BASILOSAURUS DRAZINDAI AND *BASILOTERUS HUSSAINI*, NEW ARCHAEOCETI (MAMMALIA, CETACEA) FROM THE MIDDLE EOCENE DRAZINDA FORMATION, WITH A REVISED INTERPRETATION OF AGES OF WHALE-BEARING STRATA IN THE KIRTHAR GROUP OF THE SULAIMAN RANGE, PUNJAB (PAKISTAN)

BY

PHILIP D. GINGERICH, MUHAMMAD ARIF, M. AKRAM BHATTI,
MOHAMMAD ANWAR, AND WILLIAM J. SANDERS

BASILOSAURUS DRAZINDAI AND BASILOTERUS HUSSAINI, NEW ARCHAEOCETI (MAMMALIA, CETACEA) FROM THE MIDDLE EOCENE DRAZINDA FORMATION, WITH A REVISED INTERPRETATION OF AGES OF WHALE-BEARING STRATA IN THE KIRTHAR GROUP OF THE SULAIMAN RANGE, PUNJAB (PAKISTAN)

BY

PHILIP D. GINGERICH[1], MUHAMMAD ARIF[2], M. AKRAM BHATTI[3], MOHAMMAD ANWAR[2], AND WILLIAM J. SANDERS[1]

Abstract—Two new basilosaurid archaeocetes are described from middle Eocene (Bartonian) green shales in the middle part of the Drazinda Formation in the Sulaiman Range of southwestern Punjab. *Basilosaurus drazindai*, sp. nov., has a lumbar vertebra with a centrum the size and shape of those of later *Basilosaurus*, but this differs in having an anteroposteriorly longer neural arch and neural spine, and in having more anteriorly-projecting metapophyses. *Basiloterus hussaini*, gen. et sp. nov., is smaller than *Basilosaurus* and has lumbar centra a little less elongated than those of *Basilosaurus*. Discovery of *Basilosaurus* and more careful documentation of lithological changes lead us to reinterpret previous correlation of Sulaiman Range Eocene formations to the geological time scale using the global record of eustatic sea-level change. The Habib Rahi, Domanda, Pir Koh, and Drazinda Formations now appear to span almost all of Lutetian, Bartonian, and Priabonian time. These formations can be traced for long distances parallel to the margin of the Indo-Pakistan subcontinent, they contain little silt and little or no sand, and they appear to have been deposited offshore on a passive continental margin that was remarkably stable through middle and late Eocene time.

INTRODUCTION

Basilosaurus is the largest of known Eocene archaeocete cetaceans. It is also the first archaeocete to have been named and described, by Harlan (1834), who thought it was reptilian. The type species, *B. cetoides*, was named by Owen (1839), who first called it *Zeuglodon cet-*

---

[1]Museum of Paleontology and Department of Geological Sciences, The University of Michigan, Ann Arbor, Michigan 48109-1079.

[2]Geological Survey of Pakistan, 84 H-8/1, Islamabad.

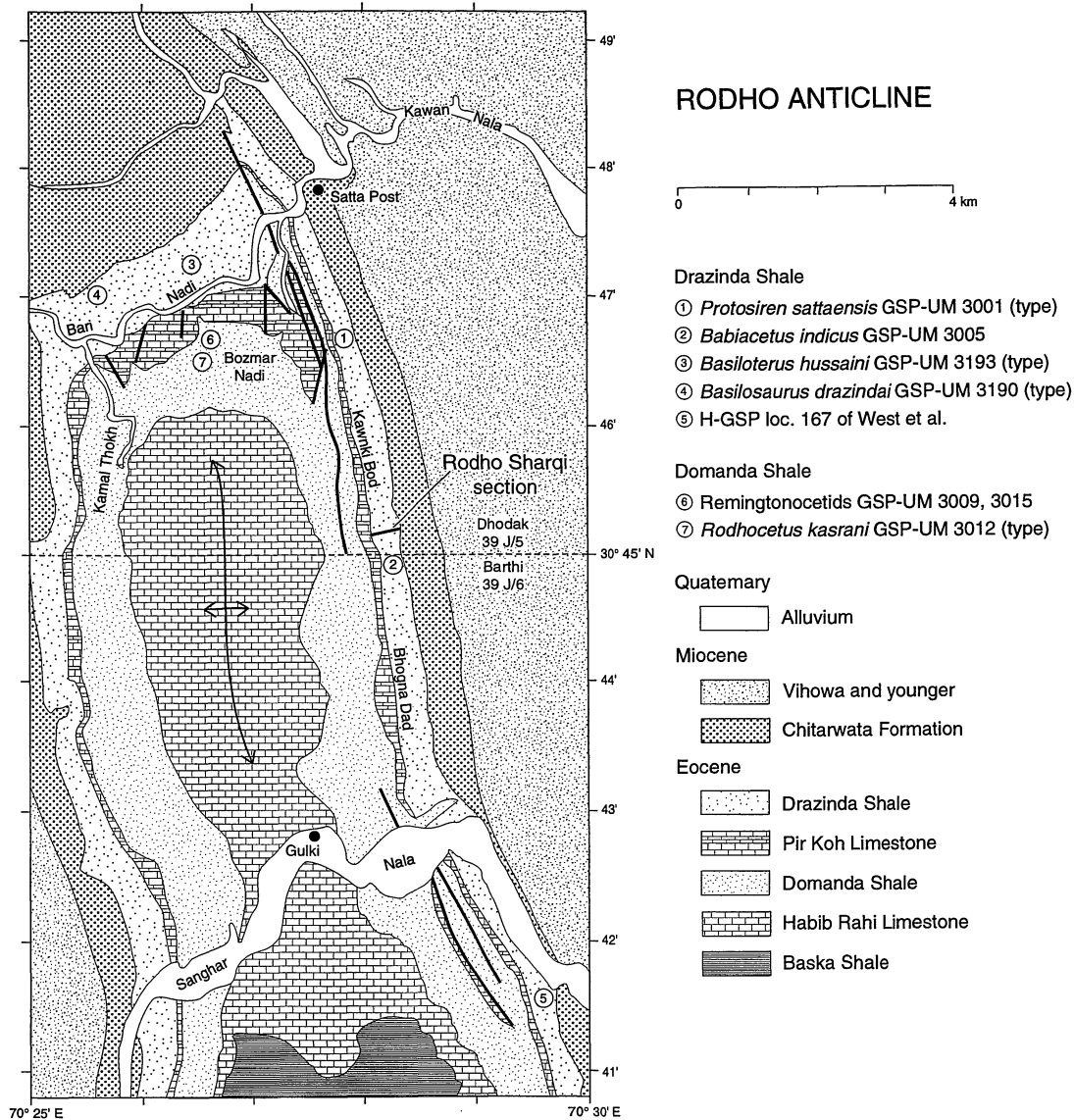[3]Geological Survey of Pakistan, Lahore.

FIG. 1—Location map showing geology of Rodho anticline in the Zinda Pir anticlinorium bordering the Sulaiman Range west of Taunsa in southwestern Punjab, Pakistan. Localities 1 and 2 are where the type specimen of *Protosiren sattaensis* and a skull and lower jaws of *Babiacetus indicus* were found (see Gingerich et al., 1995a, for details). Locality 3 is the type locality of *Basiloterus hussaini* described here. Locality 4 is the type locality of *Basilosaurus drazindai* described here. Locality 5 is the locality H-GSP 167 from the 1978 survey of West et al. (1991). Locality 6 is the source of two partial skeletons of *Remingtonocetus* cf. *R. harudiensis* described by Gingerich et al. (1993, 1995b). Locality 7 is the type locality of *Rodhocetus kasrani* described by Gingerich et al. (1994). Geology is from Bhatti et al. (1986) and Khan et al. (1986). Map modified from Gingerich et al. (1995a).

oides (*Zeuglodon* is a junior synonym of *Basilosaurus*). Harlan's original specimen of *Basilosaurus* came from the 'Tertiary formation' of Louisiana; this is now called Yazoo Clay

(Jackson in the context of Gulf Coast stages) and is Priabonian late Eocene in age (Baum and Vail, 1988), which is calibrated at 39.4-36 Ma (Haq et al., 1987, 1988). *Basilosaurus cetoides* is one of the best known archaeocetes osteologically (Kellogg, 1936). A second species of the genus, *B. isis*, was described by Beadnell in Andrews (1904; see also Andrews, 1906). It is well known from Egypt (Gingerich et al., 1990) in sediments deposited during the latest Bartonian low sea stand (Gingerich, 1992; latest middle Eocene or ca. 39.6-39.4 Ma, Haq et al., 1987, 1988).

We report here a new third species of *Basilosaurus*, and a new genus and species of closely related basilosaurid. Both were found near Satta Post (Fig. 1) in the Sulaiman Range of southwestern Punjab, Pakistan. The new specimens were found in 1996 in a green shale unit of the middle Drazinda Formation, which is just above a distinctive *Discocyclina sowerbyi* marker bed. This is the same unit that yielded the type specimen of *Protosiren sattaensis* (Gingerich et al., 1995a). In addition to whales and sea cows it commonly contains the large 15-20 cm gastropod *Conus colossus* of Eames (1952a).

Discovery of *Basilosaurus* in the Drazinda Formation is inconsistent with previous interpretations of the age of whale-bearing formations in the Sulaiman Range (Gingerich et al., 1995a,b), requiring a new interpretation based here, as before, on global sea level stratigraphy (Haq et al., 1987, 1988). Both of the new archaeocetes described here, and *Protosiren sattaensis* described previously, are middle to late Bartonian in age, or about 40.4 to 40.0 Ma on the Haq et al. (1987, 1988) time scale.

ABBREVIATIONS

CGM   — Cairo Geological Museum, Cairo (Egypt)
GSP-UM   — Geological Survey of Pakistan–University of Michigan collection, Islamabad (Pakistan)
NHML   — Natural History Museum, London (England)
UM   — Museum of Paleontology, University of Michigan, Ann Arbor (U.S.A.)

SYSTEMATIC PALEONTOLOGY

Class MAMMALIA Linnaeus, 1758
Order CETACEA Brisson, 1762
Suborder ARCHAEOCETI Flower, 1883
Family BASILOSAURIDAE Cope, 1868

Basilosaurus drazindai, new species
Fig. 2A-C

Holotype.—GSP-UM 3193, lumbar vertebra.
Type locality.—Bari Nadi west of Satta Post of the Border Military Police (Fig. 1), at 30°46.97′ north latitude, 70°25.67′ east longitude (Survey of Pakistan topographic quadrangle 39 J/5; Dhodak geological quadrangle of Bhatti et al., 1986). This locality is shown in Figures 3 and 4.
Referred specimens.—The thoracic centrum, NHML-M 26552, described by Halstead and Middleton (1972) from middle Barton beds at Highcliffe in southern England, is the right age geologically and the right size morphologically to belong to this species. It is questionably referred.

Age and distribution.—*B. drazindai* is known with certainty only from green shales of the upper middle Drazinda Formation and it is known only from the type locality. Green shales yielding *B. drazindai* are middle to late Bartonian in age (see discussion below). This part of the Drazinda Formation is calibrated at about 40.4-40.0 Ma on the time scale of Haq et al. (1987, 1988; see discussion below and summary Fig. 14).

Diagnosis.—*Basilosaurus* with lumbar vertebrae similar in size and centrum proportions to those of *B. cetoides* and *B. isis*. Differs in having a neural arch and neural spine that are longer anteroposteriorly. Further differs in having broader and more anteriorly-projecting metapophyses that extend beyond the anterior face of the centrum.

