BECOMING WHALES

Experiencing Discoveries of Whale Evolution
OR...
"The thrill of discovery... The decline of de feet"

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http://www.indiana.edu/~ensiweb/lessons/whale.ev.html

NATURE OF SCIENCE
Basic Processes

EVOLUTION
Geological/Paleontological Patterns

SYNOPSIS

Students will experience the historical **discovery** of fossils which increasingly link whales to earlier land-dwelling mammals. This experience reveals how scientists can make **predictions** about past events, based on the theory and evidence that whales evolved. Such predictions suggest the age and location of sediments where fossils of early whales would most likely be found, and even their traits. This lesson also provides confirmation, with multiple independent lines of evidence, that there IS a series of intermediate forms, showing gradual accumulation of changes, linking certain terrestrial mammal groups with modern whales.

MAIN CONCEPTS

1. The Process of science: hypotheses lead to predictions which lead to tests which can challenge the validity of those hypotheses.
2. Transitional forms are generally a mosaic of traits, suggesting that some traits evolve faster than others.

ASSOCIATED CONCEPTS

1. New evidence can lead to major changes in scientific concepts.
2. Fossils exist of certain mammals with traits intermediate between terrestrial mammals and modern whales, showing the gradual accumulation of whale traits, and the loss of terrestrial mammal traits.
3. These fossils are found in sediments of the age and with the environmental evidence appropriate to forms transitional between terrestrial mammals and modern whales.
4. Geological events have had profound influence on the pathways taken in evolution.

ASSESSABLE OBJECTIVES

1. Students will recognize the elements of the process of science as reflected in this lesson.
2. Students will recognize the role of predictions in science, and how this helped clarify whale evolution.
3. Students will explain the evidence leading to a possible revision in the likely ancestors of whales
4. Students will give examples of the mosaic nature of evolution in whales.
5. Students will identify which whale-like traits appeared earliest, and which ones appeared later.
6. Students will explain how the tectonic movement of India into Asia caused changes in the Tethys Sea, and how those changes may have contributed to the emergence of whales.

MATERIALS

1. Classroom timeline, showing the Cenozoic era (past 65 million years; 6 pages)
2. "Whale Lengths" chart (optional, for overhead) for making full size whale strips.
3. "Some Modern Whales" (optional, pictures for cutouts and overhead); 4. "Pakicetus Variations".
5. "Family Tree of Whales" (optional, for overhead) 6. "Whales as Mammals"
7. "Provisional Phylogenetic Tree of Whale Relatives, Based on DNA Analysis" (optional, for overhead)
8. "Osmoregulation Diagram of Oxygen-18 to Oxygen-16 Ratios in Whales" (optional, for overhead)
9. "Continental Drift and the Tethys Sea" (optional). 10. "Whale Collection Sites in Pakistan" (color)

For each team:

1. Timeline of the Eocene epoch (55 to 34 mya; 2 pages): provided, or to be made by each team.
2. "Whales in the Making" page of picture strips of fossils and reconstructions of 6 whale-type mammals (to be cut apart, #1-5 placed in envelopes, and # 6 handed to teacher to hold.
3. "Discovery: Whales in Transition": Three-page Background, Procedures, Narrative, and Discussion Questions (student handout)
4. "Whale Evolution Data Table" (optional), to be filled in from resources.
5. "Origin of Whales and Power of Independent Evidence" article" (excellent resource; 9 pages).

TIME: Should require no more than about one 45 min. period, but could be extended to a second session.

TEACHING STRATEGY

This lesson can be used in three different contexts:

a. As part of your introduction to the nature of science, it will provide a novel and intriguing vehicle for exploring some of the less often appreciated elements of the process of science.

b. As part of an introduction to classification, especially when you consider organisms difficult to classify, since they don't fit perfectly into one classical group or another, depending on how the diagnostic traits of the groups are defined. Makes logical segue into evolution.

c. As part of your introduction to evolution, this presents an excellent example of transitional forms (a pattern which appears again and again in the fossil record), showing the mosaic nature of evolution, and the gradual accumulation of new traits. [Probably the **best way** to use this lesson, especially for **novice teachers**, as a low-cost alternative to the "skulls lab".]

