one with two cards and one with three. Name the set of skeletons containing skeleton M Group 1, and name the other set Group 2.

3

2. Create a data table in your science notebook for recording the following information:
   - Which skeletons you put into Groups 1 and 2
   - Five similarities and five differences within each group
3. In your science notebook, copy the Venn diagram shown below.



Sample Venn Diagram to Compare Groups 1 and 2



Sample Student Response: Similarities and Differences between Groups

	Similarities	*Differences*
Group 1 skeletons (M, K, T)	• *vertebrates* • *All have tails, four limbs, jaws, and eye sockets.*	• *jaws/snouts (shape of head)* • *length of tail* • *T has front limbs that are shorter, and both back and front limbs look flipper-like.* • *shape of pelvis* • *nearness of heel bones and body to the ground* • *straightness of legs*
Group 2 skeletons (B, O)	• *vertebrates* • *All have long tails, fins, similar jaws, and flat heads.*	• *relative size of head to body* • *presence/absence of teeth* • *number of ribs* • *presence/absence of hind limb bones* • *curvature of spinal column*

7. Record your arrangement of the skeletons in your science notebook. Write a brief description of the reasoning behind your placement.
8. Obtain Student Sheet 5.1, "Whale Fossil Chart," which has more information. With that information rearrange your skeleton cards if necessary. Record any changes in your science notebook.
9. Obtain Student Sheet 5.2, "Whale Evolutionary Tree." Copy that tree into your science notebook below your arrangement of the skeletons. Record any similarities and differences you notice between the tree you copied and the arrangement you described in Step 7.

4

10. Obtain the two other cards A and D. With your partner, observe the cards and discuss where to place them on your arrangement. Record your placement of A and D on the tree you drew in your science notebook. Enter the following:
    - A claim: your conclusion about the most logical placement of A and D on the tree
    - Evidence: the evidence you gathered that supports the claim
    - Reasoning: how the evidence you gathered supports the claim

5

11. Go back to the geologic timeline you constructed in Activity 3, "Geologic Time." On Student Sheet 3.2, "Geologic Time and Major Events,"
    - record whale evolution at the appropriate time it began.
    - mark the time span in which whale evolution occurred.

6

Analysis

1. What types of skeletal changes occurred during whale evolution?
2. What change (or transition) in habitat did whales' ancestors make?
3. Which fossil organism in whale evolution do you think was the first to live mostly in water? Explain your claim with evidence and reasoning.
4. Explain the changes in the skeletons during the transition in habitat, according to the theory of natural selection.
5. a. Explain what is happening at the region of the tree where remingtonocetids are observed.
   b. What can you infer remingtonocetids looked like based on the other information you have on the tree?

KEY VOCABULARY	
evidence	evolutionary tree
evolution	**fossil**

4 Explain to students that in this activity they will follow a system of scientific argumentation that can be helpful in evaluating scientific ideas and constructing scientific explanations. Explain that while scientists do not always agree, scientific argumentation or scientific argument is different than the more common use of the word argument as a disagreement. Scientific argumentation is based on evidence and reasoning. In this system, a proposed idea or conclusion is referred to as a claim. The data or facts that support the claim are the evidence. The process of thinking and making inferences, connections, and conclusions to reach a claim based on the evidence is the reasoning. Emphasize that some claims are supported by extensive evidence and logical reasoning, while at the other extreme some claims are poorly supported by evidence or are based on faulty reasoning. Scientists evaluate proposed ideas (claims) based on the quality and quantity of evidence and on the reasoning that connects the evidence to the claim.

Explain to students that they will follow this approach to scientific discussion and argument to explain the placement of whale skeletons A and D on the tree. The following is a sample student response for the claim, evidence, and reasoning for the placement of A and D.

Claim

A is placed between K and T, and D is placed between T and B.

Evidence

A still has four limbs, but the front and back limbs are beginning to look a bit flipper-like. It is lower to the ground than K. It also has a large head for its body.

D has smaller hind legs than T, a slightly smaller head compared to its body than T, and a flatter spine than T.

Reasoning

Since A's four limbs are beginning to look flipper-like and it is lower to the ground than K, it seems logical to place it next to K. Since A's limbs are not as flipper-like and it is not as low to the ground as T, it should be placed between K and T.

D should go between T and B because it has smaller hind legs compared to T, but B has no hind legs. D also has less curve in the spine compared to T but more curve than B.

5 Students should record whale evolution from approximately 55 mya to approximately 35 mya. Remind students that these times are estimates using available fossil evidence.

