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Stanford Paleoparadoxia Fossil Skeleton Mounting

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Acknowledgments

During the quarter of a century that it took me to complete this *Paleoparadoxia* skeleton display for SLAC, I received instruction, encouragement, strong-arm help, advice, and a great deal of friendship from countless people, to all of whom I am enormously grateful. They are too numerous to be mentioned here by name, other than a very few. My hearty thanks to those that must remain anonymous are no less sincere.

I especially want to thank Charles Repenning for all the instruction and assistance he gave me from beginning to end, including the use of lab space and equipment at USGS, Menlo Park Division, for the preparation of the *Paleoparadoxia* skull from Santa Barbara; and for his many visits to SLAC to help me position the skeleton.

My thanks also go to all the helpful people at the Museum of Paleontology of the University of California at Berkeley, starting with Dr. Joe Gregory and Dr. Donald Savage, who agreed to accept the Stanford *Paleoparadoxia* specimen for the University of California museum collections in exchange for plaster casts, and the many others that were ever hospitable during my frequent appearances there. Especially helpful were those individuals entrusted with the care of the collections, Howard Hutchinson, Mark Goodwin, and later Pat Holroyd.

Clayton Ray and others of the vertebrate paleontology staff at the National Museum of Natural History, Smithsonian Institution, Washington, D.C., were always hospitable during my several visits. I profited a great deal from discussions with him and his colleagues at the museum, and by having access to the rich collections there. Several sessions that included Daryl Domning of Howard University regarding the dentitions of *Paleoparadoxia* and other desmostylians were particularly informative. C. Ray also introduced me to the preparator staff and the large, well-equipped preparation labs where the elegant fossil skeleton displays are created. I will be forever grateful for all of the information I received during those visits.

Over the years, I had opportunities to visit a number of other natural history museums where I was invariably welcomed, shown the collections and prep labs, and given many tips and suggestions on mounting of skeletons. Among these museums were Princeton University, where Don Baird was most hospitable, showed me around, and introduced me to Barbara Smith Grandstaff and John Horner, and I saw a roomful of the first baby dinosaur specimens. In Salt Lake City, I was given a complete tour of the ongoing work of casting and mounting the fine *Allosaurus* dinosaur specimens from the Cleaveland-Loydd Quarry by Jim Madsen, and many useful pointers. Other people and places I would like to mention are Yoshikazu Hasegawa at the National Science Museum in Tokyo, Japan; Malcolm McKenna at the American Museum of Natural History, New York City; John Bolt and Oroville Gilpin at the Field Museum in Chicago; and Meemann Chang at the Institute of Vertebrate Paleontology and Paleoanthropology in Beijing, China.

I clearly remember spending one informative day, many years ago, in the top floor preparation rooms at the Los Angeles County Museum, Los Angeles, California. Leonard Bessom explained in great detail how he mounted a beautiful La Brea horse skeleton in a rearing position. I gleaned many pages of notes and instructions on skeleton mounting. Thus, my thanks go to him, and also to Larry Barnes, Sam McLeod, and others of the Vertebrate Paleontology Section there, who extended their hospitality to me on several occasions, and provided important information and access to the collections.

Frank Perry, paleontologist at the Santa Cruz City Museum of Natural History, also receives my sincere gratitude for sharing the rich accumulation of *Paleoparadoxia* teeth gathered at that museum, and for introducing me to amateur collectors, Steve Kunkle and Stan Jarocki, who also made their specimens available to me. I am equally grateful to Mike Long, another amateur collector in Santa Cruz, who provided a very important incisor tooth.

Here at Stanford University, I have formed a rewarding friendship with Judy Terry Smith and her husband, Jim Smith. Judy has followed the progress of our *Paleoparadoxia* mounting project over the years, providing interest and encouragement. Being an invertebrate paleontologist, she helped me choose from the numerous invertebrate fossils also found at SLAC for inclusion in the *Paleoparadoxia* display. I am most grateful for her identification and dating of these specimens. As the skeleton is created from plaster casts, the genuine fossils scattered on the sandy floor of the display add realism to the scene.

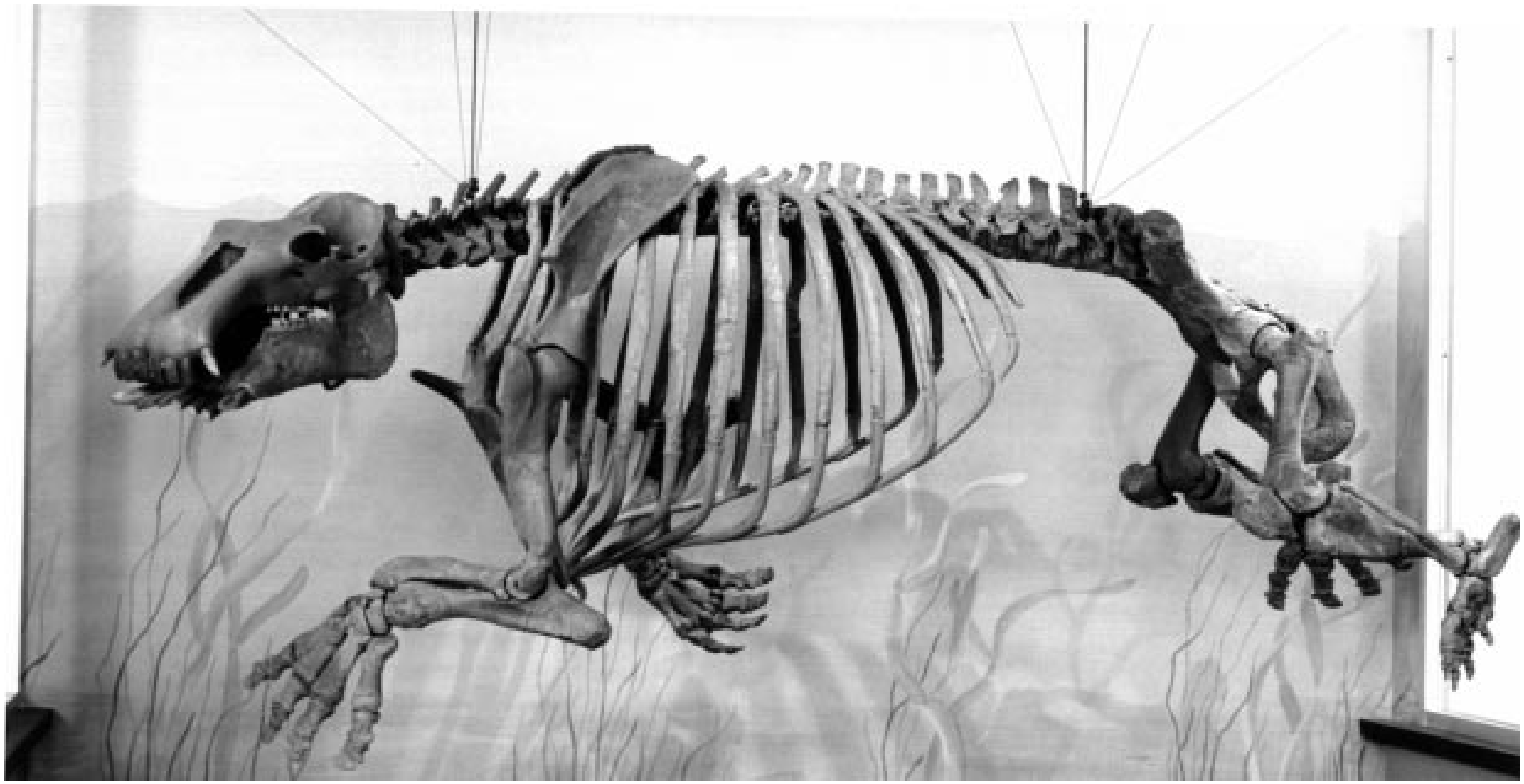
At SLAC, hundreds of people have given their assistance, out of friendship and interest in this intriguing mechanical project. I am grateful for their every suggestion and effort. Most especially, I thank Richard Jones of Plant Engineering for his dedication to the successful completion of the display and continued interest in its upkeep. John Flynn has my deepest gratitude for his ever-cheerful assistance and innovative design and fabrication of so much of the skeleton support system. A great many others at SLAC also contributed to the success of this project, including the past and present Directors of the Laboratory and their assistants.

Members of my family, children and grandchildren, helped in various important ways. Not only did my granddaughter, Catherine Panofsky, assist with some important steps in the mounting, she is the artist who painted the fine undersea mural on the back wall of the display. To all of these dear ones, and to my ever-so-patient husband, I extend my most sincere appreciation.

The final effort has been the production of this report. I deeply appreciate the corrections and suggestions given by my two reviewers, Charles Repenning and my son, Richard Panofsky. The report was made ready for printing by Maria Breaux, and the illustrations were prepared by Terry Anderson, in conjunction with the staff of the SLAC Technical Publications Department.

Thank you one and all!

Adele Panofsky
May 1, 1998



Stanford *Paleoparadoxia*

Introduction

On October 2, 1964, the astonishingly well-preserved fossil skeleton of the desmostylian genus, *Paleoparadoxia*, was discovered in the original excavations for the two-mile long linear accelerator at Stanford University. The fossil was almost entirely articulated and nearly complete. It is usually referred to as the "Stanford *Paleoparadoxia*." The bulldozers had cut away the sandstone by 8 or 10 feet of horizontal distance more than the original plan specified. Without this error the fossil would not have been discovered, and because of it, extra space had been provided so it was possible to remove the specimen without causing any loss of time on the accelerator construction project.

The first vertebrate paleontologist to see the exposed fossil was Earl L. Packard, Research Associate at Stanford University and Emeritus Professor from Oregon State University. He advised excavating the fossil because it appeared to be excellently preserved and possibly very interesting, as proved correct. Dr. Packard soon arranged to have the fossil excavation supervised by Charles A. Repenning, vertebrate paleontologist and marine mammal specialist, Menlo Park center of the U.S. Geological Survey. Dr. Repenning expressed immediate interest and took charge of the collection of the skeleton at SLAC and its removal to the paleo lab at the USGS for preparation, doing much of the work himself. Besides himself and Dr. Packard, several volunteers gave their time, among them Ray Cox, graduate student in the Stanford Geology Department and the author, Adele Panofsky. It took five weeks to complete the excavation.

Table 1 lists all the skeletal elements that were preserved and collected at the site. The specimen had been buried lying on its back on the sand of the sea floor. The ribs had fallen to the sides before burial and at least two dozen isolated shark teeth were found in the skeleton or very near to it. Bulldozing to make the discovery cut had removed the right shoulder joint and any vertebrae and other elements anterior to the second thoracic that might have been present, except for the left side of the lower jaw that was recovered under the ribs. From the standpoint of identification, this left half mandible was the most important element, identifiable as the rare herbivorous marine mammal *Paleoparadoxia,* by comparison with the only known North American specimen at that time, UCMP 40862, a right lower jaw published by Roy H. Reinhart, 1960.[1]

The SLAC sediments had previously been recognized as of marine origin, containing other fragmentary marine mammal fossils from whales, porpoises, and sea lions, and also various marine invertebrates and sharks' teeth.[2] Dr. Packard and Dr. Repenning made some preliminary studies, particularly of the nearly complete fore and rear limbs. They noted some interesting adaptations for locomotion both in and out of water, and some well-preserved pathological conditions of some bones, indicating the probable cause of death of that individual animal. These studies were published in 1990 in "Evolutionary Paleobiology of Behavior and Coevolution" edited by A. J. Boucot, in the section on Predation and Feeding Behaviors, *Locomotion of a Desmostylian and Evidence of Ancient Shark Predation* (C. A. Repenning, E. L. Packard).

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1. *A Review of the Serenia and Demostylia* by Roy H. Reinhart, University of California Publications in Geological Sciences, Volume XXVI (1960).
2. Geologic Site Investigation for Stanford Linear Accelerator Center. Report Number ABA-88. Prepared by Skjei, Conwell, Brittan, Tabor, Danehy (March 1965).

Table 1: Preserved Skeletal Elements of the Stanford *Paleoparadoxia*

Left lower jaw complete, but without teeth.
Second thoracic vertebra, neural spine and part of neural arch only.
Third thoracic vertebra through seventh lumbar vertebra, inclusive.
Seven caudal vertebrae, one of which may be two, fused by a healed break suffered during the animal's lifetime.
Left scapula, complete except for proximal joint, cut away by bulldozer.
Right scapula, distal edge of blade, including about 3 inches of its length, full width. Not used in mounted skeleton.
Left humerus, complete distal joint and slightly more than half length of the shank. Proximal joint destroyed by bulldozer.
Left ulna, and left radius, both completely preserved.
Right ulna, only the olecranon preserved, but right radius complete.
Of the left carpals, all but one are preserved: scaphoid, lunar, cuneiform, trapezoid, magnum, unciform.
Three proximal right carpals are preserved at least in part: scaphoid, lunar, cuneiform.
Of the left manus, all four metacarpals and all digit elements preserved, including four sesamoids for the second and third digits.
Of the right manus, the preserved elements are: second metacarpal complete; fourth metacarpal, the proximal joint, and more than half the length of the shaft; first phalange of third digit and first phalange of fifth digit. Also preserved but not used are the medial segment of the distal joint of the fourth metacarpal, and the distal joint surface of the first phalange of the second digit. No sesamoids.
Left ribs, 14 in number and complete, except the distal half of second rib and the head of rib number 13.
Right ribs, not completely reassembled for casting. We received partial casts of each of 11 right ribs. Two more fragments preserved in the collections were later cast for me.
Sacrum in two unfused segments.
Left and right pelvic elements, both complete.
Left femur, tibia and fibula, all complete.
Right tibia and fibula, both complete.
Left and right patellae.
All left tarsal elements complete: astragalus, calcaneum, cuboid, navicular, ectocuneiform, mesocuneiform.
All four left metatarals complete: second, third, fourth, fifth.
Five tarsal elements for the right pes preserved: astragalus, calcaneum, navicular, cuboid, ectocuneiform.
All four right metatarsals complete: second, third, fourth, fifth.
All left digits complete, including sesamoids.
Of the right pes, three digits were recovered complete: third, fourth, fifth, and all their sesamoids more or less complete.

Dr. Repenning also took the responsibility of arranging for the final disposition of the fossil. It could not be returned to the Stanford University campus, because Stanford no longer has a faculty or research facilities in this field. Therefore, it was arranged that the Stanford *Paleoparadoxia* specimen would be acquisitioned into the vertebrate paleontology collections of the University of California Museum of Paleontology, in Berkeley, where adequate storage and curating facilities are maintained. It was decided at that time that the specimen would first undergo complete and final preparation in the paleo labs at the University of California and then six sets of casts would be made for distribution and trade. Subsequent to the casting, the specimen would permanently be stored in the collections, only available for study by professional paleontologists, as the bones are quite fragile and the specimen is extremely rare, being the only entire, fully adult, postcranial skeleton of *Paleoparadoxia* in existence at this time. SLAC received one complete set of these casts in exchange for the fossil specimen. Other institutions that received sets of the casts are the National Museum of Natural History, Smithsonian Institution, Washington, D.C.; the National Science Museum, Tokyo, Japan; and U.S. Geological Survey (C. A. Repenning), Menlo Park, California.

In January of 1969 the beautifully cast fossil bones were presented to SLAC, one plaster cast piece for each bone found. A high grade of dental plaster was used, Glastone, which reproduced the actual bones in extremely fine detail. The presentation was made by Professor Donald E. Savage, Department Chairman and Director of the Museum of Paleontology at that time. Not only did SLAC receive the casts of the preserved fossil bones, it was also arranged that any restorations of missing bones that might be produced at SLAC by the author would be cast for us by the U.C. Museum of Paleontology technicians.

After some consideration and discussion with several professional paleontologists—Dr. C. Bertrand Schultz, University of Nebraska State Museum; Dr. Clayton E. Ray, National Museum of Natural History, Smithsonian Institution; and Don E. Savage and C. A. Repenning—it was decided that we would use the casts in a freestanding mount of the complete skeleton. Most advisors felt that it would be a shame to do something simpler like a wall plaque because the Stanford specimen is such an unusually complete skeleton. I did have some apprehensions, about the missing skull in particular, but Dr. Savage and Dr. Repenning generously offered to help me. Thus, I started work in March of 1969 in a small basement room at the Linear Accelerator laboratory. The SLAC directors decided, with government approval (Atomic Energy Commission), that the *Paleoparadoxia* display should be created and exhibited at minimum expense to the laboratory and lowest priority for time and materials on engineering and construction facilities. One paid worker was assigned to help me for three half days a week during the first few months, and I was happy to work as an unpaid volunteer.

Systematic Paleontology

Class	MAMMALIA, Linnaus 1758*
Order	URANOTHERIA, McKenna 1997
Suborder	TETHYTHERIA, McKenna 1986
Infraorder	BEHEMOTA, McKenna 1997
Parvorder	DESMOSTYLIA, Reinhart 1953, new rank
Family	DESMOSTYLIDAE, Osborn 1905
Genus	BEHEMOTOPS, Domning, Ray, and McKenna 1986

* This classification follows *Classification of Mammals*, Malcolm C. McKenna and Susan K. Bell (1997).

BEHEMOTOPS proteus Domning, Ray, and McKenna, 1986; Middle to Late Oligocene, Pysht Formation of Clallam County, Washington state. Referred specimen: USNM 244035, the Holotype, consists of the right mandibular ramus of an immature individual and several rear limb bones.

BEHEMOTOPS emlongi Domning, Ray, and McKenna, 1986; earliest Miocene, Yaguina Formation of Lincoln County, Oregon. Referred specimens: USNM 244033, the Holotype, consists of the left mandibular ramus of a mature individual retaining one molar tooth and all other alveoli more or less well preserved, and USNM 186889 that consists of an anterior fragment of a right mandibular ramus containing alveoli for three procumbent incisors and the external segment of the large canine tusk.

Genus CORNWALLIUS Hay, 1923.

CORNWALLIUS sookensis Hay, 1923; Early Miocene, Sooke Formation of Vancouver Island, British Columbia, Canada. No referred specimen.

Genus PALEOPARADOXIA Reinhart, 1959.

The ancestry of *Paleoparadoxia* may be theorized to stem from the early ancestors BEHEMOTA. The known species are listed here in order of their theoretical lineage.

PALEOPARADOXIA weltoni Clark, 1991; Early Miocene, Schooner Gulch Formation, Mendocino County, California. Referred specimen: UCMP 114285, the Holotype, consists of the rather complete anterior section of a skeleton from the 11th thoracic vertebra forward. The specimen includes the skull cranium and partial rostrum. Also included are the almost complete left mandibular ramus and partial right mandibular ramus, in which together the majority of teeth are preserved.

PALEOPARADOXIA tabatai Ijiri and Kamei, 1961; Miocene, Yamanouchi Formation, Gifu Prefecture, Japan. Referred specimen: NSMT P-5601 is a quite complete sub-adult skeleton that includes the skull and mandible and complete dentition. A fiberglass casting of these two important elements was available to me for my skull, jaw, and dentition restorations.

PALEOPARADOXIA tabatai Reinhart, 1959; Upper Miocene, Santa Margarita Formation (probable, although the precise locality is unknown), Santa Cruz County, California. Referred specimen: UCMP 40862, is a partial right mandibular ramus containing the third molar with complete crown, and the crownless root of the second molar. Forward of these teeth the dentary is broken, so no other cheek teeth nor alveoli for them are preserved. Anteriorly, the canine tusk is preserved as are alveoli for three procumbent incisors. The publication of this specimen furnished the basis for identification of the Stanford *Paleoparadoxia* fossil.

Discussion

Later discoveries of *Paleoparadoxia* specimens with teeth preserved in place suggest that UCMP 40862 may actually represent a larger species than *Paleoparadoxia tabatai* Ijiri and Kamei, 1961, that was contemporaneous with *Paleoparadoxia tabatai* on the east Pacific shores, because of its somewhat larger size and more highly developed tusk. Further evidence for the theory consists of the large variation in size of the individual molar specimens that are found together in some Miocene marine deposits, such as the Santa Cruz County gravel pits. Among those teeth it is possible to class some as large and the rest as small, as will be discussed later in this document. A future review of the genus *Paleoparadoxia* may designate a new species name for these larger forms.

Three other specimens containing teeth that are of importance to this study are briefly described here. It is my opinion that all three are representatives of this larger *Paleoparadoxia* species mentioned above. All are yet to be published.

PALEOPARADOXIA species (unpublished) UCMP 81302; Middle to Upper Miocene, Ladera Sandstone Formation, San Mateo County, California. It is a virtually complete postcranial skeleton which includes the left mandibular ramus without teeth, except for the internal part of the tusk and the entire root of the second premolar. One upper incisor fragment was also found. This is the specimen that was unearthed at SLAC and subsequently cast, restored, and mounted as described in this document.

PALEOPARADOXIA species (unpublished), UCMP 147527; earliest Middle Miocene, Monterey Formation, Santa Barbara County, California. The specimen was collected from tidewater at Lost Burro Beach, Santa Barbara County, California. It was embedded in a large waterworn concretion of Monterey Formation siliceous rock containing diatoms of earliest Middle Miocene age.[3] The specimen consists of a nearly complete *Paleoparadoxia* skull and mandible with complete dentition discernable. It is the largest of the known specimens.

PALEOPARADOXIA species (unpublished) LACM 131889; middle Middle Miocene, Topanga Formation, LACM locality 6064, at Mission Viejo, Orange County, California.

3. Analysis of the numerous diatoms in the matrix was performed by John A. Barron, U.S. Geological Survey, Menlo Park, California, October 1997.

> This specimen consists of fragmentary skull and postcranial elements, and the nearly complete mandible. The mandible is in two parts, the right half being complete and containing the canine tusk and all cheek teeth. The left half is partial but contains the cheek dentition. Both parts of the mandible exhibit some pathological conditions. A few upper teeth were found in association, as well as several lower incisors. The specimen is of comparably large size as the aforementioned three.

The restored skull that was created for the free-standing mounting of the UCMP 81302 *Paleoparadoxia* was based on information taken primarily from the large Santa Barbara skull specimen, UCMP 147527. The dorsal surface of the cranium had been eroded away as the concretion in which it was embedded rolled around in the tides, exposing the turbinal bones. Therefore, the information that was used to replicate the nasal, frontal, and parietal bones was taken from the fiberglass cast of the Japanese *Paleoparadoxia tabatai* skull, NSMT P-5601, it being the only other preserved skull available.

Restoration of the Missing Parts

Table 2 lists all the bones that were missing from the fossil which we were obliged to restore. I had the help of a part-time assistant, Marvin Washington, during the reconstruction of the missing parts phase of the mounting project. We were instructed by the paleo lab technicians at Berkeley to make the restorations in oil-base clay, varnished on completion with clear Glyptol varnish to seal in the oil. The molds would be made with a latex rubber compound which would soon deteriorate if contaminated by the oil from the clay. Glyptol is a sealer and varnish that can be applied successfully to greasy or oily surfaces.

Table 2: Skeletal Elements Reconstructed for the Display

Skull
Right lower jaw
Hyoid arch
Atlas, axis, and five remaining cervical vertebrae
First thoracic vertebra
Second thoracic vertebra to fit with its preserved spine and partial neural arch
Manubrium
Right first rib
Complete head of left first rib
Head, tubercle, and lower two thirds of right second rib
Complete head and lower one half of left second rib
Articular tubercle and lower one half of third right rib
Distal one fourth of the fourth right rib
Distal half of fifth right rib
Distal thirds of sixth right rib and seventh right rib

Table 2: Skeletal Elements Reconstructed for the Display

Distal one quarter of eighth right rib
More than one half the total length of the 11th right rib, distal section
All of the 12th right rib except a small tip from the head
All of the proximal section to the angle of shank (about five inches long) of the 13th right rib, a “floating” rib
Distal few inches of 14th right rib, also floating
Proximal head and part of shank of 14th left rib
Right scapula
Proximal joint for left scapula
Right humerus
Distal joint for left humerus
Right ulna except olecranon, to be fitted onto restored olecranon
Three distal carpal elements for right manus: trapezoid, magnum, and unciform
One distal carpal element for left manus: trapezoid
Metacarpals for right manus: third and fifth in their entirety, and distal half of the fourth
Most of the phalanges for digits of right manus: first, second and third phalanges for the second digit, second and third phalanges for the third digit, all three phalanges for the fourth digit, second and third phalanges for the fifth digit
Right femur
One tarsal element for right pes, mesocuneiform
The three phalanges of the second digit of the right pes

The smaller missing elements, such as toe bones, could be modeled directly from a lump of clay, the shapes determined by copying from an equivalent preserved bone. As the left limbs were more complete than the right, many of the right elements were produced by left-to-right copying by eye, making adjustments for any necessary variation for fitting together with the preserved elements. Only on the right scapula was it decided to abandon the preserved distal edge and make the complete scapula in restoration.

The elements that are long and thin, such as limb bones and ribs, or that have complicated shapes, arches, and protrusions need internal armatures because the oil clay remains soft and will not hold these shapes alone. Various methods and materials were employed in making the internal armatures. I and my assistant used simple wood scraps or dowel inside the pieces for metapodials and shorter sections of ribs. Larger, more hefty scrap lumber, such as 1-by-1 inch or 1 inch by 2 inches of suitable lengths were used in the long limb bones. The longer sections of ribs are curved, so for those we used lengths of bent curtain rod. Restorations of vertebrae required the construction of a more complicated armature to support the spine, the neural arch, and lateral processes. For these we used expanded metal webbing, which we cut with diagonal pliers. To attach the various pieces together, the cut ends of metal could be bent over each other. The drum-shaped part for the centrum would be filled with crumpled newspaper to keep it from filling up with clay (see Fig. 1).

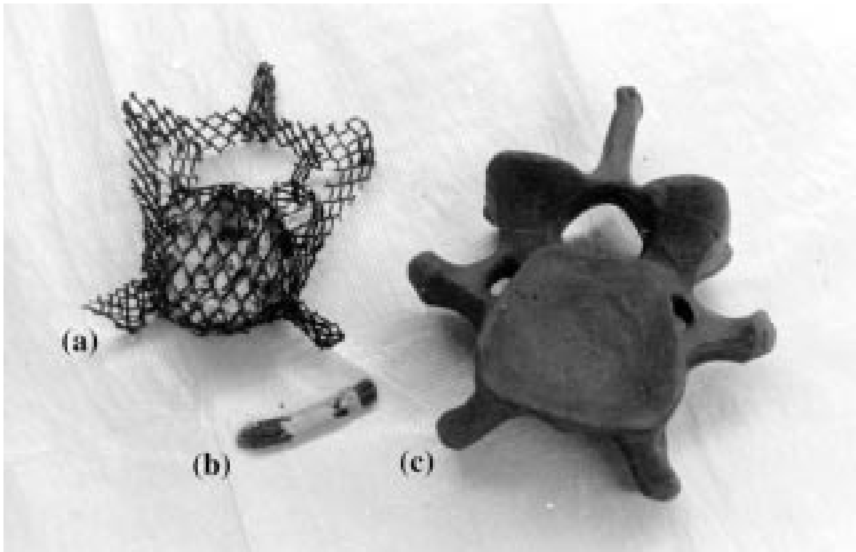

Fig. 1: Vertebra restoration: (a) Metal webbing filled with newspaper, (b) broom straw, and (c) completed vertebra restoration.

The most complicated armatures were made of sheet aluminum, cut and bent to shape, and riveted together where necessary, for the right scapula, right half of the mandible, and the skull. The internal armature, once produced, would then be covered over with the oil clay to form the approximate final shape. Then the final exact shape could be sculpted by eye to produce the left/right or right/left copied surface details, taking into account adjustments for fit, as the preserved elements from the right side were very rarely exactly the same as those on the left.

The final step in the process, to produce a bony-looking surface on the pieces, proved quite difficult for me and my assistant. We made smaller and larger holes with pointed objects, tried to simulate cracks with the sharp, rough edges of several broken pebbles, pressed the surfaces with something rough such as a piece of driftwood, and other such tricks. One of the most effective tools we made was a tiny bundle of broom-straws (about 1/2-inch diameter), lashed together tightly with string across the middle [see Fig. 1(b)]. One end of the straws was cut quite evenly and could be pressed vertically against the clay to simulate the spongy sort of bone that forms around various muscle attachments and cartilaginous joints of the actual specimen. This development was attributed to the osteo-arthritic condition of the individual. The other end of the bundle was left uneven with some curvature. This could also be pressed into the clay surface for parallel longitudinal streaks. However, none of these devices ever produced a truly bony-looking surface. It was partly for this reason that it was decided to use a different painting method for the reconstructed elements in the final display.

To produce restorations of central elements, such as vertebrae or parts that were missing both right and left, required obtaining a suitable model from which to work. Repenning loaned us a fossil specimen consisting of the distal joint of a humerus bone of a desmostylian, found at the

Dicalite Diatomite Mine in Lompoc, California, which we used as a model for the missing left humerus distal end. We had to make the proximal joint for the scapula to match. When both these pieces for the humerus and scapula were made, my assistant and I then produced the left-to-right copies of the same two complete bones for the right limb.

All the cervical vertebrae were missing from the specimen, requiring us to obtain a suitable model. A hippopotamus neck was chosen because the hippo generally has similar size and weight dimensions and somewhat similar lifestyle to the desmostylians, except for being a land, freshwater animal rather than marine. In many details of their skeletons these animals are quite dissimilar; however, the cervical vertebrae proved to be fairly similar, to judge from *Paleoparadoxia* specimens found in Japan. We styled the centra with much less concavity and convexity and also narrower than those of the hippopotamus cervicals, which seemed more characteristic of the preserved thoracic vertebrae of the specimen. A hippopotamus neck was borrowed from the California Academy of Sciences. We were able to get the first six cervicals from a dried specimen, not entirely cleaned. Before making the copies the bones had to be cleaned off and separated, which was accomplished by a combination of long soaking in BIZ laundry detergent and removal of the softened tissues with surgical knife blades. The restorations were then formed over expanded-metal armatures. At that time I had the help of a volunteer assistant, Lillian Lynch, who made the cervical restorations.

To restore the right lower jaw, a preliminary left-to-right copy was fashioned over a sheet aluminum armature. However, this piece could not be finally completed until a restoration for the skull was produced. It would be necessary that the three pieces, skull and both lower jaws, fit together properly. The restoration of the right lower jaw was therefore laid aside for several years while the skull was under construction. This was one of the great advantages of using oil-base clay, that it would not dry or shrink and could be worked again many months later.

The manubrium, that is the proximal central element of the sternum, was not part of the original casting. The *Paleoparadoxia weltoni* specimen, UCMP 114285, includes one central element of the sternum which appeared to us to be the manubrium, the most proximal bone of the sternum, such as is present in proboscideans. Dr. Repenning advised me to make one to fit our Stanford skeleton because it appeared that any such bone that our specimen might have included would have been lost to the bulldozers. I followed this advice and sculpted the piece myself in oil-base clay according to the shape I could see in my photographs of the Point Arena specimen.[4] I then produced the rubber mold for it and the plaster mother-mold to keep it in shape during casting. This was the only skeletal element that I cast myself.

Of ribs, we had received 14 left rib casts, mostly complete. However, for the right side we had only 11 casts. The right first rib was entirely missing but the left first rib was recovered almost complete, and it is a very robust, heavily constructed bone and quite short. It is therefore very distinct and could not be confused with any more posteriorly located rib. A left-to-right copy was made from it for the right side. However, two more ribs were still needed for the right side to

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4. In December of 1991, James Clark published a description of this specimen in *The Journal of Vertebrate Paleontology*, vol. II, no. 4, naming it *Paleoparadoxia weltoni*. In this article he interprets the central sternal element as the second xiphisternum, the most distal element. I do not understand his reason for this choice.

complete the 14 pairs. I located two more fragments among the fossil remains of the ribs that were not cast, one of them a rather broken and headless section of a second rib, and a small rib head that was most probably from the missing right rib number 12. The second ribs are also quite distinct from the more posterior ribs, as they are only several inches longer than the first ribs and quite flat, with a wide flange along the central part, whereas the more distal ribs become progressively almost round in cross section. I asked to have these two pieces cast, which was done. Then for right rib number 12, I made a restoration of the remaining full length of shaft below the head.

It was later determined that the two second ribs had been interchanged by mistake. The originally cast second rib was then moved to the right side, and fully restored, as were all the rest of the right ribs. The new partial second rib casting was then completely restored for the left side. In this way I completed the display with 14 pairs of ribs.

The restoration of the *Paleoparadoxia* skull was the most challenging of all. At first the only skull specimen available to me was a fiberglass cast of the *Paleoparadoxia tabatai* specimen, NSMT P-5601, discovered in Japan before World War II. The Japanese animal is about half the size of our Stanford fossil, and is considered not to be fully mature as evidenced by the condition of the well-preserved dentition. Its skull and mandible also have suffered some crushing, making it impossible for me to create a credible large adult skull from it alone.

Repenning came to the rescue again. He knew about a fossil specimen that was collected some years earlier by a zoologist named Phil C. Orr, who was at one time the Curator of the Department of Paleontology at the Santa Barbara Museum of Natural History. Repenning knew that a large marine mammal skull had been collected by Dr. Orr some years before at Lost Burro Beach off the rocks at low-low tide. The specimen was encased in a large concretion. Even though Dr. Orr had retired from the museum, his specimens were still retained by the museum, and perhaps arrangements could be made for a loan if this proved to be the right sort of animal. I made a trip there, found the specimen among others in the museum storage, and became convinced that this was a complete *Paleoparadoxia* skull of large size with at least the front dentition sufficiently preserved, even though its encasement in the concretion concealed much detail. Repenning then made the arrangements to obtain the skull on loan and transported it himself from Santa Barbara to USGS in Menlo Park.

On inspection it was immediately discerned to be embedded in a very hard siliceous matrix that could not be chipped off. Repenning said it would take at least two years to prepare; however, he didn’t have a preparator available to him at that time. I finally realized that it might never get done unless I took the matter in hand. So before long I was provided a workbench in the USGS “rock-crushing lab” with the specimen and a dentist’s discarded hand grinder set on it. After several discouraging attempts, it was decided that sandblasting would go faster. I arranged to have the skull transported to SLAC’s sandblasting shed, where I and my assistant could work on it when the sandblaster was not in use for other SLAC needs.

In this way we removed several hundred pounds of rock off the lower surface of the concretion, (where the rock was thickest), and quite a lot of thickness from the other surfaces. A heavy coat of rubber molding material was painted over the exposed bone and teeth to protect them from any stray blasting sand. When we finally decided we were now quite close to the bone, the specimen was transported back to USGS and the rock crushing lab. Here I worked with several sizes of electric hand grinders fitted with silicon carbide grinding points, two days a week for two years, until I had exposed enough of the skull to be able to make the restoration. I had uncovered all of the dorsal and posterior surfaces and the left lateral surface. We had also turned the specimen upside down and I had been able to expose a significant area of the palate and several upper and lower molar teeth, some of which had fallen out of their sockets and lay on the palate because the specimen had laid upside down with the mandible in place as the sediments were being deposited over it.

At last I decided I must stop this interesting work and get back to making the skull restoration for the mounting, as time was passing. We transported the specimen back to the SLAC bone lab for that purpose. At first I had to decide a proportional fraction to use in scaling down the size of the restoration from the actual specimen. The mandible of the Santa Barbara fossil measures about 4 inches longer than the Stanford mandible, so the specimen was from a considerably larger animal than ours. I made comparative measurements of both left mandibles and finally decided on the proportional fraction.

I placed the Santa Barbara specimen on a large piece of quadrille graph paper and drew around the entire left outline from the anterior center to the posterior center. I then folded the graph paper along the center line and traced off the right outline from the left, making an idealized symmetrical pattern. In a similar fashion I made an idealized outline for the lateral view and one for the occipital surface. Next, I drew a second set of outlines on new sheets of quadrille graph paper, with all the dimensions scaled down by my predetermined fractional proportion. From these smaller diagrams I made the patterns for the internal armature to be used in the reproduction.

I made the original pattern from a lightweight poster board and put it together with staples. When I showed this product to Repenning he approved it after making several small adjustments. Back at SLAC, I took it to the sheet metal shop, where the staples were removed and the paper pieces used as patterns for cutting out the shapes in sheet aluminum. The device was then bent up and riveted together to make the skull armature.

With the armature completely covered with oil clay it was possible for me to sculpt the outer surfaces, referring to both the Santa Barbara specimen and the Japanese fiberglass specimen. At that time I did not restore any teeth, only leaving more or less distinct alveoli for incisors and tusks. No decisions had yet been reached on how I would present the teeth; however, I did make blanks that could be modified for incisors and tusks in case they would be appropriate. For the details of sutures between the various bones of the skull, I was able to discern all that was necessary from one or the other of the two skull specimens, which was also true for various foramina and other details. I had to develop the occipital crest into prominence to indicate an older adult individual, even though that part was not preserved on the large Santa Barbara specimen. I was not able to represent the delicate turbinal bones that would be exposed within the nasal opening, so I tried to give that area the appearance of unprepared matrix filling the openings.

I did not have any information for restoring the ear bones, the bullae and external auditory meatus, and even now I do not know of any specimen in existence on which these details can be seen. However, I do believe that they are most likely well preserved on the Santa Barbara specimen and a very skilled preparator might be able to expose them to view. I would not even dare try for fear of destroying these delicate structures. I was tempted to leave off any suggestion of ear bones on the restoration, thinking maybe *Paleoparadoxias* didn't have any. But Repenning said "all mammals have ear bones." So he proceeded to manufacture something more or less copied from a cow's skull. After that I made a reverse copy of his creation for the other side.

The placement of the *Paleoparadoxia* external auditory meatus is not directly known, as mentioned above. However, it is considered by some to be in the unusual triangular cavity between the temporal and squamosal bones. A similar structure occurs in proboscideans as primitive as Moeritherium and also in Desmostylus, which may be one indication of the close relationship of these animals.[5] But Repenning and I were not cognizant of these facts at that time, and even now it is difficult to imagine how this structure could have migrated to a position above the large temporal arch support, whereas generally in mammals the external auditory meatus is closely associated with the jaw articulation, below the temporal bone. We placed our auditory restoration in the usual position, below the temporal arch and directly posterior to the mandibular articulation on the ventral surface of the skull.

Some generalized pieces were also prepared in clay for casting to represent bones for a hyoid arch for the *Paleoparadoxia* skeleton. A published specimen of the hyoid arch of a fossil camel was used as model for these pieces. Later this structure was completely revised after I had done some more extensive research on the variations of hyoids in a number of different herbivorous mammals. However, the final shapes and dimensions that we used are still generalized because there are no actual preserved *Paleoparadoxia* specimens of this structure. I made four separate bones for each side plus one central element. These would be referred to as: stylohyoid, epihyoid, ceratohyoid, thyrohyoid, and the central element the basihyoid.

On January 31, 1974, the U.C. Museum of Paleontology presented the casts of the missing parts to SLAC at a small news conference that was held in the museum paleo lab at Berkeley. The presentation was made by Dr. Joseph T. Gregory, who was then Chairman of the Paleontology Department and Director of the Museum, and several of the lab technicians who had worked on the casting were also present. Dr. Repenning was there from the USGS, and I was there to represent Stanford and SLAC. The restorations had also been cast in multiples of six or more and were distributed to the same establishments that had the original sets of the casts. Repenning and I then transported the packed crates with our new casts back to Palo Alto.

The Mock-up, Temporary Mounting

In February of 1974, casts of all bones necessary to construct a complete *Paleoparadoxia* skeleton were at hand. To begin I weighed all the casts, recording the weights of each piece and the combined weights of various elements on a chart for future reference. The entire set of casts added up to almost exactly 400 pounds (see Appendix A on page 133). This gave us some clues as to strengths of materials that would be required in the engineering of the support structures.

Before a fossil skeleton can be permanently mounted, its final position must be determined, and a steel framework must be designed of suitable size and strength to support all the bones in that position. The most modern and realistic fossil mountings are now assembled so that the support system is almost entirely concealed. Planning the relative position of the bones is not easy to do

5. See Domning, Ray, and McKenna, *Smithsonian Contributions to Paleobiology*, No. 59 (1986), page 45.

without any three-dimensional visual reference. Therefore, we felt it would be desirable to construct a temporary support system in which each main bone would be firmly clamped, but that would at the same time allow sufficient movement of each piece so that various stances could be tried. To accomplish this "mock-up" mounting, we followed the suggestions of Frank Pearce, who was then chief preparator in the Division of Vertebrate Paleontology at the National Museum of Natural History, Smithsonian Institution.

The method he suggested requires first a temporary supporting rack and platform of unfinished wood. This platform was built for me having a 1 inch thick plywood base 4 inches off the floor and 6 feet by 12 feet in area. A 1 foot wide supporting beam crosses longitudinally along the center line at a height of 6 feet above the floor of the base. It was planned that the mounted skeleton could comfortably fit within this 6 by 6 by 12 foot volume.

All the large bones had to be used in the mock-up version, which required a specially designed system of clamps and three-way steel pipes. These adjustable pipe fixtures, in use at the National Museum prep lab, were homemade of steel water pipe and matching flanges, T-joints, etc. Here at SLAC we had the good fortune of having aluminum pipe scaffolding equipment available. This type of temporary railings and supports are made by several companies, such as NU-Rail, Cinti. O.; and SPEED-RAIL, both in Cinncincinnati, Ohio. They are made to accommodate several sizes of aluminum piping and include a wide variety of fixtures such as L-corners, T-joints, swivel joints, base flanges, etc., that all clamp onto the pipe with Allen head set screws. The use of this equipment afforded us almost infinite flexibility in the construction of our temporary mounting (see Fig. 2).

The first decision I made on the final position was to have the skeleton be represented in a swimming posture. This would avoid my having to decide between the various theories of how *Paleoparadoxia* might have moved about on land. My second idea was to support the skeleton by cables from above to avoid having steel supports coming up under the body from the floor below. This would make the impression of swimming more vivid, and in my engineering inexperience it seemed to me to be simpler. It was also planned to have the left side of the skeleton designated as the front of the display because the left side of the fossil was more completely preserved. Therefore, the position should indicate the animal looking to the left, with the neck curved to the left about 45°. From the beginning I had the idea to have a see-through display which could be viewed from both sides, but in case that could not be achieved the left side would give the most advantageous view.