PREPARATION

1. **TEACHER**: Prepare a **Main Classroom Timeline** of the past 65 million years (Cenozoic Era). Use a 6-foot strip of narrow butcher paper, or assemble the **pre-printed version** (see pdf files in the **Materials** section). Ideally, use the same scale as the students will use (1 inch = 1 million years). Have it marked at every million years, clearly numbered from NOW near the top, then 1 mya, 2 mya, etc. down to near the bottom end (65 mya). This will require about 65 inches (in this scale). Next, mark and label the range of each epoch ("mya" = millions of years ago):

last 10,000 years (0.01 inch) = **Holocene**	(thin black line at top)
2 mya - 10,000 years ago = **Pleistocene**	(orange)
5-2 mya = **Pliocene**	(blue)
24-5 mya = **Miocene**	(yellow)
34-24 mya = **Oligocene**	(green)
55-34 mya = **Eocene**	(red)
65-55 mya = **Paleocene**	(brown)

[This scale - 1 inch = 1 million years - is chosen for its convenient size, especially to accomodate the whale-strips used. You might prefer using metric units; if so, we recommend 2 or 3 cm per million years so the whale strips will fit. For other scales, and suggestions for a highly recommended full classroom-size timeline for the 4.5 billion year history of our Solar System, **click here**.]

Epochs: Color-in the vertical strips with different contrasting colors for the epochs to help students see the range of each epoch more clearly (see suggested colors above). Place the name of each epoch in large letters in its proper place. (Colors and names are already done in the pdf charts provided). This chart should be placed vertically in the room so students can see the full range. Their "working" timelines will just be the Eocene epoch, but they can see where it fits relative to the other epochs shown on the classroom timeline. These ranges are the currently most accurate (1999), according to the Geological Society of America.

For easy re-use, have the timeline laminated (Kinko's does this for a moderate fee), and also have your teacher-set of whale strips plastic-laminated, to which you can affix Velcro pads or double-stick tape so you can demonstrate the activity as the class does it.

2. **TEACHER**: Cut apart the 6 strips of fossil whales (or have this done by lab assistants). Put #1-5 into an envelope* for each team. Keep all #6 (Ambulocetus) strips (to hand out to each team AFTER someone in each team has drawn the whale fossil traits expected between 46 and 55 mya.)

*[A clever alternative: put each strip into its own numbered envelope, so each team gets a set of 5 envelopes, numbered in proper sequence. This would discourage students from moving ahead and placing strips immediately at their respective time levels, and encourage them to wait for the narrative description before they remove each strip from its envelope in turn, as if the fossils were being gradually "unearthed" over time, creating a sense of anticipation and real "discovery" which emulates the real sequence of discovery over many years. This would require many more envelopes, but is probably worth it! We thank **Victoria Evashenk** (ENSI 1992) for this useful suggestion.]

3. **TEACHER**: Find and display pictures of modern whales from the two living suborders: the Odontoceti (toothed whales, e.g. sperm whales, Orcas, and porpoises), and the Mysticeti (the baleen whales, e.g. the California gray whale, humpbacks, and blue whales (largest living animal, at 90 feet long). In addition, display pictures of the skeletons of a whale from each group (examples at the end of this lesson). Prepare paper strips for students to SEE actual whale lengths (see **Extensions**).

4. Prepare copies of handouts, one copy for each team.
5. Prepare copies of resource materials (one for each team), and have available as team requests.
6. Students should work in teams of 2-4
7. **EACH TEAM** prepares its Eocene timeline, using 2 sheets of notebook paper taped together end to end in vertical format, or a two-foot strip of narrow butcher paper. **Optional**: to save time, this Eocene timeline may be pre-constructed, and used repeatedly by each class (see Materials for pdf printout).
8. **TEACHER**: Come to class on the "dig day" dressed as if you were going on a paleontological dig, with wide brimmed hat, sunglasses, hiking boots, grungy shirt and pants, and your geological pick. You can even heighten anticipation by announcing the dig the day before, providing "field trip permission slips" for parent signatures (if the school normally requires these), and ask students to wear "proper fossil-digging clothes"; lunches, and cameras are optional!