Etymology.—Named for the Drazinda Formation of Pakistan, which yielded the type specimen.

Description.—*Basilosaurus drazindai* is presently represented by a single very large vertebra, GSP-UM 3193 (Fig. 2a-c). The length of the centrum, low position of the transverse processes, anterolateral projection of the metapophyses, and moderate size of the neural canal indicate that the vertebra is a probably a lumbar, and the presence of a high neural arch is consistent with this identification (compare figs. 14-16 in Kellogg, 1936; figs. 149-150 in Slijper, 1936). It could possibly be an anterior caudal. The specimen was found on the surface, has some weathering cracks, has lost cortical bone in places, and is missing small pieces of bone from the pedicles and metapophyses, but these do not affect measurement or interpretation. The anterior and posterior margins of the apex of the neural spine are missing and it is impossible to determine its original shape; the spine has been reconstructed conservatively to preserve its structural integrity (white surfaces in Fig. 2a-c are reconstructed). Postdepositional deformation has deflected the neural spine slightly to the right (Fig. 2c). Similarly, the metapophyses are deformed and deflected ventrally (Fig. 2b): they appear to have been oriented in life at an angle of about 80° to the midsagittal plane. The right metapophysis is step-fractured and thereby artificially shortened.

The centrum lacks an anterior epiphysis, but the posterior epiphysis is present. Allowing 5 mm or so for the thickness of the missing epiphysis, the total length of the centrum was about 300 mm. Heights of the centrum at its anterior and posterior ends are 141 and 145 mm, respectively. Widths of the centrum at its anterior and posterior ends are 168 and 174 mm, respectively. There is a small amount of transverse mid-centrum constriction giving the vertebral body a slightly waisted shape (best seen in dorsal view). The anterior or cranial surface of the centrum is oval in outline and flat, with a rugose surface of radiating ridges that formed sutural contact with the missing epiphysis or endplate. The posterior or caudal surface of the centrum is also oval in outline and flat, but here a 5-10 mm thick epiphysis is present. This has a smooth flat articular surface with a small central concavity. Dorsal and ventral surfaces of the centrum are slightly concave. On the ventral surface there is an elongated depression in the middle of the centrum, and a thin midline partition of bone separates this into moieties, each with a small vascular foramen. There is no ventral keel on the centrum.

The roots of the transverse processes arise from the anterolateral margin of the vertebral body. These are large at the base (measuring 155 mm in anteroposterior length and 40 mm in width on the left side) and show that the processes were angled ventrally. The ventral position and inferred angulation are consistent with identification of the vertebra as a lumbar because transverse processes on caudals usually develop more dorsally on the vertebral body (Kellogg, 1936, plates 4-6).

The neural canal is moderate in size, with the opening measuring approximately 110 mm in width and 50 mm in height at the anterior end of the neural arch, and 115 mm by 35 mm at the posterior end of the arch. The height of pedicles between the centrum and laminae of the neural arch is only about 35 mm on each side. In contrast, the pedicles are about 105 to 109 mm in anteroposterior dimension at their shortest length, and about 121 to 130 mm anteroposteriorly at their greatest length. Sediment filling the neural canal prevents measure-
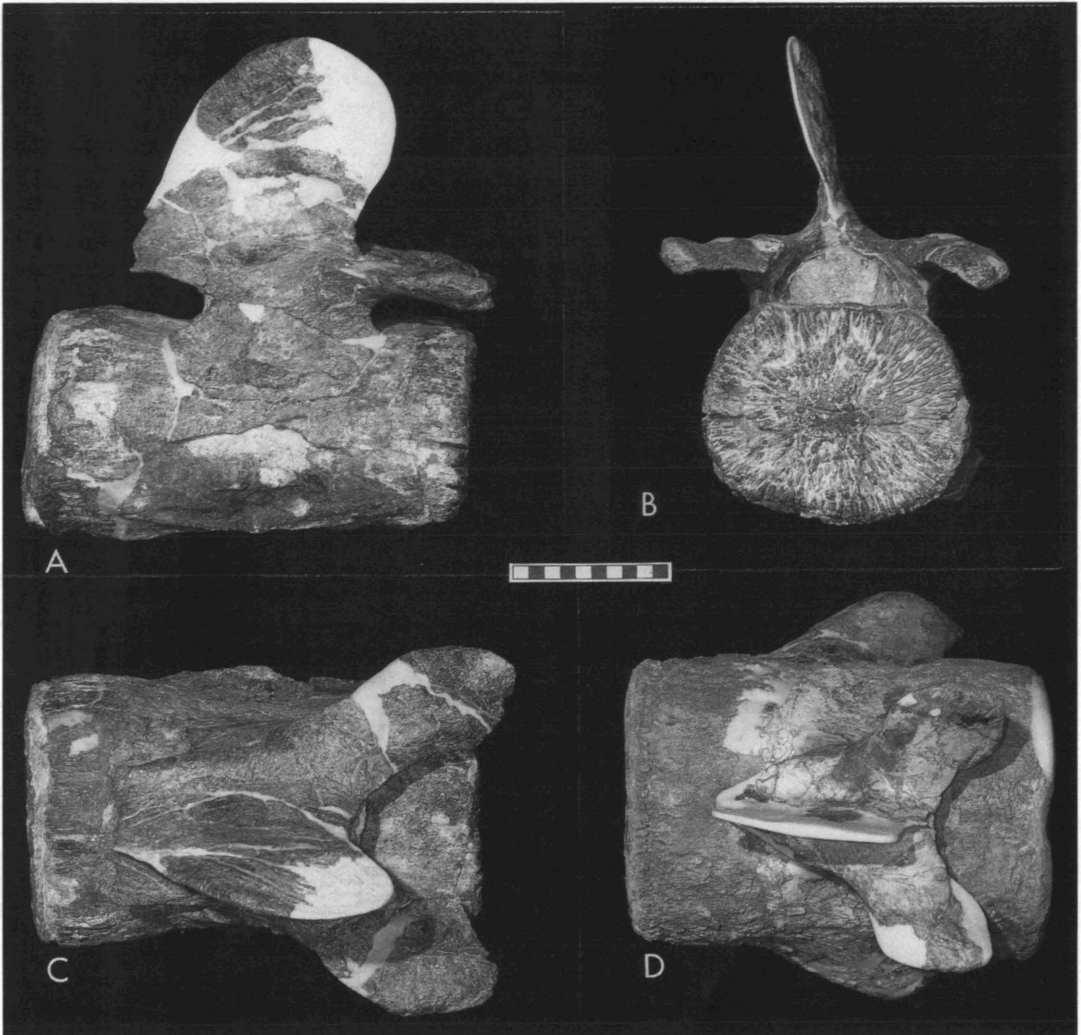
FIG. 2—Lumbar vertebra of *Basilosaurus drazindai* from Pakistan (A-C: GSP-UM 3193, holotype) compared to anterior caudal vertebra of *B. isis* from Egypt (D: UM 97525). A, type specimen of *B. drazindai* in right lateral view. B, type specimen of *B. drazindai* in anterior view. C, type specimen of *B. drazindai* in dorsal view (anterior is to right). D, anterior caudal of *B. isis* in dorsal view (anterior is to right). Differences in the shape of the centra of these two vertebrae are a reflection of different positions in the vertebral column, but *B. drazindai* has a much larger neural spine than lumbars of *B. isis*. Note large anteriorly-projecting metapophyses in *B. drazindai* extending beyond the anterior margin of the centrum. Scale is in cm.

ment of pedicle width, but these appear to be robust. As is usual in archaeocetes, the pedicles arise closer to the anterior end of the centrum than to the posterior end.

Metapophyses arise from the pedicles as thick protuberances of bone that project in an anterolateral direction, and in life they were clearly dorsally directed to some extent as well. The distal ends of the metapophyses are broad flat plates that have a compressed triangular shape. They project just beyond the anterior edge of the centrum and also extend laterally beyond the edges of the centrum. In dorsal view the metapophyses are spatulate and have a

FIG. 3—Type locality of *Basilosaurus drazindai* in Bari Nadi west of Satta Post. Locality is at 30°46.97′ north latitude, 70°25.67′ east longitude (Survey of Pakistan topographic quadrangle 39 J/5; Dhodak geological quadrangle of Bhatti et al., 1986). Holotype was found where collectors are working in the lower center of the photograph. It was found weathering from whale and sea cow-bearing green shales of the upper middle Drazinda Formation that form the light-colored slope in the lower part of the photograph. These shales are overlain by red and green shales of the upper Drazinda Formation, and the ridge top here is Oligo-Miocene Chitarwata Formation.

small sulcus for muscle or ligament attachment along their anteromedial borders. The metapophyses terminate anterolaterally as roughened tuberosities for insertion of transverso-spinal muscles. The ventral side of each metapophysis is flat and shows no sign of zygapophyseal articulation with the preceding vertebra.

There are paired, flat, left and right lateral projections at the posterior end of the neural arch, here called posterolateral processes of the neural arch, that are more narrowly spaced than the metapophyses. These may be remnants of postzygophyses, much reduced in size, but
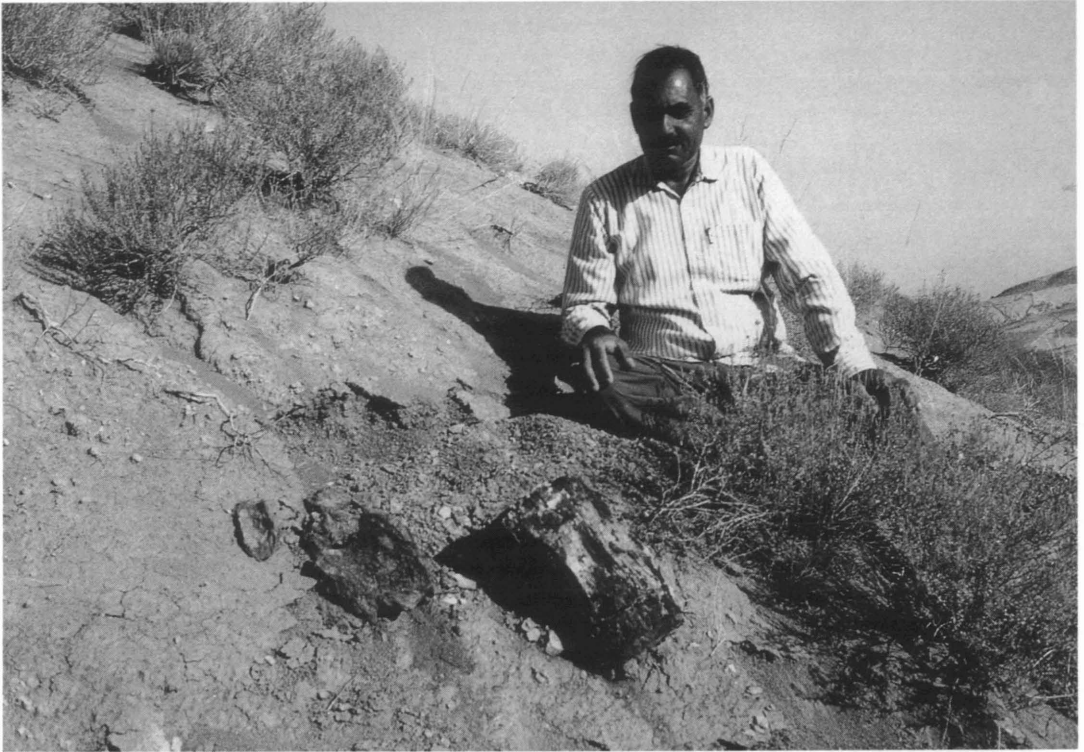
FIG. 4—Holotype of *Basilosaurus drazindai* (GSP-UM 3193) as it was found in the field in Bari Nadi west of Satta Post. Slope here is whale and sea cow-bearing green shale of the upper middle Drazinda Formation.

they have no articular facets and did not contact metapophyses of the succeeding vertebra. Lumbar vertebrae of contemporary *Basiloterus hussaini* (see below) and later species of *Basilosaurus* do not have these paired posterolateral processes but instead have a single midline projection over the posterior opening of the neural canal that Kellogg called the posterobasal angle of the neural spine (Kellogg, 1936, p. 48; this is well shown in *B. isis* in Fig. 2d).