The first elements to be placed in the mock-up were the vertebrae. I thought there should be some slight curvature in the position of the spinal column to indicate the animal in motion, rather than stretched out stiff and straight; Repenning agreed. The vertebrae were then hung up from the overhead horizontal beam following these predetermined curvatures. Each vertebra was fitted with two lengths of insulated electronic wire, strung one around the right and one around the left transverse processes and then through the neural arches. The wires were attached overhead by a series of screw-eyes screwed into the horizontal beam, two screw-eyes for each vertebra. The wire hangers afforded adequate flexibility for adjusting the relative heights and positions of each piece.

Fig. 2: The author with the temporary supporting platform and the mock-up mounting under construction.

The sacrum is the most posterior element of the vertebral column, and its position would have to be firmly determined and set because it would be necessary to support the complete pelvic girdle and the rear limbs from that point. To clamp the sacrum in place, a block of wood was shaped with tapering sides and carved out on top to permit the sacrum casting to be supported on it over its entire ventral surface. The clamp was also fitted with a steel strap manufactured from a cut-open commercial hose-clamp with tightening-screw adjustment. On the underside of this block a base-flange was mounted so that it could be supported on an aluminum pipe rising up from the floor. All the aluminum pipe used was cut to the exact desired lengths, giving plenty of flexibility in determining desirable positions.

A similar clamp was devised for each main bone in the mock-up. A suitable size and shape of wood block would be chosen for each piece. I tried to guess which surface of the bone was most likely to end up in the horizontal plane, if possible, or I would choose the most flat available surface, and then I would carve out the piece of wood with woodcarving tools to afford as snug a fit as I could manage. When attaching the plaster cast to the clamp I would place a thin sheet of styrofoam sponge between the two to prevent the wood from causing damage to the plaster. Each clamp was usually fitted with two hose-clamps. Here at SLAC those are available in a large range of sizes up to quite big. The hose-clamp of suitable length would be cut open to make two pieces. The cut ends were then filed smooth and a small hole drilled in each cut end. Each part was then attached to the clamp at the sides or underside with a little wood screw. I always inserted a double thick strip of styrofoam sheeting between the steel strap and the plaster piece to prevent damage by the sharp steel edges of the straps. In this way clamps were made for each of the 16 limb bones, and each was provided with an approximately centrally placed base-flange on its underside (see Fig. 3).

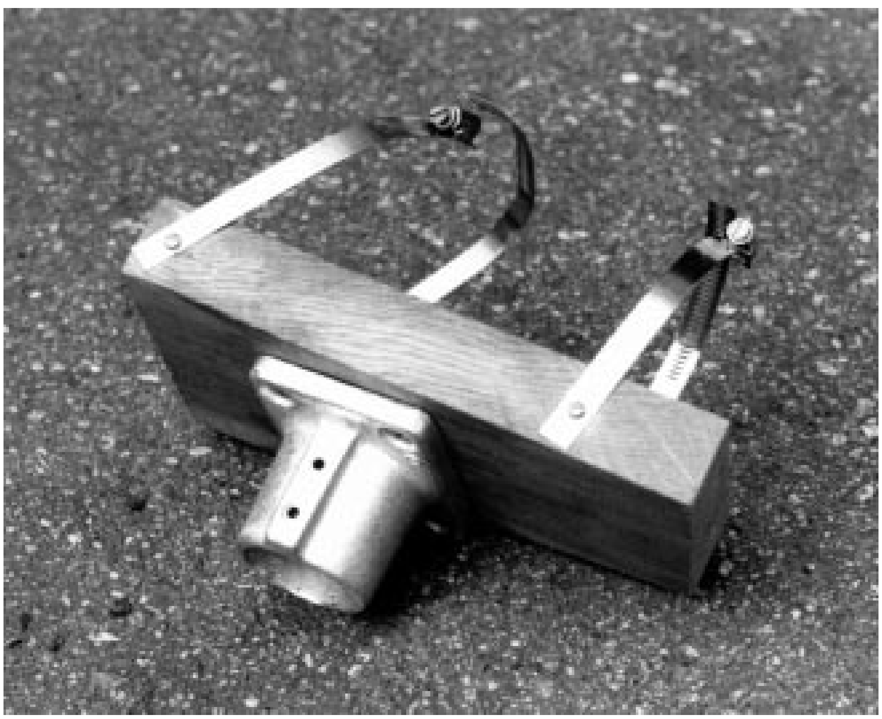


Fig. 3: Clamping device for the right tibia.

The basic principle in the designing of the mock-up system is that each piece must be provided with “all degrees of freedom” over a certain range of distance so that it can be moved about until the most desirable position is determined. To achieve this capability each clamp must be attached to the temporary base through three separate pipes and fixtures, all at approximately right angles to each other. Each pipe has the flexibility of rotating 360° in the fixture and has the distance adjustment of most of its length. When all three pipes and fixtures are combined, the requirement of "all degrees of freedom" is adequately fulfilled.

To be able to include all the bones of the feet in the mock-up, I made a sort of plaster "basket" from plaster gauze bandage for each complete foot including all the tarsal or carpal bones, metapodials, and digits. The underside of each foot-basket was fitted with a substantial block of wood well wrapped in with the plastered gauze of the basket to afford a firm base for the device. The base-flange was then screwed on into this piece of wood so that the basket could be attached into the mock-up structure with the same aluminum pipe equipment. When the final positions of several of the feet came out more vertical than horizontal, I had to add some of the insulated electronic wire across the top surfaces of the casts to prevent them from falling out of the baskets. These wires were threaded through small holes drilled in the sides of the plaster material of the baskets (see Fig. 4).

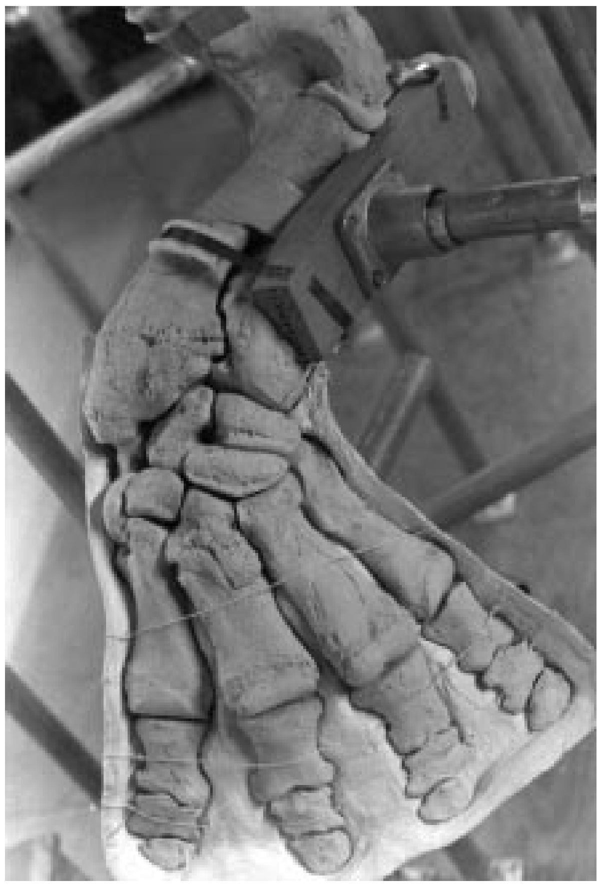


Fig. 4: Plaster basket holding casts of complete left manus.

The method I used to make the plaster baskets is as follows. First, I used dampened sand in the sandbox humped into a sizeable mound and firmed, then covered completely with Saran Wrap. The separate tarsal/carpal bones and all the digit bones of one foot were then positioned by pushing them into place in the sand mound, dorsal surfaces down, undersides up. When this arrangement would be considered satisfactory the entire array was covered with another sheet of Saran Wrap worked around into the spaces between the individual casts. The strips of wetted plaster bandage were then laid over the Saran Wrap and built up, layer after layer, until of sufficient thickness to give a good support. Several strips of scrap lumber could be added on for strength and the large wood block also thoroughly wrapped in with the plaster gauze. When the completed basket was dry and hard, the base pipe-flange was screwed into that large block of wood. Turned right-side up, the foot bone casts could be placed comfortably in this basket and the whole foot manipulated around in the mock-up mounting along with the appropriate limb bones.

Each main bone was supported in the mock-up by a pipe flange screwed into the floor of the temporary base and fitted with an upright aluminum pipe of suitable length. This pipe represents the first or vertical member of the three-way system. Another length of pipe inserted into a suitable fixture such as a T-joint or right-angled crossing would then be installed at a suitable height up the first vertical pipe. A third fixture would connect this second pipe to the pipe affixed on the base of the bone clamp to complete the three-way system. However, this basic idea often had to be modified one way or another because almost none of the bone clamps ended up at ideal angles. Usually a fourth member had to be worked into the three-way system, but in some cases more than one element could be supported from the same upright pipe rising from the floor. Several very convenient fixtures that were available had swivel-joints which allowed various angles other than 90° to be employed.

I started the construction by first deciding the positions of the sacrum and spinal column. With Repenning's help the two pelvic elements and the rear limbs were positioned. We had some difficulty determining a realistic swimming stance for the rear limbs: should they be moving fore and aft, up or down, both the same, or in opposition? To settle this question, SLAC ordered for us a movie strip from Walt Disney Educational Media Company which included a short view of a hippopotamus swimming under water. Repenning and I watched this filmstrip through many repetitions. Finally Repenning decided that both rear limbs and feet must be positioned up in a horizontal plane and facing backwards.

When I wanted help in positioning the fore-limbs, Repenning said he would need a few pairs of ribs included in the mock-up before he could determine positions for the scapulae. The addition of six pairs of ribs to the mock-up was a frustrating and complicated process; however, it finally succeeded sufficiently well to accomplish the goal.

I used the second through the seventh pairs of ribs. First I acquired a dozen laboratory clamps fitted with adjustable jaws for clamping onto cylindrical objects and also having a swivel joint in the shank, both adjustments to be tightened with wingnuts. These clamps were then modified by the SLAC machine shop so that the shank end of each could be set in a short length of our regular aluminum piping and held tightly with set screws. This modification included an overall length adjustment for each clamp. These modifications were designed by SLAC engineer Glenn Hughes, who had been assigned to help me as needed.

I built up two horizontal supporting racks from the temporary base with our aluminum scaffolding materials, their horizontal elements placed at a somewhat diverging angle under the rib cage area. Six T-joint fixtures were mounted on each horizontal bar to accommodate six rib clamps for each side [see Fig. 5(a)].

I painted latex rubber compound on the inner curved surfaces of the clamps, building up successive layers so that the tightened clamps would hold the rib casts securely and not mar the plaster. However, the clamps did not actually clamp the ribs securely because none of the ribs are really cylindrical, but all have irregular oblong cross-sections, no two alike. Therefore, I was then obliged to add a thick ring of latex rubber molding compound around each rib at the desired spot, building up the thickness by painting on many successive layers [see Fig. 5(b)].

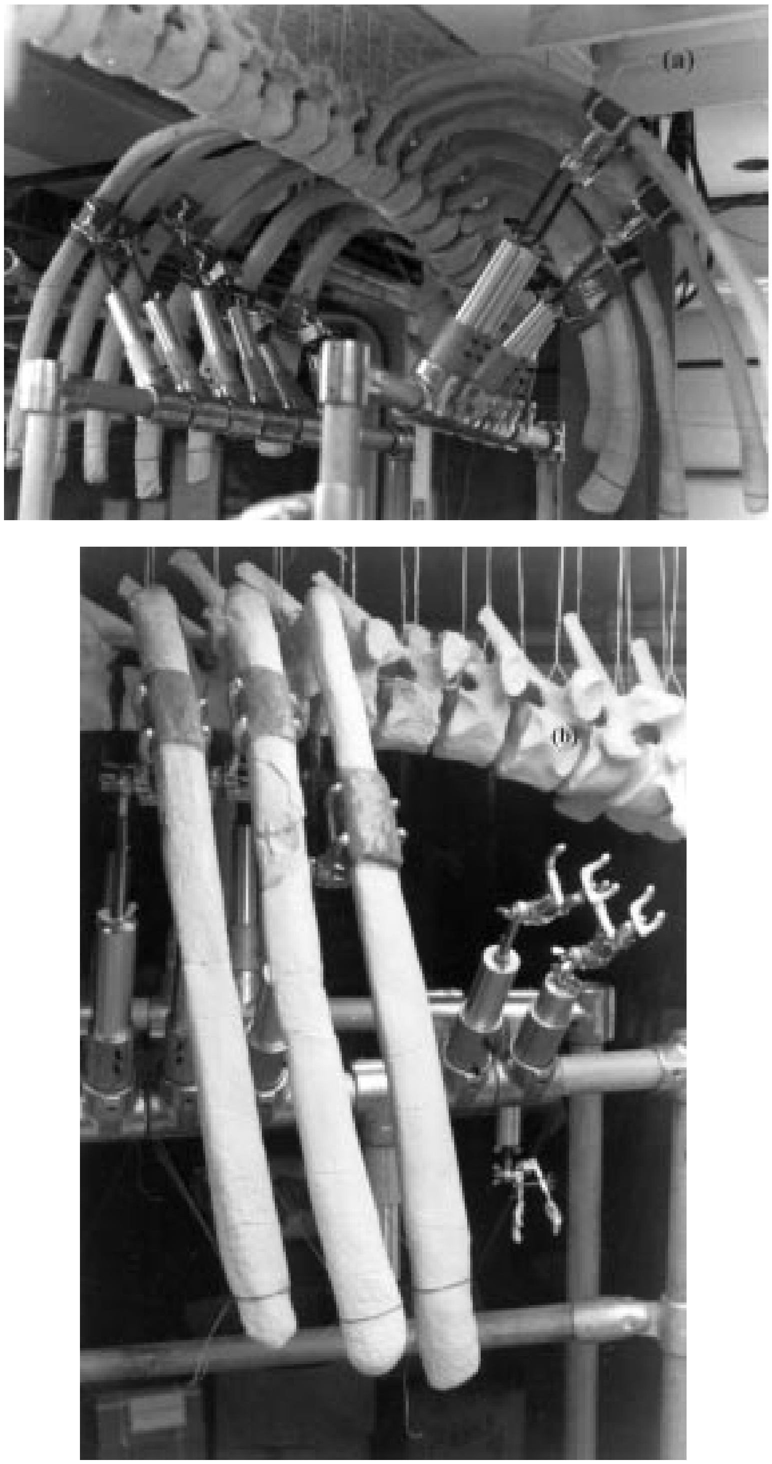


Fig. 5: Method of including six pairs of ribs in the mock-up.

At last I succeeded in placing the six pairs of ribs adequately into the mock-up, and Repenning was then able to place the shoulder blades to his satisfaction. Our aim was to create a realistic swimming position, and never was intended to imply an in-depth analysis of *Paleoparadoxia* physiology.

One prominent feature of the front limb is a large radial process that overhangs the distal articular surface of the radius by several inches over its anterior (dorsal) surface. Because of this prominent process the animal could not bend the joint sufficiently to stand on the palm of the foot, plantigrade. The toe joints at the distal ends of the metacarpals, however, are capable of rotating forward the full 90°, and the joint between the radius and carpals can be folded back by more than 90°. These joint motions are certainly specializations for the swimming action. Through them we learn, first, that the power stroke for swimming was vested in the front limbs, leaving the steering and balancing functions to the rear limbs. The tail being very small and short, it could have had no influence in the swimming action. These bone features can be seen in Fig. 4.

This radial process, extending distally over the wrist, would have provided added strength to the downstroke and prevented any upward extension of the manus during its power stroke. The capability of the foot to fold back posteriorly would allow the return stroke to have less water resistance with the returning forward movement of the manus. Also, one can readily see that the fore-limb is a much more powerfully constructed limb than the rear, and the metacarpals are about twice as long as the metatarsals. This gives the fore-foot the overall aspect of a long oar, and the rear foot more closely resembles a paddle or rudder.

Because of these features, I wanted to illustrate as much of these specializations as possible in the display so that a discerning observer could understand more about how these animals swam. I decided to position the left front limb in the power stroke action and the right fore-limb in the return stroke. Both rear limbs being arranged lifted to a horizontal position, and with the pedal soles facing posteriorly, indicate the balancing action.

Supports to include the skull and the mandible in the mock-up presented more design challenges. One had to be installed directly above the other so that the mandible could be placed in articulation with the skull, but each needed independent capability for adjustments. The clamping apparatuses could not be in conflict during manipulations. To begin, I had the basic supporting units built out of wood and fitted on the undersides with the usual aluminum base-flanges. The support for the mandible was constructed in a U shape, so that the supporting pipe for the skull could come up through this U opening. The mandibular support was basically a flat plywood tray with 4-inch high walls enclosing the right, left, and front edges. The skull support was constructed on a thick wooden beam of about 3 by 4 inches in cross-section and 28 inches long. Specially constructed supporting blocks and trays were attached strategically along the length of this central strut and two steel hose clamps were provided to strap the skull firmly onto this device. The supporting tray for the mandible was not provided with clamps. The two casts merely rested in it and their relative positions were adjusted with small sandbags and paper wadding (see Fig. 6).

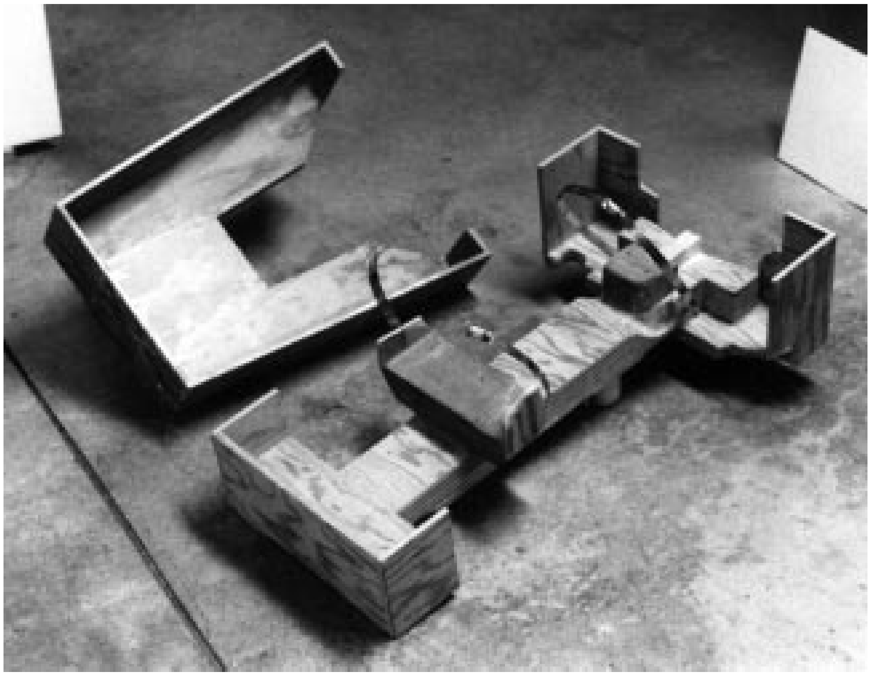


Fig. 6: Clamping devices for the skull and the mandible.

A rack made from our temporary scaffolding materials was then constructed to support the skull and jaws in their desired positions. It was a rectangular structure with four legs firmly attached to the temporary base by four floor-flanges of our aluminum scaffolding. Several cross-member pipes near the top kept the structure stiff and provided parallel railings at the top. These two top railings were oriented to be approximately parallel to the desired angle in which the head of the animal would be pointed. Then two cross-members were mounted at right angles to the rails on T-joint fixtures so that each bar could slide back and forth and therefore be positioned anywhere along them. A T-joint was mounted loosely on each cross-member to accommodate the jaw and skull clamping devices. The tray for the mandible was attached to the forward cross-member, and the skull clamping device was attached behind. In this way each piece could be manipulated anywhere within the horizontal rectangle and its angle to the vertical could be rotated by many degrees more than necessary. The height could only be adjusted by inserting a shorter or longer vertical pipe into the flange under the clamping device. In this way sufficient degrees of freedom were provided for positioning the skull and lower jaws (see Fig. 7).

Construction of this mock-up mounting took about one year to complete. During this mock-up assembly, and also the permanent assembly processes still to be described, it was often necessary to slightly modify the detail shapes of the plaster restorations in order to accomplish the best possible appearance and fit throughout, but no modifications were made on casts of the actual fossil bones. A list of these modifications is given in Appendix B on page 139. The general appearance of the completed mock-up mounting was of a complicated jumble of pipeworks. However, one could get an impression of the skeleton because of its contrasting whiteness of color showing through the jumble (see Fig. 8).

Fig. 7: Scaffolding rack for the skull and mandible.

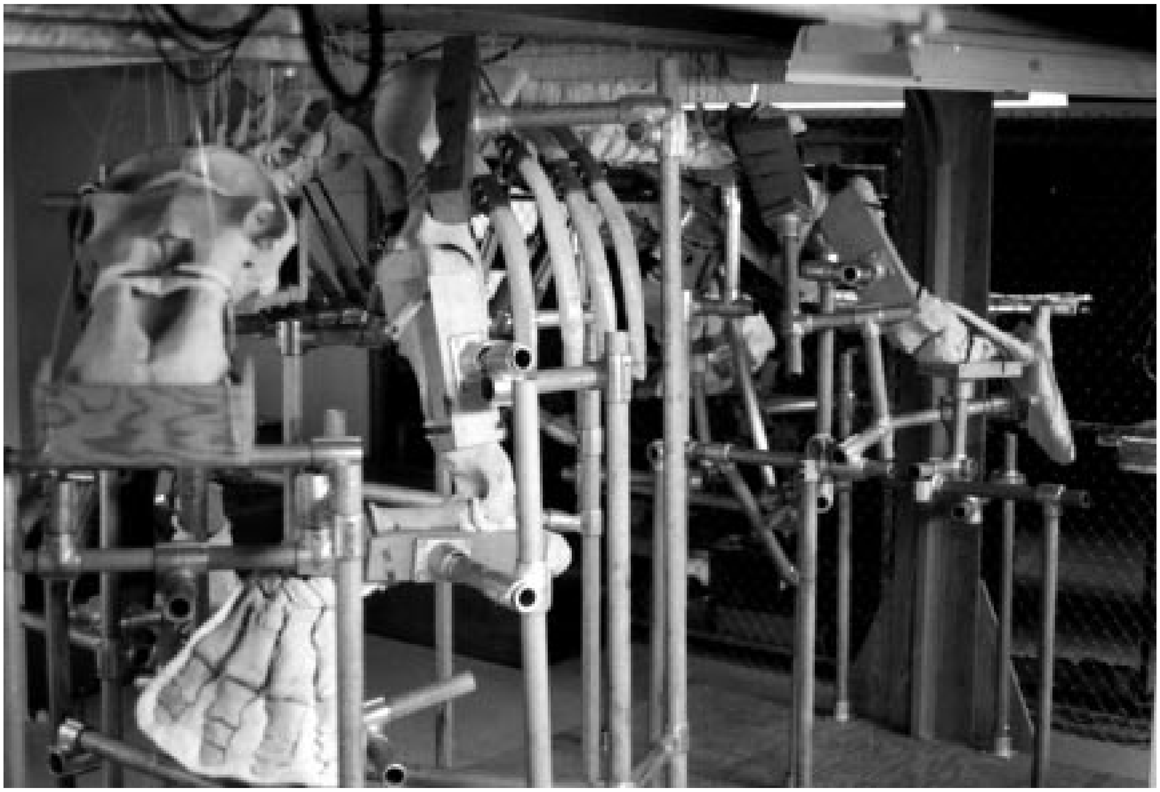


Fig. 8: Completed mock-up.

The Permanent Mounting

Now that the skeleton was firmly clamped in position, it could remain that way safely throughout the slow processes of developing the hidden steel internal supports. Leaving the mounting in this form served the purpose of preserving the desired position and relative angles between the various bones for reference in designing the permanent internal support structures. I had decided that the modern techniques now being employed by museums to conceal the steel supporting apparatus as much as possible would produce the most attractive display. The basic principle underlying this construction is that its strength is in the steel structure, and not in the plaster pieces. No bone must be expected to support more than its own weight. All the bones must be suspended individually to the support system. In other words, the strength of the skeletal structure is the steel supporting apparatus, and the plaster pieces are merely a decorative covering.

In this section I will describe our permanent mounting process as it developed in the temporal sequence of the total project, except where it will be more logical to vary from the actual sequence. At any one time there were usually several activities being carried out simultaneously, because often one would have to wait for plaster to set and dry, for some part to be put through one of the shops, or for some other reason one job would be laid aside temporarily while other work would continue. Therefore, I will describe the mounting processes, tools, and materials we used, element by element, in a more logical sequence than actually took place.

To begin, I decided to work on the right front foot first, which would then lead to the mounting of the complete right front limb. I made this choice because of all the four, this foot and limb are the least well preserved. I felt that the first element to be mounted would provide the learning and experience for the other limbs. If something didn't work out as well as I would have liked, I wouldn't be damaging the more visible part. The right side was to be the back side of the display. Experience gained on that first limb might enable me to do a more satisfactory job on the other three limbs. Starting with the foot meant that only one element needed to be removed from the mock-up, leaving all the rest intact.

Before removing any one element from the mock-up, the aluminum pipes and fixtures holding that element would be marked with various colored pencils around the periphery of the pipes to indicate the position of the fixture along it, and across the seam between fixture and pipe in two or three spots to preserve the exact orientation of the element. This was necessary so that anything removed from the mock-up could be correctly replaced.

Front Limbs

In mounting the foot it was decided to connect each two consecutive bones of each toe together at each articulation with two parallel metal pegs of 1/8 inch diameter. Aluminum rod was used to save weight at the extremity of the limb, since no great strength would be required.

The two parallel holes were oriented by eye and marked with pencil and straightedge along two lateral surfaces of each bone, front or back, and on one side (see Fig. 9 and Fig. 10). The positions of these marks had to take into account any bending of the joint that would be desirable. It was essential that the two holes be parallel to permit the two bones to be assembled together. I had acquired a beautiful little bench vise made by Stanley, model C-615, that has a special attachment that can be inserted between the jaws so that an object whose sides are not parallel may be clamped. The vise is mounted on a special stand that can be tilted and rotated so that a hole can be drilled into an object at any desired oblique angle. I also purchased a simple drill press stand suitable for a home/garage shop. A Black and Decker 1/4 inch electric drill was provided by SLAC (see Fig. 11).

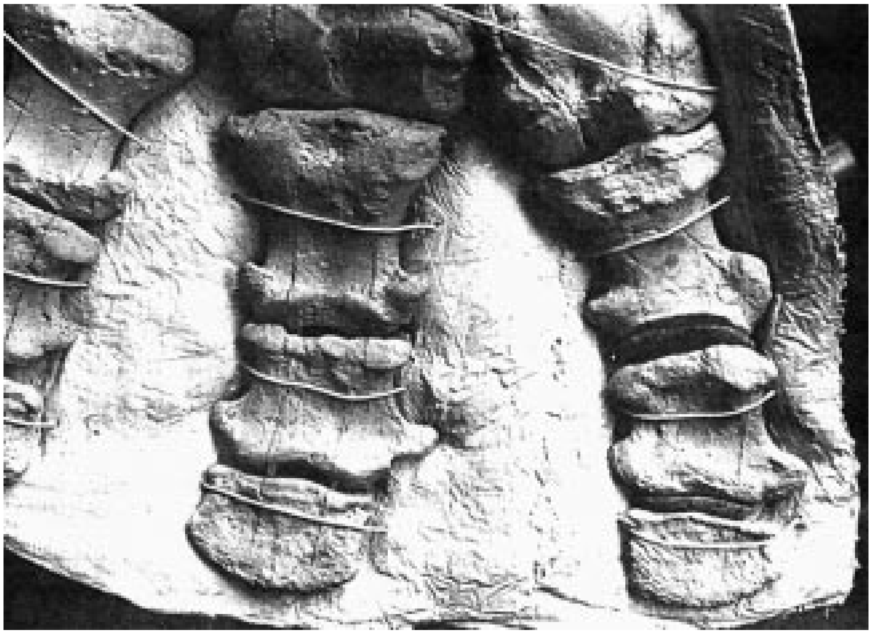


Fig. 9: Preparing for the drilling of parallel pegs. Note parallel pencil lines drawn on the casts to guide the drilling.

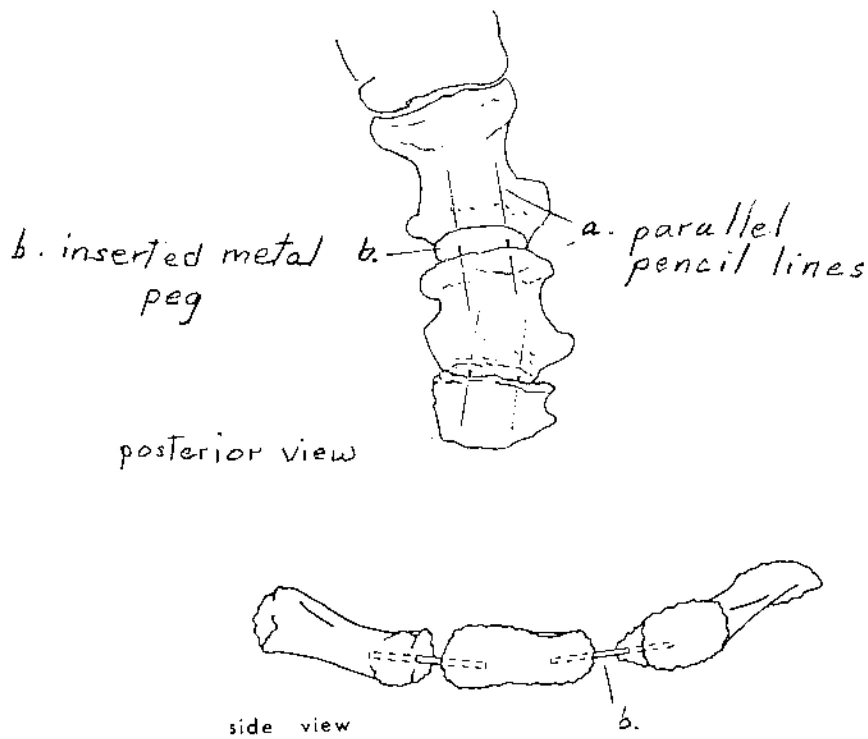


Fig. 10: Diagram showing method for attachment of two consecutive casts with parallel pegs.

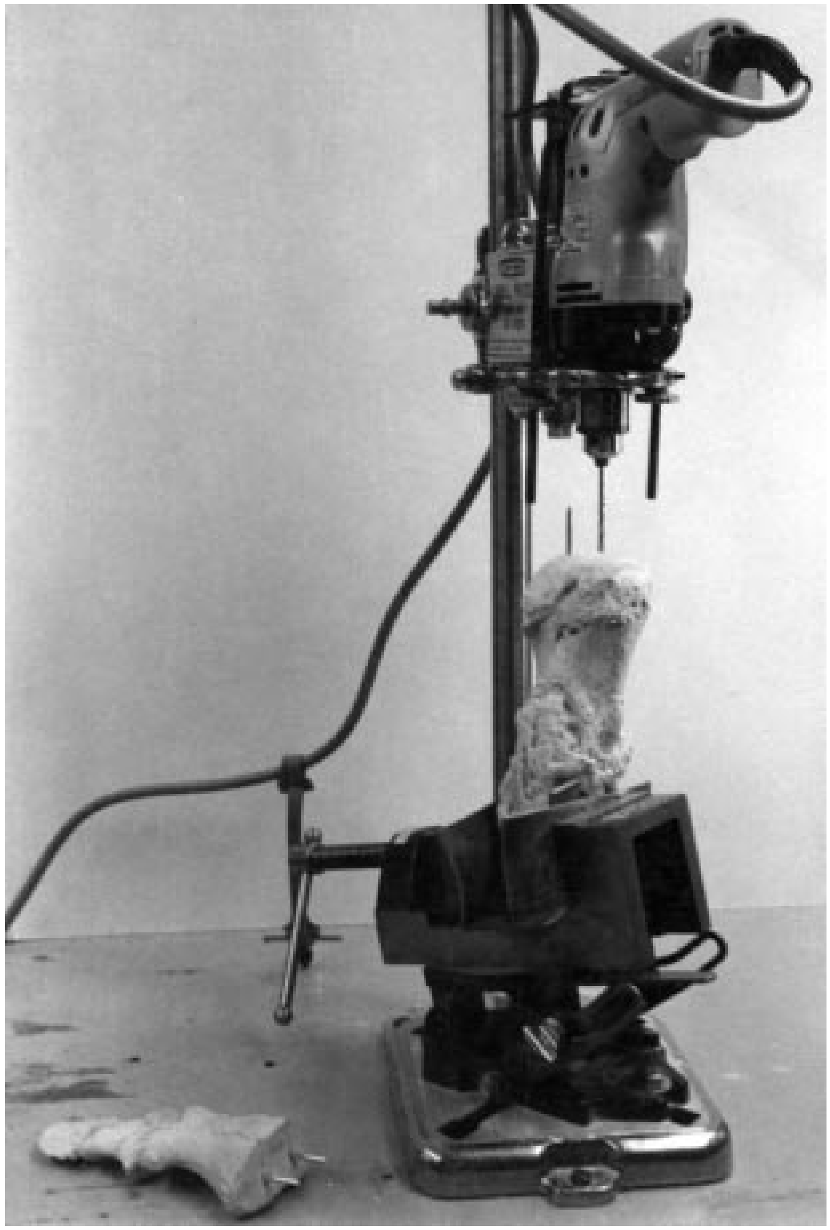


Fig. 11: Drilling parallel holes in a metacarpal.

The adjustable vise was then mounted on the drill stand base and used in place of the regular tilt-table. The holes in the plaster toe bones were drilled with an 1/8 inch masonry bit. To set up for drilling, I would first mount the electric drill on the “drill press” and check to be sure that the drill bit would move down exactly vertically. This was accomplished with two plum lines somehow hung above the drill rig at approximate right angles to each other so that the vertical orientation of the drill bit in motion could be checked from front and side. The plaster piece would then have to be clamped in the vise so that the two plumb lines would line up with the two pencil markings on the bone. When the drill bit was satisfactorily adjusted to vertical and the bone clamped in the necessary orientation for drilling, the drill press would then be rotated so that the drill bit would enter the piece at the desired spot. To ensure that it would remain correctly oriented during the beginning of the drilling process, I would usually scrape out a small dent in the plaster with a pocketknife or other sharp instrument. The plaster is fairly soft and not abrasive, so it was easy to work by hand with a pocketknife or chisel when convenient. The holes would then be drilled to suitable depths to accommodate an adequate length of aluminum rod, being careful, however, not to drill so deep as to come through to the outside surface of the casting.

When the four holes were drilled, two lengths of the 1/8 inch aluminum rod would be cut long enough to allow the two bones to be assembled leaving a narrow space between them, on the average 1/8 inch or so. This space was necessary because many of the articular surfaces on the toe bones are quite uneven and would not fit together perfectly smoothly. A filling material must then be used in the joint area between the bones in order to hide the aluminum pegs. I followed the method suggested by Frank Pearce of the National Museum of Natural History, of using 1/4 inch thick sheet cork to make these separators. When assembled, the cork separators represent the cartilage of the joints. Each cork separator was cut out a bit oversize with Exacto knife blades and fitted over the two metal pegs through small hand-cut holes. The cork would be trimmed, shaped, and smoothed with Exacto knives and sandpaper to make as perfect a fit as possible when the two bones with the cork separator between them would be assembled on the aluminum pegs. I discovered that, contrary to the plaster, the sheet cork is very abrasive, dulling the Exacto knife blades very readily. Finally I took to honing the blades frequently on the rough side of a leather belt, which prolonged their life double or triple. Nevertheless, a great quantity of Exacto knife blades were used.

Each foot has four toes, because the first digits, pollux and hallux, are all suppressed on *Paleoparadoxia*. So on each foot there are 12 phalanges, three for each digit, and four metapodials, one for each digit. It all adds up to 12 joints, 12 cork separators, and 24 aluminum pegs per foot.

The next step was to assemble each toe permanently by plastering in the aluminum pegs. To accomplish this the surfaces of each peg would be nicked in quite a few places at each end where it would be plastered in. These nicks were intended to help anchor the peg in the plaster for a firm hold. This was usually done with the sharp edge of a fairly fine half-round file, held at various angles. I avoided making any nicks in the center part that would not be encased in plaster, since that would weaken the strength of the peg.

When all was ready for assembly, the plaster bones would be soaked in clear cool water for up to half an hour or until no more small air bubbles could be seen rising to the surface. A small amount of the Glastone Plaster would be mixed to a fairly fluid consistency. Before beginning the plastering process, everything would have been laid out in sequential order on a suitably large sheet of paper that was marked with the positions and orientations of each of the pieces in the assembly: bones, pegs, and corks. The individual elements being assembled would be carefully laid out in this array, indicating into which hole and in which direction the pegs and corks must be placed, since it would be necessary to work fast. A good supply of paper towels was kept within reach.

To begin the process, the piece would be removed from the soak and excess water shaken out of the holes. A small amount of wet plaster would then be taken up in a veterinary hypodermic needle and the two holes quickly filled. The pegs were then inserted and the cork fitted over. The second toe bone would then be plastered similarly onto the other ends of the two pegs. Any excess plaster would immediately have to be cleaned off the surfaces of the cork and the toe bones, with the assembly still held firmly in one hand. A wetted toothbrush proved handy for this process. As the plaster would begin to set, the assembly would be placed in the sand box on Saran Wrap to allow the plaster to set up without disturbances.

There are a number of pitfalls that can occur in this process, but with care and experience most can be avoided. First: If the plaster piece is not wet through or the peg hole is clogged with plaster powder from the drilling, the fresh wet plaster may set up immediately, clogging the hole and preventing the assembly. Second: In the excitement and rush of getting the pieces together just right it is easy to forget about rinsing the hypodermic needle. If clear water is not flushed through the needle immediately after use the plaster will set solid in it. The hypodermic tube must also be rinsed readily. Sometimes a clogged needle can be saved by being poked out with a thin wire. Third: Even though the plaster pieces must be thoroughly soaked before beginning the plastering process, it is not good to soak them too long. Oversoaking gradually destroys the surface details of the casts. In case a piece would have to be soaked again for further plastering processes, the surfaces of the cast could gradually lose the fine detail, so they must never be forgotten in the water. Fourth: A smaller batch of plaster will set up faster than a larger one. Sometimes only a small amount would be needed, but then one would have to be prepared to work very fast, having the complete operation organized in every detail.

I used several sizes of veterinary hypodermic tubes and needles of the plastic disposable variety, which are not so expensive. I found that they could be used over many times when kept clean. For the 1/8 inch holes I used the 12 cc size. I also had a 20 cc and a 60 cc apparatus for larger plastering jobs. I purchased them at a horse and saddle shop.

I would try to assemble any one element, such as a toe, as completely as possible in any one operation so as to limit the number of times that part would need to be soaked. After doing the four toes, the six carpal bones were drilled and assembled together using the same techniques. However, no cork separators were used between the carpal elements. Several units could be assembled and plastered, then these sub-assemblies would be pinned together and plastered in a subsequent operation. In each process it was necessary to have all the drilled holes and inserted pegs in each sub-assembly be parallel in order that the two parts could be fitted together in the final plastering process.[6]

When the foot bones would be completely plastered into a single unit, it would be necessary for the unit to have a metal rod extending up from the carpus for attachment of the foot into the steel leg supporting apparatus. Although this apparatus was still to be designed, it had been determined to use 1/2 inch steel rod material for the limb support structures. Now it was necessary to design the rods for this connection. The foot was to be held in a curved-back position indicating the return stroke in swimming. The most practical route for this rod would be down through the third metacarpal and up through the intervening carpal elements to enter the distal end of the radius through a bend of some degrees formed at the point where the foot unit would join to the leg unit. To accommodate this rod a 1/2 inch diameter hole needed to be drilled through the carpus and into the third metacarpal to a depth sufficient to anchor the rod and support the foot firmly.

6. See page 36 for the description of an improved method used in planning the relative positions of the numerous pegs needed in mounting a complete foot by this method.

Because the multi-adjustable vise that had been employed for drilling the toes and other small casts was now much too small to be used, it was necessary to devise another process for the larger casts. A sturdy wooden board was installed vertically against one leg of the workbench on which the drill stand was mounted, extending from the floor to the underside of the tabletop. The drill stand itself was then mounted on the edge of the table so that the drill and drill bit could reach down over the edge of the table. The lining-up of the piece to be drilled was done by a similar process to that used for the smaller casts, with two plumb lines hanging from above the drill-rig and two straight pencil lines drawn at approximate right angles along the surface of the cast, delineating the route which the drill should follow. These guidelines were generated on the uneven surfaces of the casts so that they would appear to be straight lines only when viewed from the desired directions.

The proximal part of the assembled foot, that is the carpals and metacarpals without toes, was clamped vertically against the upright board that had been added to the front table leg. Various wood blocks and wedges, C-clamps, rubber straps, and other suitable devices were used to clamp it firmly in place. Its position was carefully adjusted by these means so that the two "straight" lines drawn, one down along one lateral edge of the foot, and the other one down the dorsal surfaces of carpals and third metacarpal, would line up with the two plumb lines hanging from above. The hole was then drilled with a long half-inch masonry bit, to a depth of about 8 inches into the third metacarpal. The route was determined so as to avoid any previously installed metal pegs (see Fig. 12).

It was then decided that the strength of this foot connection would be much improved with the addition of some metal support through one of the other toes. Otherwise, the foot would have a great tendency to rotate out of position. This "outrigger" strut was devised of 1/2 inch square aluminum stock, and welded to the 1/2 inch diameter hollow aluminum rod that was being used for the main support, at a spot just below the bend for the wrist joint. All of this metalwork was prepared for me in the SLAC machine shop because the welding of aluminum and bending of hollow rod are tricky operations.