PROCEDURES (Be sure to consider the suggested **introduction** described under **Extensions**, #1-3)

1. When all timelines are done, and fossils are cut out and in their envelopes, Announce "We're gong on a dig .... we're going to look for whale fossils. Are you with me???? Good, let's go!" ["Close your eyes and visualize!"]
2. One student in each team starts reading the "Discovery: Whales in Transition" **narrative** (Part C) to the team. **Optional**: teacher can read the narrative to the class, or do this from memory. As part of this, the teacher can show pictures of some modern whales: toothed whales (odontocetes), and baleen whales (mysticetes).
3. As each whale or near-whale species is mentioned, a partner in each team finds and places that strip on the team timeline at the appropriate time level. If desired, the teacher can do this, too, placing each whale strip on the classroom timeline as visual reinforcement for the class. Use the plastic-laminated timeline and whale strips, with velcro or double-stick tape for this.
4. Be sure to note that the sequence followed in the narrative closely reflects the **sequence of discovery**, so you get a real sense of the growing excitement amongst paleontologists as they found each fossil piece of the early whale evolution puzzle, gradually filling it in with specimens showing intermediate traits between their likely land-dwelling ancestors and the totally marine whales of today. **Advantages** of the teacher presenting the narrative: 1) all teams can be **paced** through the discovery together, and 2) the growing intrigue can be **dramatized**!.
5. When all 5 strips are in place, student teams **predict** what an intermediate form would look like to fill the critical gap between 50 and 46 mya. Circulate. As each team shows its "intermediate" drawing, hand them the last strip (#6) to place on their timeline and compare with their prediction.
6. When all fossils are placed in position, students answer the **discussion** questions. Be sure they discuss each question (and possible answers) with their teammate(s).
7. STUDENTS: be prepared to ask questions and join in classwide, teacher-directed discussion when done.
8. TEACHER: See the **Extensions** for tips and ideas you might want to include as part of class discussion.
9. HOMEWORK: As a possible take-home (or extra class day) assignment, students can be asked to gather more detailed information about each species (see details on student handout).

ASSESSMENT & EVALUATION

1. Ask students to list the elements of the process of science reflected in this lesson and give examples of each (for example):
   a. recognition of a problem: how did whales emerge from some land-dwelling mammal?
   b. hypothesis formation: they evolved by gradual change over time, losing tetrapod features, and gaining whale features.
   c. predictions based on hypothesis: what to look for (fossil whales with legs), where to look (Eocene sediments from warm shallow seas)
   d. searching for evidence: (digging for whale fossils in Pakistan, etc.)
   e. independent evidence of fossil sequence (oxygen isotope ratios in bones and teeth)
   f. popular "generally accepted" concepts replaced with new concepts, based on new evidence (DNA analysis and ankle features), suggesting mesonychids not ancestral to whales.
2. Build other questions (essay, or carefully crafted multiple choice) around the Assessable Objectives.

EXTENSIONS AND VARIATIONS

<u>A MOST EFFECTIVE AND ENGAGING INTRODUCTION TO THIS LESSON:</u>

The following suggestions would be very helpful, especially with younger students in middle school settings.
1. Obtain and place large **pictures** of modern whales near the top of the classroom timescale, along with their skeletons. Point out that the earliest odontocete and mysticete fossils are only about 34 my old (upper Eocene).

2. Next, demonstrate the **actual sizes** of some modern whales AND the fossil whales to be discovered. An easy way to do that is to prepare strips of adding machine tape cut to the appropriate lengths, each clearly labeled with the name of the whale represented, and its actual (average or maximum) length (in meters). This could be a fairly easy assignment for your students to do: each team could be assigned one or two of the whales, and cut off the needed length of paper strip to do this. [Teacher can provide a measuring strip of tape, marked off in cm, along a counter top to facilitate this.] Students can hold up their whale strips as they are discussed, or they can all be mounted on a wall in the room. Display or hand out the **Whale Sizes** data table with these lengths (pdf file in Materials section.)

A more convenient variation is to use **corrugated border strips** (which come in 50 foot lengths of various colors, available for a few dollars in educator's supply stores). These are pre-measured, and much more durable for re-use each period.

3. EXCELLENT INTRODUCTION: Establish or confirm that **whales are mammals**, and why we assume that they **must have evolved** from a particular group of four-legged land mammals millions of years ago. You can use the **"What Kind of Creature is a Whale?"** outline on your overhead (see pdf file in **Materials** section). The comparison of various features between whales and a fish or a cat is taken directly from the delightful online interactive experience: the "**Whale Evolution Kiosk**" (see Extensions and Variations, #13).