The preserved part of the neural spine reveals it to have been an anteroposteriorly long, bilaterally thin process with little apical expansion. This indicates that there was no strong supraspinous ligament and there were no powerful spinalis muscles. Similarly, the laminae do not suggest presence of a strong ligamentum flava. The neural spine is directed slightly anteriorly, suggesting that there was some anticliny in *B. drazindai*. The neural spine projects 200 mm above the dorsal surface of the centrum, rising some 145 mm above the neural arch, measures 150 mm in anteroposterior length at the base of the spine, and is ca. 12 mm thick. Thus the neural spine is large, but it is not nearly as long as the whole centrum.

Discussion.—Basilosaurus drazindai is the first record of the genus in Asia. Lumbar vertebrae of *Basilosaurus* are distinctive in being extraordinarily large for an archaeocete and they are also distinctive in having unusually long centra relative to their widths and heights. The lumbar described here is similar in size and centrum proportions to those of Egyptian *Basilosaurus isis* (Slijper, 1936) and North American *B. cetoides* (Kellogg, 1936). However, it differs in having an anteroposteriorly longer neural arch (both absolutely and relative to centrum length), with an anteroposteriorly longer neural spine. The metapophyses are broader,

more nearly horizontal, more anteriorly-projecting, and extend beyond the anterior face of the centrum. Finally, the presence of paired posterolateral processes of the neural arch is also distinctive. These differences from later *Basilosaurus*, found in a species that is a half-million or so years older geologically, are resemblances to generalized archaeocetes, and they are thus considered primitive retentions.

One of the most interesting challenges posed by *Basilosaurus* is understanding how it swam. Howell (1930, p. 198) noted that lumbars do not have articulating zygapophyses, and caudal spinous and transverse processes are short, indicating that spinal musculature was not developed to a degree where it could power flukes like those of modern cetaceans. He proposed instead a continuous symmetrically-placed bilateral finfold running the length of the tail, with progression involving caudal undulation in the vertical plane. Kellogg (1936, p. 48) noted too that the lumbar vertebrae articulated only by the nearly circular ends of their centra, separated and at the same time connected by thickened cartilaginous and probably fibrous intervertebral disks, which would have permitted free movement in almost any direction. Slijper (1946, p. 76) interpreted very strong metapophyses and comparatively low neural spines in the posterior lumbars and caudals of archaeocetes to indicate that 'snake-like' *Basilosaurus* moved by undulating movements in the lateral direction. Barnes and Mitchell (1978), on the other hand, reconstructed *Basilosaurus* as an elongated but otherwise modern looking whale with a well developed horizontal tail fluke. Gingerich et al. (1990) documented a sigmoid curve in a profile of caudal centrum lengths that they interpreted as indicating the presence of a fluke.

In a new study, Gingerich (1998) compared *Basilosaurus* to *Dorudon* using diagrams of skeletal proportion (like those shown below in Fig. 7). The comparison shows how distinctly different are the thoracic through caudal centra of *Basilosaurus*, with centrum elongation giving the genus its anguiliform body shape but coordinated increase in centrum height showing that more is happening than simple elongation. Vertebrae of *Basilosaurus* are sometimes densely mineralized and heavy when found as fossils, but when these are not secondarily permineralized they are fragilely cancellous and light. In life the centra were filled with fatty marrow, and surface-to-volume allometry means overall enlargement probably made them more buoyant. Large bouyant vertebrae suggest in turn that *Basilosaurus* may have lived predominantly at the sea surface. If true, the air-water interface is effectively an horizontal plane, and movement in this plane would be consistent with Slijper's (1946) interpretation that *Basilosaurus* moved by lateral undulation. As presently known *B. drazindai* contributes little to clarification of swimming modes in *Basilosaurus*, but it might with recovery of a more complete axial skeleton. *B. drazindai* does show that the metapophyses of early *Basilosaurus* were very strong and divergent, and the neural arch and spine were long. The short time separating *B. isis* from *B. drazindai* shows that reduction happened relatively rapidly, as might be expected if locomotion was changing in some fundamental way.

Basiloterus hussaini, new genus and species
Fig. 5

Holotype.—GSP-UM 3190, two lumbar vertebrae found within a few meters of each other and undoubtedly representing the same individual animal.

Type locality.—Bari Nadi west of Satta Post of the Border Military Police (Fig. 1), at 30°47.27′ north latitude, 70°26.43′ east longitude (Fig. 6; Survey of Pakistan topographic quadrangle 39 J/5; Dhodak geological quadrangle of Bhatti et al., 1986).

Referred specimens.—The caudal centrum, NHML-M 26553, described by Halstead and Middleton (1972) from middle Barton beds west of Barton in southern England is the right age geologically and the right size morphologically to belong to this species. It is questionably referred here.
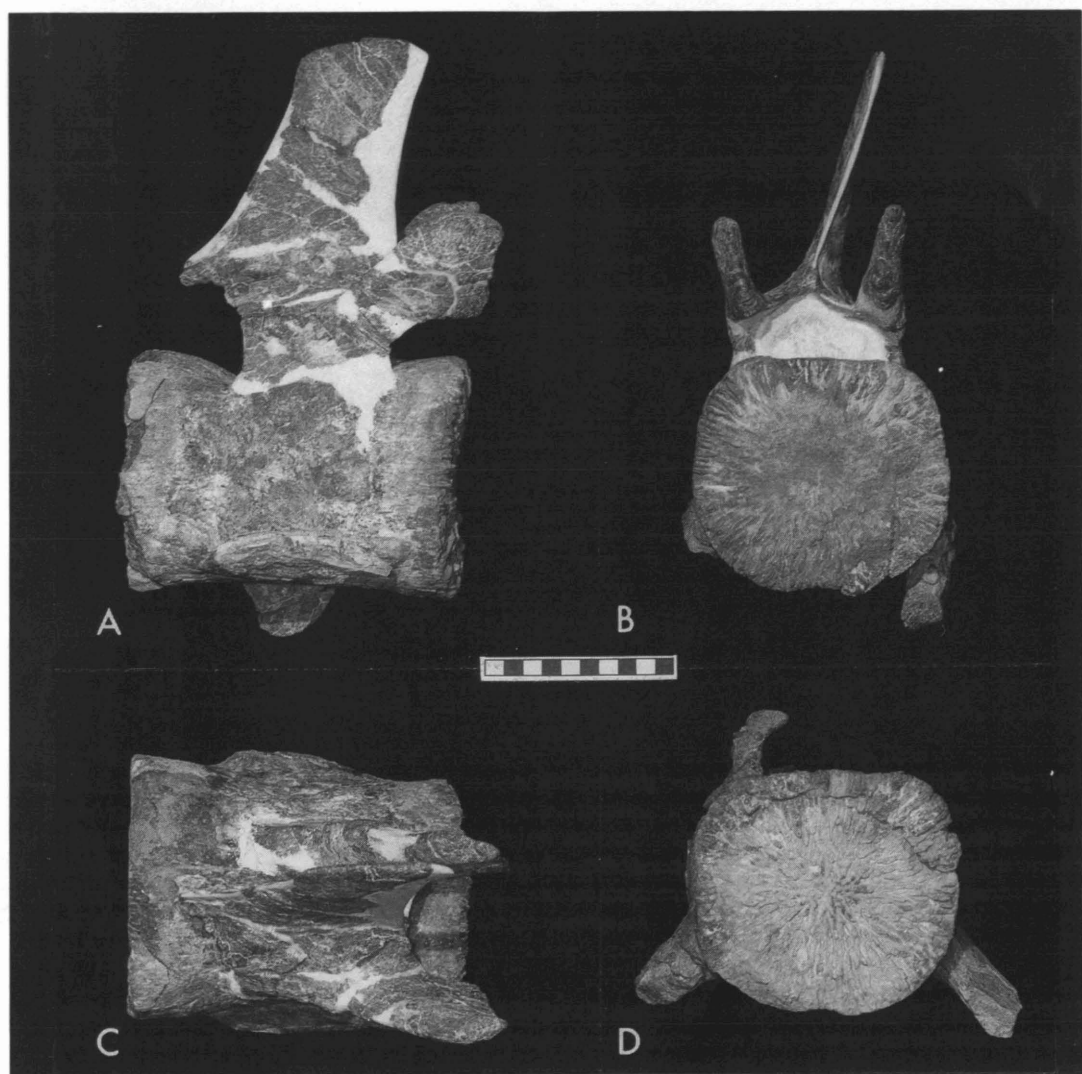
FIG. 5—Lumbar vertebrae of *Basiloterus hussaini* (GSP-UM 3190, holotype). A, more complete vertebra in right lateral view. B, more complete vertebra in anterior view. C, more complete vertebra in dorsal view (anterior is to right). D, less complete vertebra in anterior view. Note centrum enlargement with some anteroposterior elongation, but size and elongation are both less than is seen in lumbars of *Basilosaurus* (compare Fig. 2). Scale is in cm.

Age and distribution.—*B. hussaini* is known only from green shales of the upper middle Drazinda Formation, late Bartonian, at the type locality. This part of the Drazinda Formation is calibrated at about 40.4-40.0 Ma on the time scale of Haq et al. (1987, 1988; see below).

Diagnosis.—Basilosaurid differing from *Basilosaurus* in being smaller, in having lumbar vertebrae with centra a little less elongated relative to height, and in having more vertically oriented metapophyses (Fig. 7). Differs from *Pachycetus robustus*, if this is a basilosaurid, in being larger, and having lumbar centra more circular in transverse section.

FIG. 6—Type locality of *Basiloterus hussaini* in Bari Nadi west of Satta Post. Locality is at 30°47.27′ north latitude, 70°26.43′ east longitude (Survey of Pakistan topographic quadrangle 39 J/5; Dhodak geological quadrangle of Bhatti et al., 1986). Holotype vertebrae were found within a few meters of each other on the slope in the lower center of the photograph. Fossiliferous interval here is green shales of the upper middle Drazinda Formation. These shales are overlain by red and green shales of the upper Drazinda Formation, and the ridge top in the background is Oligo-Miocene Chitarwata Formation.

Etymology.—Basileus, Gr., king, and *heteros* or *oteros*, other, one of two (masc.); 'other king,' companion of *Basilosaurus*. Species is named for Dr. S. Taseer Hussain of Howard University, Washington, D.C., who sponsored the first expedition to search for vertebrate fossils in the Drazinda Formation (reported in West et al., 1991) and has made many contributions to Pakistan vertebrate paleontology.

Description.—Basiloterus hussaini is represented by two large vertebrae, GSP-UM 3190, one (Fig. 5a-c) more complete than the other (Fig. 5d). The two are very similar in all comparable parts. They may well have been successive vertebrae in the same column, but it is impossible to tell which was the more anterior. The placement of transverse processes low on the centrum, absence of zygapophyseal articulations, and slight forward angulation of the neural spine indicate that these are lumbars. Both specimens are missing anterior and posterior epiphyses, and both have suffered some postmortem breakage, cracking, and spalling of bone.