The outrigger strut was installed down the length of the fifth metacarpal, a reconstructed bone, up through one lateral corner of the cuneiform and across the base of the ulna, also a restored element. The slots for the square strut were routed into the thickness of the plaster with Dremel router bits. I had the use of a motorized flexible-shaft hand tool that can be used with any Dremel points. The tool is a Dumore Duo-Flex with a 1/15 HP motor, a 36-inch long flexible shaft, and a 5 1/4-inch long handpiece. It can be used with any bits having a shank size of up to size 16 or 11/64 of an inch. All Dremel points have a 1/8 inch shank and come in a wide variety of cutting shapes and sizes, suitable for routing channels in plaster. They can be obtained in most hobby shops and hardware stores.

With the mounted plaster foot drilled and routed and the aluminum support fixture prepared, all that remained was to plaster the fixture into the foot and restore the surfaces of the routed channels. I did not soak the entire foot for this process, but instead applied water to the holes and routed channels with the large hypodermic tube until the areas to be plastered seemed wet enough. Nicks and notches were cut into the aluminum rod and bar to help anchor the metal fixture in the plaster. The four toes, previously assembled, were also plastered on at this time. The assembled foot can be seen in Fig. 13.

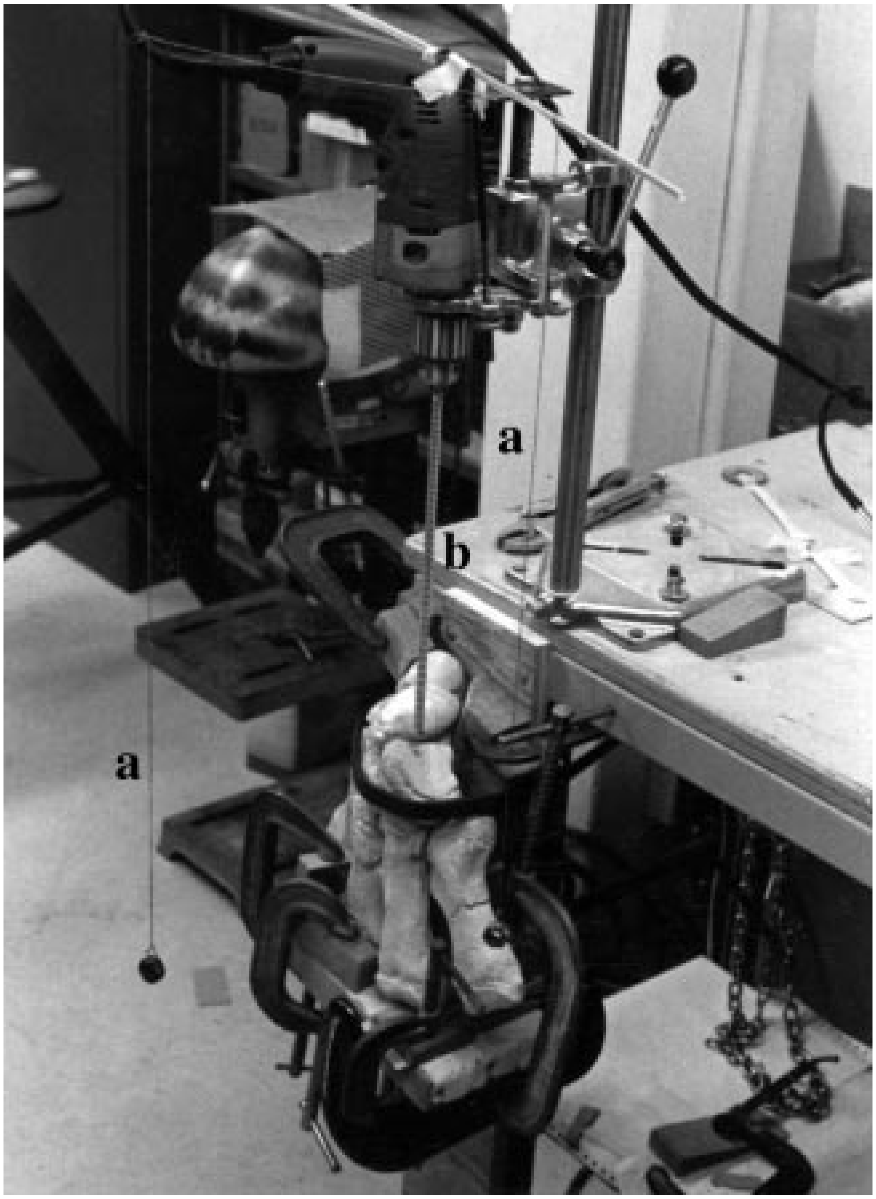


Fig. 12: Drilling the left front foot for a support rod to the lower leg: (a) The plumb lines and (b) the long masonry drill bit arranged to operate over the edge of the table.

The next step would be to design and construct the metal supports for the right limb, which, it will be remembered, is in the position of the return stroke of the swimming posture. All three joints in this limb, shoulder, elbow, and wrist, have a strong bend of almost 90° in each case. Of course, it is not possible to mount a long plaster bone over any such bend. Therefore, the metal rods must be made in several pieces, each bent in its approximate middle to the required angle for the appropriate joint. The straight parts of each bent rod would then extend into the shanks of two connecting limb bones. The complete leg assembly would require two bent rods, one coming down through the joint at the proximal end of the scapula and extending into the center part of the humerus, and a second one going from the center of the humerus and bent at the elbow joint so as to enter the radius at its proximal end and continue through the shank of the radius to meet the aluminum support rod extending up from the mounted foot (see Fig. 13 and Fig. 14).

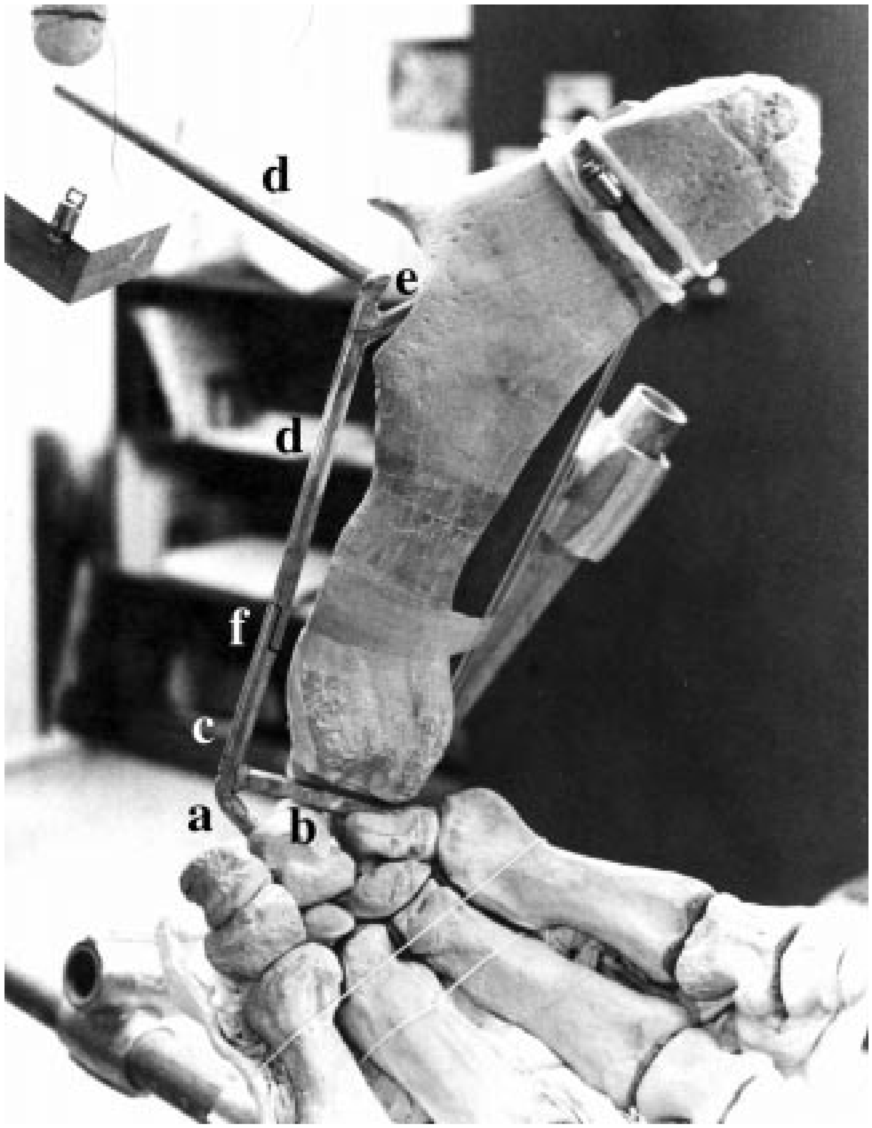


Fig. 13: Internal supporting rods in the right front limb, shown with radius and humerus removed: (a) Support rod for the foot, (b) outrigger strut, (c) support rod connecting the foot and lower radius at the ankle joint, (d) support rod connecting the radius and humerus at the elbow joint, (e) spur for the olecranon process (funny bone), and (f) keyed joint between the two rods.

All four limb support fixtures were constructed as follows. A 1/2 inch steel rod of suitable length would be bent somewhere near the middle by the desirable number of degrees for the joint it was to support. Each end of the rod would be left about 1 1/2 inches longer than the actual length needed, in order to provide enough material for "keying" the ends of two adjoining rods. The "keys" were formed by cutting away half the thickness of each rod longitudinally for about 1 1/2 inches of length, arranging the cuts so that the cutaway of one rod would match up with the opposing cutaway portion of the second rod. The limb bone would then be drilled out somewhat oversized so that the hole could be lined with a metal tubing. This would be necessary to prevent breakage of the plaster at the joining of the two rods. In most cases the tubing was made to line almost the full length of the hole. The two rods coming into the bone cast would then meet and slide together inside the tubing. The keyed joints would serve to limit rotation between the two consecutive bones. Finally the length of tubing would be plastered in place inside the hole.

When the metal fixtures would be satisfactorily manufactured, fitted, and assembled, it would be necessary to install steel pins right across each straight section of the fixture, entering one side through the plaster of the casting, continuing through the tubing lining the hole, through the steel rod, and then through the other side of the tubing, to exit on the opposite side of the plaster cast. These pins hold the plaster bones on the steel support rods, preventing the separate elements from sliding apart. In our mounting, however, we were able to return our prepared casts into the mock-up clamps which held all parts securely in position, and that allowed us to put off the pinning process until all limbs were ready (see Fig. 14).

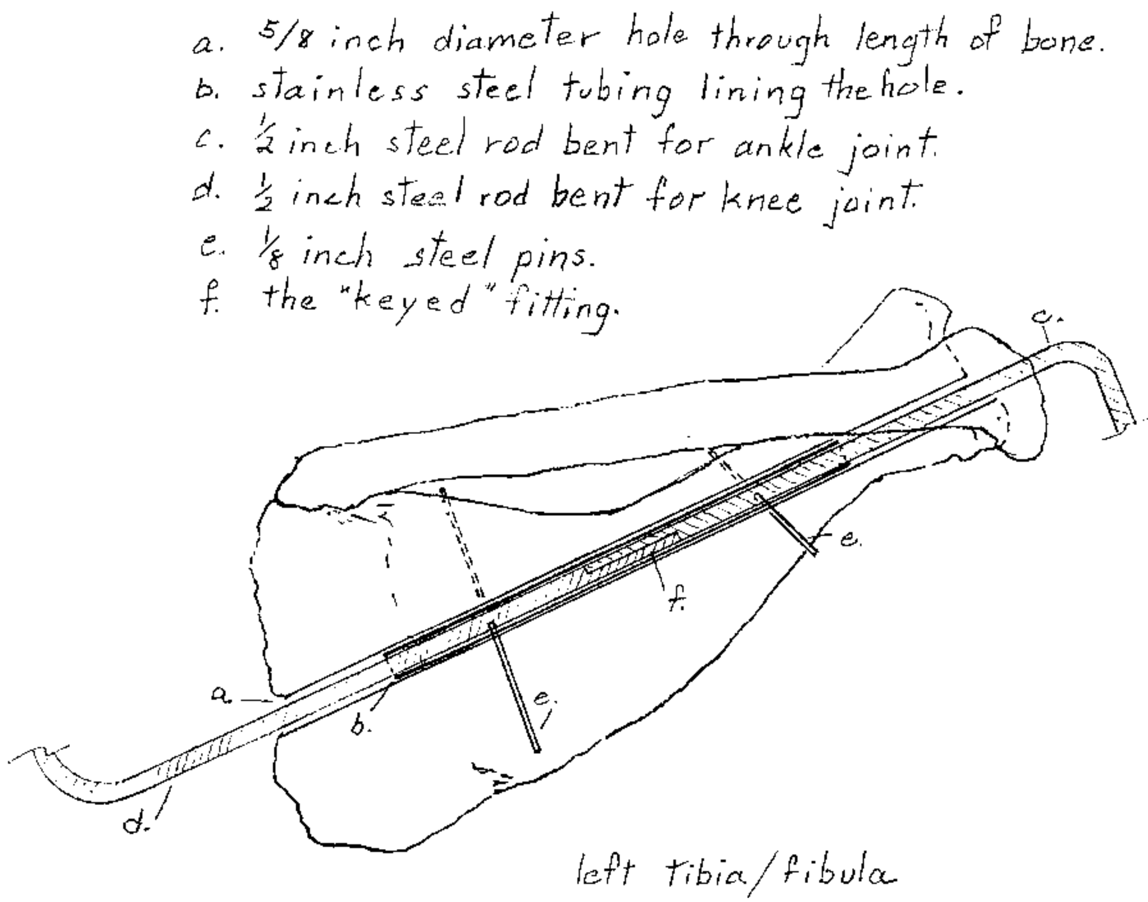


Fig. 14: Diagram illustrating the support method for limb bones.

All the limb support rods were formed of 1/2 inch diameter cold-rolled steel rod, round stock. Some stainless steel tubing was available at SLAC that had an inside diameter slightly more than 1/2 inch and an outside diameter of slightly less than 5/8 inch. This material proved convenient for lining the long holes to be drilled through the limb bone casts. I acquired a long 5/8 inch masonry bit for this drilling, and SLAC provided another electric drill having a 1/2 inch chuck that could accommodate this large masonry bit. The processes I used with this equipment were essentially the same as were used with the smaller drill; however, the drill stand bracket had to be modified to be usable with the larger drill.

To proceed with the construction of the right front limb support, drilling of the right radius/ulna complex was then undertaken (see Fig. 15). The next steel rod needed to incorporate the bend at the elbow joint and key in with the rod coming up from the manus. All three of these bones are involved in this joint. I felt that some part of the support-rod structure should also insert into the ulna even though the direct route for the rod could go straight through the radius entering directly into the humerus through a bend of approximately 90° without involving the ulna. The ulna in *Paleoparadoxia*, however, is longer, larger, and heavier than the radius, having a very prominent olecranon process for the attachment of muscles used in the swimming power-stroke. I felt it would not be wise to have this larger, heavier piece be held to the support structure only by long 1/8 inch steel pins. The steel rod designed for this joint, therefore, included a spur about 8 inches long welded on just below the 90° bend and pointing out and back, also of the same 1/2 inch cold-rolled steel rod material. To accommodate this support device a 5/8 inch hole about 8 inches deep was drilled into the olecranon of the ulna at the appropriate spot in the joint and directed in the angle necessary to fit over the prepared spur. Set-up for this drilling was rather awkward but was finally successful (see Fig. 15).

A straight-through hole then needed to be drilled into the humerus cast, which presented another new problem: The humerus is about 9 inches longer than the reach of the 5/8 inch masonry drill bit. This piece then had to be set up twice, and drilled from each end, so that the two drillings would meet inside the piece to form the straight-through hole. Both set-ups had to be prepared with great care so that the drill bit would follow the same route in both cases. This meant the alignment along the same two plumb lines had to follow the same two pencil lines along the surface of the cast in both procedures, as closely as I could manage. Much to my surprise the two holes actually met with only very little offset. This offset was straightened out with a long rat-tail file and no trouble resulted, because afterwards the hole was lined with the stainless steel tubing plastered in place.

To complete the right fore-limb assembly, steel supports needed to be devised for the shoulder joint which involves the humerus and the scapula. Eventually this structure would need to be incorporated into the not yet designed central support system of the complete skeleton. Some generous length of rod needed to be left available behind the scapula for this future attachment. It would only be hidden by clinging to the underside of the scapula and adjacent ribs because the fore-limbs of mammals do not have bony attachments to the spinal skeleton. They are supported by a complex of crisscrossing muscles from the distal edge of the scapula to the numerous vertebral processes along the length of the spinal column, and other muscles from the scapula. This provides greater flexibility of the fore-limb in exchange for a strong bony connection.

Fig. 15: Drilling for the ulna support rod spur.

The blade of the scapula is too thin to have any holes drilled through its body; however, the proximal joint at the shoulder is quite thick for 5 or 6 inches into the scapula. The support rod was therefore designed to enter into the center of the joint, exiting along the inner side of the cast about 6 inches higher. This rod was then left about 1 foot longer behind the scapular blade for eventual connection to the central support.

Next, the rod needed to enter the humerus at the center of the shoulder joint. However, this joint is not placed directly on the top end of the humerus in mammals, but at almost 90° to the long axis of the bone shaft, facing posteriorly. The joint is more or less hemispherical, the convex part on the humeral head, and the concave part on the scapular fossa. This type of joint provides many degrees of rotation and great flexibility. To be able to attach these two pieces onto a single support rod, I had to rout a sizeable slot through the head of the humerus from the exit hole previously drilled at the proximal end to the spot at the center of the humeral head where the steel support rod would enter the joint from the scapula. Once the limb mounting would be completed, this large slot would be filled with plaster and the surface restored.

Thus, the upper support rod designed for the scapular/humeral joint had two bends, the upper one of only a few degrees formed at the position of the joint between the two casts, and the lower one several inches below the first, bent to nearly 90° in a plane approximately 90° to the plane of the first bend. This second bend follows the angle of the head of the humerus with respect to the longitudinal shank of the humerus. To assemble these pieces the rod would be inserted into the prepared hole at the proximal end of the humerus and the right angle bend slid into the routed slot until the distal end of the rod would key into position with the elbow-joint rod. Now the support for the scapula would be rising up out of the head of the humerus at the proper angle to be inserted into the fossa of the scapula. That end of the rod extended up behind the blade of the scapula by about 10 inches, and no key cutaway was made there. This completed the design and construction of the metal supports for the right fore-limb unit.

Next, the design and construction of equivalent support structures for the left front limb was begun. It will be remembered that this leg was positioned to illustrate the power stroke of the swimming action. The skeleton of the lower limb, the radius/ulna complex and the complete manus, are cantilevered out parallel to the floor in a forward direction. Nevertheless, their supporting devices were designed very similarly to those used on the right fore-limb. Some variations were necessary of course, because of the difference in position. However, I will not describe them here, because this entire limb suffered a very unfortunate accident several years later, causing extensive breakage, and had to be completely redone. I made some further revisions in the second mounting, so I will only describe the final version for the mounting of this leg and foot. Another set of casts for the complete limb was provided by Repenning from his set of casts, for which I was very grateful.

Starting again with the most distal elements of the limb, I drilled and pegged the toes first and then the carpal and metacarpal elements. For this second assembly I formed a jig of oil clay covered with Saran Wrap into which all the separate bones could be placed in the desired relative positions for the completed foot (see Fig. 16). This proved to be very helpful in deciding and marking the positions of the necessary peg holes. Held like this it was much easier to draw parallel lines between the different elements. For the six carpal bones, I assembled three sub-units of two bones each, then pegged the adjacent sub-units together with two or three parallel pegs between each pair. The four metacarpals were also pegged together to make a single unit, and then a series of parallel pegs arranged to assemble all these sub-units. When the entire foot was assembled, two larger diameter holes were drilled all the way through the carpus and to some depth into the third and fourth metacarpals for the insertion of the support rods into the leg. Great care had to be taken in the placement of all these drill holes to ensure that none of the metal pegs and support rods would be in conflicting positions, otherwise the elements could not be assembled. The clay-jig holder was therefore extremely useful for visualizing and planning the routes of all these holes in their three-dimensional relationships.

Fig. 16: Clay positioner for the left manus.

In this second version of the left limb I decided to abandon the outrigger strut routed into the fifth metacarpal, and instead insert a steel rod of 3/8 inch diameter distally into the fourth metacarpal, and proximally to a depth of 6 or 8 inches into the ulna, entering at its distal articulation. The route of this rod goes down through the articular surface of the cuneiform and continues straight through the unciform and into the shank of the fourth metacarpal deep enough to anchor it firmly. The rod needs a bend at the point between the carpus and the ulna of an exact number of degrees so that it will protrude from the wrist joint exactly parallel to the main 1/2 inch support rod extending from the third metacarpal, otherwise the foot cannot be assembled on the fore-leg elements. However, the two rods need not be parallel to each other inside the foot because they could be plastered in place in two separate operations. (See Fig. 17 for an example of installed support rods.)

This modification also required that the orientations of the two holes drilled into the two lower limb bones be directed parallel to each other. A 3/8 inch hole was drilled up into the distal end of the ulnar shank deep enough to accommodate the 3/8 inch rod. This hole was then not lined with metal tubing. The radius, however, was drilled 5/8 inch in diameter through its entire length and lined with tubing, for it would contain not only the 1/2 inch support rod from the foot but also the adjoining 1/2 inch support rod from the elbow joint, meeting and keying together in the approximate center of the radius shank.

Fig. 17: Left manus with support rods installed, shown with the radius/ulna unit with drilled holes. The radius and ulna were taped together with drafting tape for convenience in handling.

The support rods forming the elbow joint and the shoulder joint were designed similarly to those used in the right front limb. A spur to support the olecranon of the ulna was provided similarly. Therefore, in this revised design the large, heavy ulna is well-supported at both ends in its cantilevered position. Also, the parallel rod connection of the foot to the leg is much more effective in preventing a downward rotation of the foot assembly.

The shoulder joint of the left leg is nearly vertical and has only a small bend, the scapula fitting onto the humeral head in a much more dorsal position. For this reason it was not necessary to rout a deep slot into the head of the humerus. It was possible to route the support rods straight through the entire length of the humerus from the joint at the head to the center of its distal joint. However, the drilling again had to be done in two operations through both ends of this long bone. The scapular/humeral support rod has only a single open bend for this joint, is keyed to the rod extending up from the elbow joint inside the humerus as usual, and extends up along the inner surface of the scapula for about 12 inches as on the right. This completed the design and construction of the support system of the left front limb.

Rear Limbs

The supporting structures for the rear limbs were designed and constructed similarly to those of the fore limbs. I began with the right pes first because this leg would be on the far side of the display, and because the foot, being the most distal part of the limb, could be removed without disturbing the rest of the system. The toes, metatarsals, and tarsals were drilled and assembled as before with two parallel pegs between each two bones, and cork separators between the adjoining toe bones. Aluminum material was again used in the rear feet to minimize weight at the extremities. The main support rod into the tibia of the lower leg was designed similarly to the one used in the right manus, with a 1/2 inch rod straight down through the tarsal elements and as deep as possible into the second metatarsal bone, and entering the distal end of the tibia through an appropriate angle bend formed at the surface of the ankle. The ankle joint is comprised of four bones. They are the astragalus and calcaneum of the tarsus, and the tibia and fibula of the lower leg. The tibia basically rotates through a cylindrical joint over the spool-shaped astragalus, and the fibula rotates partly along the circular end of the astragalus and partly along an adjacent surface of the calcaneum.

As the fibula is slender and of light weight compared to the tibia and the pes, it merely needed to be pinned to the tibia and none of the main support apparatus needed to involve it. The pes itself is a large paddle-shaped element and I felt that it should have an outrigger strut attached to one side of the main support rod to strengthen the foot, similar to the one installed in the right manus. However, I had now gained enough experience to realize that screws and bolts have some distinct advantages over welding, the most important one being that I could prepare the complete metal fixture myself without having to put any part of it through the SLAC machine shop. The main support rod, as mentioned before, was inserted through the astragalus, the distal tarsal elements, and about 2 inches into the body of the third metatarsal bone. The material used here was 1/2 inch aluminum rod. The bend for the ankle joint was formed by clamping one end of the aluminum rod in the large, free-standing shop vise that had been provided in my workroom. The piece was clamped so that the point at which the bend was to be formed was only about 1/4 inch above the top surface of the vise jaws. A longish piece of steel water pipe was then slipped over the entire extending end of the rod. By leaning my weight back while pulling on the upper end of this pipe, I could bend the aluminum rod to the desired angle.

(a).

(b)

(c)

(d)

Fig. 18: Supporting armature for the right pes: (a) Tarsal and metatarsal elements pegged together into three sub-units; (b) arrangement of the two sub-assemblies of metatarsals and lower tarsal elements, as they are supported on the main 1/2 inch rod and the smaller outrigger support; (c) the same arrangement but with the astragalus mounted over the support rod and the outrigger rod attached through the slot. To complete the assembly, the calcaneum will be attached by the two parallel pegs covering the outrigger support and slots concealing them from view; and (d) the complete foot ready for final assembly of toes and heel (calcaneum).

The outrigger strut was formed of aluminum strap having a 3/8 by 1/8 inch cross section. It was similarly bent and twisted to fit into a previously drilled 3/8 inch hole down through the cuboid of the tarsus and into the body of the fourth metatarsal. The proximal end of the strut curved through an approximate 90° bend so that it could be attached to the main support rod with a screw at a convenient point within the body of the astragalus. The hole in the main support rod was tapped to accommodate the little screw so that a nut would not be necessary. The astragalus and calcaneum pieces were then routed out with 3/8 inch slots originating on their internally connected surfaces, which would then fit over the installed strut and conceal it from view. To assemble the foot, all holes, pins, corks, strut, and central support had to be prepared in advance. The plastering sequence was carefully planned so that some elements could be formed into sub-assemblies, then into the final assembly. For example, it was necessary to plaster the main support rod into the previously assembled tarsus with second and third metatarsi attached, but minus the calcaneum, so that the drilled hole for the screw would be visible through the routed slot. With the remaining tarsal and metatarsal bones attached, still minus the calcaneum, the aluminum strut was plastered in so that the screw holes would line up, and the screw inserted in the same operation. The calcaneum could then be plastered into place concealing all the metal supports and routed slots. For this procedure no outside surfaces needed restoration. The toes were plastered onto the foot last, they being considered too vulnerable to sustain all the numerous procedures without damage (see Fig. 18).

The main lower limb bone, the tibia, was drilled straight through its length using the 5/8 inch masonry drill bit, and this hole was lined with stainless steel tubing as usual. The fibula was then attached in place on the tibia by plastering in one or two 1/8 inch steel pegs at each end, arranged parallel for easy assembly. The keyed end of the rod extending from the foot fitted into the hole in the tibia to its approximate center.

The right femur of the specimen was not recovered, as mentioned earlier, so this piece was cast from a clay restoration. At one point in the mounting process I had extra time while waiting for the machine shop to complete the forming of our central supporting beam. During this time I removed the right femur from the mock-up mount and did a lot of surface sculpturing of jagged cracks and other bone-like details, using the flexible-shaft tool and several styles of pointed routing bits, referring to the beautifully preserved and cast left femur to guide this work. The resulting appearance is quite a lot more realistic than the surfaces of most of the other restored castings. I would have liked to treat some of the others similarly, such as the right scapula and right humerus, but because it was a very time consuming process I decided against this effort.

The femur of *Paleoparadoxia* has a rather deep trochanteric fossa behind the greater trochanter on its proximal end. It was possible to drill the 5/8 inch hole directly through the entire length of the femur, extending from this trochanteric fossa to the center of the medial condyle at the distal end of the cast without breaking through the surface of the shaft, even though this bone is laterally compressed. The anterior and posterior surfaces are quite wide, however, and the two joints at either end are robust. This long hole had to be drilled from both ends of the cast following the same procedure as was used on the two humeri. I used the 5/8 inch drill in spite of the fact that it would not have been necessary to line this hole with tubing because it does not contain a split rod, but I did not have a sufficiently long 1/2 inch masonry bit to drill the entire length.

In our mounting, the rear lower limbs project straight back more or less horizontally, making an approximate right angle at each knee. Because of this position the tibia meets the femur on the posterior surfaces of the rounded femoral condyles. To connect the two bones with a single 1/2 inch bent rod it was necessary to rout a slot of 1/2 inch width in the medial condyle from the mouth of the long hole up to the level of the hole coming through the tibia. Thus, the bent rod was inserted up into this slot so that the proximal end of the rod protruded behind the greater trochanter, and its keyed distal end inserted into the tibia to meet the 1/2 inch aluminum rod extending from the foot, similarly to the arrangement used on the right shoulder joint. This routed slot is on the underside of the distal end of the cast and about 1 1/2 inches deep; therefore, the slot cannot be seen and no restoration of this cut was necessary.

The left rear limb was mounted in the same fashion as the right except for the treatment of the knee joint. Here, I was reluctant to destroy surface details on the femur, preferring not to make a deep slot in one of the condyles as I had done on the right side. Instead I decided to route the support rod between the two femoral condyles where there is a space of about 1 inch width. The bend in the support rod for the knee joint was to follow a curve having a radius of several inches so that it could be inserted up into the central hole drilled through the length of the femur with a circular motion. This could only be possible if that end of the support rod would be quite short, only several inches long, keying in with a third straight rod inserted down the length of the femur from the trochanteric fossa, as on the right. If the hole at the distal end of the femur could likewise be curved it would not be necessary to destroy any of the outer surfaces on the cast.

The curved support rod was manufactured for me by the SLAC machine shop from 1/2 inch diameter cold-rolled steel rod. The distal end, which was straight, was left long enough for me to cut the necessary key-way to the correct size and orientation to match the support rod from the foot. The shortness of the curved end, however, prevented making the usual keyed joint there, for I was afraid that the whole apparatus would be weakened by the subsequent drilling for the pins. It would not be good to expect the pin to insert through the keyed joint. Instead, a 5/8 inch sleeve several inches long was welded to the top end of the rod just above the curve. The whole sleeve was made 2 inches long, to form a 2 inch deep socket with an inside diameter of 1/2 inch. The assembly then would be carried out by first inserting the socket end of the rod into the distal end of the femur between the two condyles, rotating carefully up into place. The open end of the socket would then butt up against the distal end of the stainless steel tubing lining the hole. The straight support rod for the femur could be inserted down into the hole in the trochanteric fossa and manipulated to fit into the socket below to its full depth.

To make the curved opening between the condyles, a set of riffler files was used. These are small specialized metal-working files for fine handwork, and the set contains a wide variety of sharp-edged and rounded-edged curves and scimitars. With these little wonders I was able to form the curved part of the hole between the femoral condyles, for as I mentioned before the plaster is soft and not abrasive and can be worked with any cutting tools, even as fine as riffler files (see Fig. 19).

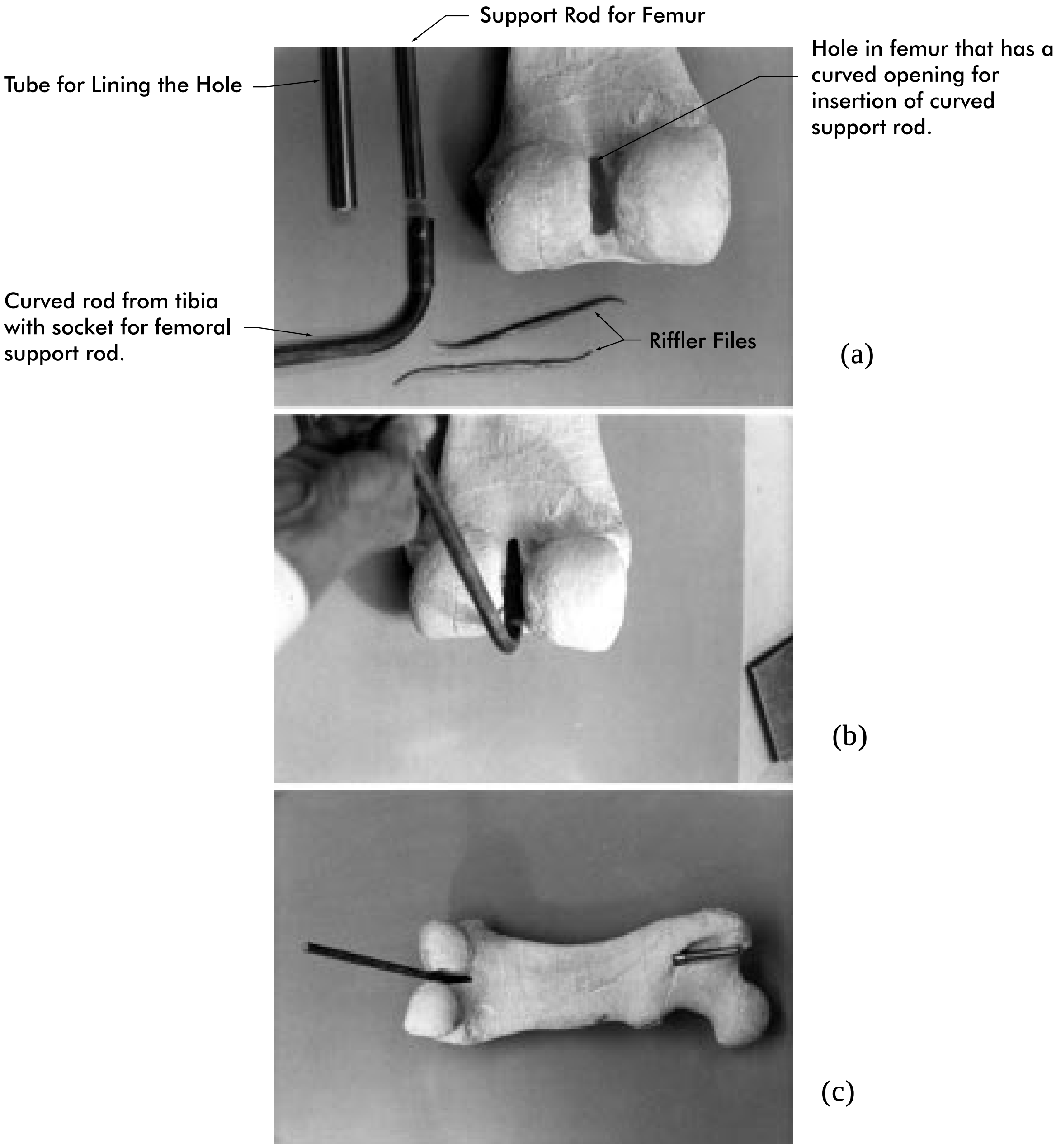


Fig. 19: Supporting arrangement for the left femur: (a) Curved support rod for the femur and riffler files; (b) insertion of the support rod into the curved opening between the femoral condyles; and (c) curved support rod inserted into femur.

The two patellae, or kneecaps, of this specimen are relatively large and chunky, and needed to be placed on the distal anterior surfaces of the two femora, which have well-preserved patellar surfaces. I chose 1/2 inch square aluminum stock for the supporting brackets to give adequate strength for the horizontally cantilevered positions of these pieces (see Fig. 20). Each length of this square stock was given two 90° bends about 1 1/2 inches apart and both in the same plane so as to form a U shape. The two legs of these U's were left between 3 and 4 inches long. In the approximate center of each of the articular surfaces of the two patellae a horizontal slot 1/2 inch wide and about two inches long was formed using the flexible shaft router. These slots were made several inches deep so that the U-brackets would be well anchored when inserted into the slots and the openings between the two bracket legs filled with plaster. Two 3/8 inch holes were then drilled at the opposing spots on each of the patellar articulations of the two femora. These holes were drilled at appropriate angles and to appropriate depths for the insertion of the square bracket legs previously installed in the patellae. All orientations and placements were sufficiently planned in advance to prevent any internal conflicts with previously installed supporting rods and apparatus inside the two femora. The two patellae were permanently assembled in place by the same plastering techniques previously described.

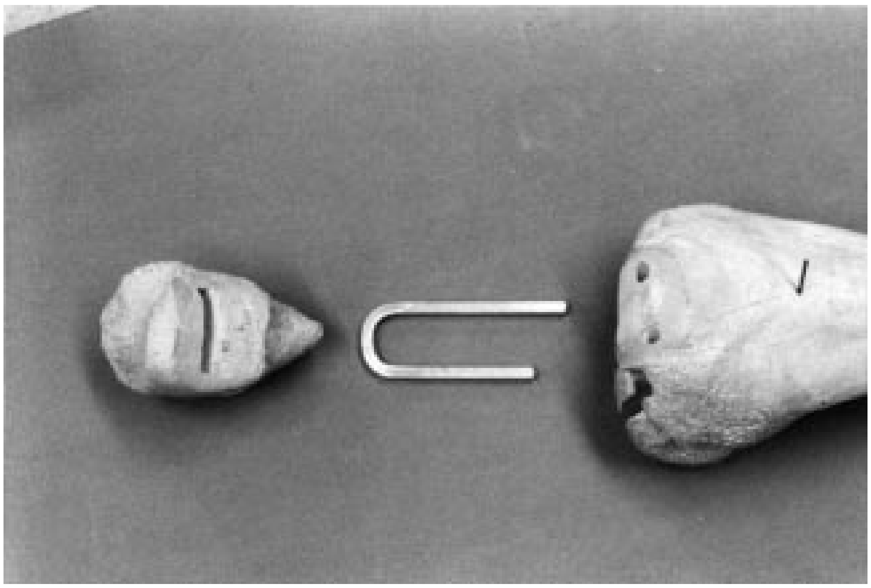


Fig. 20: The patellae support fixtures.

The Pelvic Girdle

The pelvic girdle is connected to the vertebral column by a stiff bony attachment to the sacrum, which is a series of several vertebrae fused into a single element to support the pelvic girdle, which in turn supports the rear limbs. The right and left pelvic elements each have a bony attachment to the sacrum which may be fused to it in later life. The pelvic girdle, therefore, has little flexibility, and the movability of the rear limb resides in the spherical joint between the head of the femur and the acetabular socket in the pelvis. For our mounting, a strong support mechanism would need to be designed that could maintain the rear limbs in their posteriorly cantilevered positions and still be concealed within the plaster bodies of the casts that form the pelvic girdle. This in turn had to be solidly attached to the vertebral support. It had been decided that the main central supporting beam for the entire display would be formed of 1 inch square solid steel stock to be installed through the centra of the vertebrae, and bent to follow the desired curvatures. The sacrum would be mounted at the distal end of this square beam. The caudal vertebrae would be mounted and attached later by a different method because they are too small to fit over a 1 inch square support. Therefore, the square steel beam terminates within the thickness of the sacrum.

It was decided to form a strong steel fork-like supporting apparatus for the pelvic girdle to be anchored over the main square beam, having two tines curving back at suitable angles, and concealed within the bodies of the ilia, to the end of which the legs would be mounted (see Fig. 21). These tines would be long enough to reach into the acetabular openings of the pelvic girdle. This support fixture was manufactured by the SLAC machine shop. It has a heavy-duty hardened steel square collar with two or four dog-point set screws on each of the four walls so that it can be firmly secured on the central square beam at the most desirable position. The sacrum casting is routed from the ventral surface to fit as snugly as possible over these steel supports. The two tines of the “fork” extend through the lateral surfaces of the sacrum and then curve back and down to fit into holes drilled into the adjoining pelvic surfaces. As these openings are all placed through adjoining surfaces, the metal rods are almost completely concealed. The square collar is 1/4 inch thick all around and the two tines are of 1/2 inch hardened steel rod, welded on at each side of the collar. Later, this “fork” fixture was given an additional hardening heat treatment to further strengthen it (see Fig. 21).

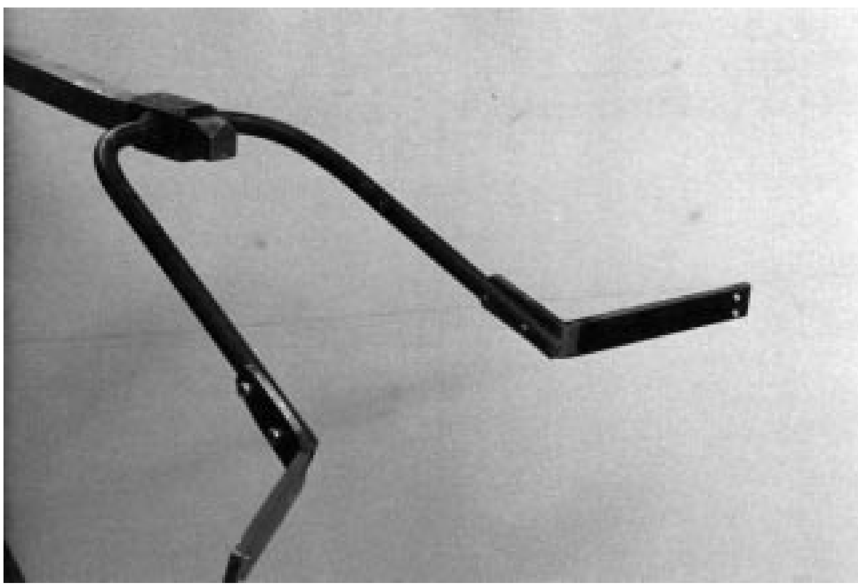


Fig. 21: Complete pelvic girdle support apparatus.

Before doing the extensive routing of the sacrum, I made a rubber mold of its ventral surface in order to preserve the original bony details. I was then able to later cast a plaster patch to cover and conceal the routed opening. This little cover is held in place with two flathead machine screws that insert through it into tapped holes in the square central beam. Both the screw heads and the inside surface of the patch are installed with washers and gaskets of blotting paper to ease pressures that might tend to crack the plaster patch (see Fig. 22).

In order to fit the plaster patch into the routed opening, I used a tedious procedure of slowly trimming the oversized cast, bit by bit, until it fitted into place perfectly. To determine where the trimming was needed I marked the metal surfaces with colored chalk. Each attempt to fit the patch in place would then form colored smudges on the clean plaster of the patch, which I trimmed off with my pocketknife. Now that all is painted to match the original fossil surfaces the patch is not noticeable to the viewer.