You could also display the picture of a **whale embryo** with a **hind limb bud!** (**click here**). You can capture the photo from that screen with your selective screen-copy function, then adjust its size with your photo handling software (e.g. Photo Deluxe, Photoshop). You could also show the picture of a **nursing whale**, and share information about **whale hair**, the most widely recognized traits of mammals.

<u>DISCUSSION EXTENSIONS AND FOLLOWUP:</u>

4. Growing out of discussion question **#3**, you might find it useful to show pictures of the ancient **Tethys Sea** which existed prior to around 55 mya between the landmass we now call India and the Asian mainland. The Mediterranean represents the westward extension of that sea, but the **continental drift** pushed India into Asia, pushing up the land mass to form the Himalayan Mountains (and Mt. Everest), and eliminating this eastern portion of the Tethys Sea. If there is an animation in your department showing **plate tectonics** (on a laser disk or CD), show it to your class, using stop action to step through the stages showing were India moves into Asia. The timing of this event coincides nicely with the Eocene, during which many long-isolated mammals on the rafting India were able to move across to the Asian mainland (and vice versa), introducing a major increase in new competitions and resulting in active selection episodes and increasing diversity. Whale evolution seems to have emerged from that geological event and the resulting biological upheavals. [See PaleoWorld video described below.]

5. During discussion question **#5**, ask for other possibilities one might expect for the body form of *Pakicetus*. Then, show the diagram of "*Pakicetus* 2", with one reconstruction found on a Greek (?) museum website, (also in the PaleoWorld video described below in #8). If possible. show the latest version on Thewissen's site (see below), based on the new post-cranial fossils. Discuss what clues might suggest the features shown here (remember, we only had skull fossils when this lesson was created, no post-cranial parts of the skeleton). Hopefully, students will point out the early whale-like teeth and ears of *Pakicetus*, so without any post-cranial bones, an artist might easily assume tail flukes. *Pakicetus* 1, shown on the strip, was found in Zimmer's book, page 203. [Pay particular attention to the whale flukes on *Pakicetus* 2; would they be there that early, especially since *Ambulocetus* probably had none?]

6. After class discussion of question **#9**, display the **Family Tree of Whales** diagram on the overhead (found on Hans Thewissen's web site, but available at end of this lesson). Note how the several archaeocetes are shown as colateral branches from the direct line of descent to modern whales. A further extension of this could be to show the **Provisional Phylogenetic Tree of Whale Relatives** (a type of cladogram) showing how whales appear to relate to hippos and other artiodactyls, based on recent DNA analyses (Nikaido, et al, 1999). The earliest mesonychids existed before the earliest artiodactyls, and cetaceans are deeply nested within the artiodactyl tree, as a sister family to the hippopotamids (suggesting that the cetaceans be re-classified as an artiodactyl family rather than their classical status as a separate order), so any connection between mesonychids and cetaceans now appears to be more remote. This close affinity to the hippo family is reinforced by the work of Gatesy, et al (1999) in which numerous DNA sequences were simultaneously analysed in several different species of cetaceans and artiodactyls, producing their "WHIPPO" data sets. See the excellent discussion of these developments in *Evolutionary Analysis* by Freeman and Herron (chapter 13). This is a chance to point out how ideas in science can change with new information and perspectives. [NOTE: This change is still not settled. Some whale scientists have shown that the DNA data are subject to different interpretaions.]

7. A very nice example of another independent line of evidence which reinforces the paleontological evidence indicates habitat changes associated with early whale evolution. This can be seen in the **Osmoregulation Diagram** showing the relative percentage of the Oxygen-18 isotope (significantly higher in the teeth and bones of marine cetaceans than in those of freshwater cetaceans). This is due to their incorporation of the particular ratio of oxygen isotopes in fresh *vs*. salt water ingested. The earliest archaeocetes (e.g. *Pakicetus* and other Pakicetids) have lower O-18 ratios, associated with a freshwater habitat, while *Indocetus* (and *Rodhocetus*), and *Zygorhiza* (*Gaviacetus*), very similar to *Prozeuglodon* and *Dorudon*, all have higher ratios, indicating a fully marine habitat. *Ambulocetus* data show a wide range of O-18 levels, suggesting they lived in a wide range of salinities, as one might expect for a clearly transitional form. The original work on this was published by Thewissen, Roe, and others in 1996.