The more complete vertebra has lost small sections of the anterior and posterior surfaces of the centrum, part of its left and all of its right transverse process, but it is otherwise a very good specimen preserving nearly the entire neural arch and spine. The neural arch as preserved is a little skewed, with the neural spine deflected to the left, and the left lamina is slightly folded, giving the neural canal an eccentric cross-section. The left metapophysis is step-fractured and artificially deflected toward the midline. The less complete vertebra lacks most of the neural arch, much of each transverse process, and much of the posterior surface of the centrum. Both vertebrae are ca. 185 mm in length as preserved (without epiphyses, meaning that their total length in life was about 195 to 200 mm). The anterior width and height of the more complete centrum are 144 and 133 mm, respectively, and the posterior width and height are 151 and 134 mm. The anterior width and height of the less complete centrum are 140 and 131 mm, respectively, and the posterior width and height are 144 and 128 mm.

Both vertebrae show some narrowing in the middle of the centrum, bilaterally and dorsoventrally, giving them a slightly waisted shape. The epiphyseal surfaces of the centra differ to some degree, with the anterior one being more circular in outline and mildly saddle-shaped, and the posterior one being more oval and flat. All are covered with radiating bony rugosities that interdigitated with the missing epiphyses. There is a deep central concavity on the ventral surface of each specimen, and this ventral concavity encloses three recessed vascular foramina divided by thin bony partitions. Neither centrum has a ventral keel.

Transverse processes arise from the anterolateral margin of the vertebral bodies, and enough remains to show that they were angled anteroventrally. Such a configuration provides mechanical advantage and an increased arc of movement for iliocostalis muscles. The distance these extend away from the centrum cannot be measured, but the base of the most complete transverse process is about 93 mm long anteroposteriorly and it is 30 mm thick.

Neural arch elements enclose a moderately large neural canal with an opening that measures 83 mm wide and 30 mm high anteriorly, and 90 mm wide and 32 mm high posteriorly. The junction between the pedicle and lamina is angular. The pedicle itself is long anteroposteriorly, measuring 82 mm at the base and 77 mm in minimum length, and it is about 20 mm wide. The pedicle is not high, rising only about 39 mm from the centrum. As is typical in basilosaurids, the pedicles are set closer to the anterior end of the centrum than to the posterior end.

Metapophyses of GSP-UM 3190 rise from the pedicles as robust pyramidal structures, triangular in cross-section, that project beyond the cranial end of the centrum but do not flare widely laterally. Viewed from the front, each is set at an angle of only about 15° relative to a midsagittal plane through the vertebra, making them much more vertical than those of *Basilosaurus drazindai*. The medial surfaces of the metapophyses are flat, but there are no articular facets. The neural spine and laminae terminate posteriorly in a diminutive posterobasal angle and there are no postzygapophyseal articulations. The dorsal margins of the metapophyses are thick and rugose for insertion of iliocostalis muscles. There are no bony recesses on the laminae or pedicles for attachment of a ligamentum flava.
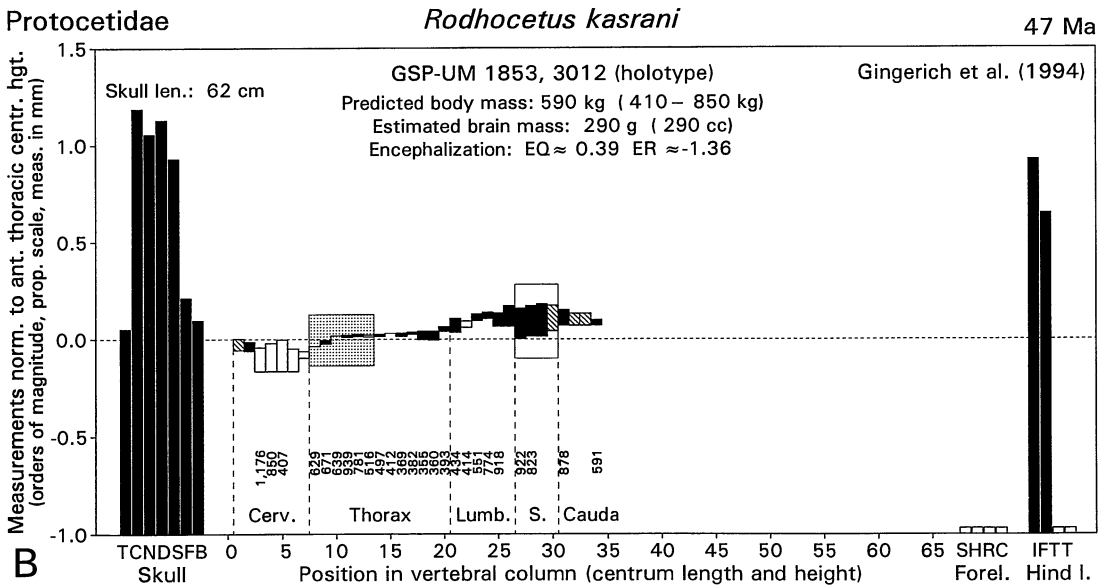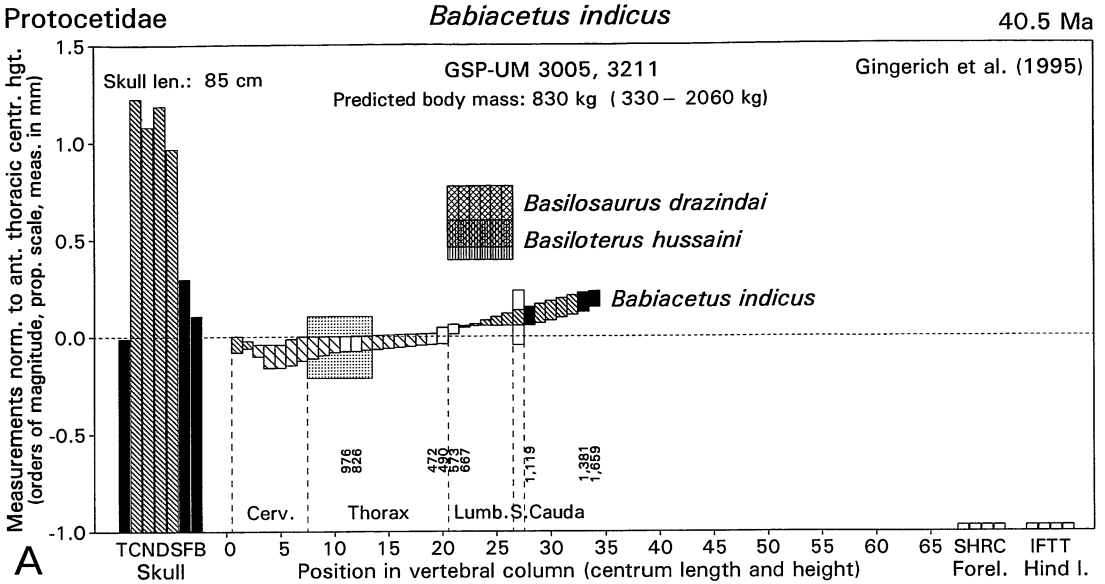
FIG. 7—Diagrams of skeletal proportion comparing skull lengths and vertebral lengths and heights for the lower middle Drazinda Formation protocetid *Babiacetus indicus* (A) with skull lengths and vertebral lengths and heights for the lower Domanda Formation protocetid *Rodhocetus kasrani* (B). In each diagram, measurements are represented as a profile of bars, normalized to the mean height of the centrum of the six anterior thoracic vertebrae (dotted baseline). Two profiles are superimposed for vertebral measurements, representing centrum length and centrum height, and the bar shown is the *difference* between these (the position of the bar represents vertebral size and the length of each bar reflects measurement difference or shape): this is solidly filled when length exceeds height (as for three caudals in A), and open when height exceeds length (as for thoracics and the anterior lumbar in A). Cranial proportions based on estimated lengths are shown with hatching. Hatched vertebrae are based on comparison to those of other protocetids (in the case of cervicals), or interpolated based on measured centra (in the case of thoracics, lumbars, sacrum, and caudals).   →

The neural spine projects dorsally from low, thin laminae to a height of 175 mm above the dorsal centrum and 140 mm above the dorsal edge of the neural canal. It rises at a forward angle of about 10°, suggesting anticliny. The neural spine is about 120 mm long anteroposteriorly at the base, while it is only about 13 mm thick. There is no lateral expansion at the apex of the neural spine, suggesting that spinalis muscles and lumbar supraspinous ligaments were weak.

Discussion.—Basiloterus hussaini was found more than a kilometer from the type locality of *Basilosaurus drazindai* (Fig. 1), but both came from the same green shales and probably lived at the same time. Morphological differences are ones of size and vertebral elongation: *Basiloterus* is smaller than *Basilosaurus*, and its centrum elongation is a little less pronounced. Both are large compared to most other archaeocetes, and both have the same distinctive elongation of lumbar centra anteriorly and posteriorly beyond the neural arch and spine.

The one archaeocete known previously from the Drazinda Formation is a protocetid, *Babiacetus indicus* (Gingerich et al., 1995a). It is known only from the skull and lower jaws, but it is large enough that we had to consider carefully whether vertebrae of *Basiloterus* might belong to *Babiacetus*. *Basiloterus* came from the green shale above the *Discocyclina sowerbyi* marker bed, while *Babiacetus* came from brown shales just below this marker bed. Fortunately, in 1996 we found part of the postcranial skeleton of a protocetid from the *Babiacetus*-bearing shales, and vertebrae of this partial skeleton (GSP-UM 3211) are compared to the Drazinda skull of *Babiacetus* (GSP-UM 3005) in the diagram of skeletal proportion in Figure 7A. The vertebrae that are known and can be measured in GSP-UM 3211 are two anterior thoracics, two posterior thoracics, two anterior lumbars, a proximal caudal, and two more-distal caudals. These yield a body mass for *Babiacetus* estimated at 830 kg, but more significantly for our purpose here show, by comparison with skeletal proportions in *Rodhocetus kasrani* (Fig. 7B), that the GSP-UM 3005 skull and the GSP-UM 3211 postcranial elements are the right size to belong to the same taxon (which does not prove that they belong together, but shows that this is plausible).

Comparison of the *Babiacetus* profile to that of *Rodhocetus* shows that *Babiacetus* has the skull size based on GSP-UM 3005 expected for a postcranial skeleton of the size shown here based on GSP-UM 3211 from the same lower middle Drazinda strata. Skull size measurements include the longest-cheek-tooth (*T*); condylobasal skull length (*C*), external narial position (*N*), dentary length (*D*), mandibular symphyseal position (*S*), greatest diameter of the mandibular foramen (*F*), and length of the auditory bulla (*B*).

Vertebral lengths and heights of protocetid archaeocetes generally increase progressively from the mid-cervicals through mid-caudals as shown here. Shaded box represents the anterior thorax where the forelimb is anchored. The sacrum (open box) is not yet known in *Babiacetus*, but it probably included a single centrum. The size of each vertebral rectangle represents its proportions when viewed laterally (high solid rectangles represent vertebrae that are long and low, high open rectangles represent vertebrae that are short and high).