FOLLOW-UP

6 Project Transparency 5.1, "Complete Whale Fossil Chart," showing the complete strata data for the whale fossils. Instruct students to observe the data and check their placement of A and D. Tell students that they will next investigate in the same way that paleontologists do with these kind of data. Give students a few minutes to discuss the data and modify their trees in their science notebooks. Also, instruct students who modified their trees to write an explanation for what evidence led them to modify their placements of A and D. Ask student volunteers to explain their placements of A and D on the tree. They will likely describe the same line of reasoning that paleontologists would: that fossils in lower strata are older than those in upper strata. The evidence supports the sample student claim that A is placed between K and T, and does not support the placement of D between B and T.

Then, project Transparency 5.2, "Whale Evolutionary Tree." Write in the correct placement of fossils A and D. A sample Student Sheet 5.2 is shown at the end of this activity.

Tell students to make any corrections to the tree they drew in their science notebook if necessary. Ask them what they think is happening at the branching point of T, B, and D. The protocetids are the common ancestor for basilosaurs and dorundontids, which diverged into two separate lineages. The basilosaur lineage went extinct, and the dorudontids led to the origin of whales. Next ask which lineage on this tree was the first to go extinct. Mesonychids were the first because the lineage branches off (diverges) and ends the furthest back in geologic time.

As you discuss Analysis Question 1, introduce students to the term vestigial structures to describe the reduced pelvic bones in whales. Explain that vestigial structures do not currently serve a useful function in the species, but are remnants of structures that did serve a function in earlier ancestors. Vestigial structures that are present in two species are evidence that they share a common evolutionary ancestry.

Instruct students to write a claim, and give evidence and reasoning for their claim in answering Analysis Question 3. Analysis Question 4 is an opportunity for a Quick Check assessment of students' understanding of the process of natural selection. A demonstration of complete understanding will incorporate the three factors that drive natural selection: heritable variation, competition for environmental resources, and differential reproduction.

SAMPLE RESPONSES

1. External hind limbs were lost, and those bones were either greatly reduced or lost entirely. The skull changed size and shape in various ways. Forelimbs evolved into fins. The tail elongated due to the reduced pelvis and lost external hind limbs, and the tail vertebrae became thicker and larger. Some students might notice a much more subtle change, which is that the enlarged neck vertebrae shrank, an indication that there is no advantage to having powerful neck muscles that support the weight of the head under water.
2. The early ancestors of whales lived on land. At some point, the descendents moved into a water habitat. They had characteristics that enabled them to live in the shallow-water environment.
3. ***Claim:***
   Either B or D was the first to live mostly in water.

   Evidence:
   They either lost their hind limbs or those limbs and pelvis were greatly reduced. The tail lengthened with large vertebrae, and the forelimbs became fins. The neck vertebrae shrank.

   Reasoning:
   B and D show characteristics for swimming and life in water, such as large vertebrae in the tail and fin-like forelimbs. They also lack characteristics for life on land, such as attached pelvis and hind limbs and large neck vertebrae.
4. ✓ Originally, there was genetic variation in the ancestor population. Although they lived on land, some had larger back legs and some had smaller back legs. Those with smaller back legs survived better because it was easier for them to swim in their transition to a water habitat, and they could catch more food. They could also escape from predators more easily, which was especially important when they were young. These whale ancestors lived to produce more young, and passed on to them the heritable trait of smaller back legs. With each generation, more whale ancestors survived with smaller back legs and a better ability to swim. Over many, many generations, the average size of the back legs in the population decreased. At the same time, the forelimbs became more flipper-like and the pelvis was attached to the backbone.

5. a. The ambulocetids branched into two lineages: the remingtonocetids and the protocetids. The remingtonocetids eventually became extinct, while the protocetids continued to evolve and branch into two more lineages, the basilosaurs and the dorudontids.

   b. Based on the physical characteristics of their ancestral ambulocetids and the related protocetids, the remingtonocetids probably had long tails, legs with feet (not webbed), and teeth. It most likely could not live in water.

REVISIT THE CHALLENGE

Review with students how paleontologists use fossil evidence to investigate the evolution of whales. Analysis Question 4 serves as a good summary of the process. Bring out the idea that while fossils of all of the transitional whales may never be found, by focusing on transitional features of fossils that are found from the same line of descent, scientists can piece together evidence and logical conclusions about the evolution of whales. Students will be reading more about this in the next activity.

NAME *Sample Student Response* DATE ____________

Whale Evolutionary Tree