8. If you can get a good **video** of whale evolution, it might provide further reinforcement and perhaps raise further questions for discussion. There is a useful 15 minute segment in the WGBH-**PBS-Evolution** series (first part of show #2). An older (1994) but interesting half-hour tape in the "**PaleoWorld**" series was entitled "Return to the Seas", possibly still available in a collection of their tapes, through Carolina Biological Supply. The major caution is that this video gives the impression that each of the "transitional whales" evolved into the next more recent species directly, even using "morphing" animation to show each species gradually changing form to become the next species in time, as a series of "links in a continuous chain of life", a long outmoded idea now replaced with the far more likely picture of "cousin" relationships. On the other hand, there are nice references to how the movement of India into the Asian continent caused the Tethys Sea to become shallow and saltier, creating a rich food supply for any creature able to take advantage of it, and providing a long term selective pressure favoring adaptations to specialize in such feeding opportunities in the marine environment. The result: whale evolution.

9. If you can, prepare and mount a scaled linear **Earth Timeline** around your room (for the past 4.5 billion years), with the last 540 million years somewhat detailed into the 3 major eras, and showing the main life forms characterizing those eras. You can nicely show where whale evolution fits into the total scheme of time, in relation to the age of dinosaurs, human evolution, and any of the many other events and features of geological time. The constant presence throughout the year of this timeline helps to reinforce the deep time concept, the spaced-out sequence of events, and provide a convenient focus from time to time to point out when various biological events occurred. For a few approaches to help with this, see the **other timeline lessons** on this site. As part of your introduction to geological time, be sure to consider the short lesson on **Deep Time** on the site, which explains how scientists actually measure time on that scale, and why they are so confident of its accuracy, providing a critical challenge to anyone claiming a Young Earth age of only several thousand years.

10. A question which may arise when students see that the archaeocetes seem to occupy the Eocene, and modern type whales are not found below the Miocene (on the classroom timeline of the Cenozoic), is "Why no whale fossils in the Oligocene?" You can find the answer to this in the abbreviated version of Kathleen Hunt's " **Transitional Vertebrate Fossils**" on this site. Read especially parts B-1 and B-3. Actually, there ARE some archaeocete fossils in the Oligocene, but they're fairly fragmentary. There is also a fair number of archaeocete fossils spread through the middle-to-upper Eocene, but they are clearly whales, very similar to *Dorudon*, so they weren't included in the lesson, and this seems to leave an **apparent** "gap" which doesn't really exist.

11. If your class has ready access to the internet, (especially for advanced classes), an excellent extension of this lesson is the tutorial on this site: "**Using Online Molecular Databases to Examine Evolutionary Questions**." This lesson takes the student through the process of gathering amino acid sequences of beta-hemoglobin in several different species from an online database, using an online tool to compare the differences in those sequences, then discussing what this indicates in terms of relationships. Comparing whale hemoglobin with that of other animals is part of this exercise. A **new lesson** now under development will expand this activity to facilitate student use of online genome analysis tools to compare DNA and several other proteins in whales and other vertebrates to answer questions of relationship. Check back from time to time, or **email the webmaster** if interested in this material.

12. **The latest chapter in whale evolution** was added with the publication in late 2001 of two reports which concur that, based on the analyses of newly found **ankle and heel** bones of early archaeocetes (in Pakistan), whale origins are strongly associated with the origin of artiodactyls (even-toed hooved animals). This is consistent with recent molecular studies which also suggest this close tie. Neither study specifies a closer hippopotamus connection necessarily. But both studies put the mesonychid connection as more remote than once thought. See the four articles listed below for 2001, in *Nature* and *Science* for details. The *Nature* article (by Thewissen et al)

also has excellent graphics of the post-cranial skeleton of *Pakicetus*, along with a very nice reconstruction by Carl Buell, who created the beautiful action picture of *Ambulocetus* shown at the beginning of this lesson. To see (and download) these images (available in high resolution versions), **click here**, or go to Thewissen's site listed below. Also. see the new addition to our "**Great Fossil Hunt**" lesson, a page with those *Pakicetus* fossils which are cut apart for students to "find" and reconstruct as they are found, then discover that it is an early WHALE!