Scapula (*S*) and forelimbs (humerus *H*, radius *R*, and longest metacarpal *C*), and innominate (*I*) and hindlimbs (femur *F*, tibia *T*, and longest metatarsal *T*) are not known for *Babiacetus*. Body masses predicted here (vertical numbers below individual vertebrae), with a median of 830 kg for *Babiacetus*, are based on a multiple regression comparison to vertebrae of marine mammals.

Lumbar vertebrae of *Basilosaurus drazindai* and *Basiloterus hussaini* from the upper middle Drazinda Formation are plotted in A (identified by cross hatching and vertical ruling, respectively) to show that they are substantially larger than expected for a protocetid the size of *Babiacetus indicus*. Vertebrae of *Basilosaurus* and *Basiloterus* are also differently shaped, having centra that are much longer relative to their height in comparison to those referred to *Babiacetus*.

Vertebrae of *Basiloterus hussaini* are plotted in Figure 7A, demonstrating that *B. hussaini* has vertebrae that are substantially larger and differently proportioned than the protocetid vertebrae referred to *Babiacetus*. *Basiloterus* may have had a skull the size of that of *Babiacetus*, but the type vertebrae are unlikely to belong to *Babiacetus* when there is a protocetid with distinctly different vertebrae known from the same beds as the skull of *Babiacetus* and the latter vertebrae are the right size to belong to *Babiacetus*.

Other specimens to which the *Basiloterus* vertebrae might be compared include two 'lumbars' catalogued as CGM 10019 that were described and illustrated by Andrews (1906, pp. 242-243). These were identified, questionably, as *Zeuglodon* [*Basilosaurus*] *isis*. Both have low neural spines, and transverse processes placed relatively high on the centrum, suggesting that they are caudals of a larger archaeocete (probably *Basilosaurus isis*) and not lumbars of *Basiloterus*.

Kuhn (1935) illustrated the type vertebra of *Pachycetus robustus*, named by van Beneden, identifying this as a lumbar, and interpreting it as being late Eocene in age, reworked with *Lophiodon* and *Propalaeotherium* into an Oligocene phosphate deposit. Kuhn compared this to *Zeuglodon* [*Basilosaurus*] *isis* but noted important differences. Whatever the type of '*Pachycetus robustus*' is, the lumbar centra of *Basiloterus* are some 25% larger and they are more circular in transverse section.

The large size and *Basilosaurus*-like proportions of *Basiloterus* vertebrae described here indicate that contemporary *Basilosaurus* is probably its closest known relative.

AGES OF WHALE-BEARING STRATA IN THE SULAIMAN RANGE

In two earlier studies (Gingerich et al., 1995a,b), we attempted to combine sea level stratigraphy (Haq et al., 1987) with micropaleontological evidence (Haq, 1972; Samanta, 1972, 1973; Köthe et al., 1988) to determine the ages of Kirthar Group Formations in the Sulaiman Range. We regarded the Habib Rahi and Pir Koh carbonates as representing deep-water parts of sea level cycles TA3.2 and 3.3, with the Domanda and Drazinda shales representing shallow-water parts of cycles TA 3.3 and 3.4, respectively. This made the entire Kirthar Group appear to be Lutetian middle Eocene in age, which we acknowledged to be partly inconsistent with Samanta's (1972, 1973) studies of planktonic foraminifera and Köthe et al.'s (1988) studies of nannoplankton. Discovery of *Basilosaurus* in 1996 prompted a new evaluation of the ages of all whale-bearing strata in the Sulaiman Range.

Our new evaluation, presented here, is again based primarily on sea level stratigraphy. We now have greater experience observing Kirthar stratigraphy in the field, having measured detailed sections in Rakhi Nala (Gingerich et al., 1997b) and in the northern plunge of the Zinda Pir anticlinorium at Rodho Sharqi (described here), as well as in the southern plunge of the Zinda Pir anticlinorium at Takra (described in Gingerich et al., 1995b). As a result, we now recognize that what looked initially like a simple repetition of two cycles is clearly more complicated. In addition, we have spent several more months collecting diagnostic fossils and observing familiar marker beds in the Habib Rahi, Domanda, and Drazinda Formations over a geographic distance of more than one hundred kilometers paralleling the Eocene shoreline, from Safed Tobah in the south to Satta in the north. Kirthar strata are remarkably uniform lithologically over this distance. Further, we have not found any evidence of a depositional hiatus nor any evidence of clastic sediment coarser than silt or fine sand in the Kirthar Group of the Sulaiman Range. The latter observations indicate that deposition took place on a passive margin with the potential to record sea level changes.

Rodho Sharqi stratigraphic section

The Drazinda Formation is well exposed on the east side of Rodho Anticline south of Satta (Fig. 1), at a place we have called Rodho Sharqi (Fig. 8). Beds here dip at 33 to 43° to the east and are weathering on slopes of about the same angles, making access relatively easy. Thicknesses of successive lithologies are recorded in Fig. 9. The Pir Koh Formation forms a resistant ridge of white limestone and marl defining the western side of the Kawnki Bod valley, and Kawnki Bod itself is largely eroded in soft olive green shales with thin resistant beds of silty marl. This is what we call lower Drazinda Formation, which is about 75 m thick.

The lower part of the middle Drazinda Formation is about 62 m thick, consisting of brown to reddish-brown gypsiferous shales with interbedded foraminiferal limestones. This is overlain by a 20-50 cm thick compact limestone marker bed packed with *Discocyclina sowerbyi* and by a 1 m thick shale packed with *Discocyclina sowerbyi* (Figs. 10-11). The upper part of the middle Drazinda Formation, yielding the whales described here, is a 31 m thick green shale with the large gastropod *Conus colossus* of Eames (1952a).

The lower part of the upper Drazinda Formation is a red and brown shale with gypsum and abundant remains of the high-spired gastropod *Turritella* overlain by highly oxidized chocolate brown shales with gypsum and beds of dark gray and brown hard calcareous nodules (Fig. 12). The entire lower part of the upper Drazinda sequence is about 55 m thick. This is overlain by a middle upper Drazinda alternation of 7 m of green shale, 14 m of reddish brown shale with gypsum, 3-4 m of green shale, 3-4 m of brown shale, a thicker 12-13 m unit of green shale, and some 24 m of reddish brown shale.

The upper part of the Drazinda Formation, the 'Tapti' beds of Eames (1952b), continues the alternation of red and green shales. At the top of the Drazinda section there is a 2 m bed of yellow ferruginous clay with brown iron-rich concretions, which is overlain by sandstones of the Chitarwata Formation.

Additional *Protosiren sattaensis*

Drazinda Formation archaeocetes are most common in the middle Drazinda, but we have also found a weathered partial skeleton in the lower Drazinda. Levels producing *Babiacetus*, *Protosiren*, *Basilosaurus*, and *Basiloterus* are indicated in Fig. 9. The interval just above the *Discocyclina sowerbyi* marker bed is of special interest because it has yielded many specimens of the sirenian *Protosiren*. It not only yielded the two specimens known when the species *Protosiren sattaensis* was described (Gingerich et al., 1995b), but it has yielded six additional partial skeletons. Among these is GSP-UM 3197 (Fig. 13) with the innominate of a second pelvis showing the large obturator foramen distinguishing *P. sattaensis* from *P. smithae* of the latest Bartonian of Egypt (Domning and Gingerich, 1994). GSP-UM 3197 also includes the first femur of *P. sattaensis* that can be compared to the femur of *P. smithae*—both femora are similar, but that of the former is a little larger, both absolutely and relative to the size of the innominate, as would be expected in a more primitive and slightly less fully-aquatic species. All in all, the new remains of *Protosiren* indicate that middle Drazinda bed yielding *P. sattaensis* are just a little older geologically than latest Bartonian beds in Egypt yielding *P. smithae*. These similarities and differences in *Protosiren* support correlation of southern Tethys faunas of Pakistan and Egypt based on the stage of evolution of *Basilosaurus*.

FIG. 8—Photograph of Rodho Sharqi section on the eastern flank of Rodho anticline. View is to north. Section was measured on the divide between Kawnki Bod draining north into Kawan Nala and Bhogna Dad draining south into Sanghar Nala. White marl at left at the base of the section is Pir Koh Formation. Valley overlying this is eroded in green shales of the lower Drazinda Formation. Slope of reddish brown shales in the center of photograph is lower middle Drazinda Formation, capped by the *Discocyclina sowerbyi* marker bed, with the next valley eroded in green shales of the upper middle Drazinda Formation. Slope at right of photograph is alternating reddish brown and green shales of the upper Drazinda Formation. Sandstone at top of section is Chitarwata Formation. See Figure 9 on facing page for measured thicknesses.

Synthetic model stratigraphic section based on sea level change

Discovery of *Basilosaurus* showed that our initial correlation of Kirthar strata to the geological time scale based on sea level stratigraphy was questionable. Also, measurement of the Drazinda section in Figure 9 showed that sea level change was more complicated than initially appreciated. Consequently we made another attempt at correlation by developing a synthetic model stratigraphic section based on sea level change to compare with the actual section observed in the field. This was done knowing that the great lateral continuity of Kirthar lithologies and absence of coarse clastics suggested minimal local tectonic influence. Thus, if the pattern of eustatic sea level change developed elsewhere has an important effect on marginal marine sedimentation globally, this should be recorded on the Kirthar shelf.

The only rules that governed construction of the synthetic model were (1) that carbonates are generally deposited in deeper shelf settings farther from shore where they are free of much detrital influence (although the Kirthar carbonates are marly rather than pure limestone); (2) that green shales are deposited at intermediate depths and distances from shore where detri-
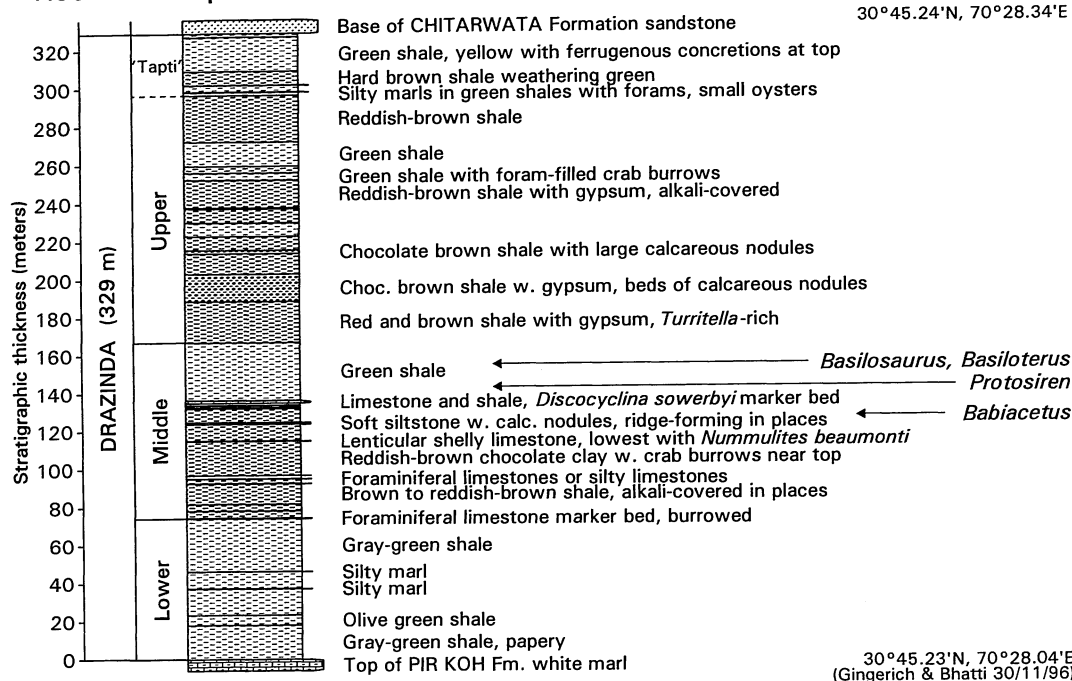
Rodho Sharqi section

FIG. 9—Rodho Sharqi stratigraphic section on the eastern flank of Rodho anticline. Section was measured at the southern edge of Survey of Pakistan topographic quadrangle 39 J/5 and Dhodak geological quadrangle of Bhatti et al. (1986). *Babiacetus* skull described by Gingerich et al. (1995a) came from brown shales just below the *Discocyclina sowerbyi* marker bed. *Protosiren sattaensis* type skeleton came from green shales just above the *Discocyclina sowerbyi* marker bed. *Basilosaurus drazindai* and *Basiloterus hussaini* type specimens described here came from the upper part of the green shale in the upper middle Drazinda Formation.

tal influence is substantial but there is little oxidation; and (3) that brown and red shales are deposited at shallower depths closer to shore where detrital influence is substantial and there is more oxidation. What is important of course is not so much sea level, but water depth and proximity to shore, which depend on the rate of sea level rise or fall relative to more or less constant sea floor subsidence on a passive continental margin (Pitman, 1978).