Fig. 22: Sacrum patch on the ventral surface of the sacrum.

Drilling of the two right and left pelvic elements was awkward because of their clumsy shapes and large sizes. The 5/8 inch masonry bit was used because it has the longest reach, and the holes were lined with steel tubing as usual. The drill holes extend from the articular surfaces of the ilia, down through the shanks of the ilia, directly into the centers of the acetabular concavities. The two distal ends of the “fork” were cut longitudinally by half their thicknesses to form flat surfaces against which the supporting bars for the two hind limbs could be firmly bolted. These flats were made several inches long, which was the full length of the section of rod exposed in the acetabular depressions (see Fig. 21).

Both right and left pelvic elements were supported in the way just described; however, the two pieces could not be equally well fitted in position. In the original fossil the left pelvic unit had suffered multiple breakages and was preserved with several severe cracks that had telescoped against each other so that the left element is about 3 inches shorter than the right. This meant that either one or both, the proximal articulation with the sacrum, and the distal articulation between the two ischia, would need to be offset from a perfect fit. It was finally decided that the general appearance of the completed display would be better if the two pelvic elements articulated correctly between the two ischia posteriorly, leaving an imperfect fit at the anterior end. The last lumbar vertebra, the seventh, has very wide, expanded, transverse processes indicating that it served as a forward extension of the sacrum and in life was sutured (grown together) with the proximal ends of the ilia. In our mounting, this suture between the seventh lumbar vertebra and the proximal ilium on the right side fits quite well, but the equivalent suture on the left is separated by approximately 3 inches.

To attach the right and left mounted rear limbs into the skeletal structure, each femoral head was slotted through its thickness with a vertically oriented slot 1/4 inch wide and 1 inch deep. An L-shaped bar was manufactured for each side from 1/4 inch thick cold-rolled steel stock, 1 inch wide. The exact angles and degrees of bends for these pieces were determined by making cardboard patterns in place, which were then used by the machinist to form the L-bars. (These L-bars can be seen in Fig. 21.) The short leg end of each L-bar was drilled with two holes for suitably robust machine screws, and two matching holes were drilled through the flats at the distal ends of the pelvic supporting "fork" within the acetabular concavities. These last holes were tapped to accommodate the four bolts so that nuts would not be needed. The long-leg end of each L-bar was cut long enough to fit right through the slotted femoral head and continue behind the bone of the femoral neck and trochanter to connect with the support rod extending up from the rear limb into the trochanteric fossa. The exposed ends of these support rods had also been cut longitudinally to give them flat surfaces against which the two L-shaped bars could be bolted. Matching holes were then drilled and tapped in all four pieces to accommodate the bolts that would be used to hold the legs in place. The assembly of each rear limb is accomplished by first securing the L-shaped bar to the pelvic support rod in the acetabulum with the two bolts, then sliding the head of the femur over the protruding leg of the bar until it fits snugly into the acetabulum, at which point the prepared holes in the end of the bar line up with the tapped holes in the leg support rod. As the complete leg assemblies are heavy and awkward, this process needs at least two people after the mock-up clamping system is no longer in place. The leg assembly must be held firmly in position while the two Allen-head bolts are inserted and tightened. This completes the design and construction of the support system for the rear limbs (see Fig. 23).

Fig. 23: The proximal end of the left femur with reinforced vertical slot as it appeared when mounted. Posterior view.

To complete the description for the mounting of the four limbs, I will describe the addition of the sesamoid bones to the four feet. Our *Paleoparadoxia* specimen is unusual in having had almost all of these sesamoid bones preserved and recovered. The sesamoids are small new-moon shaped bones that articulate with the distal ends of all the metapodials on their ventral surfaces and serve as fulcra for the muscles that bend the toes. There are two, a right and a left, on each metapodial. As stated in Table 1 on page 4, which lists all preserved bones of this specimen, all the sesamoids for both left and right pes were recovered, and half the number for the left manus but none for the right manus. To complete the two fore-feet I did not bother to make restorations of these little bones. Instead, Repenning let me use the sesamoids from his set of castings. Because the sesamoid bones are all very similar and not individually distinct, I merely chose suitable casts from this extra supply to fit the missing spots. Each sesamoid was fitted with a small cork pad on the articular surface, attached with Duco Cement glue. These little assemblies were then mounted in place, also with Duco Cement.

Pinning

As mentioned earlier, after all of the interior supporting devices were fabricated and installed within their respective casts, all the limb bones were then returned to their mock-up clamps to be held in their proper final positions, because the rods could slip out of their prepared holes until locking pins could be installed. It was planned that each limb bone that contains a split rod, or a support rod in two keyed segments, would be provided with a locking pin through each rod segment. The pins are of 1/8 inch steel rod material, and originally cut in each case an inch or two longer than the thickness through which it was to pass. The holes to accommodate these pins had to be drilled right through the plaster of the casts, the steel tubes lining the holes, and the installed 1/2 inch support rods inside the tubes. This drilling would have to be performed in place so that all the elements would remain in their predetermined positions and relationships.

Of all the processes entered into in the course of this mounting project, this drilling for the pins presented the most difficulties. First, a drill rig needed to be designed that would have sufficient flexibility to be placed at just about any angle and direction at any necessary height, and still be stable and steady. Several designs were tried until a successful device was created for the purpose by one of our SLAC machinists, Glenn Howard. It was he who determined that the only way to control the drill bit with a firm but even pressure throughout the drilling process would be to include a screw-drive for the drilling tool. He therefore manufactured, from aluminum stock, a screw-driven device that utilized the handpiece of our flexible shaft tool as the chuck for the 1/8 inch drill bits. The flexible shaft was threaded through the barrel of this device and the handpiece then mounted inside the barrel at its forward end so that the chuck for the drill bits would be accessible. The device could be mounted on the top end of a 2 inch vertical steel pipe and secured with Allen-head set screws. This mounting rotated within a strong supporting U-shaped bracket that held the cyclindrical barrel and screw-drive mechanism on a horizontal pivot so that its angle could be rotated vertically through more than 90°. The socket that fitted over the 2 inch pipe could be rotated horizontally a full 360°. Therefore, the tool gave more than adequate flexibility of direction of drilling. The 2 inch pipe was held vertically in a three-legged stand sturdily welded of heavy-duty steel pipe that had an arrangement of two steel rings with heavy-duty, hex-head set-screws, so that the length of 2 inch pipe in use could be lifted or lowered several inches for adjustments. For greater adjustments a longer or shorter 2 inch pipe would be used. This tripod support also had the feature that the three feet could be bolted to the wood base (see Fig. 24).

Each hole to be drilled had to be set up with great care so that the locking pin could be inserted all the way through all three elements as closely as possible through the center of the internal rod. In almost every case it was very difficult to estimate the position of the internal rod, because very little of it could be seen; in fact, only a glimpse might be had at each end between the bones of the joints. Once the direction of the drilling was determined, all equipment in use had to be secured so that there would be no position changes. I would draw outlines for the tripod feet on the floor of the wood base to maintain its position, and often some for my own feet, because the flexibility of the wood base could change the direction of the drill rig by several degrees just from a shift in my weight standing next to the tripod. The next difficulties encountered were caused by the variation in hardness between the three materials that the drill was expected to cut. The plaster is relatively quite soft, but the stainless steel tubing is very hard, and presented the additional inconvenience that it is difficult to start a drill hole on a narrowly convex surface, especially if the drill has missed the center mark by even a small amount. It would have been better to have used a softer material for the tubing in the first place, but by the time I realized this, it was too late to start over. (Drilling through a tibia is illustrated in Fig. 25.)

I then discovered that the entire mock-up clamping system retained an unexpected amount of flexibility, so that as soon as the drill bit would reach the stainless tubing, the entire piece would begin to move away instead of being cut. This motion soon would change the direction of the drill bit sufficiently to alter its alignment and bind in the already drilled plaster hole. To counteract this motion, I designed a strapping method to maintain the exact desired distance between the plaster piece and the drill rig. This strapping device was adjustable, having been made from two car battery lifting straps and two long threaded lengths of rod material for adjusting the distance. However, a piece of wood cut to the exact necessary length also had to be placed securely between the two elements, otherwise the flexibility of the clamping system would allow the strapping yoke to be tightened too much, which would bring the drill out of line in the opposite direction. Thus, when I would be satisfied that the alignment of the drill rig was set in the best position determinable and it had been secured in that position relative to the piece to be drilled so they could neither move closer together nor farther apart during the drilling process, the actual drilling procedure was carried out in the following steps:

1. A 1/8 inch masonry bit would first be used to drill through the thickness of the plaster cast. Either a 3-inch long or a 6-inch long bit could be used according to the thickness through which the drill would pass. It was best to begin with the 3 inch length in all cases, since a tool of a shorter length runs more true and therefore makes a better starting hole.

2. When the masonry bit would reach the stainless tubing, it would be removed from the hole and exchanged for an especially hard 1/32 inch diameter pilot-hole bit to start the cut into the stainless steel. If the distance of the tubing from the outside of the cast were short, a very fine, but short, cobalt pilot bit could be used. Each drilling situation was different, so a variety of pilot bits, styles, and lengths had to be available. We also tried a spring-loaded center punch slightly modified for a longer reach, but it was not strong enough to dent the convex surface of the stainless tubing.

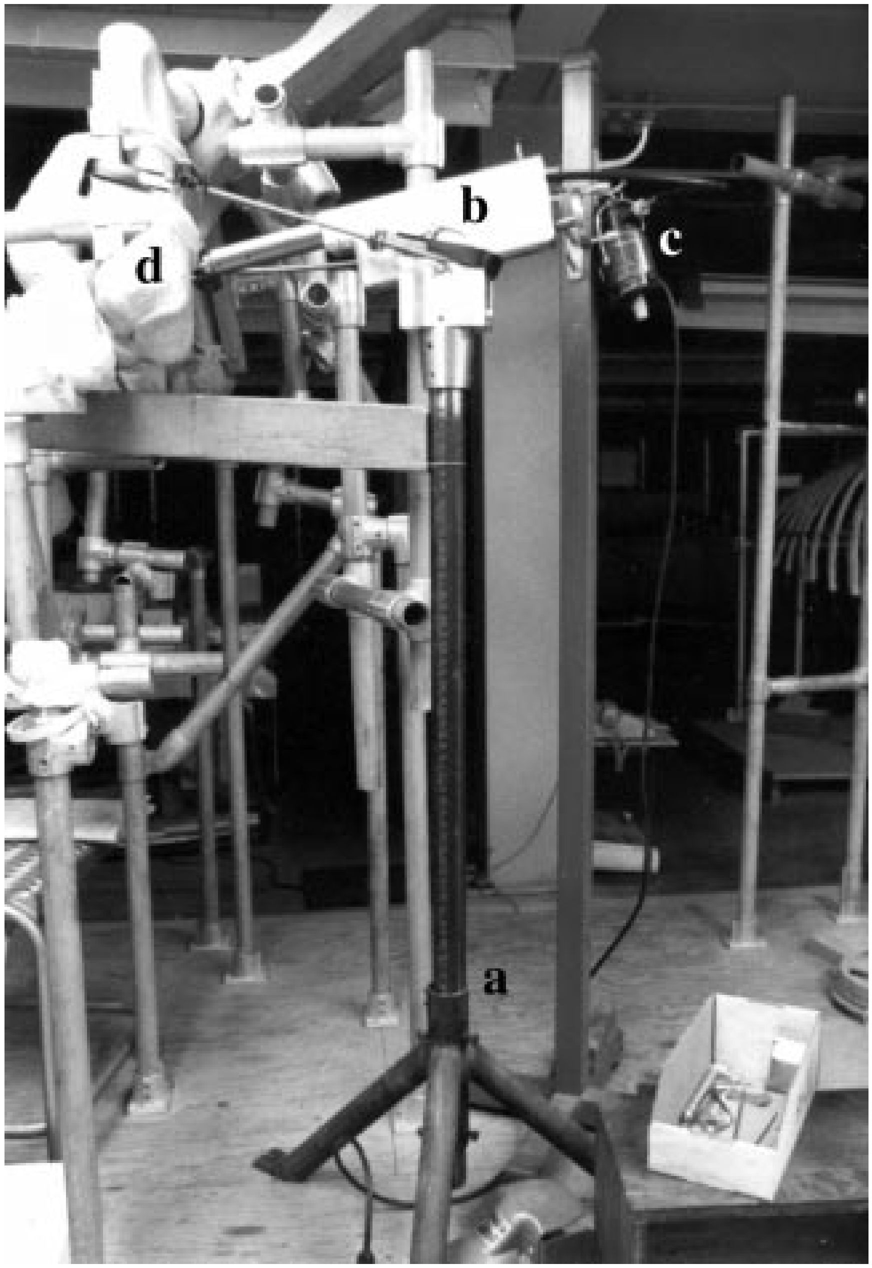


Fig. 24: Pinning drill rig complete with stand: (a) Three-legged stand bolted to the floor, (b) drill rig assembly with the flexible shaft tool installed, (c) motor drive for the flexible shaft tool, and (d) right femur (to be drilled).

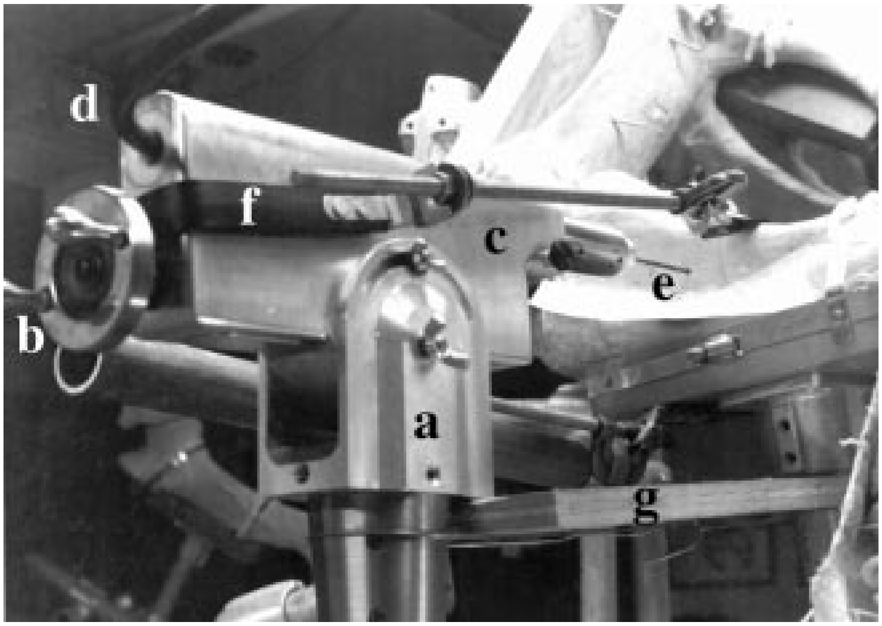


Fig. 25: Drilling through the left tibia: (a) Adjustable support mechanism for the drill rig, (b) handle for screw-drive control, (c) housing for the flexible shaft handpiece, (d) flexible shaft, (e) drill bit, (f) straps arranged to keep the drill rig from moving away from the cast to be drilled, and (g) wooden board to keep the drill rig from moving closer to the cast to be drilled.

3. Once the pilot hole was made, the tool would again be withdrawn from the hole and the bit exchanged for a regular 1/8 inch high speed steel drill of suitable length to complete the cut through all the metal parts. There was very little difficulty in the drilling of the cold-rolled steel support rods because these are of a softer metal. Also, the problems encountered in the first stainless cut would not be repeated for the second cut because the drill bit would now be guided inside the hole through the support rod, and the tip could pierce through the concave surface much more easily than through the convex surface.

4. As soon as it would be felt that the cut was through the stainless steel and entering the plaster, the high speed bit would be exchanged for a masonry bit and the cut completed.

5. If possible geometrically, the 1/8 inch steel pin for that hole would be inserted through the far side of the hole as the drill bit was being withdrawn, because there would often be some slight shifting of the tubing or the rod which would make it very difficult to insert the pin when the drill was completely removed. When installed, a short length of the pin would extend from the hole at each end so that it could be removed and replaced when needed during the construction phase of the mounting.

This procedure was followed for all the major bones of the four limbs. Once the construction of the mounting would be completed it would be necessary to cut each of the pins down to a size slightly shorter than the length of the hole so that it could be concealed within before painting. However, it seemed best to preserve a record of the individual positions of every pin in case it would ever be necessary to locate one or more. Therefore, I made a photo record of black and white prints using a micro-lens on the camera in such a way as to record the details of the surface sculpturing around each hole on both its openings. This photo record must be carefully preserved.

Central Support Beam

As mentioned in the previous section, the main supporting beam of this mounting is fashioned from 1 inch square solid steel stock which has been bent to conform to the planned curvatures that give the mounting a dynamic life-like appearance illustrating the swimming action. In order to indicate the desired curvatures for the beam to the SLAC machine shop that would manufacture it, I had a special plywood jig built for them by the SLAC Carpenter Shop. This large device was constructed on a sturdy plywood base, 28 inches wide by 92 inches long and nearly 3 inches thick. Seven-ply, 1 inch thick plywood was used. Along the length of this base were placed, cross-wise, 32 upright vanes, each about 12 inches wide and each having a 1-by-1 inch notch centered on its top edge. These notched vanes were so placed along the base as to determine the exact necessary curvatures for the square beam, which was to be bent so it would exactly fit into the notches for its full length (see Fig. 26).

I prepared a pattern for the placement of the square notches by tacking a long sheet of quadrille graph paper along the floor under the mock-up mounting. Using a plumb-bob on a long string that I had marked off in inches, I determined a spot position and a length measured between each two consecutive vertebrae from the approximate height of the centers of their centra. I was then able to provide the carpenter, George Petrick, with the graph showing the horizontal curvatures needed and the chart of lengths that would determine the curvature in the vertical plane. He constructed one notched vane for each measured position.

The machinists ran into some problems in shaping the beam according to my specifications. In the end it was not possible to bend the 1 inch square stock sufficiently for my desired curvature at the head end, so the material was cut at a point close to the tightest curvature and diminished so that a length of 3/4-by-3/4 inch square stock could be welded on. A very good weld was made at that point and the remainder of the curvatures produced. This solution has proven to be quite satisfactory and more than adequately strong for the support of the skull, mandible, and neck casts. Some extra length of material was left at each end so that I could cut them to exact size myself as needed.

Everything to be mounted on the square beam would need a square hole, which may sound like a difficulty. However, the overriding advantage is that once installed on it, the pieces cannot rotate and so will remain properly oriented without pins or any other mechanism. In fact, the plaster cast material is quite easy to cut, and the sheet cork material could be cut with Exacto knives, so only the metal parts had to have the square holes or sockets made for me in the shops.

Along with the forming of the square supporting beam, I had requested a similar length of 1/2 inch diameter aluminum rod to be bent in the exact same curvatures as the main beam. This 1/2 inch diameter rod was needed for the preliminary aligning of each successive vertebra by the process to be described below. All square holes through the casts were to be enlarged by hand from pre-drilled 1/2 inch round holes.

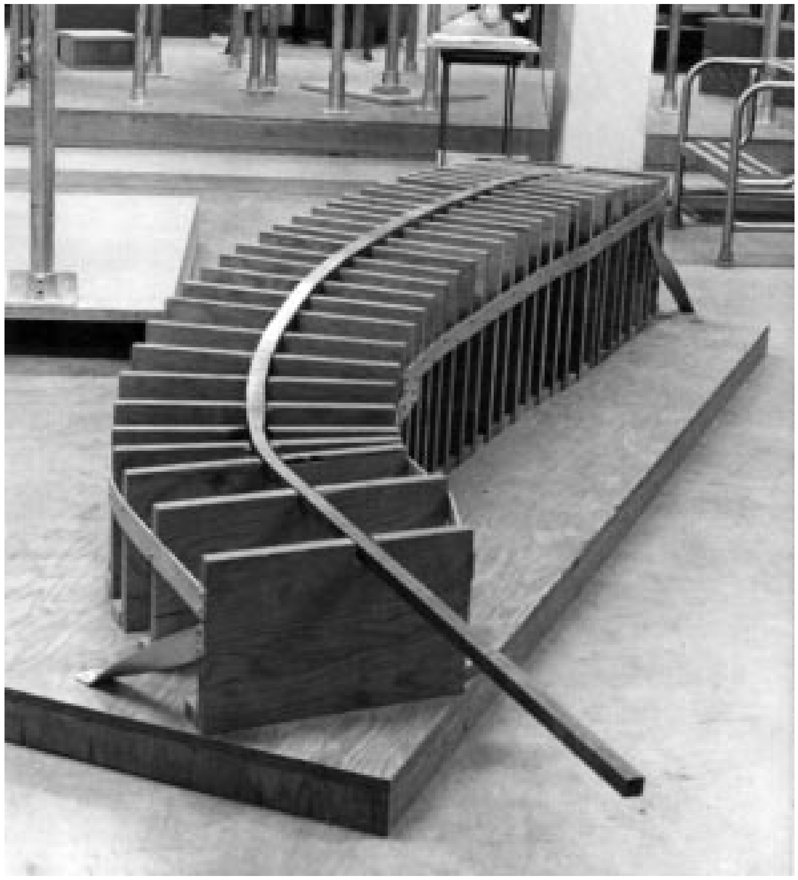
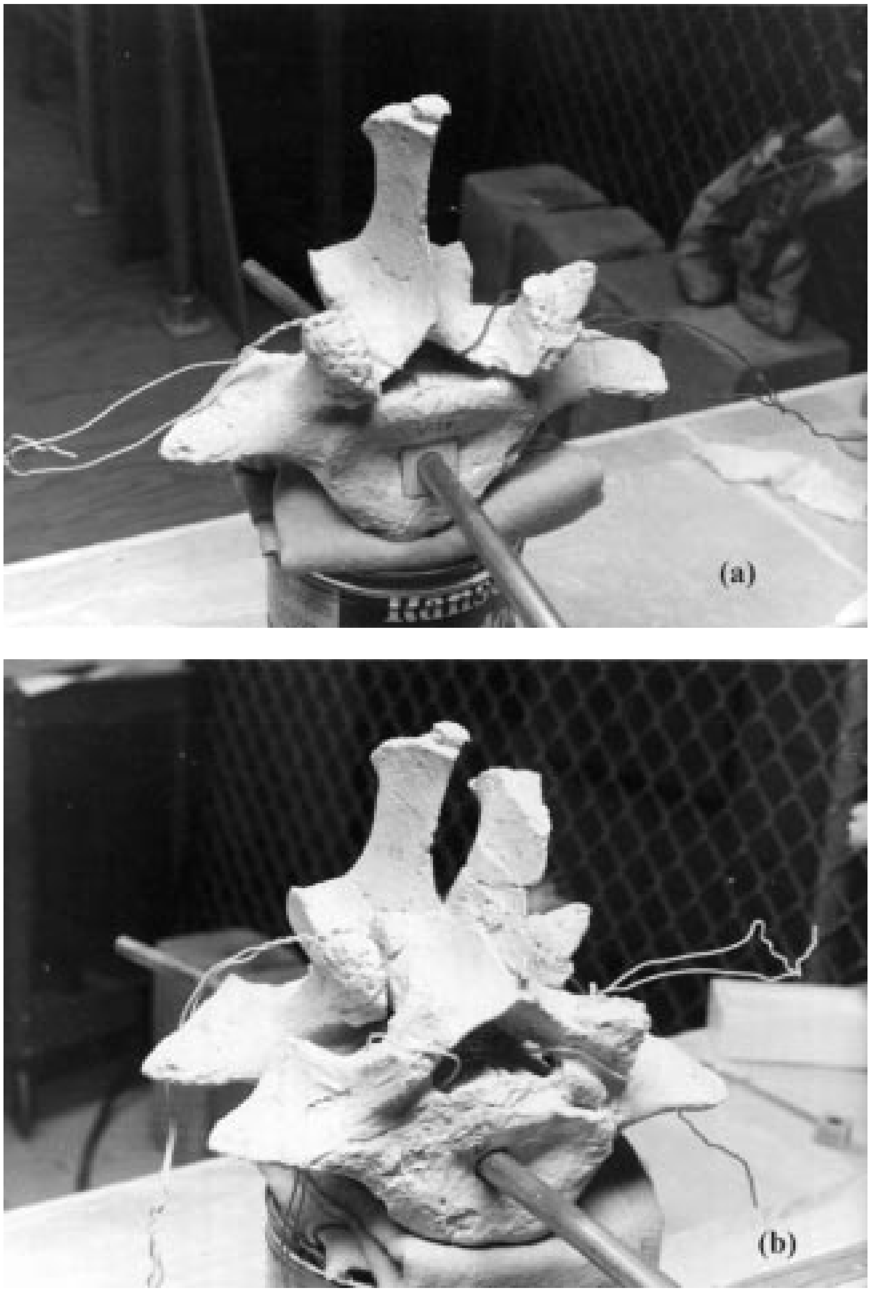


Fig. 26: The square steel beam central supporting element on the specially prepared plywood jig.

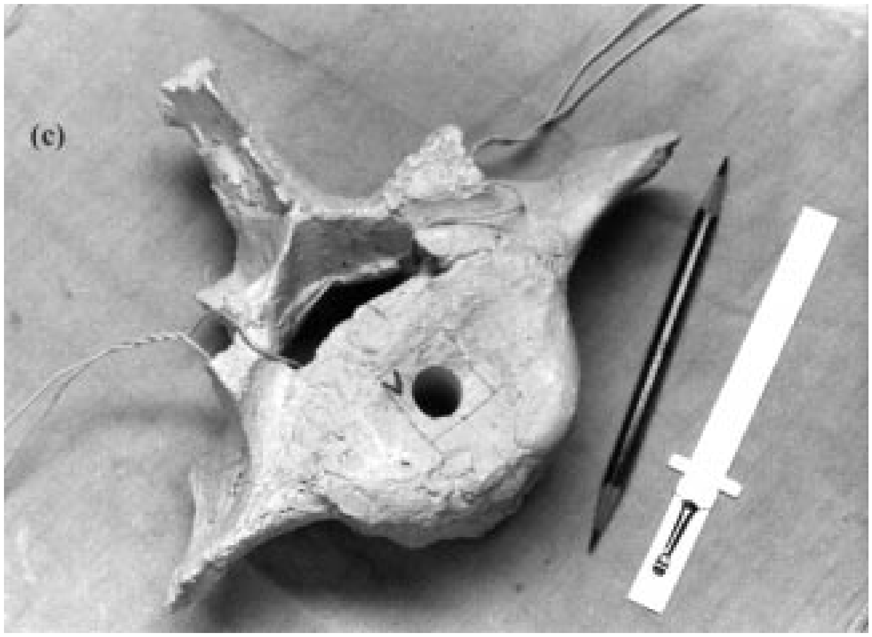
The plan which we followed called for suspending the skeleton from a structural roof beam by two strong cables. The aircraft cable used is 1/8 inch A/C cable, swaged onto a steel plate through a hole below its pointed apex and clamped securely with a swage fitting. The plate is of .074 inch steel sheet material, 2-1/2-by 3-inches and having a 1-by-1 inch square hole cut through its center and a smaller round hole near the apex for the cable. Two of these were made, each having a cable length of about 8 feet attached for a long reach in case of need. (See Fig. 37 on page 77 for an illustration of this device.)

The carpenter also built four wood stands with wide-spread stable bases and 1 inch wide notches centered on the top edge of each. The stands are of four different heights, one each of 6 inches high, 10-1/2 inches high, 11 inches high, and 12 inches high. These stands were used to support the square beam while square holes were being cut in the vertebrae and being fitted successively in place. Each hole was made by first drilling a 1/2 inch round hole through the approximate center of the plaster cast vertebra, then enlarging it to a 1 inch square with my pocketknife or other suitable cutting tool.

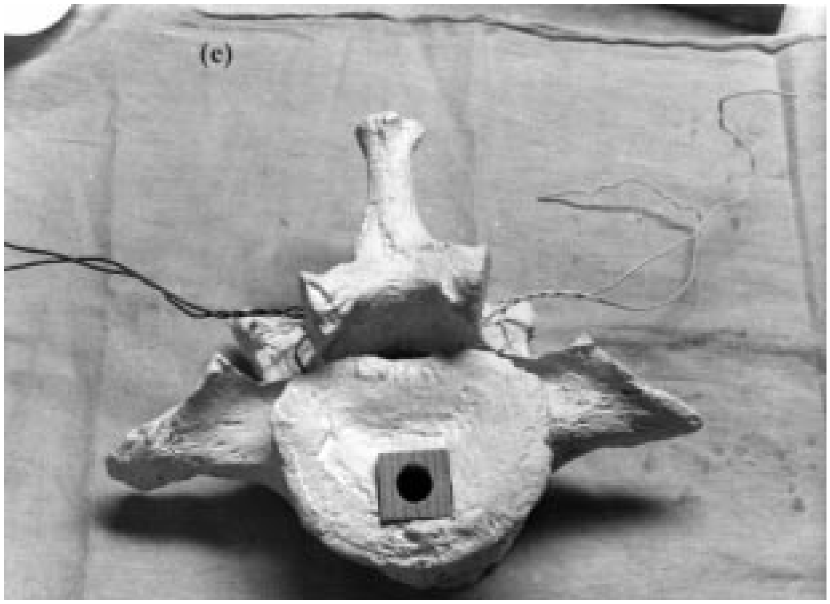
There is a sharp bend of several degrees at the rear end of the square beam which determines the position of the sacrum. The anterior surface of the sacrum was to be mounted at this bend. The extra length of square rod, about 4 inches, was sawed off so that the remaining length would fit entirely within the body of the sacrum cast. Because the sacrum would be mounted on the end of the beam first, all the remaining vertebrae would need to be assembled in turn from the front end of the beam, sliding along it up and around the various curves, the last one first. The sequence of cutting square holes in the vertebra is shown in Fig. 27(a) through Fig. 27(h).



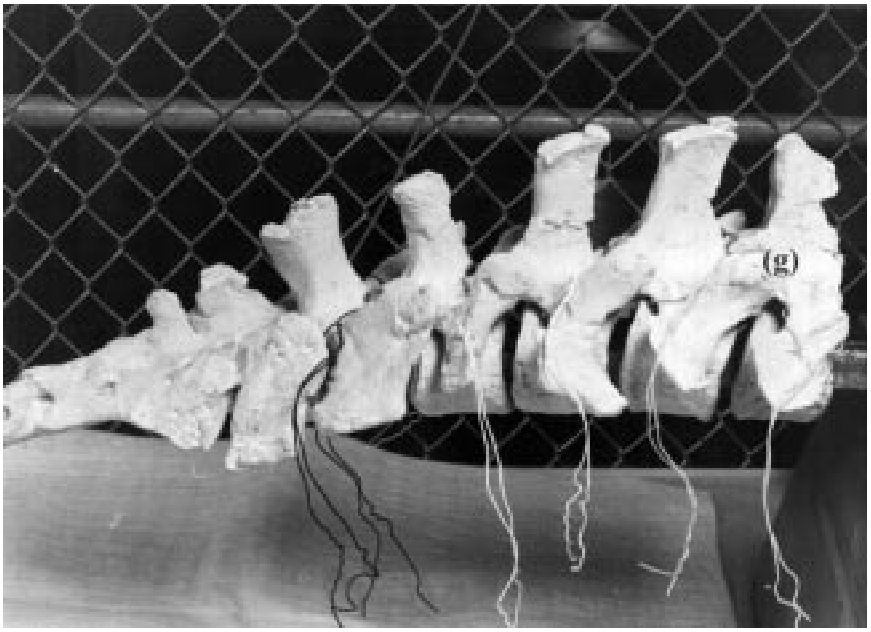
Figures 27(a) and 27(b)



Figures 27(c) and 27(d)



Figures 27(e) and 27(f)



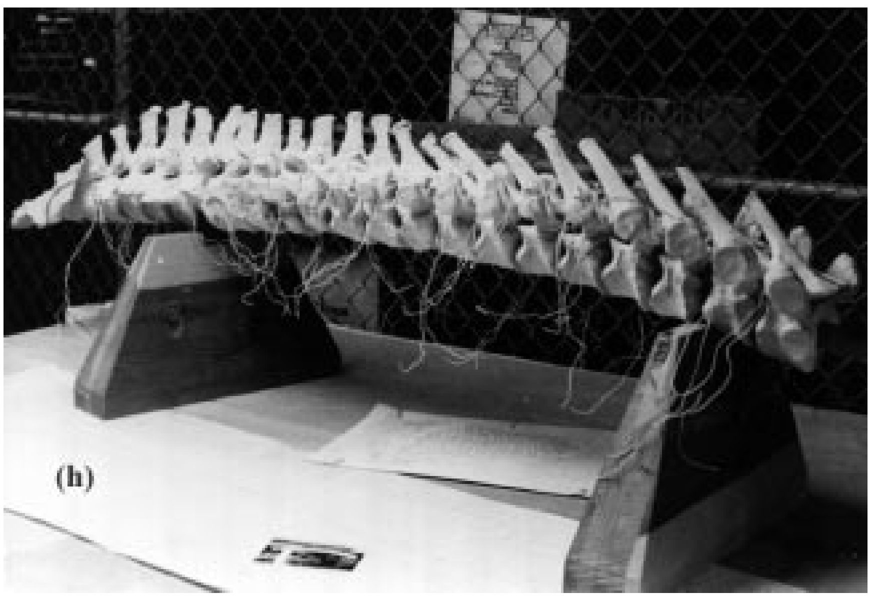


Fig. 27: Cutting of square holes in the centra of vertebrae—sequential procedure: (a) Fourth lumbar vertebra with square hole completed and filled with a small wood block, and mounted on the 1/2 inch round rod; (b) third lumbar with 1/2 inch round hole mounted next to the fourth lumbar so that the position for the square cut can be determined; (c) third lumbar removed in preparation for squaring the hole; (d) squaring the hole—third lumbar cast; (e) the square hole completed and wood block installed for continuation of this process on the second lumbar cast; (f) the fourth and third lumbars mounted on the square beam; (g) third through seventh lumbar vertebrae and the sacrum fitted onto the square support beam; and (h) the entire spinal column fitted on the supporting beam, from first thoracic at right to the sacrum.

In preparation for the mounting of the sacrum, the fork fixture described earlier (page 44) that would support the pelvic girdle and rear limbs was secured in place near the end of the square beam, and the sacrum cast was routed out from the ventral surface to fit snugly over it. The sacrum could be placed over the fork and lifted off again as needed, because it was not permanently mounted until much later.

Next, the square holes through the centra of each of the vertebrae were oriented and cut by the following process. This mechanism was devised in order to orient each successive square hole so that the adjacent vertebrae when assembled would appear to be naturally aligned. As mentioned above, these holes were enlarged by hand to a 1-by-1 inch square, starting from a pre-drilled 1/2-inch diameter round hole. To begin, two blocks of wood were fashioned to the same size and shape so as to fit closely into the routed-out spaces in the sacrum. Each block had a 1/2 inch round hole drilled horizontally through its center. With these blocks fitted inside the sacrum, it could be placed on the end of the half-inch diameter aluminum rod curved to match the square beam.

Next, the last lumbar vertebra (or proximal section of sacrum) was drilled horizontally through the approximate center of its centrum with a 1/2 inch round hole. The piece was then slid up onto the curved aluminum rod to its desired position next to the sacrum cast, and the best orientation for the square hole estimated by eye and marked with pencil. The horizontal direction of the hole within the thickness of the centrum also needed to be estimated and a second square, hopefully exactly parallel to the first one already drawn on the posterior surface, would be marked in pencil on the anterior surface. When I would be satisfied that the pencil marks were drawn to the best estimate that could be managed, I would enlarge the hole to the 1 inch square with hand tools according to the pencil marks, as shown in Fig. 27(d). If the anterior and posterior squares had not been drawn having exactly parallel sides, the hole would come out twisty, so great care had to be taken to prevent this.

Once this new hole seemed to be satisfactory, the two pieces could be tested for appearance on the square beam [see Fig. 27(f)]. However, to continue the process forward for each successive vertebra, the casts already having the square holes would be provided with 1 inch square wood blocks having 1/2 inch diameter round holes drilled through their centers. When replaced on the curved aluminum rod, the process was repeated for each succeeding vertebra [see Fig. 27(e)]. Because the casts could rotate on the round rod, I would not keep more than two or three pieces on it at a time. Instead I kept the completed section in final position on the square beam being supported on the four wood stands at the back of the table and gradually the completed section grew in length [see Fig. 27(g) and (h)].

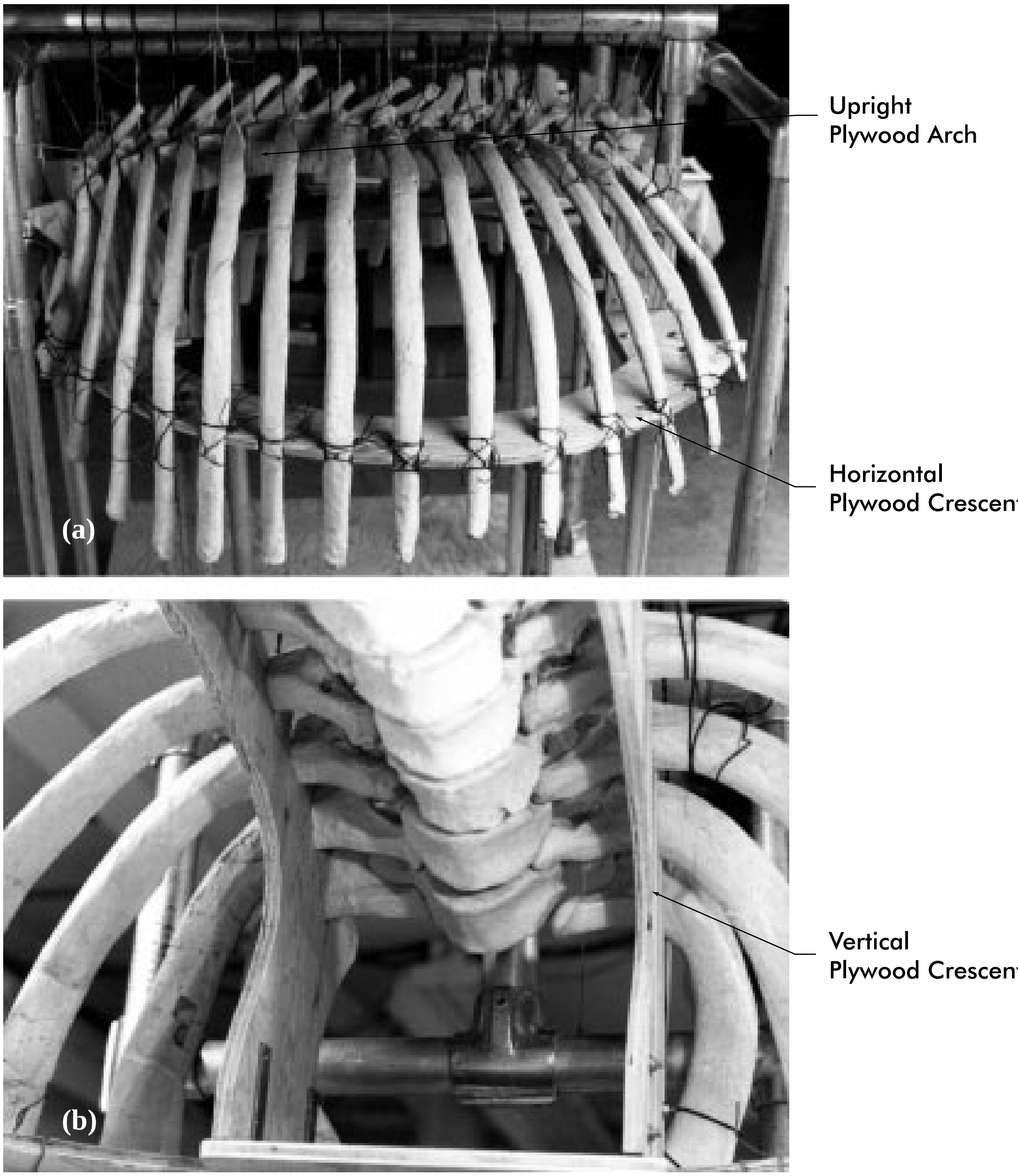
A space of approximately 1/2 inch or less was allowed between each two vertebrae for the cork spacer that would be fashioned to simulate the cartilage so as to hide the various metal apparatuses from view. This space is also necessary for a proper fit between the articular processes of the adjoining vertebrae. It was not possible to prevent some mis-estimates of direction in this process of making the square holes successively one at a time, for small errors would gradually add up to an unworkable position. When I could see that this was happening I would backtrack, revise the directions of one or two previously completed holes by cutting a little more from one side, then gluing in cardboard shims on the opposite side as needed. In this way a good fit would be maintained and the overall appearance kept in adjustment until all the vertebrae had square holes and were held in place along the length of the square beam [see Fig. 27(h)].

Rib Cage

The rib cage and sternum assembly was constructed as a separate unit on a nearby temporary supporting rack. This support had a wood base similar to the floor of the main mock-up temporary support. Its dimensions are 4-by-6 feet raised about 5 inches off the floor. The supporting rack was built of temporary scaffolding fixtures and aluminum pipes, as used on the main mock-up mounting. The rack was made on four upright supports about 5 feet high, with several horizontal members for stability and special support uses. The first phase of work was the determination of all the relative positions between vertebrae, ribs, and sternum in a mock-up arrangement. For this process, Repenning generously loaned me the thoracic vertebrae from the USGS set of casts, so it would not be necessary to remove the SLAC ones from the main mock-up. These we suspended from an aluminum scaffolding pipe centrally mounted across the top of the mock-up supporting rack. I had several small bends put in along this length of pipe to approximate the desired spinal curvature of the central square beam. The casts were hung from this curved pipe by lengths of insulated electronic wire in their proper sequence. Two curved crescents of plywood were then mounted horizontally at a convenient height below the vertebrae, one along the left and one along the right sides of the mock-up rack. The center area of the mock-up structure was kept open for accessibility to inner surfaces. The distal ends of the individual ribs would be supported along the outer curved edges of these crescents. To support the upper ends of the ribs near their articulations with the vertebrae, two upright sheets of plywood, cut into arches of suitable curvature, were mounted vertically from the two ends of each horizontal crescent. Working in pairs right and left, from front to back, notches were cut in the edges of the plywood arches and plywood crescents so as to fix the exact positions of the individual ribs when properly articulated against their respective vertebrae. There were also two more horizontal aluminum pipes mounted left and right above the support structure, from which each rib was suspended by a wire. In this way the rib was supported while its position was being determined. When the notches for a rib had been decided and cut into the plywood, cup-hooks were provided at each side of the notches and the rib secured in place with insulated electronic wire wound around the cup-hooks [see Fig. 28(a) and 28(b)].