13. **VISIT THE WHALE EVOLUTION KIOSK**. This is a new, very clever interactive online experience for your students, created by Lara Sox-Harris at San Jose State University, who has kindly consented to this link. When you click on the title (Whale Evolution Kiosk) above, it will take you into a self-guided tutorial on the necessary elements of whale anatomy, fossils, DNA, and classification. These will all provide the mutually reinforcing evidence for whale evolution, all in delightful animations and interactions. If the link doesn't work, check with the **ENSI web master** for the latest URL. To give your students a guided tour of the kiosk, providing more focus, and a means for you to confirm that they probably did a thorough visit to the site, give them the **Whale Evolution Kiosk Worksheet**. This was developed and kindly shared with us by **Gail Bromiley** of DeBakey H.S. in Houston, TX. Gail also provides a key to facilitate your discussion of the site and worksheet.

RESOURCES

Books:

Freeman, Scott & Jon C. Herron. 2001. *Evolutionary Analysis*. Prentice Hall.

Zimmer, Carl. 1998. *At the Water's Edge.* The Free Press. An excellent, recent treatment of the search for evidence of whale evolution, macroevolution in general, and some of the "behind the scenes" stories of the scientists involved. Highly recommended, for teacher and interested students.

Articles:

Thewissen, J.G.M., et al. 2001. "Skeletons of terrestrial cetaceans and the relationship of whales to artiodactyls." *Nature*, 413:217-281 (20 Sep 2001). This report hinges largely on new postcranial fossils of Pakicetus. To see excellent figures and brief descriptions, click here. (thanks to David N. Brown for this link).

de Muizen, Christian. 2001. "Walking with whales." *Nature*, 413:259-260 (20 Sep 2001). A summary discussion of Thewissen's report.

Gingerich, P.D. et al. 2001. "Origin of Whales from Early Artiodactyls: Hands and Feet of Eocene Protocetidae from Pakistan." *Science*, 293:2239-2242 (21 Sep). This report hinges largely on new fossils of Rodhocetus.

Rose, Kenneth. 2001. "The Ancestry of Whales." *Science*, 293:2216-2217. This is a summary of Gingerich's report, and includes a cladogram showing the proposed ancestry.

Sutera, Raymond. 2000. "The Origin of Whales and the Power of Independent Evidence". In *Reports of the National Center for Science Education*, vol.20, no.5 (Sep/Oct 2000), pp. 33-41. An excellent overview of cetacean evolution, and pointing to several different independent lines of evidence in support of the process. (Mildly critical of creationist veiws). [Copy available at end of lesson]

Gatesey, J.M. et al 1999. "Stability of cladistic relationships between Cetacea an higher-level artiodactyl taxa." *Systematic Biology* 48(1):6-20.

Nikaido, Masato, et al. 1999. "Phylogenetic relationships among cetartiodactyls based on [DNA] insertions of short and long interspersed elements: Hippopotamuses are the closest extant relatives of whales." *Proc. Natl. Acad. Sci. USA*, vol.96, pp. 10261-10266.

Thewissen, J.G.M., L. J. Roe, et al. 1996. "Evolution of cetacean osmoregulation." *Nature*, vol.381, 30 May 1996, pp. 379 380. Study showing oxygen isotope ratios associated with freshwater ingestion vs. seawater ingestion, and whale evolution. [Also see "Osmoregulation" on Thewissen's website]

Blackburn, Daniel G. 1995. "Paleontology Meets the Creationist Challenge". *Creation/Evolution* Issue 36 (July 1995), pp. 30-31 on whale evolution. [Available from NCSE; see website listings below].

Zimmer, Carl. 1995. "Back to the Sea" January 1995 *Discover Magazine*, pp. 82-84.

Wells, Neil. 1994. Review of *Darwinism: Science or Philosophy,*. In *Creation/Evolution* Issue 38 (July 1996), pp. 20-21 on whale evolution, rebuttals to views of Johnson, Behe and Gish. [from NCSE].

Wilford, John N. 1994. "How the Whale Lost Its Legs And Returned to the Sea." In *The Science Times Book of Fossils and Evolution*, ed. by Nicholas Wade, 1998, The New York Times, pp 143-148.

Gould, Stephen Jay. 1994. "Hooking Leviathan by Its Past". May 1994 *Natural History Magazine.*

Gingerich, Philip D. 1994. "The Whales of Tehthys". April 1994 *Natural History Magazine.*

Berta, Annalisa. 1994. "What is a Whale?" *Science* 14 Jan. 1994 (vol.263, pp. 180-181).

Novacek, Michael. 1993 "Genes tell a new whale tale." 28 January 1993 *Nature* (vol. 361, pp 298-299.