A composite Rakhi Nala stratigraphic section representing the entire Sulaiman Range Kirthar Group is shown in the lefthand stratigraphic column of Figure 14. It is based both on the section measured at Rakhi Nala (Gingerich et al., 1997b) and on the Rodho Sharqi section published here (Fig. 9). Rakhi Nala is the classic Sulaiman Range Kirthar section and the succession of lithologies and thickness of beds is well known there. The thickness of the Drazinda Formation is virtually the same at both Rakhi Nala and Rodho Sharqi; however, the Drazinda Formation is better exposed at Rodho Sharqi. The three principal lithologies observed in the field are shown with (1) a blocked pattern representing limestone and/or marl, (2) an open shale pattern representing the lighter green shales, and (3) a denser shale pattern representing the darker reddish brown shales.

Our synthetic model stratigraphic section based on sea level change is shown in the righthand stratigraphic column of Figure 14. The three lithologies generated by the model are the same as those in the composite field section. We have lumped all sea level rise from the latest Ypresian into the early Lutetian into one limestone unit, and we have combined the next inter-

FIG. 10—Cross-section of *Discocyclina sowerbyi* marker bed separating lower and upper parts of the middle Drazinda Formation. Photograph was taken in Bari Nadi. View is to north. *Discocyclina sowerbyi* is a large (ca. 5 cm diameter), saddle-shaped, discoidal foram. The lower part of the marker bed is a hard limestone 30 cm thick that is packed with *Discocyclina*. The upper part of the marker bed is not well indurated, is about 1 m thick, and is packed with broken pieces of *Discocyclina*. Slope in the background is the whale and sea cow-bearing green shale yielding the *Basilosaurus* and *Basiloterus* specimens described here. The large gastropod *Conus colossus* of Eames (1952a) is commonly found in this green shale.
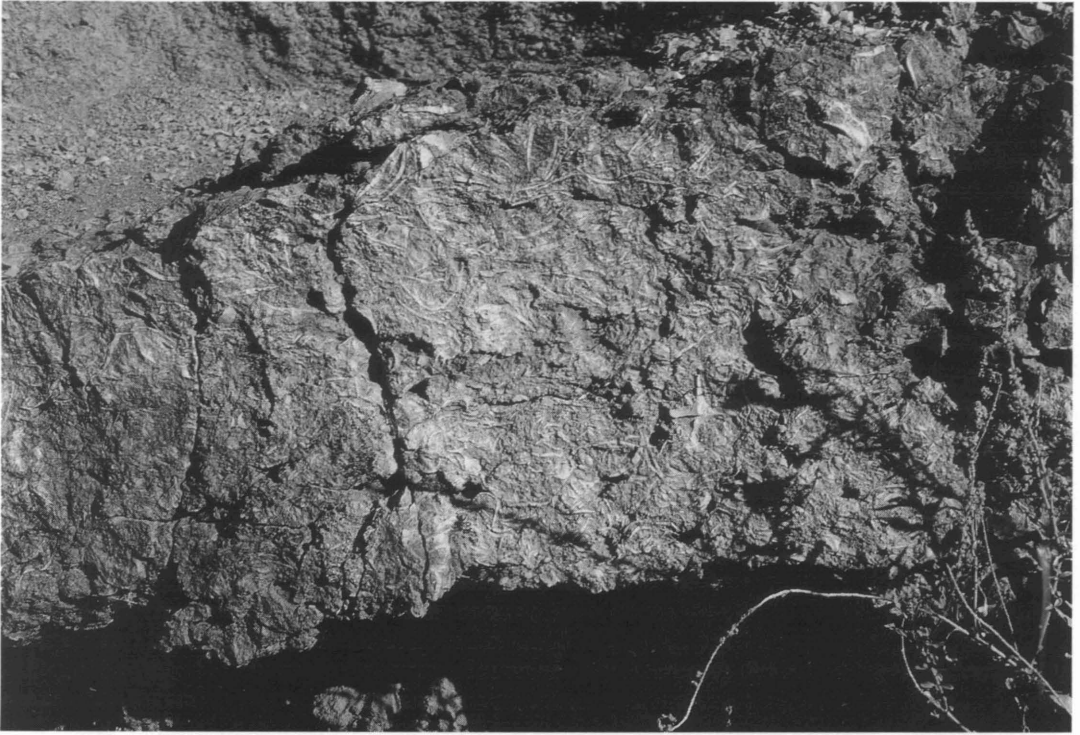
FIG. 11—Detail of indurated part of *Discocyclina sowerbyi* marker bed separating lower and upper parts of the middle Drazinda Formation. Photograph was taken in Bari Nadi. Note large pieces of *Discocyclina* resembling thinly-sliced potato crisps or chips. Indurated bed shown here is ca. 20 cm thick.

val of slightly falling sea level with the following interval of sea rise, showing both as green shale because these fall in a long duration of high sea stand. The remainder of the section follows only the simple rules outlined above.

The synthetic section is surprisingly similar to the section observed in the field. This can be seen by matching limestones and light and dark shale patterns between the two. We have lettered the fifteen successive stratigraphic units in the field section A through O, and these are matched by units in the synthetic model lettered A through O. The two limestone/marl units in the observed field section, the Habib Rahi Formation (unit A) and the Pir Koh Formation (unit F) were previously correlated with the high sea stands at the end of units A and B in the model (Gingerich et al., 1995a,b) but are here correlated with high sea stands in units A and F of the model.

There is archaeocete support for the correlation at two points. The first indicates correlation of unit C in the field, containing *Gaviacetus* with a single-centrum sacrum (Gingerich et al., 1995b), with unit C in the synthetic model, the level of *Protocetus* in Egypt with a similar single-centrum sacrum (Fraas, 1904). The second archaeocete bearing on the correlation is the *Basilosaurus* that prompted this reevaluation. *Basilosaurus drazindai* described here from unit I is similar but slightly more primitive and probably slightly older than latest Bartonian *Basilosaurus isis* from unit J in Egypt.

Haq's (1972) identification of nannofossils from 'lower chocolate' Domanda Formation shales as NP15 is consistent with our new interpretation, but his attribution of nannofossils

FIG. 12—Field exposure of low shallowly-sloping hills of chocolate and reddish brown shale with gypsum, abundant shells of high-spired *Turritella*, and beds of fist-sized black-weathering calcareous nodules. These beds are near the base of the upper Drazinda Formation in the Rodho Sharqi section (Fig. 9) and appear to represent a conspicuous interval of low sea stand following deposition of green shales yielding the fossils described here. View is to the east. Upper slopes are alternating red and green shales of the upper Drazinda Formation. Ridge on skyline is Chitarwata Formation.

from 'upper chocolate' Drazinda Formation shales to NP16 is not. Samanta's (1972, 1973) identification of planktonic foraminifera from the lower Drazinda as P12-13 is not consistent with our new interpretation, but his identification of planktonic foraminifera from the middle and upper Drazinda and 'Tapti' beds as P 14 and P15-17 is consistent (Samanta's results must be interpreted by referring to the Rakhi Nala stratigraphic section of Rieb and Bayliss published by Siddiqui, 1971). Köthe et al.'s (1988) identification of nannofossils from the Habib Rahi Formation limestone as NP14-NP15 is consistent with our new interpretation, but their identification of nannofossils in the Pir Koh Formation as NP15 is not. Köthe et al.'s identification of nannofossils from the '*Discocyclina* marl' (between units I and J here) as NP16 and NP17 is partially consistent, inclusion of lower 'Tapti' *Pellatispira* beds in NP17 is inconsistent, but inclusion of upper 'Tapti' *Pellatispira* beds in NP18 and NP19/20 is consistent. In a new study of planktonic and benthic foraminiferans from the Sulaiman Range, Afzal (pers. comm.) has emphasized that the Pir Koh marl is largely in zone P13, while *Pellatispira* is only found in the Priabonian stage. All of this evidence taken together supports the correlation of whale-bearing formations shown in Figure 14 rather than our earlier interpretation.

FIG. 13—Left innominate (A) and left femur (B) of a new specimen of *Protosiren sattaensis*, GSP-UM 3197, compared to cast of right femur (C) of Egyptian *Protosiren smithae* (CGM 42292, holotype; cast is UM 94810). Innominate is in lateral view. Femora are in anterior view. *P. sattaensis* comes from low in green shales of the upper middle Drazinda Formation. GSP-UM 3197 was found at the same stratigraphic level and in the same general area as the type of *P. sattaensis* (Gingerich et al., 1995a). Pelvis resembles that of Egyptian *P. smithae* of latest Bartonian age but differs in retaining a larger obturator foramen (Domning and Gingerich, 1994). Femur resembles that of *P. smithae* but differs in retaining a greater diaphyseal length. These differences show that *P. sattaensis* is a little more primitive and probably slightly older than latest Bartonian *P. smithae*. Scale is in cm.