To determine positions for the first four pairs of ribs, it was necessary to devise a way to hold the sternum assembly in place at the anterior end of this rib cage mock-up. It will be noticed that the sternum plates that were recovered (see Table 1 on page 4, last item) numbered four on the left and three on the right. It is not possible to determine whether this inequality indicates an abnormality of this individual animal, or that one of three left sternum plates was broken into two segments. However, if the three right are placed end to end without intervening spaces, the overall length of these three is almost as long as the four plates of the left side similarly arranged. It was therefore decided to mount the entire sternum as if it were a pathological specimen, with an unequal number of plates on the two sides. Some intervening spaces would need to be left between adjacent bones for the cartilaginous attachments between them; these spaces were arranged so that the overall dimensions of the two (right and left) sides would be about equal. Three parallel holes of 1/8 inch diameter were drilled into the thickness of each two adjoining sternum plates so they could be joined together with 1/8 inch steel pegs in a similar manner as the adjacent toe bones had been. Before plastering the parallel pegs permanently into the two pegged units (that is, the right with three and the left with four), they were laid into a suitably curved “basket” formed of a sheet of expanded metal and secured in their desired relative positions with nylon cable ties. The cast of the restored manubrium was wired on above them, centrally located.

All of this wired-together assembly was then suspended in the rib cage mock-up in the desired position from an anterior cross-member of the mock-up support structure by more wires. Its lower end was rested on some blocks of wood so that it could be held at an angle reaching under the belly of the skeleton.



Figures 28(a) and 28(b)

Fig. 28: The crescent-shaped plywood supports, vertical and horizontal, devised to hold ribs in the mock-up: (a) Completed rib cage mock-up viewed from the left, (b) the same seen from below—ventral view, and (c) the sternum structure, inside view.

The position of the first pair of ribs was then arranged so that their distal ends would join the two proximal surfaces of the first sternal plates, and the manubrium would join this structure centrally and above these articulations, very similar to the arrangement in elephant skeletons. Repenning approved; however, he warned that the manubrium should dip forward so that a sufficiently wide opening would remain at the throat for the passage of large volumes of food that this kind of animal would have needed to eat. The proximal ribs in mammals are usually joined to the sternum directly by cartilaginous attachments that extend from each rib end to the cartilaginous area between each two sternum bones, in successive order. A certain amount of fudging of this arrangement was necessary to have our uneven sternum accommodate four ribs on each side, as can be seen in Fig. 28(c).

When the entire rib cage mock-up assembly was completed and approved by Repenning, the next phase of work was commenced, which was to manufacture steel reinforcements to be inserted down the length of each rib and fitted into a slot within the rib thickness for concealment. It had been decided to recreate the entire rib cage, including costal cartilages all reinforced with steel straps, to give the rib cage structure enough internal strength so that the use of an external horizontal steel support across all ribs could be avoided. The final appearance of the completed rib cage on this mounting is indeed very satisfactory, but the amount of extra work that this method necessitated was far more time-consuming than expected. It should not be undertaken without thoughtful consideration.

It was planned that each pair of ribs would be supported together on a T-shaped steel plate, manufactured with a 1-inch square hole in its center, to be mounted on the central support beam between each two thoracic vertebrae and adjusted so that the rib heads would appear to fit into the well-preserved rib facets on these vertebrae (see Fig. 29). To accomplish this, the support straps needed to extend from the rib head far enough for the placement of two screws several inches apart to fit through two matching holes prepared in the upper region of the steel plate. In most cases the two straps extending from the right and left ribs had to be screwed down, one above the other, so that the two screws would be sufficiently far apart for stability. The rib reinforcing straps also had to extend some length beyond the distal end of each rib to form the support for the costal cartilaginous attachment. The steel plates with 1 inch square holes at their centers were produced for me by the SLAC machine shop. Twenty T-shaped plates were made for me from .065 inch mild steel sheet. Their overall dimensions were generous with the expectation that each one used would be trimmed as necessary to fit its individual placement. In most cases some bending of the plate surface was also necessary.

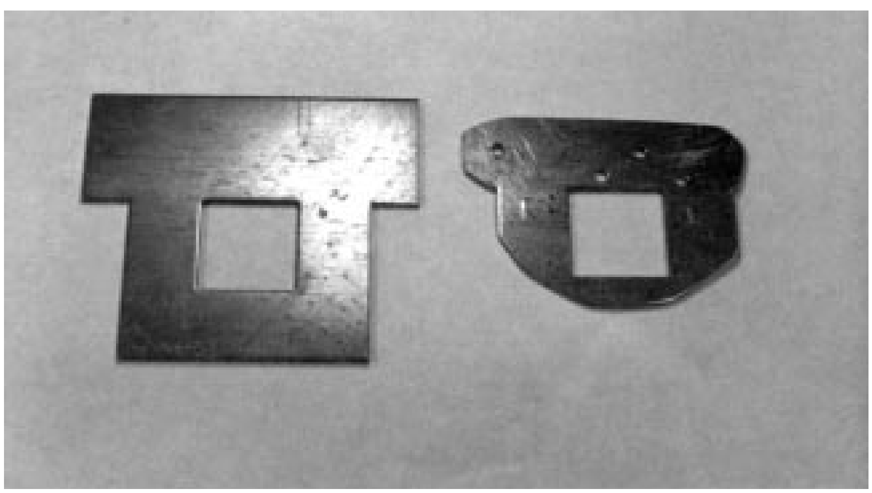
(a)  (b)

Fig. 29: T-shaped steel plates for attaching rib pairs: (a) One T-shaped plate unmodified and (b) modified for concealment between two vertebrae and drilled for the right and left rib straps.

The strap material used for the rib reinforcements was cold-rolled steel stock, having a cross section of 1/4-by-1/8 inch. I could obtain this material in long lengths which I cut with a hacksaw as needed. To reinforce a rib adequately, the strap material needed to be bent into a similar curve as that of the rib, so it could be inserted into the body of the rib and concealed. Each strap for each rib was individually bent so that the larger 1/4 inch dimension maintained the original plane of the strap and the smaller 1/8 inch dimension received the curvature, in order to take advantage of the stiffness that was thus provided. In order to bend the strap material in that direction, I had two long-handled bending tools made for the job. The pattern for these bending tools was given to me by Oroville Gilpin, who was head preparator at the Field Museum in Chicago when I visited there in 1975. Each tool is made from heavy steel bar material 1/4-by-1/2 inches in cross section and has a 3/8 inch wide, U-shaped opening placed on one of its wider sides at the top end. Viewed from the open end, one sees that the lower limb of the U is really elongated by more than 1 inch, which extends beyond the handle about 1/8 of an inch to one side and about 3/4 of an inch to the other side. The pair of tools was made with this extension to the right on one and to the left on the other. The handles are each about 16 inches long. When manipulated together over the strap to be bent, one in each hand, great mechanical advantage is available and also great versatility, for each tool can be used in either hand, and at any distance apart, either facing up or down. In this way very minor adjustments could be made in the curvatures of the straps, even after the general curve had been formed. Of course each strap was individually bent for each individual rib, as no two are the same (see Fig. 30).

Before the straps could be made the individual slots would have to be cut. The first four pairs of ribs were slotted along their posterior surfaces, because these ribs are flat in the antero-posterior direction and fairly wide transversely. The slots were cut 1/4 inch wide and deep enough to place the 1/8 inch thick strap approximately centrally within the thickness of the rib. Beyond the fourth pair of ribs their cross section becomes more round than flat, so the remaining 10 pairs were slotted along the internal surface. These slots were made 1/8 inch wide and deep enough to place the strap well inside the body of the rib so that it would be possible to seal the metal completely and firmly inside the slot. As each pair of ribs was slotted and the strap reinforcements made, they were temporarily held together with three or four paper wads firmly packed in the slot around the metal. It was felt that it would be wise to maintain flexibility for changes and so the reinforcing straps were not permanently plastered in until much later.

To cut the slots in the rib casts, the flexible shaft tool was used with steel router points by Dremel. I obtained 1/8 inch router points in a variety of shapes and lengths. In order to control the plaster dust created by this operation I had a shop-vac (vacuum cleaner) set up on a tall crate behind my work bench. A stiff water pipe several feet long was fitted into the hole for the cleaner hose, and to the other end of this pipe I attached a homemade paper hood that extended out over the table under which I could work. So that the vacuum cleaner would run only when the router tool was in use, a “dead-man” switch with two outlets was put together for me, operated by a foot pedal.

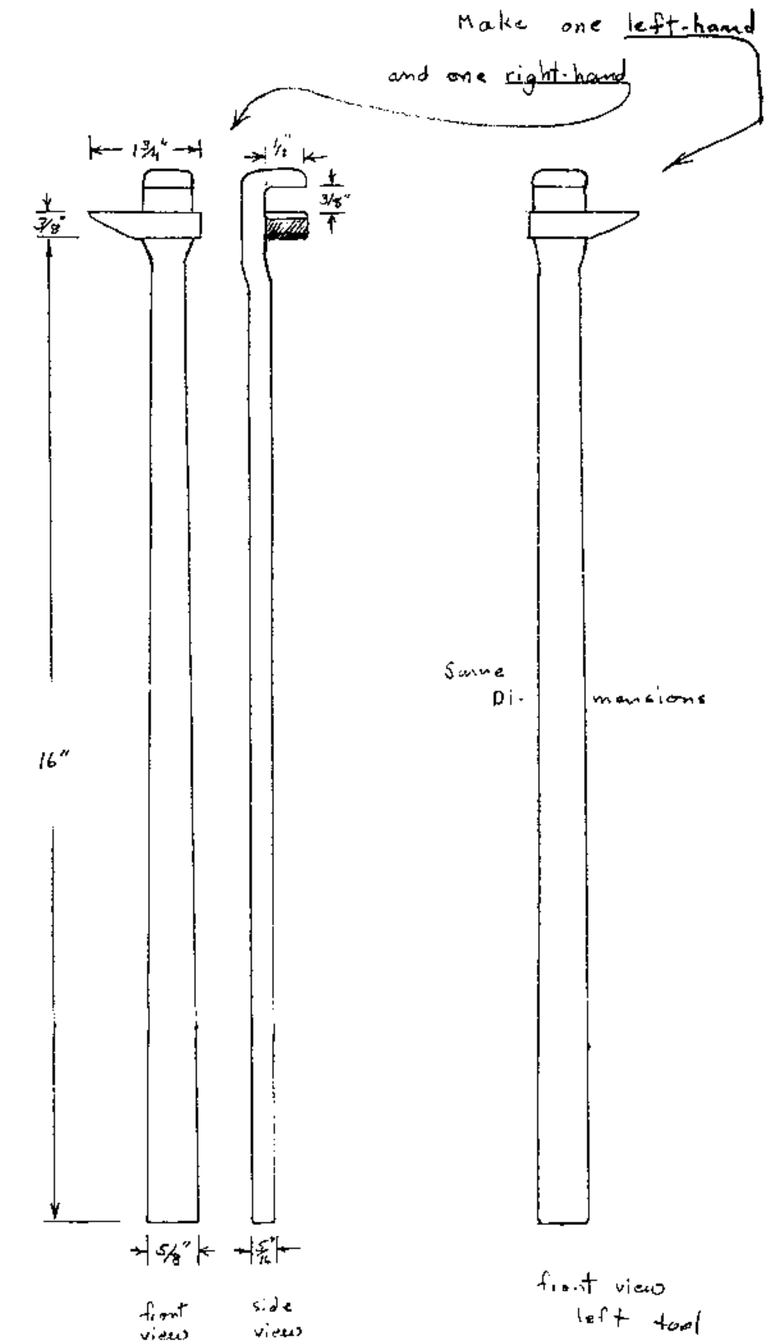


Fig. 30: Diagram of benders.

To begin the slot a straight line pencilled on by hand would be marked along the inner curvature of the rib, as best as possible, running from the center of the proximal articulation in the rib-head all the way to the approximate center of the distal end. When the generation of the line was judged satisfactory it would be doubled in order to delineate a 1/8 inch wide plane cutting through the rib. It was also necessary to determine the approximate vertical direction of the completed slot within the body of the rib. I felt that the slots should be cut to be as close fitting as reasonably possible around the steel strap to be inserted. When all these things had been determined, and the slot for the strap was cut to the approximate desired depth, an adequate length of the steel strap material would be cut and filed smooth at each end.

By clamping the steel strip in the large shop vise with the flat side horizontal, the desired curvature would be produced using the two long-handled bending tools. I would start near the middle and work out towards the two ends. When I had the desired curvature approximated, I could slip the strap down into the prepared slot to test the fit, then make further adjustments until I could feel that it was pretty well in place. I would then rub carpenter's blue chalk along the edge of the outer curvature, insert the strap into the slot, and slide it back and forth a very short distance in the slot. In this way the plaster would be marked to indicate where contact had or had not been made. By cutting away the high spots in the slots with further routing and adjusting the curvature of the strap, after many successive tests and operations, the strap would make contact with the plaster at the bottom of the slot for its entire length. The proximal end extending from the rib head would be adjusted so that it would extend horizontally between the two thoracic vertebrae when replaced in the mock-up. The distal end would also need to be bent in such a way that it would come forward to meet suitable extensions from the sternum unit. In this way each of the 28 rib casts was reinforced.

Before the final curvatures of the distal ends of the rib reinforcements could be exactly determined, it was necessary to complete the metal reinforcement structure of the sternum. At this point the plaster cast sternum plates were removed from the expanded metal "basket" and a permanent support structure built that would hold the eight sternal casts in a single skeletal unit. This construction was made mostly of the 1/4-by-1/8 inch strap material also used for the rib reinforcements. A central strip was placed vertically from top to bottom, bent outward and forward at the top end to support the manubrium, curved slightly as it descended between the right and left sternal units, and spreading into a Y shape at the distal end beyond the sternal plates for the support of a xiphisternum of "cartilage" which I envisioned should extend beyond the preserved bones.

Supports for the attachment of the costal cartilages were added horizontally between the bony plates and secured to the vertical strut with 1/4 inch 6/32 pan-head machine screws. To avoid the need for nuts, in each case one of the two straps to be assembled together was provided with threaded holes. In order to succeed in drilling these many holes in the center of the 1/4 inch strap material, a small jig was made for me from a thick piece of heavy steel (see Fig. 31). The jig has a longitudinal slot right through its length, 1/4-by-1/8 inch in cross section, and two small guide holes placed at right angles to this slot and oriented to reach the slot at the center of its 1/4 inch dimension. The jig would be firmly clamped in the large shop vise and the strap to be drilled slipped down into the slot to the appropriate depth so that a pilot hole could be drilled through the strap with a small drill bit inserted into one of the small guide holes in the jig. This device was used for all the very many screw holes that were needed in the rib cage construction. For the sternum assembly, only one small weld had to be made for me by the shop welder to attach the extra limb of the Y-shaped strut for the xiphisternum. All the rest of the attachments were made with screws and tapped holes, allowing me to disassemble and reassemble any part or all of the rib cage as needed.

Fig. 31: Jig for pilot holes in rib strap material, with a section of strap inserted.

To complete the sternum mounting, some strap material was inserted between the three sternal plates of the right side and the upper three of the left side. As mentioned earlier, the right and left sets of plates had already been attached together, but not plastered in, with three parallel pegs between each two casts. Now the cross-struts that joined the central vertical strut to the costal cartilages were each provided with a second short strip drilled and tapped with four holes. Each of the horizontal struts was drilled with four matching holes to accommodate 6/32 screws. When assembled, the main struts passed between the two casts below the exposed sections of the three parallel pegs and the matching short sections were each placed on top of the three parallel pegs. When the four screws would be inserted and tightened, these double crossbars would clamp firmly onto the parallel pegs between the casts to create a sturdy unit. Another long crossbar was routed into the thickness of the two most distal sternal plates, screwed to the vertical strut at its approximate middle, and extended out at each side sufficiently far to reach the appropriate pair of costal cartilages. These last two slots needed to be plastered over to conceal the metal and hold the pieces firmly. This was accomplished by the same process and materials that were used in the filling and restoration of the rib slots. The method and materials used in these processes will be described later. Paper wads were also used temporarily in these slots, visible in the rib ends seen in Fig. 28 (c).

To complete the metal work for the rib cage, the steel reinforcements for the costal cartilages had to be bent into the successive curves that join the whole structure to the sternal unit. After much trial and error, and repeated frustrations, the whole was finally accomplished satisfactorily. All joinings of straps were made with 1/4 inch 6/32 screws. The last two pairs of ribs, numbers 13 and 14, were determined to be “floaters” by the shapes of their proximal articulations and so do not connect distally to the rest of the rib cage structure.

The next step was to incorporate the spinal column, that is the vertebrae mounted on the square central support beam, in place within the reinforced rib cage in the rib cage mock-up. The extra set of vertebral casts that had been used in that mock-up initially were now removed and returned to Repenning. The prepared vertebrae were removed from the support beam, and the beam was suspended in place in the rib cage mock-up. It was positioned so that the reinforcement straps extending from the rib-head articulations would be situated above the square beam. The beam was temporarily supported on stands placed at each end outside the mock-up unit. The lumbar vertebrae were mounted on it with hand-fashioned cork separators, also having 1 inch square holes, placed between each two. The separators were made from 1/2 inch thick sheet cork (two 1/4 inch sheets glued together) and hand-fashioned similarly to the cork separators used between the toe bones. After the seventh lumbar vertebra was installed, two 1/4 inch thick cork separators were made for the next space. Between these two corks the steel suspension plate with its attached length of aircraft cable was mounted. It was now possible to suspend the square beam by this cable to the mock-up structure. However, the front end of the square beam had to remain propped so that it would continue to be possible to slide on, in turn, all the various elements with square holes: vertebrae, cork separators, and steel plates. The reinforced ribs had to be temporarily removed from the mock-up and were placed in an ordered array on a table nearby. The remaining lumbar vertebrae were then mounted on the beam and cork separators fashioned to go in between them.

As each pair of ribs was incorporated into the structure, a steel T-shaped plate would be prepared to fit between the two successive vertebrae. The outside outline of the T would be trimmed with a hacksaw so that it would not protrude around the edges (see Fig. 29). A horizontal bend of a few degrees was usually necessary at the approximate level of the dorsal margin of the centrum because the bodies of the vertebral centra tend to articulate with a small angle to the vertical, the ventral edges being more posterior than the dorsal. In our specimen, however, the articular surfaces have comparatively little convexity and concavity so the flat steel plates with this small horizontal bend, or fold, could be readily adjusted to fit. The four holes would then be positioned and drilled in the rib reinforcement straps and the upper part of the steel plate for the 1/4 inch 6/32 screws that would attach the ribs in place. In all cases the screws were inserted through the steel plates to screw into threaded holes in the straps. Thus, no nuts were needed in the construction of the rib cage (see Fig. 29). After the cork separator was fashioned to conceal the steel plate, straps, and screws, the next forward vertebra would be slid into place and the next pair of ribs prepared as before. In this way, continually working from the rear forward, the entire rib cage was constructed separately from the main skeleton, on the central support beam that would remain in the final mounting.

It was then convenient to complete the spinal column mounting by forming the remaining cork separators between the cervical vertebrae. The aircraft cable hanger was installed between the fifth and sixth cervicals and from that time on the rib cage structure was suspended from the upper horizontal member of the rib cage mock-up support rack with this device. The rib cage assembly was then completed by forming the necessary connections between the sternum assembly and the costal cartilage extensions protruding from the distal ends of the ribs. The physiological reason for these connections being formed of cartilage is to provide sufficient flexibility of the rib cage to allow for the expansion and contraction of the lungs in breathing. For our purposes in the mounting these restored structures had the opposite purpose, to provide stiffness to the structure as mentioned above. It was planned to eventually cover the steel strap material with a suitable coating and paint to match the cork material that was to also represent cartilage. However, that process was reserved until much later because it would still be necessary to disassemble and reassemble the rib cage several times.

Now that all the elements of the rib cage were satisfactorily assembled into a single unit separate from the main skeleton, it needed to be transferred to its final position in the mounting so that the overall appearance and fit could be judged when all parts would be together. Changes could still be made if deemed necessary. To accomplish this, the entire unit needed to be disassembled so that the square beam could be manipulated into position without jeopardy to any plaster casts. I disassembled the rib cage placing the ribs again in the ordered array on the worktable, and the vertebrae of the complete spinal column in sequence also on the table, along with cork separators and steel plates, etc. The next step was to fit the main supporting beam into place in the main skeleton mock-up, from the sacrum at the posterior end, coming forward between the limbs and into position for supporting the head. For the time being the skull had to be removed from the mock-up, as it would have been in conflict with the square beam in place. The beam needed to be supported in this position so that it would still be possible to slide the various elements on and off for assembly and disassembly of the spinal column and rib cage.

The beam needed at least two supports at all times; if three were available, any one of them could be removed for the passage of one element along the beam, and so by successively removing each of the three supports in turn, a piece could be slid down the entire length of the beam. The design for the three supports that were made for this purpose was inspired by supports created and in use by a local auto muffler repair shop. Their bases were manufactured from discarded automobile brake drums to provide an adequately heavy but still movable foundation. The vertical stands were each made from two lengths of telescoping water pipe, the larger diameter pipes welded into the axle holes of the brake drums (see Fig. 32). These outer pipes are about 46 inches long, and somewhere near the top each has two large bolts inserting into it through one side, each bolt provided with a T-handle. These are placed on opposite sides of the pipe, and screw in through a matching nut welded onto the outside surface of the pipe over the hole. These two bolts act as set-screws that can be tightened down onto the inner water pipe to hold it as high as needed. The inner pipes are about 50 inches long and each has a 1-1/4 inch wide steel strap, bent up into a half circle welded onto its top end, with a diameter of approximately 4 inches across the open end. These devices could then be placed under the square support beam and the height of each adjusted so that the beam was held in the desired position. To install any piece on the beam, the piece would be fitted on through its square hole and slid along the beam up to the first support stand at the head end. This support would be lowered sufficiently to allow the piece to pass over it and then raised again to support the beam. The inner telescoping pipes were marked around the circumference with colored pencil at the level of the tops of the outer pipes so that the stand could always be returned to the originally determined correct height. The process would be repeated for passing the centrally placed second stand and also the third stand at the rear if necessary.

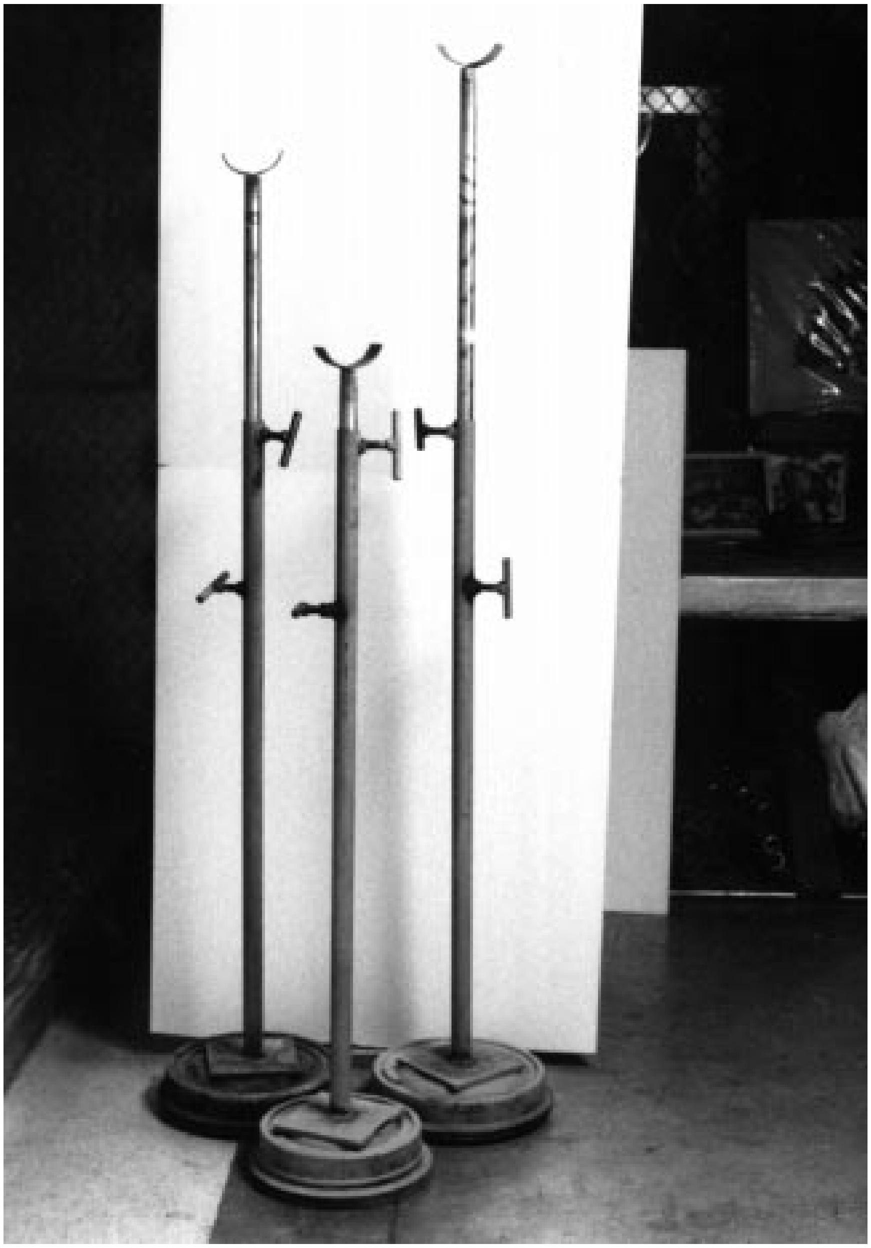
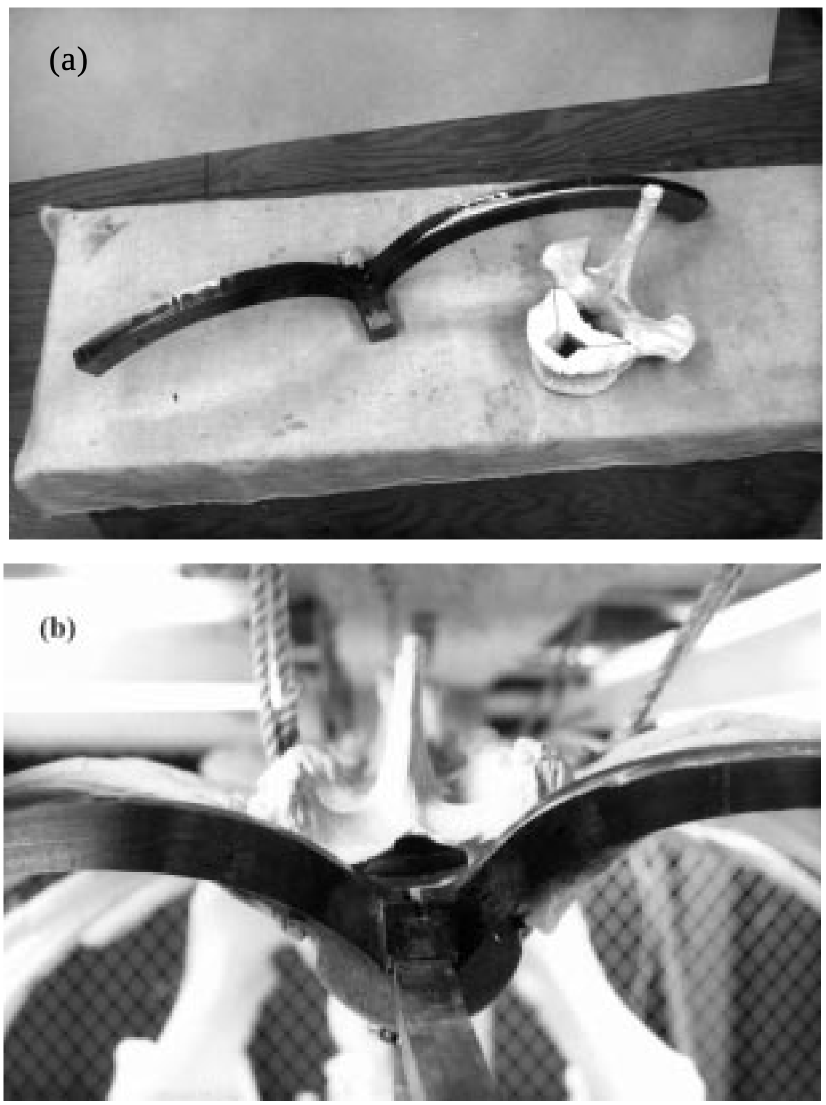


Fig. 32: The three adjustable support stands.

Each piece of the complete spinal column was mounted on the square beam in order, from back to front: vertebral casts, corks, steel plates, etc. When the beam would have casts in place it was necessary to adjust the position and height of the supporting stand so that the ventral surface of one of the cast vertebrae would rest in the circular strap at the top of the stand. The surface of the cast would be protected from damage by the strap with several layers of styrofoam sheeting. The position of the stand-base would be marked on the floor of the temporary base with a flow-pen circle, because there would be gradual shifts in position during the repeated installation processes. After the lumbar vertebrae were in place, the ribs were assembled with the thoracic vertebrae and cork separators, etc., and afterwards the sternum and costal cartilages assembled as before. When the cervical vertebrae were also assembled in place we could judge the appearance of the complete post-cranial skeleton, including the limbs. Repenning approved it without changes or adjustments.

The next undertaking was the engineering, designing, and fabrication of the support mechanism for the attachment of the front limbs. As mentioned before, the fore-limbs do not have a bony connection to the axial skeleton, so it was not possible to entirely conceal this support fixture within the thickness of the casts. Therefore, it was planned to camouflage the support by shaping it to the approximate size and curvature of an adjacent pair of ribs for connection of the limbs from the main support beam to the undersides of the scapulae. When installed between two pairs of ribs and painted dark brown, it is hardly noticeable to the display viewer. The most convenient placement for this support is between the fourth and fifth pairs of ribs with its central 1 inch square socket to be concealed within the body of the fourth thoracic vertebra. In order to design the exact shape necessary, all the cervical vertebrae, the first four thoracics with their ribs and also the sternum assembly, were again removed from the mock-up, giving us free access to the region in question. The device was designed by SLAC engineer John Flynn and manufactured by the SLAC machine shop [see Fig. 33(a)].



Figures 33(a) and 33(b)

Fig. 33: Shoulder girdle armature, three consecutive views: (a) The shoulder bracket supported on a short section of 1 inch square support beam. The routed-out fourth thoracic vertebra, posterior surface, is also shown; (b) the shoulder bracket mounted on the square beam in front of the fifth thoracic vertebra and its cork separator, viewed from the front; and (c) the fourth thoracic mounted on the support beam fits over and conceals the body of the shoulder bracket.

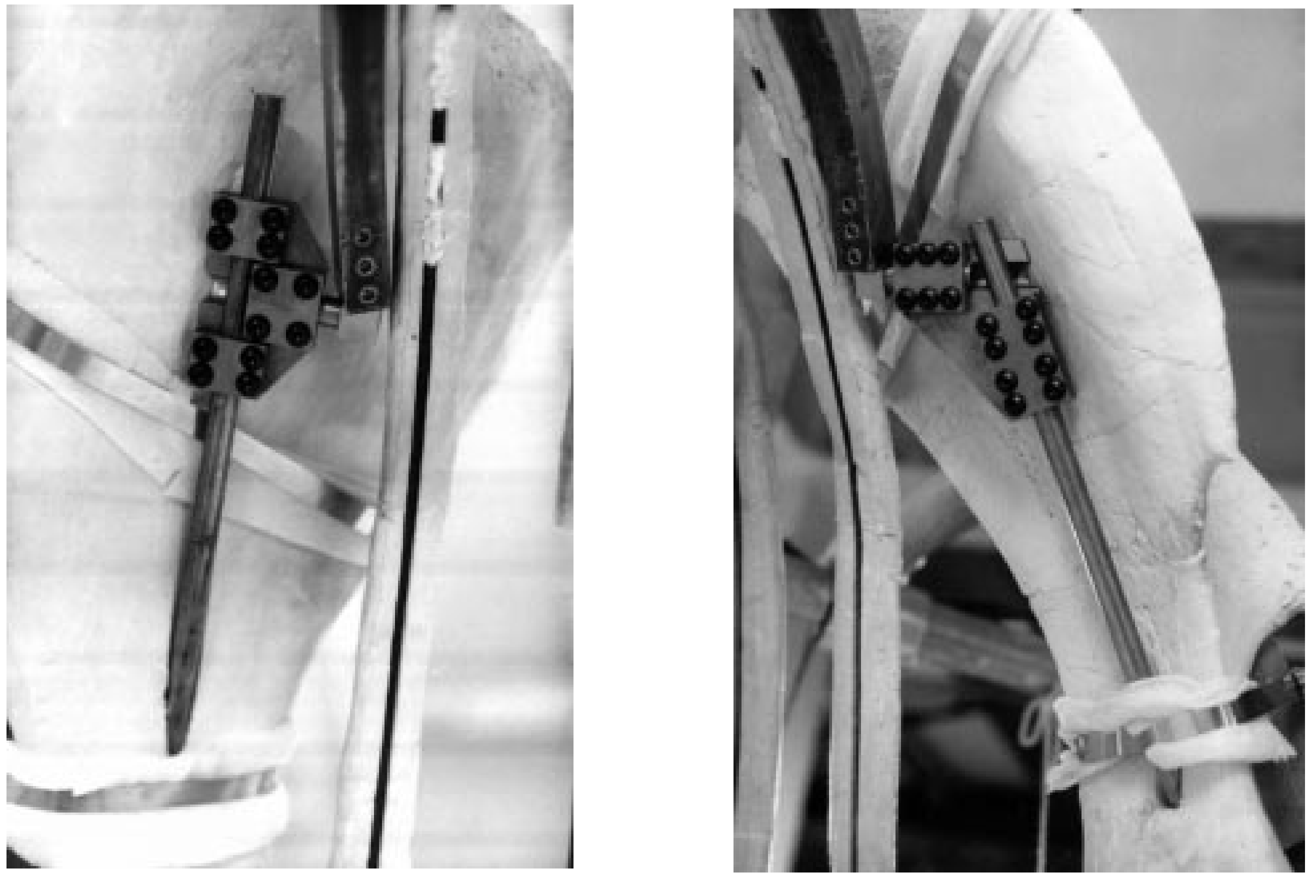
The bracket was machined from a heavy steel plate more than 1-1/4 inches thick. It has a centrally placed 1 inch wide groove on the under side for a tight fit up against the central support beam and two 3/4 inch thick arms, reaching right and left, to connect to the support rods from each forelimb that had been left extending vertically behind the two scapulae. These two arms are shaped to conform to the curvatures of the fifth pair of ribs and are situated directly against their anterior surfaces. The curvatures were flame-cut to the pattern that we provided, having an approximate 1-inch thick radial dimension. The anterior surfaces of the arms were milled away leaving them 3/4 inch thick. The central section of the bracket has a cross section of 1-1/4 inches horizontally by 1-1/2 inches vertically and is 1-1/4 inches long, extending forward from the curving arms by about 1/2 inch. The 1 inch wide grove cut along its lower surface is 1/4 inch deep, leaving two 1/8 inch thick lips on either side for a snug fit over the square central beam to ensure a correct lateral placement.

The central socket also has a second groove of 1/4-by-1/4 inch cross section milled down the length of the top surface and two holes, about 3/4 of an inch apart, drilled through from the upper groove to the lower groove to accommodate two hex-head Allen bolts. [These details can be seen in Fig. 33(b).] With the bracket in its final position, pilot holes were drilled through these two holes right through the main square beam, then enlarged and tapped from below. Thus, the assembly of the bracket required only the two Allen bolts, inserted and tightened from above, without need for nuts.

The fourth thoracic vertebra was routed out so that it would slide over the central body of the shoulder bracket and fit up snugly against the separator cork as before. This completely conceals the central socket device and the bases of the two curving arms that then extend between the fourth and fifth pairs of ribs to reach under the two scapulae. Being made from a single piece of steel it is very strong [see Fig. 33(c)].

John Flynn designed some rather complicated devices for the attachment of the forelimbs that would allow minor adjustments of position horizontally, vertically, and rotationally. To permit all these degrees of freedom a three-way system is necessary, as described before on page 17 when used in our mock-up clamping method. The two devices, right and left, are different in detail because the right and left scapulae are not exactly symmetrical and the two limbs are in different positions in order to illustrate the swimming action (see Fig. 34). Basically they consist of 1/2 inch diameter steel rod connectors that are clamped tightly in their desired relative positions between two 3/8 inch thick steel plates, each grooved and knurled to accommodate the 1/2 inch connector rods. Each set of two plates is held together by six or eight button-head, socket-cap screws, 3/4 inches long with 1/4-28 threads. The first connector rod fits into the end of the curved arm of the bracket to a depth of 1-1/4 inches and is held in place by three set screws installed through the inner surface of the bracket arm. The second connector rod extends at an approximate right angle to the first, also 1/2 inch in diameter and 1-1/4 inches long. These two rods are in actuality machined from a single piece of steel 1/2 inch thick, leaving a cube of steel at the corner where the two rods meet. The right and left devices are not identical because the angle between the two connector rods varies slightly from 90° in each case, and the amount of this variation is somewhat different right and left. The third connecting rods are the limb support rods that rise up vertically behind the scapulae. In each case, there is a single grooved steel plate against which the second and third connector rods are clamped by opposing steel plates, assembled with the button-head socket screws from the inside surface, as shown in the photographs. In finalizing the display, all of these metal parts are painted an even dark brown color to match the fossil and so are hardly noticeable to the viewer.

At this point, the entire rib cage and spinal column was again dismantled so that the rib reinforcement straps could be permanently sealed inside the ribs in place of the temporary paper wads. At the same time, certain other revisions and improvements were undertaken to strengthen the pelvic supports for the rear limbs. The improvements included a second heat treatment to the forked sacrum support, as mentioned earlier. This fixture was also modified to be assembled with Allen-head bolts of a larger size than was previously used. The 1-by-1/4 inch horizontal slot through the head of the left femur was lined with a strip of sheet aluminum bent to size [see Fig. 23 on page 47], because this casting had not been strong enough to sustain the forces exerted by the weight of the limb and the plaster had cracked. After the aluminum lining was installed inside the slot, the broken-out plaster was repaired and the surface restored. This repair was done with the same material and tools as were used in the filling of the rib slots, that process to be described next.



(a) (b)

Fig. 34: Attachment devices used for the forelimbs to the shoulder brace, (a) left fixture in place and (b) right fixture in place.

The filling material is mixed from a formula given to me by Frank Pearce of the prep labs at the National Museum of Natural History when I visited there in 1970. It is called “Guck.” The recipe for this material requires polyvinyl acetate beads as the basic ingredient. Place an amount of the polyvinyl acetate beads in a clean paint can that has a tight-fitting cover; the can should be less than half full. To this add enough clean acetone to generously cover the beads and stir as well as possible with a stout stirring rod. Cover the can tightly and allow it to sit over night, or several days, until the mixture has become a thick transparent syrup similar to Duco Cement. Prepare a combination of dry ingredients in an amount at least equal to the amount of the dissolved beads, consisting of one half dry casting plaster powder and one half filler material such as powdered chalk or powdered talc. Stir the dry ingredients into the glue mixture until it has the consistency of putty. The mixture is very sticky and therefore difficult to use, but with some experience one learns the most practical consistency for the job — not too runny, not too stiff.

The greatest advantage I found in using Guck over epoxy-type materials is that it dries hard fairly quickly merely by evaporation of the acetone, and it can be re-softened at any later time in case one is dissatisfied with the previous application merely by brushing on more acetone. The greatest disadvantage is that it is so sticky that each tool can only touch it once and then must be cleaned off with acetone before the next motion, or all is messed up again. I used a number of different small screwdrivers, an ice-pick, a hat pin, and other such small pointed tools, plus all 10 fingers in turn to work the Guck thoroughly into the complete depth of each rib slot and close-packed all the way around the full length of the metal reinforcement strap until flush with the outer surface of the casting. These tools would then be used to restore surface details such as ridges and cracks across the filled strip. When painted, the filled straps are almost undetectable; however, it would not be possible to use an acetone-based lacquer paint (see Fig. 35).

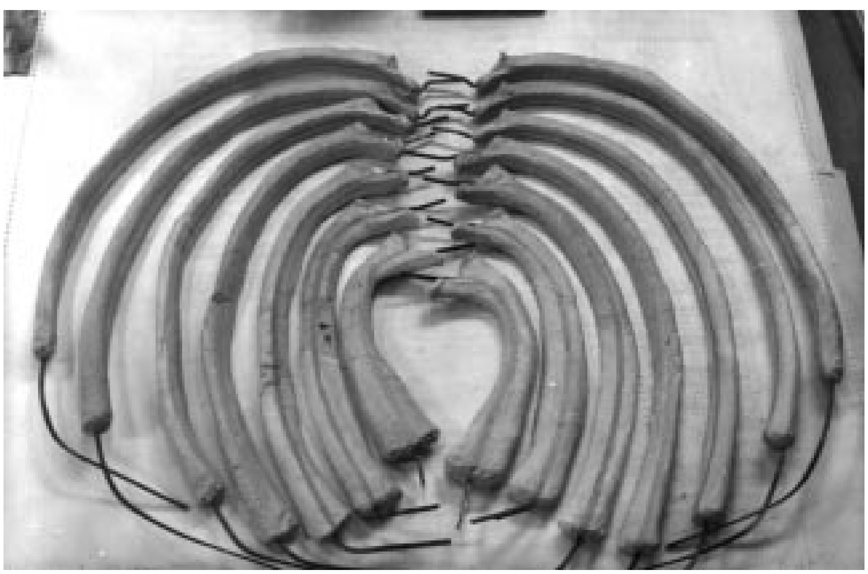


Fig. 35: Array of completed ribs, pairs one through seven.