Landau, Matthew. 1982. "Whales: Can Evolution Account for Them?" *Creation/Evolution*, Issue X (Fall 1982)., pp. 14-19. [Available from NCSE; see website listings below].

Conrad, Ernest C. 1982. “True Vestigial Structures in Whales and Dolphins.” *Creation/Evolution*, Issue X (Fall 1982), pp. 8-13. [Available from NCSE]. Ref. to hind limb buds in whale embryos, etc.

Web Links (if a listed site is not working, please let us know, and try a Google search):

WHALE EVOLUTION

Thewissen: Whale evolution <http://www.neoucom.edu/Depts/ANAT/Thewissen.html>
Transitional Whales <http://www.talkorigins.org/faqs/faq-transitional/part2b.html>
Cetacean Evolution <http://www.ucmp.berkeley.edu/mammal/cetacea/cetacean.html>
Ambulocetus as Transitional Fossil <http://members.home.net/fsteiger/whales.htm>
A Whale of a Tale <http://detnews.com/1997/discover/9707/10/07070019.htm>
Primitive Whales <http://www.enchantedlearning.com/subjects/whales/allabout/Evol.shtml>
Whale embryo hind limb bud picture:
<http://imiloa.wcc.hawaii.edu/krupp/BIOL101/present/lcture15/sld034.htm>>
Whale nursing: <http://www.seaworld.org/infobooks/KillerWhale/birthkw.html>
Whale hair info: <http://whale.wheelock.edu/archives/ask97/0252.html> and <...ask99/0336.html>
Whale hair picture: <http://www.coreresearch.org/what.htm>

GENERAL EVOLUTION

Evolution on line (WGBH/PBS-Evolution Web Site) <http://www.pbs.org/evolution>
NAS (National Academy of Sciences): *Teaching About Evol. and Nat. of Sci.*
<http://www.nap.edu/readingroom/books/evolution98/evol2.html>
NCSE (National Center for Science Education): <http://www.ncseweb.org> e-mail: ncse@ncseweb.org

GEOLOGIC TIME SCALES (CURRENT)

USGS short version <http://geology.er.usgs.gov/paleo/geotime.shtml>
USGS w/ details <http://vulcan.wr.usgs.gov/Glossary/geo_time_scale.html>
Time Machine (ENSI) <http://www.indiana.edu/~ensiweb/lessons/time.mac.html> (Extensions, Other Res.)

ATTRIBUTIONS

1. Original Source: Larry Flammer (lesson conceived 10/8/1997)
2. Edited / Revised for website by L. Flammer 8/31/2001; updated and extensively revised 10/2002
3. Front painting of *Ambulocetus*, courtesy of artist Carl Buell.
4. Re-Drawings for graphic pages, courtesy of artist Janet Dreyer
5. See “List of Credits” for original sources of all illustrations used in this lesson.

WHALES IN THE MAKING
List of Credits: Sources for Illustrations

ILLUSTRATIONS (all redrawn for this lesson by Janet Dreyer, Illustrator)

1. Primitive Whales, e.g.: *Dorudon*, *Prozeuglodon*,) ~ 36 mya
   - a. *Dorudon atrox*: Gingerich and Uhen, 1996
   - b. *Prozeuglodon*: Rich *et al*, 1996
   - c. *Prozeuglodon*: Rich *et al*, 1996

2. Mesonychids (Extinct Land Mammals, with whale-like teeth, e.g. *Pachyaena*,*Sinonyx*) ~ 55 mya
   - a. *Pachyaena ossifraga*: Gingerich et al, 1994
   - b. *Sinonyx jiashanensis*: Zhou et al, 1995
   - c. *Pachyaena*: Zimmer/Buell, 1998, p. 157

3. (1983) *Pakicetus inachus* (skull and teeth only) ~ 50 mya
   - a.Zimmer/Buell, p. 165
   - b. Gingerich 1983
   - c. Zimmer/Buell, p. 203

4. (1990) *Basilosaurus isis* (hind leg found) ~ 37 mya
   - a. Thewissen's web site
   - b. Gingerich, 1990
   - c. National Academy of Sciences

5. (1994) *Rodhocetus kasrani* ~ 46 mya
   - a. Gingerich, 1994
   - b. Zimmer/Buell, p. 195

6. (1994) *Ambulocetus natans* ~ 48 mya
   - a. Thewissen, 1994
   - b. National Academy of Sciences

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