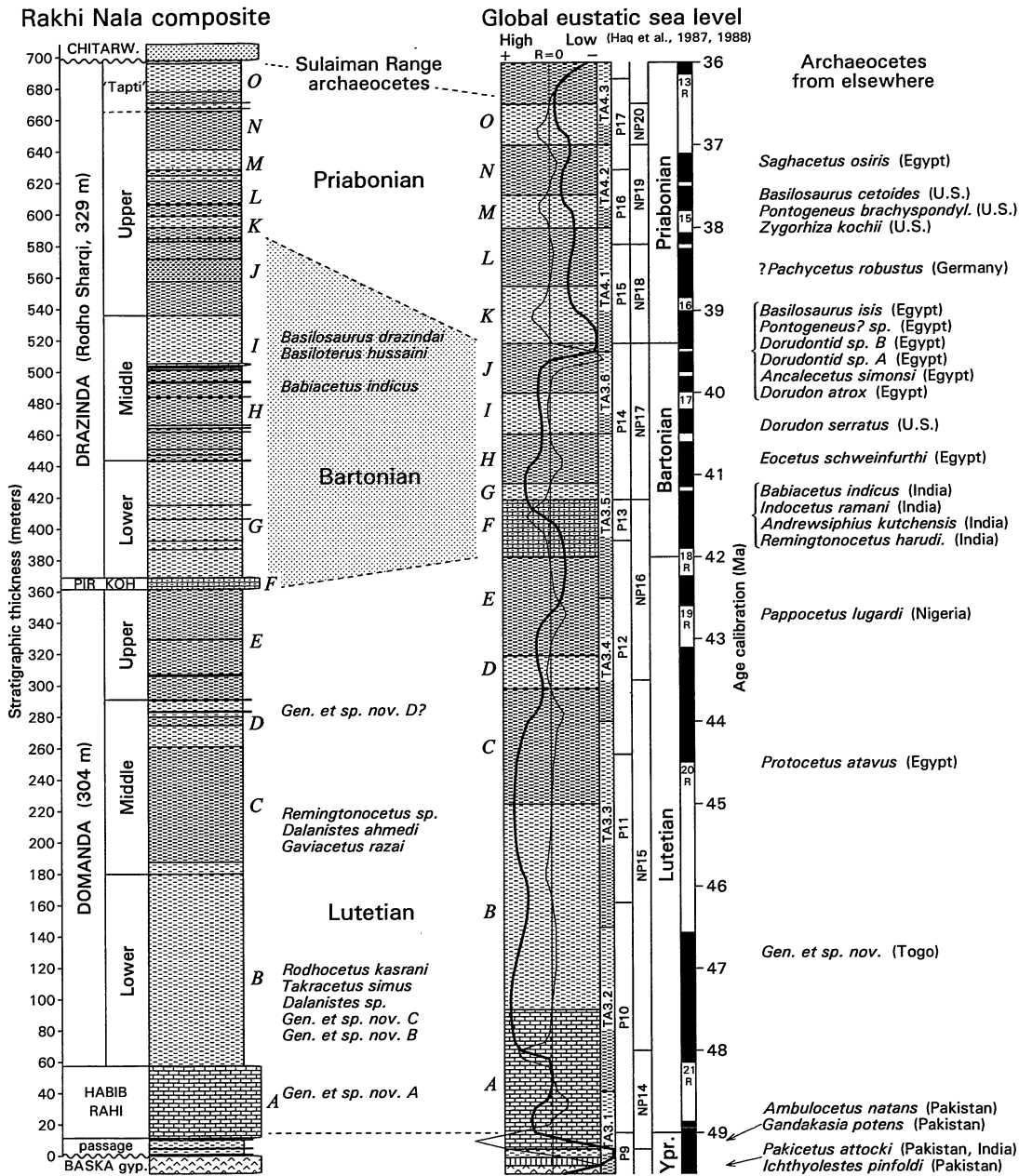## AGE OF WHALE-BEARING STRATA IN KUTCH

Good specimens of archaeocete whales are now known from six intervals in the Habib Rahi, Domanda, and Drazinda Formations of the Sulaiman Range in Pakistan. These six intervals

are shown in Figure 14. The one Kirthar formation that has not yielded archaeocetes in Pakistan is the Pir Koh Formation of early Bartonian age. Whale-bearing Kirthar-age strata are also found on the eastern margin of Indo-Pakistan farther to the south in Kutch (Gujarat State, India). These have been described by Tandon (1971), Sahni and Mishra (1972, 1975), Trivedy and Satsangi (1984), Kumar and Sahni (1986), and Bajpai et al. (1996). From the beginning these were described as Lutetian middle Eocene, where middle Eocene was generally considered to mean Lutetian and vice-versa. Study of planktonic foraminifera and calcareous nannoplankton in Kutch sections leaves no doubt that these strata are Bartonian.

Mohan and Soodan (1970) called the archaeocete-bearing Kutch strata Lutetian, but their foraminiferal zonation includes clear evidence only of the *Orbulinoides beckmanni* planktonic foraminiferal zone (P13) with foram-bearing strata below and above this (presumably upper P12 and lower P14). Jauhari and Vimal (1978) found the *Globorotalia lehneri* and *Orbulinoides beckmanni* planktonic foraminiferal zones (upper P12 and P13), and Biswas (1992) records *Truncorotaloides topilensis*, *Orbulinoides beckmanni*, and *Truncorotaloides rohri* (upper P12, P13, and P14). Singh and Singh (1991) studied calcareous nannoplankton and found the Harudi Formation in Kutch to be early Bartonian (NP16) and the Fulra Limestone to be late early to early late Bartonian (NP17). Biswas (1992, p. 17) described the archaeocete-bearing Babian stage of Kutch as representing the highest stand of the sea during the Eocene in India, which is consistent with early Bartonian transgression. The Kutch sequence was deposited during the Bartonian 'Kirthar transgression' of McGowran (1978a, 1990), a warm interval coinciding with establishment of *Discocyclina* assemblages in neritic carbonates (McGowran, 1978b). Note that McGowran's Kirthar transgression is just part of the Kirthar transgression of Nagappa (1959, pp. 149, 170) beginning in the early Lutetian.

FIG. 14 (facing page)—Revised correlation of the Habib Rahi, Domanda, Pir Koh, and Drazinda Formations to the geological time scale. New correlation is based on comparison of observed lithological succession in the field (lefthand column) with a synthetic model succession derived from global eustatic sea level (righthand column; eustatic curve from Haq et al., 1987, 1988). Sulaiman Range stratigraphic sections were measured at Rakhi Nala (Gingerich et al., 1997b; compare Takra section in Gingerich et al., 1995b) and at Rodho Sharqi (Fig. 9 here). In the model, subsidence and sediment accumulation are assumed to be continuous. Deposition of limestone and marl units (A and F) occurs when eustatic sea level (heavier curve) is high and the rate of change (R, lighter curve) is positive and generally relatively high. Deposition of green shales (light shale pattern; units B, D, G, I, K, M, and O) occurs when sea level is rising and the rate of change is positive. Deposition of red and brown shales (dark shale pattern; units C, E, H, J, L, and N) occurs when sea level is falling and the rate of change is negative. Sedimentary cycles are not bounded by unconformities but do conform to 3rd order sequence cycles (TA3.1, TA3.2, etc.) of Haq et al. (1987, 1988) in the upper part of the chart (TA3.6-TA4.3, though interpretation of lithologies is reversed).

Each stratigraphic unit A through O in the model can be matched in the Sulaiman sequence, which indicates both that deposition occurred on a remarkably stable passively-subsiding continental margin and that sea level stratigraphy can be a powerful tool for correlation. Paleontological evidence for correlation of particular units is provided by *Basilosaurus* and *Protosiren* in Pakistan (unit I in the field) vis-à-vis more advanced species of each in Egypt (unit J in the model) and by *Gaviacetus* in Pakistan and *Protocetus* of similar grade in Egypt (unit C in the field and in the model). Correlation here supersedes that of Gingerich et al. (1995a,b, 1997b). Oberhänsli (1996) indicates that the base

Rakhi Nala composite

Global eustatic sea level

Archaeocetes from elsewhere

Saghacetus osiris (Egypt)

Basilosaurus cetoides (U.S.)
Pontogeneus brachyspondyl. (U.S.)
Zygorhiza kochii (U.S.)

?Pachycetus robustus (Germany)

Basilosaurus isis (Egypt)
Pontogeneus? sp. (Egypt)
Dorudontid sp. B (Egypt)
Dorudontid sp. A (Egypt)
Ancalecetus simonsi (Egypt)
Dorudon atrox (Egypt)

Dorudon serratus (U.S.)

Eocetus schweinfurthi (Egypt)

Babiacetus indicus (India)
Indocetus ramani (India)
Andrewsiphius kutchensis (India)
Remingtonocetus harudi. (India)

Pappocetus lugardi (Nigeria)

Protocetus atavus (Egypt)

Gen. et sp. nov. (Togo)

Ambulocetus natans (Pakistan)
Gandakasia potens (Pakistan)
Pakicetus attocki (Pakistan, India)
Ichthyolestes pinfoldi (Pakistan)

of planktonic foraminiferal zone P10 and zone P13 were times of warm Eocene climate, which may help to explain deposition of carbonate in both and supports the correlation of units A and F shown here.

Sulaiman Range archaeocetes are now a large fraction of archaeocetes known worldwide. Archaeocetes from elsewhere are correlated to the geological time scale following Gingerich (1992) and other sources.

DISCUSSION

Discovery of *Basilosaurus* in Pakistan is important in extending the geographic range of this distinctive taxon into eastern Tethys, but it is even more important for having forced us to reevaluate our understanding of the chronology of archaeocete evolution in South Asia. When the Kutch fauna is included, marine archaeocete faunas are now known from seven temporal intervals in Indo-Pakistan, spanning the Lutetian through Bartonian ages. Archaeocetes from the lower and upper Kuldana Formation in Pakistan and Subathu Formation in India add at least two more continental-to-marginal-marine archaeocete faunas in the late Ypresian. This is an extraordinary fossil record of early whale evolution. It has almost all been recovered in the past twenty-five years, and we are only beginning to realize its full potential.

One tenet of current stratigraphic theory is that biotic, climatic, and oceanic changes are 'events' that happen fast. As McGowran (1986) has emphasized, "wholesale diachronism no longer is a useful paradigm; we are better off thinking in terms of virtually isochronous shifts in climate, watermass, and in planktonic and benthonic assemblages." This does not mean that such shifts are isochronous on the time scale of our lives, but that they happen rapidly compared to the million-year scale of biotic zones.

Comparison of lithological change observed in Kirthar stratigraphic sections in the field with lithological change predicted for the same interval by changing sea level in our synthetic model shows that the patterns are remarkably similar. This similarity has implications that go beyond revision of the chronology of archaeocete evolution. Resemblance of stratigraphic sections observed locally in Pakistan to the model stratigraphic section based on eustatic sea level change means that the local sections accumulated on a passive continental margin. Further, it corroborates the idea that sea level change on passive margins is a powerful tool for worldwide correlation.

Finally, it is difficult to imagine how the northwestern margin of Indo-Pakistan could be so passive that it would record global eustatic sea level change if continent-continent tectonic collision of Indo-Pakistan and Eurasia was actively underway, as Jaeger et al. (1989), McGowran (1990), Beck et al. (1995), and others have suggested. There were tectonic encounters with faulted sea floor to be sure (e.g., mammal-bearing Ghazij Islands of Gingerich et al., 1997a), but Tethys was not closed, and the uniformity of Kirthar formations over broad areas of continental shelf, absence of sand and coarser clastics, and preservation of a record of global sea level change all suggest that it was not actively being closed. Patriat and Achache (1984) found the interval between paleomagnetic anomalies 21 and 13 to be a time of slowed convergence of Indo-Pakistan with Eurasia and a time of erratic continental movement before stable northward convergence resumed. The interval of anomalies 21 to 13 is exactly the Lutetian through Priabonian interval studied here.

ACKNOWLEDGMENTS

LITERATURE CITED

ANDREWS, C. W. 1904. Further notes on the mammals of the Eocene of Egypt, Part III. Geological Magazine, series V, 1: 211-215.

———. 1906. A descriptive catalogue of the Tertiary Vertebrata of the Fayum, Egypt. British Museum (Natural History), London, 324 pp.

BAJPAI, S., J. G. M. THEWISSEN, and A. SAHNI. 1996. *Indocetus* (Cetacea, Mammalia) endocasts from Kachchh (India). Journal of Vertebrate Paleontology, 16: 582-584.

BARNES, L. G. and E. D. MITCHELL. 1978. Cetacea. *In*: Evolution of African Mammals, V. J. Maglio and H. B. S. Cooke (eds.), Harvard University Press, Cambridge, 582-602.