To finish the sternum assembly, a new batch of Guck was mixed and colored with dry pigments to match as closely as possible the color of the cork separators. The cork had been used to indicate cartilage and, as the material of the costal attachments and between the sternum bones is cartilage in mammals, it was felt that these elements should be represented in the same color. The dry pigments used were two measures of burnt umber to three measures of yellow ochre. At first the majority of the thickness to be filled was done with the uncolored Guck. The material sticks better and stays in place better if the surfaces to which it is to be applied are brushed wet with clean acetone immediately before the application. When all the webbing, screws, and strap materials were concealed between the sternal casts, a smooth top layer of the tinted Guck was applied.

The Tail

The last skeletal element to be mounted was the tail. There were seven caudal vertebrae preserved, two of them rather deformed. It appears likely that the deformities were caused by some early breakage of the tail bones that had healed during the life of the animal. The longer of the two deformed bones may be two caudal vertebrae that had been crushed at their articulation and subsequently grown together, which would then bring the total count of caudal vertebrae to eight or possibly more. To determine the best fit and most likely order in which to mount the tail casts, it was necessary to study carefully the preserved fossil bones which were then borrowed from the UCMP collections for this purpose. However, even then several possible interpretations could have been made. I decided to mount the unit so that the "healed break" interpretation would be illustrated. The sequence of the casts was determined by the cross-section thicknesses of the separate pieces, arranged in descending order posteriorly. The two deformed pieces are placed in the fourth and fifth positions so that the tail acquires a downward, and to the right, bend at that point. This brings it very closely positioned against the dorsal part of the pelvis so that in the living animal it would have been tightly pressed against the buttocks and barely visible.

Each two adjacent tail casts were mounted together with two parallel 1/8 inch steel pegs as had been utilized in the mounting of all the toe bones. A small cork separator was fashioned to fit between each pair of bones, except between the two deformed pieces, four and five. These were plastered together without cork to illustrate the healed breaks. The first element was not pegged to the second, nor to the sacrum, but was drilled through longitudinally to accommodate a 10-24 size steel screw-rod, not threaded. A 10-inch long length of this size screw rod was acquired for the tail mounting. One end of it was prepared with nicks so that it could be plastered into the previously mounted tail unit several inches into the centers of the second and third casts. The first cast and its corks were left free to rotate on the rod. The anterior exposed end of the screw rod was provided with 10-24 size threads for more than 1 inch of length. A matching hole was then drilled horizontally through the caudal articulation of the sacrum until it reached to the center of the posterior end of the square central support beam. By using this last hole through the plaster of the sacrum to guide the direction of the drill bit, a tap-size hole for the 10-24 screw rod was drilled into the square support beam to the depth of about 1-1/2 inches and the hole tapped with this size screw threads. With the complete tail assembled and plastered onto the drill rod (see Fig. 36), it is easy to mount in place by inserting the rod through the sacrum until it can be screwed into the prepared hole by gently rotating the bent tail arrangement until it is screwed in against the loose first caudal and its two corks. It must be adjusted so that the dorsal arches will be on the dorsal surfaces and it does not need to be very tight, only snug. The reason why the first caudal cast needed to be allowed to rotate freely is that there is a preserved dorsal projection of bone extending back from the posterior articulation of the sacrum, and this would be in conflict with the first caudal vertebra if that piece had to rotate against it. Therefore, in screwing in the tail unit, the first caudal does not have to rotate but merely rests freely on the rod. When the mounting will be partially disassembled for moving, the tail unit will also be removed because it would be quite vulnerable left extending at the end of the rib cage/spinal column unit (see Fig. 36).

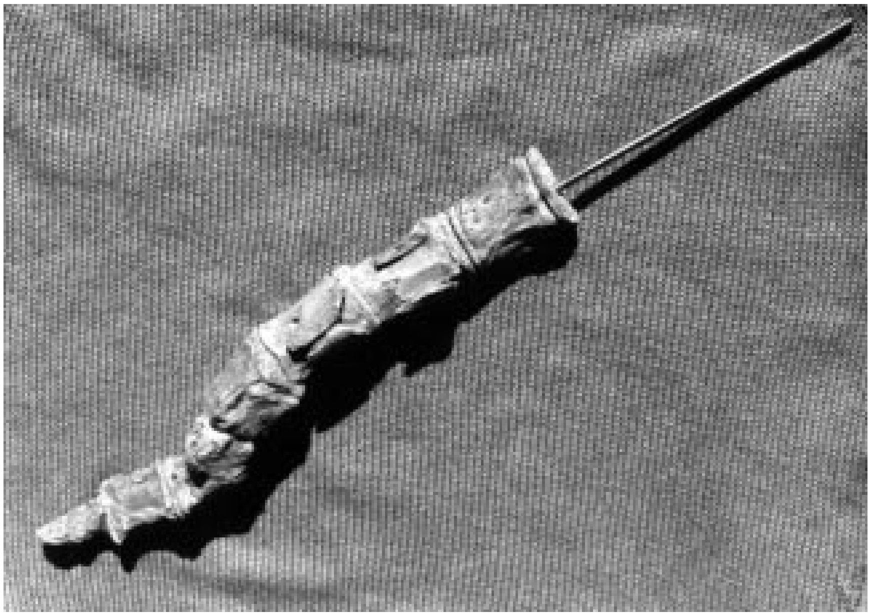


Fig. 36: Mounted tail.

Final Assembly

After the above mentioned improvements had been made to strengthen the pelvic and rear limb supports, reassembly of the remaining post-cranial skeleton was carried out. At this time, the final aircraft-cable hangers were put in place so that the mounting could henceforth be suspended by them and the temporary support stands laid aside. As described earlier on page 53, these two cable devices were fabricated of steel plates having 1 inch square holes in their centers and a strong length of aircraft cable through a small hole near the dorsal apex of each, attached with a swaged eye (see Fig. 37). Four special clamps were now designed by engineer John Flynn and produced in the SLAC machine shop. Each of these consists of two machined aluminum blocks that each contain two matching longitudinal semicircular grooves large enough to accommodate the aircraft cable diameter when closed over it. Each pair of blocks is held together by three socket-head 1/4-20 bolts so that the blocks can be tightened down onto the cable which has been passed up through one of the two grooves and returned down through the other groove. Two of these clamps were necessary for each cable, so that in case of adjustments needed to the height of the display each could be loosened and moved in turn so that the skeleton would never be left unsupported. In the lab these cable clamps were quite visible, just above the skeleton; however, it was expected that they would finally be positioned a lot higher up above the display, just under the roof of the building and so out of the view of the spectator. In order to be sure that the aircraft cables would not develop any unsightly kinks in all their long lengths, they were each temporarily installed in the mock-up support, wrapped over a short length of 2-inch pipe.

Thus, to assemble the rear cable, the hanger plate was slid onto the square beam and along its length until it fitted snugly against the posterior cork separator in front of the seventh lumbar vertebra. The end of the cable was then threaded up through one side of the lower cable clamp, on up through a large hole drilled through the upper wooden cross-beam of the mock-up support, on up through one side of the second cable clamp, then up through an additional wooden beam that had been installed about 1 foot above the mock-up structure close under the ceiling, with suitably positioned holes drilled vertically through it. The cable was then doubled back through this second cross beam over a short length of the 2-inch pipe, then threaded down through the upper clamping device, down through the lower wooden cross beam and the lower of the two clamps. When the desired height would be determined, the cable clamps would be firmly tightened with Allen wrenches. The assembly of the anterior cork and the remaining lumbar vertebrae and their corks was continued. At this point the rear, or third, support stand could be removed; however, each rear limb was temporarily secured by the tibia being returned to its original mock-up clamp to insure that the skeleton would not swing around during the continuation of the assembly process.

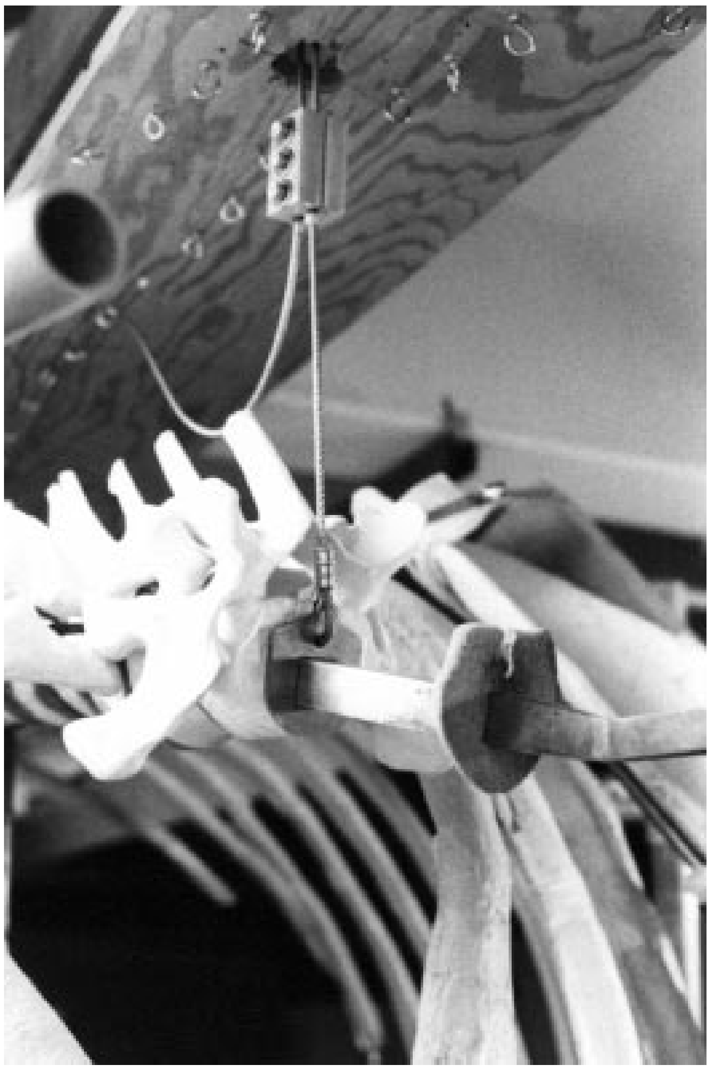


Fig. 37: The anterior cable hanger plate with swaged cable, and the lower of two cable clamps in view.

After completion of the lumbar section, the thoracic vertebrae and ribs were reassembled in place along with their cork separators, and the shoulder armature and bracket assembly for the front limbs also put in place in its turn. The front limb assemblies were then positioned on the bracket and tightened in place. To facilitate this positioning, small indentation marks had been incised into the adjoining metal parts so that the desired relative positions would be preserved and reproducible. After this, the remainder of the rib cage, the sternum unit, and the seven cervicals were assembled as before. Now the entire rib cage was a more solid construction because the paper wads had been eliminated and the metal straps firmly enclosed. Ahead of the sixth cervical vertebra, the anterior aircraft cable hanger was put in place up over a piece of 2-inch pipe and clamped at the desired height by the same process as was described for the posterior cable. Now all three of the temporary support stands could be laid aside; however, the two humeri of the front limbs were replaced in their original mock-up clamps to keep the mounting steady while work continued. There were also usually several safety ropes attached here and there in case of earthquake or other disaster. Most of the remainder of the original pipe clamping system was removed to improve access to the skeleton.

The last step in the completion of the rib cage was now undertaken, to restore the costal cartilages, heretofore only represented by the 1/4-by-1/8 inch steel straps attached together with many 6-32 1/4-inch screws. All of them would need to be covered and built up to suitable thicknesses. The final outer appearance must match the restored cartilaginous filling that had been applied to the sternum unit. I was reluctant to use the Guck material in such thickness as would be necessary, for several reasons. First, a very large quantity would be needed, all of which I would have had to make myself, and which would have added a lot of weight to the display. Second, it would need to be applied in several consecutive coats because the drying time for a thick coat might be excessive and the material very difficult to keep in place without sagging. Third, it is such a frustrating medium that I could not face the amount of work and time that would be necessary. Therefore, I decided to cover the steel straps first with plaster-treated gauze bandage, building up the desired shape and thickness with successive layers until nearly the desired size. The plaster bandage comes in boxes of 12 handy, separately wrapped rolls and is available in various widths. It can be easily obtained at medical supply houses, home nursing stores, or even in some pharmacies. I used rolls in both 2-inch and 4-inch widths and I used several boxes of each.

The remaining thickness necessary to complete the restoration of the costal cartilages with Guck was applied as an outside coat over the plaster bandage and finalized to match the “cartilaginous” filling that I had used on the sternum unit. The tinted Guck was again used and applied with similar artistry (see Fig. 38).

This completes the mounting of the entire post-cranial skeleton.

Fig. 38: Covering of the rib-cage support straps, viewed from inside the rib cage.

The Head: Skull and Mandible

It was now possible to determine the length of the main square support rod needed to support the skull in place. The rod material forward of the sharp bend for the curvature of the neck had been reduced to 3/4 inch square material as mentioned earlier. This part had been left with plenty of extra length so that it could be cut to exact size when that dimension would be known. The plan was to have the beam enter the skull through the foramen magnum between the occipital condyles and extend within the plaster forward toward the nasal opening as far as could be managed without breaking through the surface. This distance was measured to be 12 inches, so the beam was cut with a hacksaw leaving exactly 12 inches extending beyond the atlas, that is the first cervical vertebra. The cut end of the beam was filed smooth and each of the four corners truncated into small triangular surfaces to facilitate entry into the plaster opening.

It would now be necessary to cut a square hole 3/4-by-3/4 inches in cross section, extending 12 inches deep into the plaster of the skull, but *not* breaking through into the nasal opening. The remaining length of the square rod material that had been cut off was used to make a tool for this purpose. With the help of the machine shop at SLAC, it was made into a sort of *broach* to be slowly pounded through the plaster in order to cut a round hole into a square hole [see Fig. 39(a)]. It was planned to start with a 5/8 inch diameter round hole that would then be enlarged to a 3/4 inch square hole. The remaining full length of the square beam material was used, which was 18-1/2 inches. One end was cut down to a 5/8 inch diameter round cross section for 3 inches of length, and this rod given four longitudinal flutings to prevent the buildup of plaster powder in the hole. At the adjoining point, the four corners of the remaining square were truncated into triangles for about 1/2 inch in length.

I modified this tool by hand by cutting roughness with a sharp-cornered file into these triangles and the flat surfaces between them until it resembled a primitive sort of file. It must be remembered that the dental plaster material is quite soft, not abrasive, and could be cut easily with any metal tool. The cutting process was to be carried out by slowly working the broach down into the skull with light taps of a hammer [see Fig. 39(b)]. The 3-inch long round leader would guide the direction of the broach to follow the 5/8 inch pilot hole in the skull.

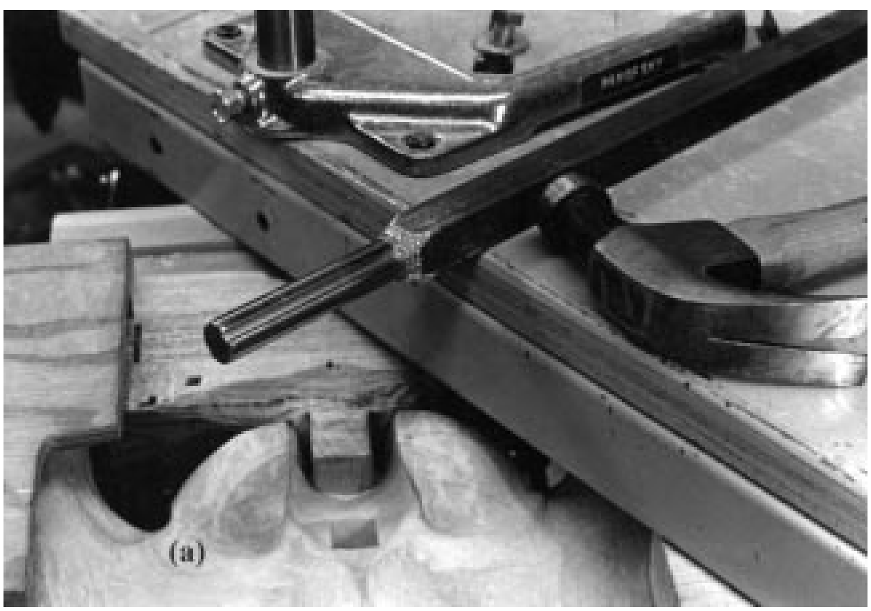


Figure 39(a)

Fig. 39: "Sort of a broach." A home-made tool for cutting the square hole: (a) The broach tool with fluted 3 inch long leader and roughened cutting surfaces, and (b) the broach being pounded into the plaster.

First, the direction of the 5/8 inch drill hole was determined by generating two straight pencil lines on the outer surface of the casting. One of the lines followed the saggital plane on the dorsal surface of the skull, a line easy to determine between the right and left bones of the cranium. The other line was generated on the lateral surface of the temporal arch and the maxillary under the orbit. The skull was then mounted vertically against the leg of the worktable so that the generated pencil lines could be lined up with two plumb lines attached to the drill rig above, as described previously. The skull needed to be very firmly clamped in position for it is quite heavy, weighing a full 50 pounds (see Fig. 40).

The 5/8 inch masonry bit had to be extended by 4 inches in length to provide sufficient length for it to descend a full 12 inches between the condyles. This extension was added by the SLAC machine shop because it was important that it be done well so that the shaft remain straight, otherwise the bit would not run true.

When all was ready, the 5/8 inch hole was successfully drilled to the depth of 12 inches. Then began the tedious process of tapping in the broach tool. This work went very slowly because I was so afraid that the whole skull might crack up with heavy pounding. The tool did cut, however, and it did make a perfect, smooth, square hole. The 3-inch long, 5/8 inch leader guided the square hole true, so bit by bit the square hole was produced. To prevent an excess of plaster dust in the hole, I arranged a narrow plastic hose on the end of my shop vac so that the accumulation of dust could occasionally be sucked out. When the square hole reached 9 inches of depth, I had the shop remove the round leader from the end of the broach, for now the direction of the square hole was well determined so that it would guide the tool automatically. The remaining 3 inches of depth were cut and the square hole completed without breaking through to the outside surface of the cast, nor cracking the plaster of the skull.

Fig. 40: Drilling of a 5/8" pilot hole to 12" deep in the skull cast. View shows clamping of the skull, plumb lines, and lengthened drill bit.

To facilitate the process of sliding the skull cast in place over the horizontal square beam, a rolling trolley having two sets of pulley ropes, about 11 inches apart, was constructed for me [see Fig. 41(a)]. It rolled along a sturdy steel beam of 1-1/2-by-1/4 inches cross section, mounted below the ceiling of the workroom, in a direction exactly above and parallel to the square support beam. Two strong harnesses made from heavy burlap sacking were fitted around the skull casting, one forward of the temporal arches and one posteriorly through the temporal arches. Each harness was attached to one of the two sets of pulley ropes for lifting the skull. When the pulley ropes were being installed, or removed, the skull was rested on a steel roll-cart wheeled in place below the trolley. Then, by successively raising first one pulley hook and the other a few inches at a time, the skull could be lifted to the necessary height and the horizontal angle accurately adjusted and then slipped onto the square beam and pushed into place by one person alone. I felt this to be necessary because the heavy skull would need to be removed and replaced a number of times before finalization.

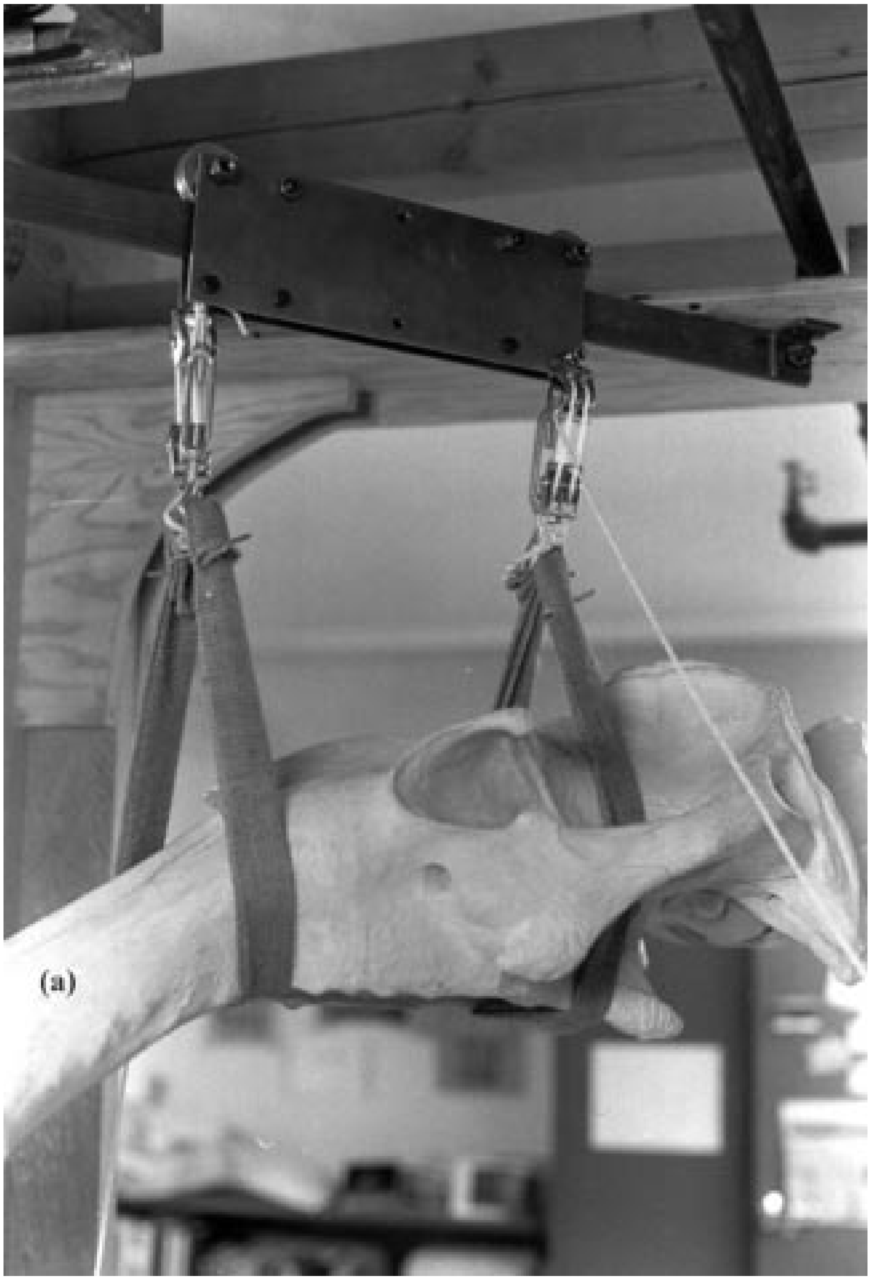


Figure 41(a)

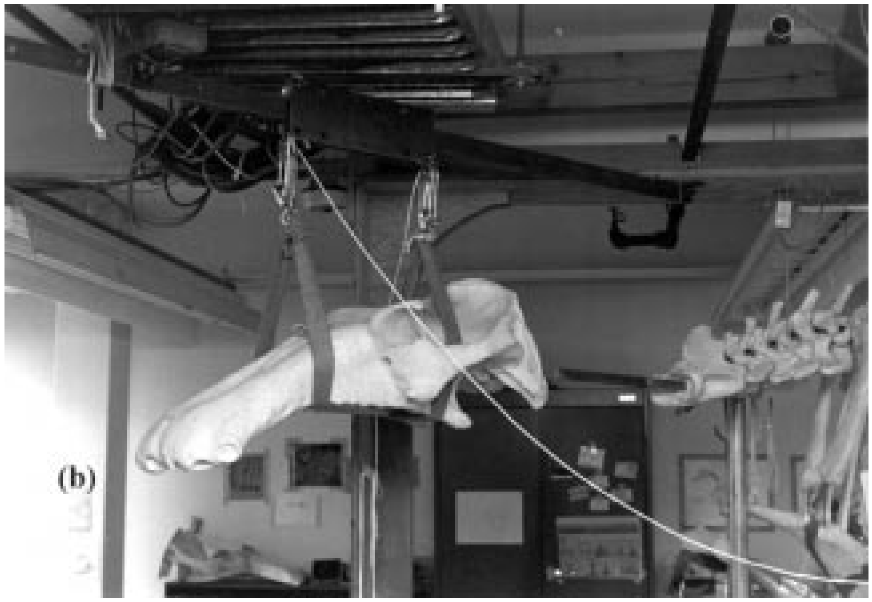


Fig. 41: Pulley trolley for lifting the skull up into place to move it into position on the square beam: (a) Rolling trolley with two sets of pulley ropes and (b) the trolley rolling the skull horizontally onto the square beam.

In order to determine the exact relative positions desired between the right and left branches of the mandible and the skull, it was necessary to see them placed together temporarily. With the skull cast mounted in position on the square beam, the two mandibular casts were propped up temporarily in place beneath it. They were held in the original wooden cradle that had been used to hold them in the mock-up mounting. However, now the wooden cradle could not be supported by the original pipe scaffolding arrangement that had been constructed for it, so it had to be supported on a “Mickey Mouse” construction of blocks, boxes, and shims. The relative positions of the parts of the mandible were maintained in the cradle with small sandbags, blocks of wood, and lots of paper wadding. It was necessary that the right and left mandibular condyles be positioned correctly below their articular surfaces on the skull. The symphysis between the two lower jaws needed to be manipulated so that the condyles and cornoid processes would appear properly placed in relation to the skull. On the left lower jaw, the region of the symphysis is more or less completely preserved and no adjustments could be considered, but the right lower jaw, being a restoration, then received some whittling by pocketknife to improve these relationships. It was also possible to make small changes to the glenoid fossae, which are the mandibular articulations on the skull, because the skull is also a complete restoration.

When the three pieces appeared to be in a satisfactory relationship to each other, a method was devised to make a jig that would maintain these positions so that the two lower jaws could be prepared to be joined together and reinforced in the final desired relationship. The jig needed to be formed to fit the ventral surfaces of the pieces so that each, or both, of the jaws could be set down in it. However, the ventral surfaces were not available while the two pieces were propped in place in the wooden cradle, so it was necessary to first create a jig over the available dorsal surfaces. When this would be made, the two casts could then be removed from the temporary propping and placed upside-down in this jig to maintain their relative relationship. The ventral surfaces would then be exposed and a second jig manufactured. These jigs were made from plaster gauze bandage, as used before, and reinforced as needed with pieces of wood. The two mandibular casts are quite heavy and could distort the plaster jigs to some extent, so plywood frames were built in which the jigs are placed to prevent minor variations of the relative positions.

It had been decided that the rather heavy complete mandibular unit should be engineered to attach directly to the central square support beam on which the skull is also supported. To accomplish this, an apparatus was designed that would both reinforce the assembled mandibular casts and also hold the mandibular structure in place below the skull by attachment to the central square beam through the skull casting. This apparatus is shown in Fig. 42, as described next.

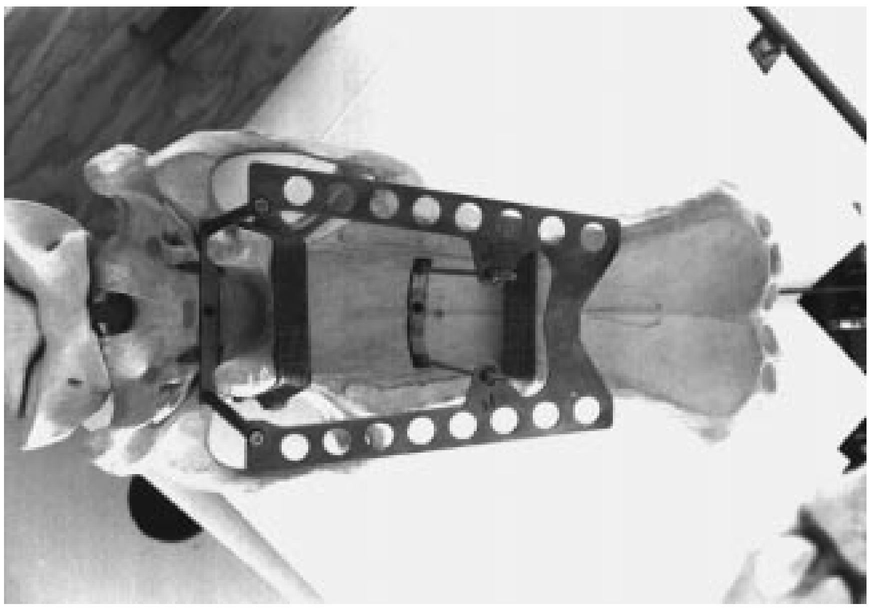


Fig. 42: Mandibular supporting apparatus shown bolted through the skull cast, minus the mandibular casts.

A large steel reinforcement plate, designed to be inserted within the body of the assembled mandibular casts, is basically U-shaped, machined from 1/4-inch thick, cold-rolled steel, and is large enough to extend through the entire length of the dentaries and well into the symphyseal region across the front. However, the depth to which this reinforcement plate could be extended inside the anterior horizontal ramus of the left half of the mandible is limited by a broken-out section along the ventral part of the symphysis that forms the alveolus of the first incisor tooth. There is also some breakage to the second incisor alveolus. Therefore, the steel reinforcement plate is designed to extend deeper into this horizontal ramus in the lateral regions of the third incisor and tusk alveoli. Incorporated in the design are four “ears” approximately 1-by-1 inch in area, rounded without corners, that extend medially into the area of the mouth. These “ears” each have a 1/4-inch diameter hole drilled through for the attachment of the two supporting steel yokes that suspend the completed jaw unit from the skull support beam. The plate tapers from about 11 inches wide posteriorly to 7 1/2 inches wide at the anterior end, and is 13 inches long overall. Some larger circular openings are cut through the plate to minimize weight, yet not so large as to weaken it.

Two 1/4 inch wide slots needed to be routed horizontally into the thicknesses of the right and left branches of the mandible, and it would be a great deal easier to do the routing before the two casts would be plastered together at the symphysis, to maintain access to the deep-seated regions of the cuts. The directions of the two routings needed to extend in the same flat plane within both pieces when they would be in the correct spatial relationship to each other.

To begin, the two jaw casts were placed upright in the second specially made plaster jig holder, and a stiff corrugated cardboard form was cut and trimmed to fit between them at the desired horizontal level for the slots. Using it as a template, two straight pencil lines 1/4 inch apart were drawn along the medial surfaces of the two casts. The routing was done by hand with a 1/4 inch wide wood-carving chisel, only very shallowly in the beginning. Each cast would be removed individually for the actual cutting process. The two slots were deepened at the posterior end sufficiently to permit the entry of the anterior part of the steel plate for a short distance. Using blue chalk rubbed along the outer edges of the plate, it was possible to gradually deepen the two slots working forward bit by bit by scraping away the chalk-marked plaster. Each cast would be removed for the cutting process and the two would be replaced in the jig for the testing operation and successive blue-chalk marking. Thus, little by little, the slots were cut.

When the deep areas within the horizontal ramus were reached, the 1/4 inch chisel, with 4-inch long shank, was too short to continue the routing. An extensive search of hardware stores and tool suppliers failed to find a 1/4 inch chisel with a longer shank. Such a thing is not made because the usual materials cut by a chisel are much harder than dental plaster and so require adequate strength in the shank, which must neither bend nor break. Therefore, it was necessary for me to have a 1/4 inch screwdriver, with a 7-inch long shank, modified into a sort of chisel. Although somewhat awkward to use, this served the purpose sufficiently well and the slots were satisfactorily cut (see Fig. 43).

Next, two yokes were designed to mount the 1/4 inch steel plate to the square beam through the skull. When the steel plate is inserted in the casts from the rear forward to the full depth of the prepared slots, the four attachment “ears” protrude into the mouth cavity, two of them forward near the symphysis, one right and one left, and the other two at the right and left rear, inside the angles of the jaw. The two yokes bolt directly onto the central square support beam through holes routed through the plaster of the skull cast. The beam, it will be remembered, extends forward by a full 12 inches down the center line inside the skull, so the most advantageous positions for the attachment of the two yokes could be easily located. Because the skull casting is quite thick, the yoke fixtures could be planned to insert up into the plaster and thus be essentially out of view. There are two important advantages to this design. The first one is that the weight of the heavy mandible assembly is directly supported on the main structural support beam and not on the plaster of the skull cast. The second advantage is that once the mandible unit is bolted through the skull into the beam, the skull can no longer slide off; it is permanently in place. However, if necessary, the mandible can be readily detached by removing the two bolts and the skull then removed and replaced when necessary. (These yokes can be seen in Fig. 42 and Fig. 44.)

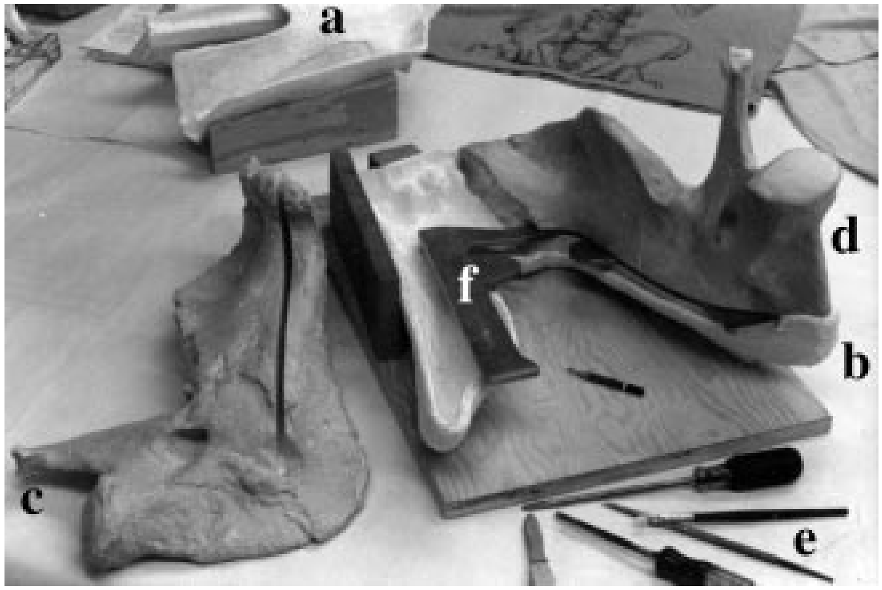


Fig. 43: Method of cutting the two slots in order to make them both delineate the same plane of orientation, using a screwdriver as a chisel for the deeper regions: (a) The first plaster jig that holds the mandibular casts ventral surfaces up; (b) second plaster jig for holding the mandibular casts dorsal surfaces up; (c) left half of the mandible removed from the jig so that the groove is available for cutting; (d) right half of the mandible held upright in the jig, and the groove being tested for direction and depth by the insertion of the steel reinforcing plate; and (e) the various tools that were used for cutting the slots.

Each yoke consists of two upright rods joined at the top by a laterally oriented crossbar that incorporates a sturdy socket for attachment to the 3/4 inch square central beam within the skull. These sockets are positioned centrally along the crossbars. The crossbars connect to the exposed “ears” of the mandibular support plate by suitable lengths of 1/4-by-20 threaded steel rod at each end. Thus, the two anteriorly placed ears support the anterior yoke that extends upward through a routed opening in the skull palate to reach the square beam. The two posterior ears support the posterior yoke similarly by two lengths of 1/4-by-20 threaded rod. That yoke reaches the square beam through the basioccipital of the skull, shallowly routed out through its ventral curvature to expose the square beam. (See Fig. 42 on page 85.)

The two sockets for these yokes are designed similarly to the one used for the attachment of the front limb armature to the square central beam. They are machined from cold-rolled steel stock, as are the two crossbars, and are thick enough to fit up exactly against the square beam when the crossbars are inserted to the depths of the routed slots. Each is machined to have 1/16 inch wide and high lips bordering their lateral edges to hold the yokes well in place against the beam.

The crossbar for the anterior yoke is 5/8 inch wide and about 1/2 inch thick, and is curved in an arch to conform to the curvature of the palate. It is designed to be embedded within the skull cast reaching up to fit snugly against the square beam so that its lower curved surface is flush with the surface of the palate. The socket is firmly brazed in place onto the crossbar, so that together the overall height of the bar and socket is about 2 inches.

The crossbar of the posterior yoke is flat, 8 inches long, and rests up against the skull cast directly forward of the ear bones. It is routed into the plaster only across the curvature of the basioccipital. This crossbar has a cross section of 5/8 inch wide by 5/16 inch thick, and with the socket brazed centrally on its dorsal surface it totals 3/4 inch in height to fit firmly against the square beam.

Both the anterior and posterior yokes are drilled vertically through the entire thickness of the socketed fixture and countersunk through their centers to accommodate a long 1/4-by-20 Allen-head bolt. Then, with the two yokes held in their final desired positions, the square beam was drilled through vertically with matching holes and tapped for the 1/4-by-20 bolts.

To complete the yokes, both crossbars are drilled through at each end and countersunk for 1/4-by-20 bolts. Each is provided with a suitable length of 1/4-by-20 threaded steel rod instead of bolts, and these rods are long enough to reach down through the exposed “ears” in the mandibular support plate when it is inserted in place. The threaded rods on the anterior yoke hang vertically, attached by hex-nuts from above, and are tightened with small lock-nuts under the bar. These rods are about 9 inches long, extend down through the drilled “ears” of the support plate, and are held on with nuts on the underside of the “ears.” When the mandible is assembled on the plate, the assembly can be adjusted to the most desirable position by screwing the lower nuts up or down the threaded rods protruding below it. The skull cast was removed from the mounting during the routing process, and the long square shaft of the broach tool inserted into the square hole in place of the actual beam to permit making an accurate fit between the square beam and the supporting yokes and sockets (see Fig. 44).

Fig. 44: Detail of supporting yokes with mandible assembled in place, seen from below.

The threaded rods on the posterior yoke descend from positions anterior to the auditory bullae, but must spread laterally to reach the posterior “ears” of the mandibular reinforcement plate. The holes at the ends of this yoke bar are countersunk spherically and are sufficiently oversized to allow the threaded rods to pass through them at an angle. The lower openings of the two holes in the posterior ears of the reinforcement plate are also countersunk spherically. Acorn-style nuts are used at the upper and the lower ends of the 1/4-by-20 threaded rods that attach the posterior yoke to the plate so that the spherical surfaces can rest comfortably in the countersinkings. The two lengths of threaded rod are about 7 1/2 inches long, and their sections that pass between the upper yoke and the reinforcement plate below are covered with carefully measured, close-fitting lengths of 1/2 inch OD steel tubing. The angles of the top and bottom openings of these tubes are hand-filed to fit perfectly against the steel reinforcement surfaces to prevent undesirable rocking of the acorn nuts in their respective countersunk holes. The use of the acorn nuts in the spherical countersinkings permits the threaded rods to descend from the yoke at their most comfortable respective angles from the vertical. These angles are intrinsic because the width between the posterior angles of the right and left sides of the mandible is some inches wider than the width across the back of the skull between the coronoid processes. Each rod descends in its own best direction and so their angles from the vertical are not exactly symmetrical. This means that the nuts must be tightened up on the threaded rods until the covering tubes on each side fit correctly against the upper and lower steel surfaces between which they reside and so adjustments to the length of the posterior yoke may not be made.

When all this fitting was satisfactorily accomplished, the two halves of the mandible were plastered together at the symphysis with the reinforcement plate inside the slots, making the reinforced mandible into a permanent single unit. The plastering process needed to be very thoroughly planned in advance to ensure that the three parts, two casts and the steel plate, would go together exactly as desired with the steel plate firmly sealed inside the slots and the two casts in their exact proper relationship. Two people would be required, because it would be necessary to work fast while the plaster began to set up. My 18-year-old granddaughter, Catherine Panofsky, and I made this team and we succeeded without hitches on the first try; however, it took us one full day to complete. Care was taken to properly soak the casts in water sufficiently long that no more air bubbles were escaping and to apply a sufficient amount of wet plaster to fully bond the reinforcement plate within the depth of the slots. The first plaster bandage jig made over the dorsal surfaces of the mandibles was used to hold the assembly in position while the plaster was setting up. This arrangement allowed us to restore the new plaster surfaces and clean up all drips and smears of wet plaster all around, especially in the symphyseal region where some artistic restoration was also necessary. Unfortunately, no photographs could be taken of this important phase of the project for it was not possible to pause long enough to make a photographic record.

Subsequently, the two yoke assemblies were mounted and adjusted in place to their most desirable position, thus completing the mandibular unit for the display. All these exposed metal parts are painted an even dark brown to blend with the coloration of the display. Model train lacquer paint, color "Roof Brown," was used on all exposed metal.

The Hyoid Arch

Except for the teeth and tusks, the last remaining structure belonging to the head assembly was the hyoid arch. Repenning had felt that this part should also be restored for completeness of the mounting. As mentioned earlier, I had made some investigations into the variations and general configurations of the hyoid structure in a number of extant herbivores, namely horse, cow, pig, elephant, hippo, manatee, and others. I used the originally cast hyoid elements, most of them moderately or extensively modified, and also cast several more parts for each side, right and left. These were assembled in the usual way with short aluminum pegs plastered into adjoining holes. Many of the pegs had to be bent at the joint, and all was assembled on a temporary jig formed of styrofoam blocks. Once assembled according to plan, another temporary propping arrangement was devised under the skull with the mandible in position in order to see the assembly in place and to plan the method for its attachment. At this point, I noticed that this configuration of the hyoid structure would severely restrict the opening of the throat, because it was descending centrally between the large pterygoid processes. That would never do, so it was necessary to revise it again. The two stylohyoid elements were then interchanged, right and left, and more modifications were made to most of the other elements. The epihyoids had to be remade in entirety. This second revision allows the assembled arch to be positioned laterally to and somewhat behind the pterygoid processes, leaving the throat opening unencumbered.

It was then decided that the hyoid arch assembly should not be permanently attached to the skull, as in life, but should be held in place with screws. It would need to be removable and replaceable because otherwise this vulnerable structure would be seriously hampering when the skull or mandible would need to be removed for preparation and installation of the teeth or any other necessary operations. In life, the hyoid arch has cartilaginous attachments from its proximal tips to the ventral surface of the skull directly anterior to the auditory bullae of the ears. However, it was possible for us to arrange that the proximal tips of the arch would connect to the skull in the correct position, but to actually support it there with two specially designed metal fixtures that attach with screws to the crossbar of the posterior yoke of the mandibular support structure. These two little fixtures are individually designed to fit on the right and left end of the support bar. At each end of the bar, directly medial to the descending element of the mandibular support yoke, a hole was drilled through and tapped for an Allen-head 6-32 screw by which the bracket is attached to the bar. A small bracket with a 90° bend was then machined for each end, their exact shapes and angles predetermined in place, with hand-formed, sheet-aluminum patterns. As the right and left sides of the mandible are not exactly symmetrical, nor is the skull, the hyoid arch and its support fixtures can also not be exactly symmetrical. Each little support fixture is therefore unique to its position.

These two fixtures each consist of a small cylindrical yoke made from 1 inch OD steel tubing 5/8 inches long, and cut in half longitudinally [see Fig. 45(a) and (b)]. Two halves of one tube fit around the proximal neck of each stylohyoid cast. They are connected together through centrally positioned holes in all three pieces with a 6-32 machine screw 2 inches long. To provide a stable connection for this long screw one end of a short length of steel rod is securely welded to the center of the anterior half of cut tubing, and the subsequent drilling and tapping done through their combined length. This hole also continues through the stylohyoid cast and the other half of the yoke. The fixtures are assembled around the necks of the stylohyoids on the long screws from the posterior surfaces, and secured to the 90° brackets with star washer lock-nuts. Details of these little yokes are shown in the accompanying photograph. When all parts are properly in place, the proximal tips of the two stylohyoids, painted as cartilage, fit directly up to the base of the skull anterior to the auditory bullae, as planned, and the metal yokes and right-angle brackets are painted Roof Brown.

Except for the teeth and tusks, the assembly of the skeleton was now complete.

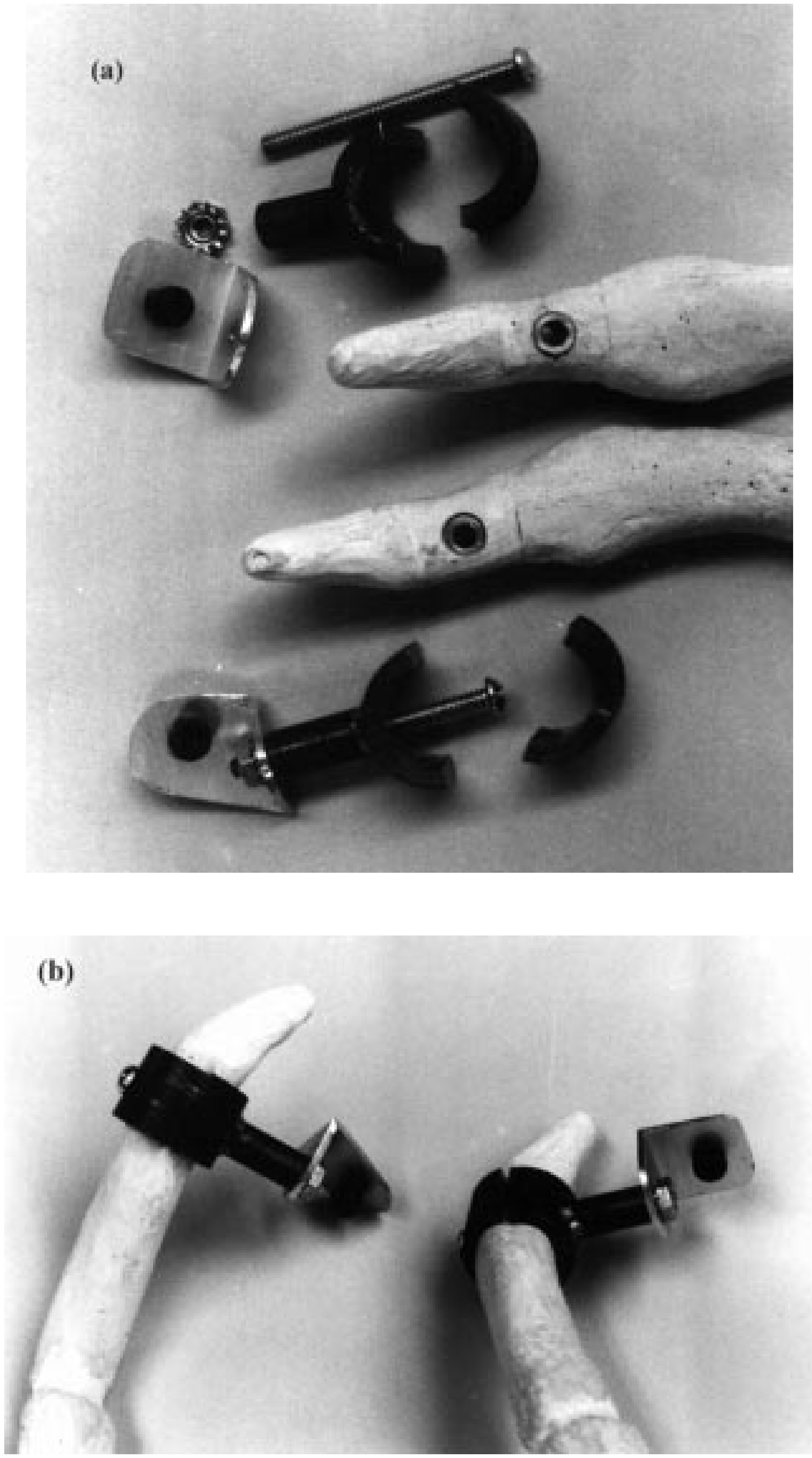


Fig. 45: Hyoid arch—two views showing the small fixtures constructed to support the hyoid arch in place: (a) Elements used in the stylohyoid fixtures and (b) the fixtures in place on the stylohyoid casts.

The Hanging Test

An essential operation for the completion of this mounting I have called "the hanging test." The purpose of this procedure was to learn if, and how, the completed skeleton mounting would hang when supported only by the two aircraft cables from above. To that date, April 19, 1989, the mounting had never been completely released from all the original temporary support clamps, because even after the final assembly one bone of each limb had been returned to its support clamps for stability and security. Neither myself nor engineer John Flynn had complete confidence that the skeleton would not dip to one side or one corner when released, or perhaps just droop from the weights of the extremities. If such results would be discovered during the test, more engineering would be needed, such as the addition of concealed compensating weights, or perhaps extra guy-wires from each drooping limb to the ceiling.

In order to have sufficient manpower on hand in case the test would uncover any serious difficulties, we invited four extra people to participate, one to manipulate the release of each limb. John Flynn directed the crew and I was the (nervous) observer watching for possible difficulties. Fortunately, all went well, and in about 1 minute the skeleton settled into a nice, relaxed, slow-motion swimming position, actually nicer than it had appeared when clamped. The hanging test was a success! However, safety ropes were reinstalled after the test to prevent the display from swinging around during work on it and also as a precaution against a severe earthquake.

Painting

The original Stanford *Paleoparadoxia* fossil bones are brown. However, the brown coloration varies from bone to bone and even some individual bones show some variation of the general color from one area to another. There is also a good deal of rusty discoloration on the surfaces, from dark red-orange to yellows. I felt that this variation in the surface coloration was one of the most important factors for distinguishing the specimen as actual fossil bone material. For this reason I decided to paint the plaster casts in such a way as to simulate the variable colorations on those casts of the actual fossil bones. As the casts of the restorations did not have a truly bony-looking surface, I felt it would be better to paint them without any of the rusty staining, which would have the advantage of indicating to the more observant viewers which elements of the fossil were recovered and which had been restored for the display.

Some of the variation in the coloration of different bones was related to the preparation of the fossil. Those bones that proved more fragile needed more or different hardening applications, or glue, and so appear darker or lighter, more glossy or more chalky, etc. It was necessary to settle on one shade of brown for a base color that would approximately match some of the least discolored, better preserved areas of the fossil specimen. I had decided to paint the entire skeleton in this base-color brown, and I determined that it would be easier to copy the rusty discolorations directly from the actual bone specimens than to try to simulate them without any reference. The casts of the restorations would then remain the base-color brown without rust.

The brown color was finally matched to a smooth, evenly-colored area on the ventral surface of the sacrum. The paint used is a water-based acrylic artist paint and is mixed by a reproducible formula from determined proportions of raw umber, burnt umber, raw sienna, and titanium white. The paint was mixed with water to a quite thin consistency to facilitate spreading so that an even, smooth coat could be applied without buildup of texture; however, it was always necessary to apply at least two coats to achieve an even color.

Four more colors were prepared and used to indicate the rusty discolorations. First a smaller amount of the base-color brown was separately mixed with an additional measured amount of titanium white to produce a rather light grayish color, which was needed to rub over some more chalky-looking surfaces and to accentuate surface cracks and blemishes. Then, two rust colors were mixed: one more yellowish from yellow oxide, raw sienna, burnt sienna, and titanium white in specified proportions; and one more orangey of raw sienna only, thinned with water. A small amount of a very dark brown color was also used in a few places that had rather blackish stains of either a mold or manganese oxide. This color was mixed from the base-color brown with black paint added. The use of this limited "palette" of colors in various combinations of mixtures has given the finished skeleton a uniformity of coloration along with the appearance of a real fossil.

Because I have access to the Stanford *Paleoparadoxia* specimen in the UCMP collections in Berkeley, it was arranged that I could take out on loan a few elements at a time so that their actual colorations could be directly copied in my workroom at SLAC. The first bone borrowed was the left ulna. I used the somewhat damaged but nearly complete left ulna cast that I had kept after the serious breakage of the left front limb on which to practice and develop my technique. When I was satisfied with the result of this attempt, I commenced the actual painting process on the display.

Even though the *Paleoparadoxia* seems to be a very large animal, for which a great deal of paint and large paint brushes would be necessary, I found that in fact the paint spread evenly in very thin coats and so did not require large amounts; big brushes did not give as satisfactory results as small ones. The time-consuming part of the application of the base-color brown, always put on first, was getting the paint to completely cover the numerous cracks, indentations, micropores, roughnesses, and other complicated surfaces, all of which required small brushes. The tiniest little brush I could get received the most use and had to be replaced several times before the painting was completed.

It will be remembered that the steel support rods inside the limb bones are secured with 1/8 inch diameter locking pins that pass all the way through the pieces. These had been left oversized, so that assembly or disassembly could be done in case of need. I found that it was much better to remove each foot in turn for painting because the feet, more than any other part, have so many hard to reach surfaces. It was fortunate that the locking pins were still available. However, once the foot would be painted and replaced on the mounting, it would be necessary to finalize the limb by cutting each locking pin down to about 1/8 inch too short so that it could be concealed inside. As mentioned earlier, I had taken the precaution to make a detailed photographic record of the placement of each locking pin. In many cases the originally inserted pins were slightly bent or rusty so entirely new pins were made to replace those. When the pin would be inserted within the surfaces, the two holes would be filled with Guck and any surface details restored. The painting process could then proceed.

The following process that I generally used can be described in the following steps:

1. The actual fossil bone specimen that I had on loan would be arranged in a padded box lid or styrofoam tray (such as are used in shipping typewriters, computers, etc.) and placed close by so that it could be referred to continuously.

2. The plaster piece would receive the base-color brown paint in as many coats as necessary to attain a smooth, even, brown cover. This would require several coats overall but each coat would dry in a few minutes so that time would not be lost between coats. However, the paint resisted entering small cracks and openings, so all of those needed to be individually treated with very small brushes. This process was the most time-consuming phase. It was necessary to shine light on the piece from as many angles as possible in order to detect all the small indentations and crevices that had been missed.

3. When the base-color was judged to be satisfactory, the lighter brown color would be applied as determined by inspection of the actual specimen. On most of the real bones there are some areas of the surface that have a whitish or chalky sheen. To simulate this coloration, the light brown paint could be lightly rubbed over that surface with the fingers. Also, many of the surface cracks on the real bones appear grayish due to remnants of matrix within. All of these would then be painted on the cast with the tiniest of watercolor brushes. This delicate detail work produces a very effective realism. Some other cracks and openings, however, appear very dark on the actual fossil bones, so in those cases the reality was enhanced by the contrast between dark base-color brown in the equivalent cracks of the cast highlighted by the chalky sheen of the surface.

4. Next, attention was turned to the areas of yellow rust. These vary on the specimens from light yellow gold to a quite bright golden yellow stain, which usually appear on the well-developed muscle attachments and joints, particularly those that exhibit the osteo-arthritic over-developments. There are also some surface areas that have a golden sheen instead of a chalky one. The yellow rust color would be lightly rubbed over these surfaces to simulate that effect. Yellow rust patches were applied to all the rusted spots, small and large, and on any of the actually rusty-looking areas on the fossil except those that appear truly orange. Frequently, there were narrow cracks that required the yellow color rather than the light brown, which was applied similarly with the tiniest 5-hair watercolor brush. This method does not distinguish between light yellow and bright yellow, but the overall effect of realism is maintained because the entire restored skeleton has a more homogeneous coloration than the actual individual fossil elements. In a few spots a slightly greenish tinge was needed, which was simulated with a mixture of the light brown and the yellow rust paints.

5. The orange rust was usually applied last to only those spots, areas, and cracks that appear truly orange on the fossil bones. It was sometimes quite difficult and even arbitrary to decide if a certain spot should be yellow or orange, in which cases “artistic license” could be resorted to.

6. Any black stains could be added if necessary, using the very dark brown.

Even though these processes sound very painstaking and tedious, they have given extremely satisfactory results overall. The water-base acrylics provided a number of advantages:

- No solvents, and resulting fumes, were needed.

- The paint itself dries to a smooth film of acrylic plastic as the water evaporates. Any additional coat or retouch seemed to be instantly embodied into the original plastic film and so never left a trace of overlap or brush marks. This permitted infinite patch-up and retouching.

- The paint is opaque, allowing the making of changes by painting over any previous work.
- Even though some colors will settle out to the bottom of a mixture and others float to the top surface (some pigments are lighter, some heavier), once the paint has been thoroughly stirred the color will be the same as when first mixed. The mixed colors are stable.

Most of the skeleton was painted while assembled. However, it proved much easier to do the feet each as a separate unit removed from the assembly. In this way the mounted foot could be supported on a padded surface and turned in any direction as needed to reach down between the toes and the separate ankle and wrist bones. The other elements that were removed from the mounting for painting were the skull and the mandible.

To reach the high upper surfaces of the vertebrae, the scapulae, and the pelvic elements, I had the use of several step stools and the remnants of the original mock-up scaffolding. These aluminum pipe units were remaining from the forelimb supports, one on the right and one on the left, giving a sturdy foothold to raise me above the fore-part of the skeleton. The skeleton was also lowered by 6 inches, accomplished by adjusting the lengths of the two supporting cables with the specially designed cable clamps previously described. This adjustment in the overall height made it possible to see and reach all the dorsal surfaces.

Teeth

Repenning and I ultimately decided that it would be best to restore *all* the teeth as accurately as could be determined, even though hardly a vestige of the teeth had been recovered with the fossil. There was one incisor fragment with a preserved naturally worn occlusal tip found in association with the fossil, and the complete tusk root still remains in the left half of the mandible. There is also the complete root of the anterior-most premolar remaining in the mandible and all molar and incisor alveoli are also preserved. Thus, quite a lot of information about the dentition was available from the specimen itself (see Fig. 46).

Fig. 46: Stanford *Paleoparadoxia*, left dentary in medial view, 1/4 times natural size. Preserved portions of canine and of P-1 crosshatched.

Dr. Henry Jones of Stanford Medical School, Radiology Department, very kindly made some very nice x-ray photos of the mandible, and also of the left half of the mandible from the Point Arena *Paleoparadoxia* specimen mentioned earlier (see Fig. 47). From these x-rays we were able to see and measure the width and depth of each alveolus and know the exact number and positions of all the teeth. There are only five *Paleoparadoxia* specimens about which I have any knowledge that have teeth in place, and only two of these can be considered to have the complete dentition preserved, which are the Izumi *Paleoparadoxia tabatai*, and the skull specimen from Santa Barbara, California. However, there are also a number of isolated tooth specimens in various collections, and I was able to locate and obtain casts of 29 of these. My original hope was to locate enough isolated tooth specimens to be able to choose among them a tooth for each molar position. However, I discovered that there is a great deal of individual variation, in size especially, but also in the number of cusps developed, the amount of cingulum, and amount of wear, evident in my available selection. I soon realized that it would not be possible to fill every molar position with a real tooth cast.

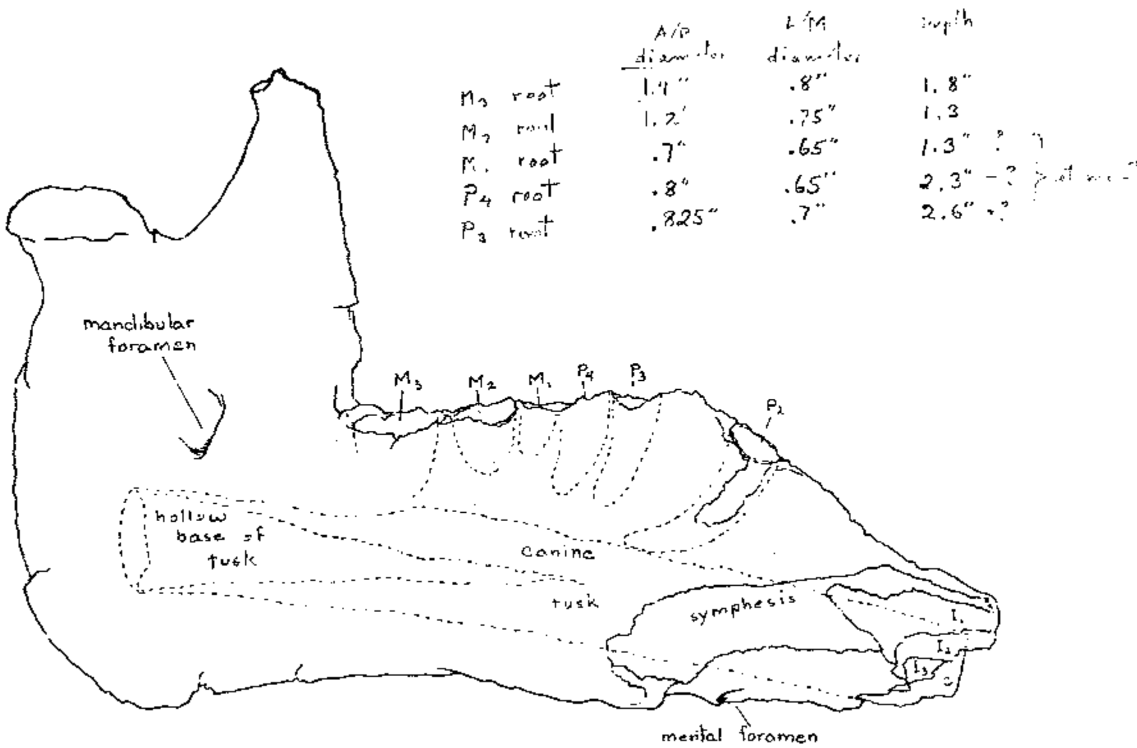


Fig. 47: Stanford *Paleoparadoxia*, left dentary in medial view, 2/5 times natural size. Broken lines indicate position and extent of the preserved dental features as revealed by x-ray photographs.

My best available choice for incisor teeth and the canine tusks was to modify the plaster-cast blanks that I had made originally. For the incisors I could use several fragmentary incisor specimens that were available, to determine the configuration of the terminal wear surfaces and coloration. Of the five *Paleoparadoxia* specimens with teeth in place, three have more or less complete canine tusks preserved from which I could have the necessary information for restoration of the four tusks.

The dental formula for *Paleoparadoxia* is 3-1-3-3-/3-1-3-3. Only one premolar is suppressed from the complete mammalian formula, which I consider to be the P-1 in both upper and lower jaws. There is a long diastema in each case, between the anteriorly projecting canine tusk and the beginning of the molar tooth row, which leads me to the above conclusion. However, this view is not universal among all of the paleontologists that have studied these animals. I shall refer to the teeth that I studied and restored according to that formula for consistency in this document, which means that I considered the necessary tooth positions to be filled to be: I-1, I-2, I-3, C-1, P-2, P-3, P-4, M-1, M-2, and M-3, in each of the four quadrants.

The five *Paleoparadoxia* specimens with preserved teeth in place that were available for my research are described in the Systematic Paleontology, page 6–7, and are again listed here.

1. The Japanese “Izumi” specimen, *Paleoparadoxia tabatai* (NSMT P-5601), fiberglass casts that reproduce the complete dentition as preserved.

2. The “Point Arena” specimen, *Paleoparadoxia weltoni* (UCMP 114285), in which many of the molar teeth are preserved in place.

3. The “Reinhart” specimen, *Paleoparadoxia tabatai* (UCMP 40862), a partial right mandible. The specimen, of which I have only seen casts, contains the complete canine tusk, complete M-3, and the root of M-2 without crown.

4. The “Mission Viejo” specimen (LACM 131889), recently discovered in Orange County, California, consists of the complete right half of the mandible with complete tusk and molar dentition in place. Only the central section of the left side of the mandible, poorly preserved but with P-2 through M-2 more or less in place, was found. Some lower incisors were recovered in association. Several isolated upper teeth are also preserved.

5. The “Santa Barbara” specimen has recently been transferred from the Santa Barbara Natural History Museum to the University of California Museum of Paleontology on permanent loan. It has been assigned the collections number UCMP 147527. The preserved dentition is probably complete but not all was sufficiently well prepared to have been 100% useful for my research.

My assemblage of isolated *Paleoparadoxia* teeth was collected over the span of the 20 years of this project, coming to the final total of 29 separate teeth. At first, when my collection was still small, I could not even distinguish upper from lower, or left from right, among my selection of cheek-tooth specimens. I finally came to understand that, in general, the lower cheek teeth of mammals are oblong with the transverse measurement the narrower, and the upper cheek teeth are more round. The basic reason for this difference is that the upper and lower cheek tooth rows terminate posteriorly at the approximate same posterior position. However, the lower cheek teeth occlude anteriorly to the uppers in the premolar region, and the lower canine is always positioned anterior to the upper canine when the mouth is closed. This means that the lower cheek tooth row must be somewhat longer than the upper. With this in mind I was able to see that the lower molars were those having a longer and narrower outline with two parallel rows of cusps, and the upper molars were those with cusps arranged in a more or less circular pattern.

When preparation work on the Santa Barbara specimen had proceeded sufficiently to reveal the occlusal surfaces of the preserved molar teeth, I could see these details more clearly. Particularly helpful was the removal of the preserved lower M_3 from its original position as fossilized in the palate of the specimen, where it had fallen from the lower jaw prior to burial, so that it could be manually held and manipulated in occlusion with the upper molars. This tooth had been cut away from the palate of the specimen with a very thin rotary diamond cutting blade by Repenning. A small part of the preserved bone of the palate was necessarily destroyed in this process, but the advantageous gain outweighs the loss. This tooth could then be molded and cast, making a valuable addition to the collection of isolated tooth specimens. However, it could not be considered for use in the Stanford *Paleoparadoxia* display because of the disparity in sizes between the Stanford and Santa Barbara specimens; it would be too large.

In October of 1977, while attending the Society of Vertebrate Paleontology annual meeting being hosted by the Los Angeles County Museum, I took the opportunity to visit the LACM Collections in search of isolated *Paleoparadoxia* teeth. I was fortunate in finding four specimens listed, three of them being beautifully preserved molars, and one caniniform premolar. I was allowed to borrow these specimens for the sole purpose of molding and casting, with the understanding that after making casts for our Stanford restoration project, the specimens and also the rubber molds would be returned to LACM. These three molar specimens became an important addition to my collection, and two were used in the final display. At the time when I had the specimens in my possession I made several casts of each tooth so as to have extras. I then took the precaution of painting one cast of each to match its original as closely as possible. In this way I retained the exact appearances of the specimens for later reference.

The Museum of Paleontology at the University of California, Berkeley, originally made rubber molds for me of five *Paleoparadoxia* cheek teeth in the UCMP collections, and much later three more isolated molar specimens were located there that I was allowed to have on loan for molding and casting. One more was located in the NMNH Collections of the Smithsonian Institution in Washington, D.C. At this point, I had a total of 14 cheek tooth specimens.

Much later I made the acquaintance of Frank Perry, who does preparation, curation, and display work for the Santa Cruz City Museum in Santa Cruz, California. Through him I acquired casts of 15 more recently collected *Paleoparadoxia* molar specimens, a number of which were also used in the final display. In nearly every case some slight or significant modifications needed to be made on the casts that were used in order to conform to the size and state of wear necessary for a realistic fit. These modifications will be described later.

In January of 1990, Dr. Lawrence Barnes, Curator of Vertebrate Paleontology at the Los Angeles County Museum, kindly invited me to spend a day or two there to view and photograph the recently discovered Mission Viejo specimen with the understanding that I would only use the information thus gained to help me understand *Paleoparadoxia* dentition for the sole purpose of the restoration work of our display, and not ever for original publication on my part. He gave me to understand that the specimen had been promised for study and publication to a prominent marine mammal paleontologist at another institution.

At the Los Angeles County Museum, Larry Barnes assigned me to a large, well-lighted work space and provided not only the prepared Mission Viejo specimen, but also the casts of all

Paleoparadoxia specimens that have teeth preserved in place that happened to be in the LACM Collections. This included all but the Santa Barbara specimen, which was then in my laboratory at Stanford, and which has never yet been cast. This arrangement allowed me to make valuable comparisons and a quite complete set of photographs for future reference. Table 1 lists all the above isolated cheek teeth and indicates their provenance, most likely position, and other descriptive details. Table 2 lists the five skull and/or mandibular *Paleoparadoxia* specimens with preserved teeth in place, describing all of those teeth in a similar manner. Further comments, relevant details of appearances, abnormalities, and comparisons are listed below, in the same order as the specimens are described in the two tables.

1. UCMP 32076. This tooth was discovered at Monocline Ridge in Fresno County, California, in 1933 or 1935, by V. L. VanderHoof. The deposit contained about 200 *Desmostylus* teeth, along with this one molar tooth that was obviously different. For that reason VanderHoof did not include it in his 1937 publication on *Desmostylus*. Twenty years later, Roy H. Reinhart recognized the similarity of this specimen to the preserved molar in another specimen, labelled UMCP no. 40862, the right half of a mandible recovered from the Santa Margarita Formation in Santa Cruz County. In his 1959 publication he described these two specimens, giving them a new genus name, *Paleoparadoxia*, and designating UCMP 32076 as the type specimen.

2. UCMP 11371. An upper right third molar was also discovered by V. L. VanderHoof at the Bean Creek locality in Santa Cruz County in 1940. A significant scrap of the bony palate remains attached to this specimen so that its actual position in the upper tooth row is determined. The occlusal surface has been worn nearly to the bases of the cusps, proving it to have belonged to an older animal of moderately large size.

3. UCMP 81857. A fairly small lower molar crown without preserved root. Only the three anterior cusps have some wear, the two posterior cusps being unworn. The exterior surfaces of the cusps and the complete cingulum are still deeply sculptured all the way around, indicating very little wear during life. I have placed it as a good candidate for a right lower M_2, permanent or deciduous. It is comparatively small.

4. UCMP 64117. This small tooth from the Bean Creek locality retains only one of perhaps three tightly appressed cusps that would have originally formed the crown. Some length of the single long root is also preserved so that its original extent of crown can be estimated. The one remaining cusp is worn down until a small circular “lake” has developed at the center, demonstrating moderate wear. A likely position of upper third premolar was assigned for its resemblance to the upper third premolars preserved in the Izumi specimen from Japan.

5. UCMP 45274.[1] Another very small cheek tooth, having four or five tiny, moderately worn cusps all having tiny central lakes. All of the swollen cingulum and a short length of root are also preserved. The position of lower left P_4 was assigned to it because of its similarity to the fourth premolars preserved in place in the Point Arena *Paleoparadoxia weltoni* specimen, and also to the one uncovered on the palate of the Santa Barbara specimen.

1. Published by Mitchell and Repenning, “The Chronology and Geographic Range of Desmostylians,” in *Contributions in Science* no. 78 (1963).

Table 1: Isolated Tooth Specimens

Specimen and Provenance	Locality	Position	Overall size (inches)	No. of cusps		Wear	Relative size of cusps
				main	extra		
UCMP 32076, Type Specimen	Monocline Ridge, V-3301 (Temblor)	Rt. M2 lower	1.35 x 1.0	6		medium to heavy	medium
UCMP 11371, Sta. Margarita	Bean Creak 1, V-4004	Rt. M3 upper	1.25 x 1.13	4	2 or 3	medium	medium
UCMP 81857, Temblor	Monocline Ridge, V-3301	Rt. M2 lower	1.2 x 0.85	5		slight	small
UCMP 64117, Sta. Margarita	Bean Creek, V-5555	Rt. P3 upper	0.7 x 0.58	1		medium	large
UCMP 45274, Sta. Margarita	Bean Creek, V-5555	Lft. P4 lower	0.9 x 0.74	4	1	medium to heavy	large
UCMP 64116, Sta. Margarita	Bean Creek, V-5555	?	0.93 x 0.7?	1?		extreme	large?
UCMP 63981, Sta. Margarita	Bean Creek, V-4004	Rt. M2 upper	0.9 x 0.7?	5	1	moderate	very small
LACM 116953, Temblor	Monocline Ridge (site), 1020	Rt. M3 lower	1.35 x 1.05	5	1	extreme	large
LACM 116951, Temblor	Monocline Ridge, 1012	Lft. M2 lower	1.2 x 0.85	5	1	heavy	medium
LACM 116954, Temblor	Monocline Ridge, 1012	Lft. M2 lower	0.65 x 1.0	3		heavy	medium
LACM 4371, (Mitchell) Hemingfordian	Wilson Cove, V-81001	Lft. M3 or M2	1.6 x 1.0	4	6	none	not completely formed
USNM 11367 probably Temblor	Corona, California	Lft. M2 or M3 lower	1.24 x 0.9	6		medium	medium to small
UCMP 95944, Sta. Margarita	Bean Creek 2, V-5555	Rt. M2 or M3 lower	1.3 x 0.9	6		medium to heavy	medium
SK 34, Sta. Margarita	Lone Star Sand Quarry, Santa Cruz County	Lft. M3 lower	1.35 x 1.0	5		almost none	large

Table 1: Isolated Tooth Specimens

Specimen and Provenance	Locality	Position	Overall size (inches)	No. of cusps		Wear	Relative size of cusps
				main	extra		
SK 35, Sta. Margarita	Lone Star Sand Quarry, Santa Cruz County	Rt. M2 or M3 upper	1.0 x 0.95	5		medium	medium to small
SK 36, Sta. Margarita	Lone Star Sand Quarry, Santa Cruz County	Rt. M? lower	1.0 x 0.8	5		none	small
SK 37, Sta. Margarita	Kaiser Sand Quarry, Santa Cruz County	R. M2 (posterior half)	0.7 x 0.82	2 (remaining)	1	medium to light	small
SK 33, Sta. Margarita	Lone Star Sand Quarry, Santa Cruz County	Rt. P4 upper	0.8 x 0.8	4		very heavy	medium
SJ 100, Sta. Margarita	Lone Star Sand Quarry, Santa Cruz County	Rt. M2 or M3 upper	1.25 x 1.1	6	1	medium	large
SJ 99, Sta. Margarita	Lone Star Sand Quarry, Santa Cruz County	Lft. M2 upper	1.3 x 1.0	5	2	fairly heavy	large
SJ 95, Sta. Margarita	Lone Star Sand Quarry, Santa Cruz County	Rt. M2 lower	1.3 x 0.92	5	1?	heavy	large
SJ 94, Sta. Margarita	Lone Star Sand Quarry, Santa Cruz County	Rt. M2 lower	1.1 x 0.88	5	1	medium	medium
SJ 96, Sta. Margarita	Lone Star Sand Quarry, Santa Cruz County	Rt. M2 lower	1.3 x 0.75	5		heavy	medium
SJ 93, Sta. Margarita	Lone Star Sand Quarry, Santa Cruz County	Lft. M2 lower	1.11 x 0.9	4	3 or 4	light	medium
SJ98, Sta. Margarita	Lone Star Sand Quarry, Santa Cruz County	Lft. M2 upper or ?M1	0.98 x 0.73	5		heavy	very small

6. UCMP 64116. Another from the Santa Cruz County gravel pits, so poorly preserved that it is not possible to discern its original configuration. However, it is unusual in having three distinctly separate roots grown tightly appressed together so as to function as a single, elongated, conical root such as is the usual form in *Paleoparadoxia*.

7. UCMP 63981. Again from Bean Creek, this is also a very small molar, both in its overall size and also in the sizes of its six or seven tiny preserved cusps. However, the tooth is broken, having lost several cusps from the lingual side, perhaps two or three, meaning that it originally could have had as many as 10 cusps. The occlusal surfaces all have smaller or larger lakes worn into the cusp centers. In the surface of the broken-out section it is possible to see the inner construction of the tooth and the thickness of the enamel surface, which measures about 1/16 inch thick on the lateral surface. I find this tooth to be enigmatic in having so many and such tiny cusps as if it had belonged to a different pigmy species, or had perhaps been a deciduous premolar from a juvenile animal, even though it does not appear to have a dissolved or dissolving root as far as I can discern from the plaster casts. I have not seen the actual specimen, however. The idea that the deciduous premolar might have had an excessive number of cusps compared to its permanent replacement comes from the fact that the human deciduous second premolars, for instance, each have three roots and four or five cusps, whereas the adult replacements are called "bicuspids" because they have only two cusps and a single root. This same pattern is also seen in pigs and many other mammals.[2] The specimen shows moderate wear and tiny lakes in most cusps. This tooth was one of several figured and discussed by Mitchell and Repenning, 1963.[1]

8. LACM 116953. This is a very large molar, well preserved, in a state of extreme wear. The remaining crown indicates it to have had the usual five cusps at least. It has a well-developed cingulum all the way around that still shows both longitudinal and transverse creases. It was placed in the lower third molar position because of its large size and the presence of a prominent smooth facet along the anterior surface, showing its development and original eruption into the mouth against the second molar previously in place. This facet could also form on a second molar erupting against a first molar already in place; however, in the selection of single tooth specimens available to me, this facet appears commonly on third molars but not on second molars. On the other hand, the extremely worn condition is unusual for a third molar. In *Paleoparadoxia* the third molars do not seem to erupt into the mouth until the first molars are already worn away to featureless stubs and there would already be significant wear on the second molars. Therefore, this tooth could conceivably be a second molar; however, I prefer to call it a lower right M_3.

9. LACM 116951. Another very well-preserved, complete specimen including the root. It is of medium size and fairly evenly worn almost to the bases of the cusps. Longitudinal and transverse sculpturing is still visible all around the complete cingulum. I have placed it in the lower left M_2 position.

10. LACM 116954. A well-preserved specimen that has lost the anterior segment of the crown and root. The posterior segment retains its complete length of root, and two complete and half of a third cusps, all having enough wear to expose small lakes on the occlusal surfaces. The

2. Reference from Simon Hillson, "Teeth," *Cambridge Manuals in Archeology* (1986).

cingulum is prominent and still shows sculpturing. An interesting feature is the exposure of the inner tooth construction along the surface of the break. This specimen agrees closely in size and configuration with LACM 116951, described previously, so I have also designated it as a lower left M_2.

11. LACM 4371. A strange, incompletely formed molar tooth crown which has suffered some breakage. It has been identified as *Paleoparadoxia* by Ed Mitchell and still retains 10 cusps in a formative state; several more might have been broken away. I have only a cast from a cast, and have never seen the actual tooth. It would have been a lower left permanent molar in my estimation. Perhaps when fully developed, the four or five main cusps would coalesce around and over the many smaller budding cusps visible in the undeveloped state. The tooth is very large to be identified as a deciduous premolar; however, such a possibility could be considered.

12. USNM 11367. Discovered at Corona in Riverside County, southern California, in 1913. The specimen is complete with long root preserved. I cannot remember if I made my rubber mold on a cast of this tooth or if I had the actual specimen loaned to me for molding and casting. There is an open lake in the center of each of the seven cusps that together exhibit a steeply sloping wear surface, the anterior lingual cusp being the highest as usual. Even though this tooth has an extra central cusp, its overall shape is oblong and not round. Therefore, I have assigned it to the position of lower left M_2.

13. UCMP 95944. This was located in the U.C. Berkeley collections for me several years ago. I was allowed to have it on loan for molding and casting. It is a well-preserved, complete molar crown with much of its root also preserved. It also has a steeply sloping wear surface of the same form as the Corona tooth described above. There are six cusps, each with a small open lake on the occlusal surface. As there is also an anterior facet present, I am considering it to be a lower right third molar.

14. SK 34. A large size, complete, lower left third molar from the Santa Cruz County aggregate deposits. Although the specimen appears somewhat water-worn and its root seems to have been bored into by shipworms, it is quite well-preserved in a nearly unworn state having four tall cusps and one shorter one surrounded by a well-developed cingulum. A perfect specimen.

15. SK 35. A much smaller specimen; a complete molar crown of five medium to small cusps, all having enough wear to exhibit small or tiny open lakes. The shape is quite round and almost completely surrounded by a longitudinally sculptured, swollen cingulum. The root is not preserved and the surface of the underside of the crown is curiously shaped as if it might be a shed deciduous fourth premolar whose root had been resorbed. However, the circular arrangement of the five cusps does not match with any premolars in any of the extant specimens. Therefore, I have retained it as a small upper right second or third molar, because it is morphologically a good match to the equivalent teeth in the Santa Barbara specimen.

16. SK 36. This comes from the same locality as the previous two, the Lone Star Sand Quarry in Santa Cruz County. It is also round in outline; however, the cusps are arranged in the typical two-cusp rows and a fifth single cusp anteriorly, which would typify a lower molar. The nearly complete crown has been patched by the collector so that it appears to be complete in the cast product. At least half the length of the root is also preserved. The longitudinally sculptured,

swollen cingulum is preserved around the anterior and buccal perimeters. The unworn cusps again are of unequal height, the anterior pair being the taller and the lingual anterior cusp the highest. From this beginning it is easy to infer the development of the sloping wear pattern seen in the USNM 11367 specimen from Corona, California, and the UCMP 95944 specimen from Bean Creek near Santa Cruz, and also several other specimens from that locality. However, this commonly encountered inequality in the height of the molar tooth cusps, both in newly erupted teeth and teeth exhibiting occlusal wear, *is not seen in any* of the teeth preserved *in place* in the skull or mandibular *Paleoparadoxia* specimens. In those cases the wear surfaces are not generally sloping but are unequally flat.

17. SK 37. This specimen, also from a Santa Cruz County sand quarry, consists of the posterior segment of a lower molar split longitudinally, exposing the inner construction. Preserved are the two posterior cusps and a tiny buccal cuspule. The exterior perimeter retains a well-developed swollen cingulum expanded posteriorly into two more tiny cuspules. The specimen is comparatively small. I have assigned it to the lower right second molar position for its resemblance to LACM 116951.

18. SK 33. A very interesting small specimen with a complete heavily-worn crown and some length of preserved root exhibiting some curvature. It appears to have had four cusps, the anterior two worn to open lakes and the posterior two worn on a steep caudally facing slope all the way to the base of the cingulum, forming a large coalesced open lake. Remaining outer edges of the lateral enamel surfaces could still have provided some cutting action in the mastication in spite of the extreme wear. I assume that the curved root indicates an upper cheek tooth, the concave outline directed forward in the dentary. Thus oriented, this tooth forms a transverse ridge to conform to the offset occlusal pattern between the upper and lower premolars that is seen in both the Point Arena and the Izumi specimens. This tooth compares well with the upper right and left fourth premolar specimens found in direct association with the Mission Viejo *Paleoparadoxia* specimen. I have placed it in right upper fourth premolar position and used it in the final display.

19. SJ 100. This specimen and all the remaining specimens catalogued under the initials SJ were collected from the Lone Star Sand Quarry locality in Santa Cruz County. SJ 100 is a large molar rather heavily worn and without preserved root, but otherwise complete. There is only a small remnant of sculptured cingulum remaining, the rest worn away or broken away. Even though its general outline is oblong, it does not conform well to the usual lower molar pattern. It can quite conceivably be considered to be an upper molar for its similarity to the more heavily worn right upper second molar in the Santa Barbara specimen. Therefore, I am considering it to be a left upper second molar; however, others might interpret it to be a lower molar.

20. SJ 99. This specimen has suffered some breakage to two of its posterior cusps and is without a preserved root. The occlusal wear is fairly heavy as some of the cusps have been reduced to the level of the prominently developed swollen and longitudinally sculptured cingulum. As exposed in the breakout, it has a quite thick enamel layer on the lateral surface, measuring about 1/8 inch. This tooth can be seen either as an upper or a lower permanent molar. It appears to have a facet formed against another molar on the posterior lateral surface, only if the tooth is placed in the position of an upper left second molar. In that case the fore and aft

orientation of the specimen would resemble the upper second molar in the Santa Barbara specimen. If, on the other hand, one ignores the problematical lateral facet, the tooth can be rotated a few degrees so that it exhibits the usual lower molar pattern of two double rows of cusps and a fifth one centrally located. However, I have chosen to retain it as an upper left second molar and have placed it in this position in the final display.

21. SJ 95. This heavily worn specimen retains only a small remnant of root. Besides the natural occlusal wear seen by the fairly large open lakes in the cusp surfaces, the specimen is heavily water-worn by wave action which has damaged several enamel surfaces and almost entirely worn off traces of cingulum. It is a relatively large molar narrowly oval so I have placed it with some uncertainty as a right lower second molar.