BAUM, G. R. and P. R. VAIL. 1988. Sequence stratigraphic concepts applied to Paleogene outcrops, Gulf and Atlantic Basins. *In*: Sea-Level Changes: an Integrated Approach, C. K. Wilgus, C. A. Ross, B. S. Hastings, H. Posamentier, J. Van Wagoner, and C. G. St. C. Kendall (eds.), Society of Economic Paleontologists and Mineralogists, Special Publication, Tulsa, 42: 309-327.

BECK, R. A., D. W. BURBANK, W. J. SERCOMBE, G. W. RILEY, J. K. BARNDT, J. R. BERRY, J. AFZAL, A. M. KHAN, H. JURGEN, J. METJE, A. CHEEMA, N. A. SHAFIQUE, R. D. LAWRENCE, and M. A. KHAN. 1995. Stratigraphic evidence for an early collision between northwest India and Asia. Nature, 373: 55-58.

BHATTI, M. A., M. AKHTAR, and M.-H. ABBASI. 1986. Geological map of Dhodak. Geological Survey of Pakistan, Geological Map Series, 4: 157 (one sheet).

BISWAS, S. K. 1992. Tertiary stratigraphy of Kutch. Journal of the Palaeontological Society of India, 37: 1-29.

DOMNING, D. P. and P. D. GINGERICH. 1994. *Protosiren smithae*, new species (Mammalia, Sirenia), from the late middle Eocene of Wadi Hitan, Egypt. Contributions from the Museum of Paleontology, University of Michigan, 29: 69-87.

EAMES, F. E. 1952a. A contribution to the study of the Eocene in western Pakistan and western India. C. The description of the Scaphopoda and Gastropoda from standard sections in the Rakhi Nala and Zinda Pir areas of the western Punjab and in the Kohat District. Philosophical Transactions of the Royal Society of London, Series B, 236: 1-168.

———. 1952b. A contribution to the study of the Eocene in western Pakistan and western India: D. Discussion of the faunas of certain standard sections, and their bearing on the classification and correlation of the Eocene in western Pakistan and western India. Quarterly Journal of the Geological Society of London, 107: 173-196.

FRAAS, E. 1904. Neue Zeuglodonten aus dem unteren Mitteleocän vom Mokattam bei Cairo. Geologische und Paläontologische Abhandlungen, Jena, Neue Folge, 6: 197-220.

GINGERICH, P. D. 1992. Marine mammals (Cetacea and Sirenia) from the Eocene of Gebel Mokattam and Fayum, Egypt: stratigraphy, age, and paleoenvironments. University of Michigan Papers on Paleontology, 30: 1-84.

———. 1998. Paleobiological perspectives on Mesonychia, Archaeoceti, and the origin of whales. *In*: The Emergence of Whales, J. G. M. Thewissen (ed.), Plenum Publishing Corporation, New York, in press.

———, S. G. ABBAS, and M. ARIF. 1997a. Early Eocene *Quettacyon parachai* (Condylarthra) from the Ghazij Formation of Baluchistan (Pakistan): oldest Cenozoic land-mammal from South Asia. Journal of Vertebrate Paleontology, in press.

———, M. ARIF, M. A. BHATTI, and W. C. CLYDE. 1997b. Middle Eocene stratigraphy and marine mammals (Cetacea and Sirenia) of the Sulaiman Range, Pakistan. Bulletin of the Carnegie Museum of Natural History, in press.

———, M. ARIF, M. A. BHATTI, H. A. RAZA, and S. M. RAZA. 1995a. *Protosiren* and *Babiacetus* (Mammalia, Sirenia and Cetacea) from the middle Eocene Drazinda Formation, Sulaiman Range, Punjab (Pakistan). Contributions from the Museum of Paleontology, University of Michigan, 29: 331-357.

———, M. ARIF, and W. C. CLYDE. 1995b. New archaeocetes (Mammalia, Cetacea) from the middle Eocene Domanda Formation of the Sulaiman Range, Punjab (Pakistan). Contributions from the Museum of Paleontology, University of Michigan, 29: 291-330.

————, S. M. RAZA, M. ARIF, M. ANWAR, and X. ZHOU. 1993. Partial skeletons of *Indocetus ramani* (Mammalia, Cetacea) from the lower middle Eocene Domanda Shale in the Sulaiman Range of Pakistan. Contributions from the Museum of Paleontology, University of Michigan, 28: 393-416.

————, S. M. RAZA, M. ARIF, M. ANWAR, and X. ZHOU. 1994. New whale from the Eocene of Pakistan and the origin of cetacean swimming. Nature, 368: 844-847.

————, B. H. SMITH, and E. L. SIMONS. 1990. Hind limbs of Eocene *Basilosaurus isis*: evidence of feet in whales. Science, 249: 154-157.

HALSTEAD, L. B. and J. A. MIDDLETON. 1972. Notes on fossil whales from the upper Eocene of Barton, Hampshire. Proceedings of the Geologists Association, London, 83: 185-190.

HAQ, B. u. 1972. Paleogene calcareous nannoflora. IV. Paleogene nannoplankton biostratigraphy and evolutionary rates in Cenozoic calcareous nannoplankton. Stockholm Contributions in Geology, 25: 129-158.

————, J. HARDENBOL, and P. R. VAIL. 1987. Chronology of fluctuating sea levels since the Triassic. Science, 235: 1156-1167.

————, J. HARDENBOL, and P. R. VAIL. 1988. Mesozoic and Cenozoic chronostratigraphy and cycles of sea-level change. *In*: Sea-Level Changes: an Integrated Approach, C. K. Wilgus, C. A. Ross, B. S. Hastings, H. Posamentier, J. Van Wagoner, and C. G. St. C. Kendall (eds.), Society of Economic Paleontologists and Mineralogists, Special Publication, Tulsa, 42: 71-108.

HARLAN, R. 1834. Notice of fossil bones found in the Tertiary formation of the State of Louisiana. Transactions of the American Philosophical Society, 4: 397-403.

HOWELL, A. B. 1930. Aquatic Mammals. Charles C. Thomas, Springfield, Ill., 1-338.

JAEGER, J.-J., V. COURTILLOT, and P. TAPPONIER. 1989. Paleontological view of the ages of the Deccan traps, the Cretaceous/Tertiary boundary, and the India-Asia collision. Geology, 17: 316-319.

JAUHARI, A. K. and K. P. VIMAL. 1978. Some observations on the Foraminifera from the Tertiary rocks of the Vinjhan-Miani area, Kutch. Journal of the Geological Society of India, 19: 154-159.

KÖTHE, A., A. M. KHAN, and M. ASHRAF. 1988. Biostratigraphy of the Surghar Range, Salt Range, Sulaiman Range and the Kohat area, Pakistan, according to Jurassic through Paleogene calcareous nannofossils and Paleogene dinoflagellates. Geologisches Jahrbuch, Hannover, Reihe B, 71: 1-87.

KELLOGG, R. 1936. A review of the Archaeoceti. Carnegie Institution of Washington Publications, 482: 1-366.

KHAN, A. A., M. AKHTAR, I. HUSSAIN, and T. MASOOD. 1986. Geological map of Barthi. Geological Survey of Pakistan, Geological Map Series, 4: 176 (one sheet).

KUHN, O. 1935. Archäoceten aus dem norddeutschen Alttertiär. Zentralblatt für Mineralogie, Geologie und Paläontologie, Abteilung B, Stuttgart, 1935: 219-226.

KUMAR, K. and A. SAHNI. 1986. *Remingtonocetus harudiensis*, new combination, a middle Eocene archaeocete (Mammalia, Cetacea) from western Kutch, India. Journal of Vertebrate Paleontology, 6: 326-349.

MCGOWRAN, B. 1978a. Stratigraphic record of early Tertiary oceanic and continental events in the Indian Ocean region. Marine Geology, 26: 1-39.

————. 1978b. Maestrichtian to Eocene foraminiferal assemblages in the northern and eastern Indian Ocean region: correlations and historical patterns. *In*: Indian Ocean Geology and Biostratigraphy, J. R. Heirtzler, H. M. Bolli, and J. G. Sclater (eds.), American Geophysical Union, Washington, 417-458.

————. 1986. Cainozoic oceanic and climatic events: the Indo-Pacific foraminiferal biostratigraphic record. Palaeogeography, Palaeoclimatology, Palaeoecology, 55: 247-265.

————. 1990. Fifty million years ago. American Scientist, 78: 29-39.

MOHAN, M. and K. S. SOODAN. 1970. Middle Eocene planktonic foraminiferal zonation of Kutch, India. Micropaleontology, 16: 37-46.

NAGAPPA, Y. 1959. Foraminiferal biostratigraphy of the Cretaceous-Eocene succession in the India-Pakistan-Burma region. Micropaleontology, 5: 145-192.

OBERHÄNSLI, H. 1996. Klimatische und ozeanographische Veränderungen im Eocän. Zeitschrift der Deutschen Geologischen Gesellschaft, 147: 303-413.

OWEN, R. 1839. Proceedings of the Geological Society. Athenaeum, London, No. 585: 35-36.

PATRIAT, P. and J. ACHACHE. 1984. India-Eurasia collision chronology has implications for crustal shortening and driving mechanism of plates. Nature, 311: 615-621.

PITMAN, W. C. 1978. Relationship between eustacy and stratigraphic sequences of passive margins. Geological Society of America Bulletin, 89: 1389-1403.

SAHNI, A. and V. P. MISHRA. 1972. A new species of *Protocetus* (Cetacea) from the middle Eocene of Kutch, western India. Palaeontology, 15: 490-495.

———— and V. P. MISHRA. 1975. Lower Tertiary vertebrates from western India. Monograph of the Paleontological Society of India, 3: 1-48.

SAMANTA, B. K. 1972. Planktonic foraminiferal biostratigraphy of the early Tertiary of the Rakhi Nala section, Sulaiman Range, West Pakistan. Journal of the Geological Society of India, 13: 317-328.

————. 1973. Planktonic foraminifera from the Paleocene-Eocene succession in the Rakhi Nala, Sulaiman Range, Pakistan. Bulletin of the British Museum (Natural History), Geology, 22: 421-482.

SIDDIQUI, Q. A. 1971. Early Tertiary Ostracoda of the family Trachyleberididae from West Pakistan. Bulletin of the British Museum (Natural History), Geology Supplement 9, pp. 1-98.

SINGH, P. and M. P. SINGH. 1991. Nannofloral biostratigraphy of the late middle Eocene strata of Kachchh region, Gujarat State, India. Geoscience Journal, 12: 17-51.

SLIJPER, E. J. 1936. Die Cetaceen, Vergleichend-Anatomisch und Systematisch. Capita Zoologica, 6-7: 1-590.

————. 1946. Comparative biologic-anatomical investigations on the vertebral column and spinal musculature of mammals. Verhandelingen der Koninklijke Nederlandsche Akademie van Wetenschappen, Amsterdam. Afdeling Natuurkunde. Tweede Sectie., 42: 1-128.

TANDON, K. K. 1971. On the discovery of mammalian and reptilian remains from the middle Eocene rocks of S. W. Kutch, India. Current Science, 40: 436-437.

TRIVEDY, A. N. and P. P. SATSANGI. 1984. A new archaeocete (whale) from the Eocene of India. N. A. Bogdanov (ed.), Abstracts of 27th International Geological Congress, Moscow, 1: 322-323.

WEST, R. M., J. R. LUKACS, S. T. HUSSAIN, and M. ARIF. 1991. Geology and palaeontology of the Eocene Drazinda Shale Member of the Kirthar Formation, central Western Pakistan. Part I: Introduction. Tertiary Research, Leiden, 12: 97-103.