22. SJ 94. A medium-sized specimen having the usual oblong contour and two double rows of cusps, the anterior ones taller than the posterior. The cingulum is worn almost smooth but is still visible all the way around. There are small open lakes worn into the occlusal surfaces of each cusp, and there appear to be both an anterior and a posterior wear facet at each end. This places the tooth in the right lower M_2 position. It might conceivably be a right lower M_1. However, none of the five specimens with preserved teeth in place give any information about the cusp pattern of any first molar, because in every case the first molars are worn down to featureless stubs, even on those specimens identified as juvenile. Therefore, I have no comparative material for first molars.

23. SJ 96. This medium-sized specimen retains an unusual occlusal wear pattern and an exceptionally elongated outline. It appears to have had only a minor development of sculptured cingulum, four tall main cusps and one low but much elongated heel-like extension posteriorly that seemingly is not developed into a true cusp. The occlusal wear on the four main cusps has developed a “hip-roof” configuration that I have only seen once before on the Mission Viejo specimen. The crest of the “hip-roof” is oriented fore and aft, and each cusp has a good-sized open lake on its occlusal surface. I have assigned it to the right lower second molar position; however, it could as well be a third molar for a minor facet might be interpreted on its anterior surface.

24. SJ 93. A lower cheek tooth of medium size and excellent preservation has the common sloping outline, its highest cusp is the anterior lingual one and the lowest is the posterior buccal. It has the usual four main cusps of a lower molar and a posterior bulge that would probably wear into one or even two open lakes resembling cusps. It is unusual, however, in having an extra cuspule developed on the anterior surfaces of each of the two tall anterior main cusps. The tooth has moderate wear showing small open lakes on the four main cusps and incipient openings on the two extra anterior cuspules. There is a short length of root preserved but only minor traces of sculptured swollen cingulum. It has been assigned to the left lower M_2 position.

25. SJ 98. Another very small but extensively worn molar having a generally round outline. All five of its main cusps have an open lake on the occlusal surface, two of them coalesced. The root is almost entirely broken away and the tooth does not have the usual heavily sculptured swollen cingulum. In spite of is small size it conforms to the common upper molar pattern, as seen in the Santa Barbara specimen, and therefore is placed as an upper left second molar for first choice. From its small size it might be better placed as M-1, but in the case that a pigmy

species might have existed, as intimated before, it could also be considered for the third molar position.

A number of general observations and conclusions can be noted from this listing of the individual details of these molars, but such a discussion will be more complete if comparison can also be made between the individual teeth and the molars preserved in place in the available *Paleoparadoxia* skull and mandibular specimens. For that reason, I will now comment on the notable variations in the dentitions observable on those five specimens. Following a similar format as used in the previous listing, I shall comment on the preserved molar dentition in each of the five specimens in the same order as listed in Table 2.

Table 2: Specimens with Cheek Teeth in Place*

Specimen — Age	Teeth Preserved	Relative Size	No. of Cusps	Wear	Type of Crown Base
UCMP 114285 *Point Arena — Arikareean, Early Miocene*	Rt. M_3 (lower)	small	4	medium	Smoothly swollen with trace of cingular shelf.
Schooner Gulch Formation	Rt. M_2	small	5	medium	Same as Rt. M_3 above.
	Lft. M_3	small	4	medium	Same as Rt. M_3 above.
	Lft. M_2	small	5	medium	Same as Rt. M_2 above.
	Lft. P_4	very small	5	medium	Smoothly swollen, no trace of cingular shelf.
	Lft. P_3	small	1	medium	Caniniform with one incipient cusp posterior.
NSMT P-5601 *Izumi* (cast) — Mid-Miocene	Rt. M^3 (upper)	medium	4	slight	Cingular shelf and several incipient cusps present (two or three).
Yamanouchi Formation	Rt. M^2	medium	5	medium	Cingular shelf and some incipient cusps present.
	Rt. M^1	small	—	extreme	All crown detail obliterated by extreme wear.
	Rt. P^4	small	3	medium	Smooth base with cingular shelf joining the three cusps.
	Rt. P^3	small	3	medium	Smooth swollen base, little or no cingular shelf.
	Lft. M^3	medium	4	slight	Swollen base with traces of cingular shelf and incipient cusps.

Table 2: Specimens with Cheek Teeth in Place*

Specimen — Age	Teeth Preserved	Relative Size	No. of Cusps	Wear	Type of Crown Base
	Lft. M^2	medium	5	medium	Same as M^3 above.
	Lft. M^1	small	—	extreme	Entire crown worn down to root, no details remaining.
	Lft. P^4	small	3	medium	Cingular shelf and some incipient cusps present.
	Lft. P^3	small	3	medium	Trace of cingular shelf.
	Rt. M_3	medium	5	unworn	Cingular shelf with some incipient cusps present.
	Rt. M_2	medium	5	light to medium	Smoothly swollen base with only trace of cingular shelf.
	Rt. M_1	small	—	extreme	Only butt end of root remains.
	Rt. P_4	small	4	light to medium	Smoothly swollen base without ornamentation.
	Rt. P_3	small	3	some wear	Three cusps bunched into a caniniform point; no cingular shelf.
	Rt. P_2	small	1	tip slightly worn	Caniniform tooth without cingulum.
	Lft. M_3	medium	5	no wear	Swollen base with posteriorly developed cingular shelf plus several incipient cusps.
	Lft. M_2	medium	5	medium	Smoothly swollen base without ornamentation on buccal side; can't observe remainder.
	Lft. M_1	small	—	extreme	Only butt of root remaining.
	Lft. P_4	small	4	medium	Smoothly swollen base without ornamentation.

Table 2: Specimens with Cheek Teeth in Place*

Specimen — Age	Teeth Preserved	Relative Size	No. of Cusps	Wear	Type of Crown Base
	Lft. P_3	small	3	some wear	Three cusps bunched into a caniniform point with enlarged but smooth base.
LACM 131889 Mission Viejo — middle Middle Micocene	Rt. M_3	large	5	minimal	Smoothly swollen base with several incipient cusps.
Topanga Formation	Rt. M_2	large	4 discernable	heavy; hip-roof with a central longitudinal ridge	Smoothly swollen base without ornamentation.
	Rt. M_1	medium	—	extreme; hip-roof as above	Wear too advanced to see original shape or style of base.
	Rt. P_4	medium to small	4	heavy; hip-roof as above	Smooth base without cingular shelf or other ornamentation.
	Rt. P_3	small	3	heavy; flat	Could be three or four bunched cusps; smooth base without ornamentation.
	Rt. P_2	medium and tall	1	heavy	Caniniform tooth, strangely worn, with tiny remnant of enamel at tip (buccal).
	Lft. M_2	medium	4	heavy; hip-roof as rt. M's	Little discernable due to heavy wear and poor preservation.
	Lft. M_1	small	—	extreme; hip-roof	Wear too advanced to judge base shape or style.
	Lft. P_4	small	4	heavy; hip-roof	Smooth base without ornamentation on visible part.

Table 2: Specimens with Cheek Teeth in Place*

Specimen — Age	Teeth Preserved	Relative Size	No. of Cusps	Wear	Type of Crown Base
UCMP 40862 Reinhart — Upper Miocene Santa Margarita Formation	Rt. M_3	large	6	medium; very flat	Cingulum around entire base is ornamented with vertical creases forming several incipient cusps around upper edge of cingular shelf.
UCMP 147527 Santa Barbara Specimen — earliest Middle Miocene	Rt. M^3	very large	4 + ?2	rather heavy	Smoothly swollen base without ornamentation on visible part.
Monterey Formation	Rt. M^2	very large	4 + ?2	heavy	Very little of base visible, appears smooth.
	Rt. M^1	medium	—	extreme	Crown completely worn away.
	Rt. P^4	small	4	heavy	Base of crown not visible.
	Rt. P^3	small	1 + ?	very heavy	Mostly worn to base of crown but remnants appear smooth.
	Rt. P^2	small	1	very heavy	Straight cylindrical shaft with obliquely worn single cusp.
	Lft. M^3	large	(occlusal surface not visible)		Labial surface smoothly swollen without ornamentation.
	Lft. M^2	large	same as Lft. M^3		Same as Lft. M^3 above.
	Rt. M_3	very large	5	medium to heavy	Base smoothly swollen lingually, labially cingulum faintly ornamented with vertical creases.
	Rt. M_2	large	5	heavy	Lingual surface visible, smoothly swollen without ornamentation.
	Rt. P_4	small	5	heavy	Lingual surface visible, smoothly swollen without ornamentation.

Table 2: Specimens with Cheek Teeth in Place*

Specimen — Age	Teeth Preserved	Relative Size	No. of Cusps	Wear	Type of Crown Base
	?Rt. P_3 or $_2$	small	1	very heavy	Single cusp with one short incipient cusplet, smooth base, except enamel incompletely formed or completely worn through (?) bucca-lly.
	Lft. M_3	very large	5 (?)	medium to heavy	Occlusal surface incom-pletely prepared, but sufficiently to see that occlusal wear is very similar, though not identical, to that of Rt. M_3. Crown base smooth without ornamentation.
	Lft. M_2	large	?	heavy	Minimal preparation on this tooth so far.
	Lft. P_4	small	?	heavy	Smooth swollen base only minimally visible. Tooth crown removed from specimen, poorly preserved, and not pre-pared. Large part of root had to be destroyed to continue preparation of remaining specimen.

* Comparison of age, size, and type of crown base. Data taken mostly from photos.

1. UCMP 114285. The Point Arena, northern California specimen, *Paleoparadoxia weltoni* (Clark, 1991), includes a nearly complete mandible separated at the symphysis into right and left sections. This fossil represents the smallest and most primitive of the five specimens (see Fig. 48). Its primitive features are: 1. an adult animal of small size; 2. presence of double rooted molars; and 3. canines not developed into tusks. It is believed to be of Early Miocene age (Arikareean Schooner Gulch Formation). All the preserved molars show considerable wear exhibiting the more common, more or less level, wear pattern with open lakes on the second and third molar cusps. All of those teeth have only four or five cusps arranged as usual in two transverse rows of two, and a fifth centrally located on the posterior ends of the two second molars. There are no extra cusplets around the swollen cingula. However, x-ray photographs reveal each of these four teeth to have double roots. Both first molars are missing but the small stubs of two roots appear to remain in the left half mandible. However, I am unable to distinguish their presence on the x-ray photo. The fourth and third premolars preserved in the

left mandible are both worn down fore and aft at fairly steep angles, forming a profile of two sharp points when viewed laterally. Presumably these points occlude between similarly worn upper premolars, the upper fourth crest posterior to the lower fourth crest, in accordance with the usual mammalian pattern mentioned earlier. A third and a fourth premolar for the left mandible were found closely associated, and they also possess the pointed lateral profiles of occlusal wear pattern. All the cheek teeth preserved in this specimen are smaller than comparable isolated teeth in my collection of separate tooth specimens. Measurements for them are given in J. Clark's publication on *Paleoparadoxia weltoni*, JVP issue of December 1991 (see Fig. 48).

(a)

(b)

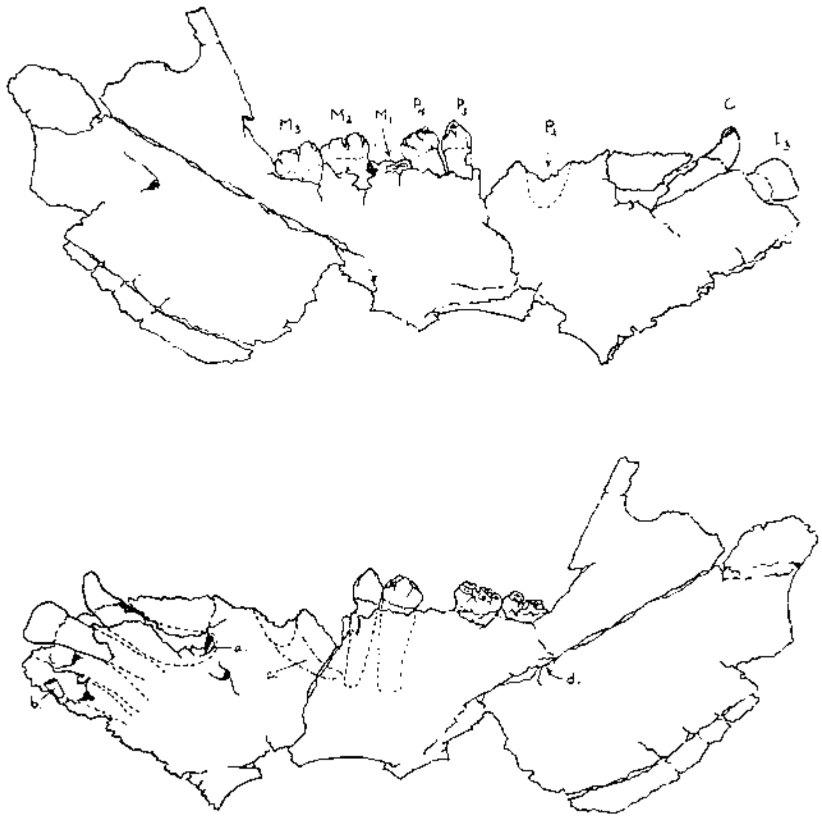


Fig. 48: (a) Point Arena *Paleoparadoxia*, left dentary in medial view, 1/3 natural size; (b) Point Arena *Paleoparadoxia*, left dentary in lateral view, 1/3 natural size.

2. NSMT P-5601. *Paleoparadoxia tabatai*, or The Izumi Specimen, from Japan. This fossil discovery includes the complete skull and both right and left sections of the mandible and the complete dentition in place (see Fig. 49). It is considerably larger than the Point Arena *Paleoparadoxia weltoni* specimen, and it has at least the lower canines developed into tusks. It is considered to be juvenile, or sub-adult, because the third molars are in process of erupting and show little or no wear. However, the lower right third molar was found fallen about halfway out of its alveolus, and was retained in that position during and after preparation of the specimen. For that reason all the Japanese mountings of this fossil are arranged with the mouth wide open. The general configuration of the molars, even the unworn M_3's, is the more commonly seen pattern of cusps having sub-equal heights and the more level style of occlusal wear.

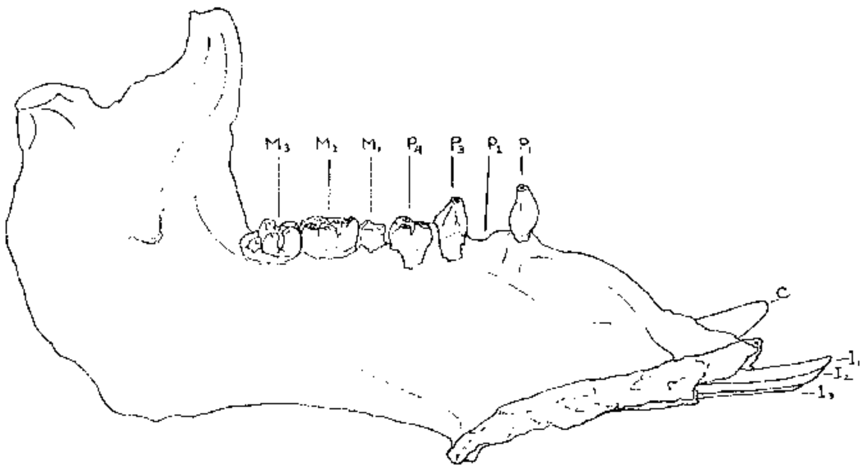


Fig. 49: *Paleoparadoxia tabatai*, Izumi specimen in medial view, 1/4 natural size. Dentition according to Ijiri and Kamei, 1961.

All four first molars are worn down so far as to have no cusps remaining. The two lower M_1's are featureless stubs, retaining neither enamel nor cingula swellings. The upper M^1's have wide open shallow basins for occlusal surfaces, whose approximately circular edges retain some narrow remnants of enamel that appear to have been part of enamel-covered swollen cingula at the extreme bases of the crowns. The second molars, both uppers and lowers, show moderate wear with open lakes developed on almost all cusps. The anterior-most lingual cusps on the lower second and third molars are tallest to occlude with the shorter posterior cusps of their opposing uppers. Here, the short length of the upper molar rows, compared to the lower rows, are accentuated by the unusual development of only four cusps on those M_3's, whereas the lower M_3's each have the usual five cusps.

Ijiri and Kamei, 1961, state that most of the cheek teeth in the Izumi specimen have multiple roots, as seen in x-ray exposures. I believe this feature would indicate a more primitive evolutionary condition for *Paleoparadoxia tabatai* compared to the many single-rooted specimens that have been collected; in that feature it compares more closely to *Paleoparadoxia weltoni*. Only one of the 27 teeth that were found individually, no. 6 in the previous listing, positively has a preserved multiple root.

3. LACM 131889, the "Mission Viejo" specimen. This specimen compares in size and evolutionary development to the large California discoveries from Stanford and Santa Barbara, and it contains the complete cheek dentition in place in the right half of the mandible. All teeth appear to be single-rooted with the usual numbers of cusps. The third molar appears to be essentially without wear, suggesting a sub-adult age for the individual at time of death. However, as seen before, all details of cusp pattern are worn away from the first molar. This is also true of the first molar in place in the less well preserved left lower jaw.

   The most striking difference between this specimen and almost all other *Paleoparadoxia* specimens that I have been able to study is the development of the unusual "hip-roof" occlusal wear pattern. Every cheek tooth preserved in place is worn down in this strange way, with both lateral areas worn away at a steep angle, leaving a rather sharply developed high ridge running along the centers of the crowns in a fore and aft direction. It is unfortunate that the skull with cheek teeth in place was not recovered, for without the opposing teeth it is hard to imagine how these unusual wear surfaces could have formed. One feature of this fossil may give a partial explanation: The articular surface of the condylar process appears rough and pathologically misshapen.

4. UCMP 40862. A partial right mandible published by Roy Reinhart, 1959, along with the single tooth UCMP 32076. Only one molar crown is preserved in this specimen, the complete right third molar. This mandible and the tooth agree well in size to the Stanford and the Santa Barbara specimens, and also to the Mission Viejo specimen discussed above. At the time of the discovery of the Stanford *Paleoparadoxia* in 1964, its similarity to UCMP 40862 furnished the most convincing evidence of the generic affinity of our newly found fossil. The tooth has an almost completely flat horizontal occlusal wear surface and a well-developed cingulum deeply sculptured by vertical ridges. There are six strong cusps seemingly worn almost to their bases. As mentioned before, I have never seen the actual specimen, only casts, so it is difficult to interpret the occlusal wear. It might be possible that the almost perfectly flat horizontal surface is merely an artifact of the collection process and not the true wear surface. No part of the ascending ramus is preserved vertically higher than the tooth.

5. UCMP 147527, the Santa Barbara specimen. It is the largest of all our *Paleoparadoxia* fossils with preserved teeth in place, and is also the most complete. I have noted that the skull and both mandibles are preserved in articulation and encased in a siliceous chert of hardness seven that is very difficult to prepare. However, a great deal of information became available from it in spite of the fact that I did not feel myself to be adequately skilled to attempt complete preparation of the preserved dentition. Enough work was accomplished so that I could see that, except for the large size, the development of cusps and cingula, and also of the occlusal wear patterns, agrees well with the majority of other *Paleoparadoxia* specimens, including those preserved as individual teeth and those preserved in place in dentaries.

The preparation work for the teeth was mostly done with the skull resting on the dorsal surface as fossilized. The rock matrix was ground away from the area between the two sides of the mandible until the bony palate was reached. In this position one sees that the right mandibular ramus had been displaced laterally, and probably broken, in such a way that the cheek teeth could fall out of their alveoli. They were found lying on the palate in order of placement with their lingual surfaces exposed. Their labial surfaces are encased in the thin matrix that was deposited on the surface of the palate. Because the left lower jaw was not otherwise disoriented, but remained almost perfectly articulated with the skull, the left lower molars merely slipped vertically almost out of their alveoli. It is possible to see their inner lateral surfaces, and the outer lateral surfaces of the upper molars are partially visible from the outside of the specimen. For this reason most of the information was taken from the more available right dentition where the occlusal surface of the complete upper tooth row is exposed and the lower dentition is also available.

In assessment of the overall amount of wear exhibited by these teeth, one can guess that this specimen represents a fully mature animal without obvious pathological defects and therefore the best model available with respect to restoration of the Stanford *Paleoparadoxia* dentition. Most of my ultimate decisions were favorably compared to what I could see here.

The upper third and second molars are both quite large and comparatively circular in outline. The occlusal surfaces are heavily worn to open coalesced lakes. Each appears to have five main cusps somewhat grouped into three anterior and two posterior in position. The wear is of the generally horizontal pattern that lacks extreme high points or low basins. Of the first molar, only a well-worn stub remains, bearing not a vestige of enamel. It is closely fitted between the well-preserved second molar and fourth premolar. The latter tooth has four heavily worn cusps, two larger ones anteriorly and two much smaller ones posteriorly. The remains of the heavily worn third premolar indicate this to have been a very small tooth, and the second premolar is even smaller. The third premolar crown is so worn that one can only try to see that it probably originally possessed the usual three cusps. The second premolar is also very heavily worn, so that the crown is essentially gone, but the stub is truncated at an approximate 45° angle sloping to its highest point anterolaterally, I believe. This slope was presumably formed by occlusion against the conically shaped lower third premolar. There might still be a trace of enamel on the anterior outer edge which is developed into a point. However, the tooth has rotated and fallen somewhat sideways, so that part is not exposed in my preparation, and the angle and orientation of the wear surface cannot be determined precisely.

The lower molars are lying in parallel formation on the palate with their lingual sides and complete roots in view. As the normal crown wear is always greater anteriorly and lingually, these occlusal surfaces are undercut against the palate and therefore somewhat difficult to see and to prepare. It was necessary to work with a mirror and also to photograph the occlusal surfaces by mirror image. To avoid damaging these teeth under such awkward conditions, I stopped short of entirely removing the rock from the undercut occlusal surface; however, the remaining thin matrix allows an adequate view of the cusp and wear patterns when moistened with water.

Both the third and second lower molars have five prominent cusps worn down to open lakes. The arrangement of cusps is the usual, two pairs of two, and a fifth centered posteriorly. The second molar is more heavily worn than the third, as would be expected, with most of these lakes coalesced. All that remains of the first molar is the poorly preserved root resting on the palate between and under the second molar and fourth premolar. The fourth premolar also has five cusps, similarly arranged but much smaller than those of the permanent molars, and quite heavily worn to open lakes with the anterior pair being coalesced.

The third premolar was not preserved in this neat array. However, a small tooth crown having a single heavily worn cusp was uncovered in the anterior left corner of the palate. I cannot determine its original position: upper, lower, left, or right. It might conceivably have been part or all of the crown of the lower right third premolar.

I have now described all of the material that was available to me on which I could base the decisions for the restoration of the cheek teeth in our display.

Discussion

Through consideration of all the characteristics of the available *Paleoparadoxia* cheek teeth noted in the two lists above, several conclusions and speculations come to mind. First, I notice that there is a tremendous variability in the selection, particularly as to overall size, number of cusps, and arrangement of cusps. There is also a great deal of variation in the development of cingulum which can be sculptured in various ways. In some cases the cingula are heavily ornamented with either, or both, horizontal or vertical ridges and often having an ornamented upper rim. Frequently, these upper ornamentations are so well developed as to form extra cusplets that later become incorporated into the occlusal surface with wear. However, some of the specimens do not exhibit any sculpturing, merely having a smooth swollen cingulum around the base. I have been told that the sculpturing that appears on the newly erupted tooth may wear off smooth during the life of the animal, possibly explaining the smooth specimens. But no such sculpturing is present on the unworn third molars that are in an eruption stage on either the Japanese Izumi specimen or the Mission Viejo specimen. It is interesting, therefore, to speculate on the possibility that some of these variations indicate the presence of several *Paleoparadoxia* species in our sample.

Another highly variable characteristic is that of occlusal wear. It is assumed here that these animals were primarily herbivores of marine habitat. Their food would then consist of a variety of sea grasses, sea weeds, and salt marsh plants. These plants, particularly grasses and rushes, but all of them to some extent, are very abrasive because they have siliceous spicules in them, and they therefore cause much tooth abrasion to all animals that feed on them. This would be the main cause of so much tooth wear. The condylar processes of the mandible normally have spherically shaped articular surfaces which would permit some circular or rocking action in mastication, either fore and aft or transverse. I envision the cutting action in the chewing process to have been performed by the robust enamel rims that surround the open lakes of worn cusps. The opposing enamel rims of uppers and lowers passing across each other would grind the food. The occlusal wear surfaces would be determined by this mastication process.

There seem to be several different styles of occlusal wear that commonly occur and can be noted in our available selection. The most common pattern is more or less horizontally level, the newly erupted tooth having at least four or five prominent vertical cusps that rise from a swollen base to sub-equal heights. The anterior lingual cusp is usually tallest and the posterior buccal cusp somewhat shorter. The most common wear pattern for these teeth is the formation of a sub-level surface having taller ridges anteriorly and deeper basins posteriorly. This condition is illustrated with the type specimen UCMP 32076, Fig. 50(a). All of the cheek teeth in the Santa Barbara specimen exhibit this wear pattern, as well as half the collection of isolated teeth and the majority of cheek teeth preserved in place in the other specimens.

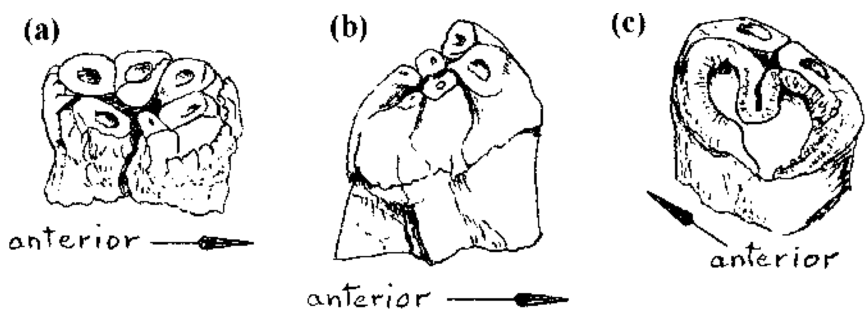


Fig. 50: Wear pattern conditions: (a) UCMP 32076 Type specimen. tilted slightly to show occlusal surface. Lower right M-2; (b) UCMP 95944 Lower right M-3; and (c) Mission Viejo Lower right M-2. Oblique view in postero-lingual aspect.

Less commonly, but still frequently, the unworn tooth erupts with a very prominent exaggeration of the vertical profile where the anterior lingual cusp is so much taller than the posterior buccal cusp that the occlusal surface will have a very decided slope even from the beginning. Figure Fig. 50(b) illustrates this condition with UCMP 95944 from the Bean Creek locality in Santa Cruz County, California; but *none* of the teeth preserved in place in the five specimens listed exhibit this wear pattern.

A third wear pattern is observable on several specimens which I have described as "hip-roof." These wear surfaces are strongly developed on the Mission Viejo specimen and are also noticeable on several of the separate fossil teeth. It is formed of two steep slopes, one bucally and the other lingually, with a high ridge between them running fore and aft along the center. This unusual form is difficult to explain. The condition is here illustrated in Fig. 50(c) by the right lower second molar in the Mission Viejo mandible.

I do not know how to evaluate the differences and variations that are to be seen in this selection of specimens. Do they indicate several different species or one widely variable species? We know that the five specimens with teeth in place represent a significant span of time, as described in the Systematic Paleontology on pages 6 through 7, which should be taken into the consideration of these questions. Some of the Santa Cruz County individual teeth resemble in size and form the preserved cheek teeth in the most primitive Point Arena specimen, *Paleoparadoxia weltoni*. But all of the Santa Cruz County specimens, large and small, were found in the same gravel pits. Does this mean that the more primitive and more advanced forms cohabited? Or more likely, that the Santa Cruz gravel deposits contain a wide temporal range of specimens? Perhaps some day sufficient new material will be discovered to help resolve these enigmas.

Final Choices for Cheek Teeth Restoration

Ultimately, a choice had to be made for each cheek tooth position in the final mounting. As stated previously, the Stanford *Paleoparadoxia* mandible contains no preserved tooth crowns, so all teeth that would be used in the display needed to be chosen from the available selection of separate teeth, listed in Table 1 (page 100, also described starting on page 99). These choices were based on the sometimes meager information that could be gleaned from the five specimens with teeth preserved in place, listed in Table 2 (page 106, described starting on page 110).

I felt that the best policy would be to choose as many real teeth as possible and only resort to creating right to left, or left to right, copies when necessary. The choices needed to be restricted to teeth whose sizes would conform to the preserved alveoli in the Stanford mandible. It also seemed wisest to make these choices from those specimens having the more common pattern of four or five prominent cusps and a single long root. These restrictions served to eliminate a sizable fraction of the available specimens, making the choices easier to decide. However, as all of the teeth to actually be inserted would be plaster casts, I felt that it would be reasonable for me to modify any occlusal wear surface from the actual preserved wear pattern in order to make a more realistic restoration of the dentition. This, then, allowed more flexibility of choices from the available selection.

The first tooth decided upon was the upper right third molar specimen, UCMP 111371, that had been collected by VanderHoof at the Bean Creek site, Santa Cruz County, in 1940. There were three reasons for this choice. First, it is of a reasonable size and morphology to fit the Stanford specimen; second, its placement is, without question, determined by the remaining fragment of maxillary bone; and third, it was collected by V. L. VanderHoof, to whose memory our *Paleoparadoxia* display is dedicated. It was used without any modification to the preserved occlusal wear surface and painted as the real tooth.

Once this decision had been made, all further choices needed to conform to it in size and morphological features, which had the effect of greatly limiting the possibilities and thereby simplifying the process.

To fill the third molar position in the left upper row, there was no specimen in the available selection that could be used, so a right to left copy of UCMP 111371 was fashioned from a cylindrical plaster blank carved out by eye and then molded and cast so that duplicates could be available.

In opposition to these teeth, two large lower molars were needed. Specimen number SK 34 from Santa Cruz County is of the correct size and has a long single root that fits quite well into the preserved alveolus in the Stanford mandible. This specimen, having five prominent cusps and a smooth cingulum with only a moderate development of cusplets, was the best choice for this spot. A cast of it was modified to have an occlusal wear pattern similar to that seen on the Santa Barbara specimen lower M_3 and arranged in its position in the mandible so as to occlude with the upper dentition in a similar manner. Then, it was necessary to sculpture from another cylindrical plaster blank a left to right copy of the lower third molar I had put on the left side, as had been done for the upper third molars.

The next important decision made was to use UCMP 32076, the type specimen for *Paleoparadoxia*, in the lower right second molar position. This decision was also made for three reasons. First, it is of a suitable size and morphology for that spot; second, it exhibits a suitable occlusal wear surface for the position and the maturity of the Stanford specimen, and could be used without modifications; and third, it carries the important status of being the type specimen which was, incidentally, also collected by V. L. VanderHoof at Monocline Ridge in the 1930s.

In the equivalent position on the left side, LACM 116954 was used. This specimen consists of the posterior half of the molar crown, with three cusps preserved and most of its long root, which could be satisfactorily fitted into the preserved second molar alveolus in the Stanford mandible. Even though the anterior half of the crown is missing, a view of the interior construction of the tooth is exhibited. The overall size of the preserved part of the crown compares favorably to that of the specimen that was used on the right side. Some enlargement of the open lakes on the three cusps was made to match the amount of wear to the presumed maturity of our specimen.

In opposition to the preceding tooth, the upper second molar position on the left was filled by specimen number SJ 99 which has also sustained some damage to the crown. In this specimen there is some breakage to the lateral surfaces of the posterior labial cusps which also exhibits the interior tooth construction. Its occlusal surface is worn into the most common sub-level pattern with noticeable, but not extreme, crests and basins and could be used without significant modifications to the wear surface. Only the open lakes on the five large cusps were enlarged to indicate more extensive wear for the second molar position. In size this tooth also conforms well.

As was resorted to previously, a left to right copy of SJ 99 had to be created for the upper right second molar position because there was no suitable choice of specimen in our available selection. This restoration eliminated the breakage that had occurred to the original so that the copy appears as a whole tooth without breakage. The occlusal wear was simulated to match the previous choices for the right molar dentition.

It was assumed that, at the apparent advanced age of the Stanford specimen at death, there would only be remnant stubs without crowns remaining in all four first molar positions. The first molar alveolus in the Stanford mandible is equally as well preserved as the others even though its dimensions are much narrower than either that of the second or third molars, and also that of the fourth premolar which appears to have been quite a large tooth. For this reason, it was decided to restore all four first molars as only the stubs of their roots without any remaining crowns. These stubs were all formed from casts of the same well-preserved complete root, that of LACM 116951. This tooth is a very fine specimen of a lower left second molar, but it was not quite large enough to be used in that position in our display. Each of the cast roots was modified and rotated differently according to which of the first molars it was to represent. It was felt that the use of some part cast from a real tooth would have a more realistic appearance than completely fabricated restorations.

The first molars preserved in the Japanese Izumi specimen provided the models for these tooth remnants. In that specimen the lower two appear as mere featureless stubs having somewhat convex top surfaces. The upper two appear more concavely excavated with perhaps a very thin remnant of a swollen cingulum base preserved in some places. These features were used as a general guide in the shaping of the four first molars; however, in our restoration of the complete dentition, the posterior sections of the upper first molars are envisioned as occluding with the anterior cusps of the lower second molars and the anterior sections as occluding with the posterior halves of the lower first molar stubs. These orientations are in accordance with the general pattern of molar tooth occlusal arrangements for mammals discussed earlier. I felt that it was important to illustrate how the opposing rows of teeth would have been arranged to provide the living animal with a dentition reasonably adequate to its presumed needs. Anterior to the permanent molar positioning, the upper and lower premolar positions would be alternating so that the lower premolars could occlude anteriorly to the equivalent uppers. This arrangement is evident on the well preserved upper and lower dentitions of the Izumi *Paleoparadoxia*, and also detectable on the Santa Barbara skull.

The selection of separate tooth specimens was quite limited in teeth that could be identified with certainty as adult premolars, P_4, P_3, and P_2. It was determined that, at least in the cases of the lower fourth premolars, some less certain specimens might be modified for use in these positions. A feature of the Stanford mandibular specimen is the large size of the preserved alveolus for the fourth premolar, which is considerably larger than that preserved for the first permanent molar, and also the alveolus for the third premolar is almost as large. The preserved complete root of the second premolar that remains in place in this mandible also has a large diameter and length. Therefore, this individual seems to have possessed characteristically large-sized premolars. The smaller size of the alveolus for the first molar might be an indication that the adult fourth premolar had developed and erupted after the first molar was extensively worn and being slowly extruded from its alveolus by the pressure of growth of the two adjacent teeth, the second molar and the fourth premolar. These equivalent teeth preserved in the Santa Barbara and Izumi specimens are relatively of much narrower diameters compared to the molar dentition. However, I was obliged to place teeth of adequate size to fill the alveoli preserved in the Stanford mandible, so the choices of specimens or restorations were decided accordingly.

In the entire collection of single tooth specimens I had none that could be positively identified as lower fourth premolars with only four main cusps. I had determined by comparison of the *Paleoparadoxia* specimens with teeth preserved in place that I should restore these premolars as each having four cusps (see Table 2, page 106). For this reason two molar specimens were chosen that have the appropriate root diameters with intention to modify the crowns as necessary to conform to the fourth premolar cusp patterns. Specimen SJ 94 was assigned to the right and SJ 93 was used on the left. Both of these teeth show very little wear and both have six cusps. SJ 93 is unusual in having two smaller and shorter cusps pressed *anteriorly* against the two tall main anterior cusps. These two cusps were completely removed and the anterior surface restored to the more common smooth and swollen enamel surface. The posterior cingulum of this specimen is also developed into an enlarged boss that could eventually be worn into one or two open lakes resembling cusps. This posterior surface was also trimmed to appear as a minor cingular cusplet worn open, as seen on the Santa Barbara P_4. The four remaining cusps were also extensively modified to appear rather heavily worn with open lakes on each. The lateral profile is shaped with a higher transverse ridge across the anterior cusps and a transverse valley across the posterior cusps to simulate the aforementioned occlusal arrangement between lower and upper cheek dentitions.

Specimen SJ 94 was similarly modified for the right lower P_4. In this case, the posterior two cusps were greatly reduced, leaving only a small openly worn remnant. The four main cusps were also shortened to wide open lakes and the transverse profile developed in a similar fashion to that made on SJ 93. These modifications rendered two teeth that compare favorably to the preserved lower fourth premolar in the Santa Barbara specimen and the other mandibular *Paleoparadoxia* specimens, except for being relatively larger.

The opposing upper fourth premolars needed to appear to occlude into the posterior valleys developed on the lower P_4's. An interesting specimen, SK 33, could be considered for this position in spite of its rather small size. I believe that it is in actuality an upper fourth premolar in a heavily worn condition. It has a curved root that I believe denotes an upper tooth. If this curvature is placed so that the concave side is oriented anteriorly, the wear surface has a prominent transverse ridge that would occlude well with the lower teeth as restored. It might have originally been somewhat larger because a small part of the posterior cingulum seems to have broken away due to the extremely worn condition of that area. As far as can be determined from those few specimens that have any upper dentition preserved in place, this choice for an upper fourth premolar for the Stanford specimen is not unreasonably small because the upper premolars appear normally somewhat smaller than the equivalent lowers on several of the specimens with teeth preserved in place, namely the Izumi specimen see (Ijiri and Kamei, 1961), and the Santa Barbara skull, UCMP 147527. Therefore, it was placed without modification in the upper right fourth premolar position.

A right to left restoration was fashioned for the upper left P^4 position with a similarly worn surface, but without any breakage to the posterior cingular remnant. The restoration was made by hand-carving of a cylindrical plaster blank that was subsequently molded and cast as usual.

Specimen number UCMP 64117 is considered to be part of an upper third premolar of *Paleoparadoxia* of which only one of three original cusps remains, as described on page 99, number 4. Shapes and sizes of the two missing cusps can be surmised from the preserved adjoining surfaces on the one remaining cusp, the diameter of the remains of the cylindrical root, and the preserved occlusal wear surface. Both the Izumi *Paleoparadoxia* from Japan and the *Paleoparadoxia weltoni* specimen from Point Arena, California have three-cusp upper third premolars, so I am presuming that the Stanford specimen would have also had third premolars with three cusps, that are grown together into a sub-conical arrangement. A cast of this tooth was used without modifications in the upper right third premolar position.

A right to left restoration of UCMP 64117 was then made to fill the equivalent position on the left side. Its crown was restored with all three cusps complete so that it conforms reasonably to the upper third premolars preserved in place in the Izumi specimen but with a much more advanced state of occlusal wear. Its lateral profile repeats the centrally positioned ridge and fore and aft directed slopes that would allow this tooth to occlude with the anterior slope of the lower fourth premolar, and the posterior slope of the lower third premolar to simulate the desired upper to lower occlusal pattern.

It was then necessary to make complete restorations of both right and left lower third premolars because there are no such specimens included in the available collection. These teeth are patterned after the equivalent teeth preserved in place in the Izumi specimen. The occlusal surfaces are sculptured to indicate fairly heavy wear on the three cusps, all with wide open lakes. A rather sharp transverse ridge is prominently developed across the approximate center of each to continue the offset occlusal pattern between the lower and upper dentitions.

The last two teeth in the sequence of cheek teeth are the upper second premolars. These are envisioned to have been quite small, single-cusp, caniniform teeth that would occlude with the anterior slope of the lower third premolars. Ijiri and Kamei, in their publication of 1961,[3] claim that a small root of the upper left second premolar is preserved in the Izumi *Paleoparadoxia* skull; however, its presence cannot be detected on the fiberglass cast. An extensively worn stub in the second premolar position is also preserved in the Santa Barbara skull. Then, to fill these positions, two similar restorations were manufactured, patterned on the steeply truncated stub preserved in place in the Santa Barbara skull. A rubber mold was formed over the well-preserved root of LACM 116954. This root is incomplete; however, the full length of about two-thirds of its cross section exists. The rubber mold was formed over this preserved exterior surface only. Afterwards the two longitudinal edges of the rubber mold were sealed together, making a complete mold for a much narrower root. When cast, these restorations appear much more realistic than a purely artistic rendition could have achieved. The truncated wear surfaces were formed and positioned according to the stub of the equivalent tooth preserved in the Santa Barbara specimen.

The lower second premolars are separated from the more posterior cheek teeth by a long diastema and so do not function in the cheek tooth series. For this reason they will be discussed separately in the following section. A summary of the preceding descriptions of choices for restoration of cheek teeth in the display follows in Table 3.

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3. Shoji Ijiri and Tadao Kamei, "On the skull of Desmostylus mirabilis NAGAO from South Sakhalin and of Paleoparadoxia tabatai (TOKUNAGA) from Gifu Prefecture, Japan," reprinted from *Earth Sciences, Journal of the Geological Collaboration in Japan*, no. 53 (1961).

Table 3: Summary—Cheek Teeth Restorations

Upper Cheek Dentition, left:	Upper Cheek Dentition, right:
P-2 Root of LACM 116954 modified	P-2 Root of LACM 116954 modified
P-3 Right/left restoration of UCMP 64117	P-3 UCMP 64117
P-4 Right/left restoration of SK-33	P-4 SK-33
M-1 LACM 116951 root	M-1 LACM 116951 root
M-2 SJ-99	M-2 Left/right restoration of SJ-99
M-3 Right/left restoration of UCMP 111371	M-3 UCMP 111371
Lower Cheek Dentition, left:	**Lower Cheek Dentition, right:**
P-3 Restoration	P-3 Restoration
P-4 SJ-93, modified	P-4 SJ-94, modified
M-1 LACM 116951 root	M-1 LACM 116951 root
M-2 LACM 116954	M-2 UCMP 32076, type
M-3 SK-34, modified	M-3 Left/right restoration of SK-34, modified

The occlusion between the upper and lower cheek teeth, and resulting wear surfaces that were presumed and restored accordingly, are illustrated in Fig. 51.

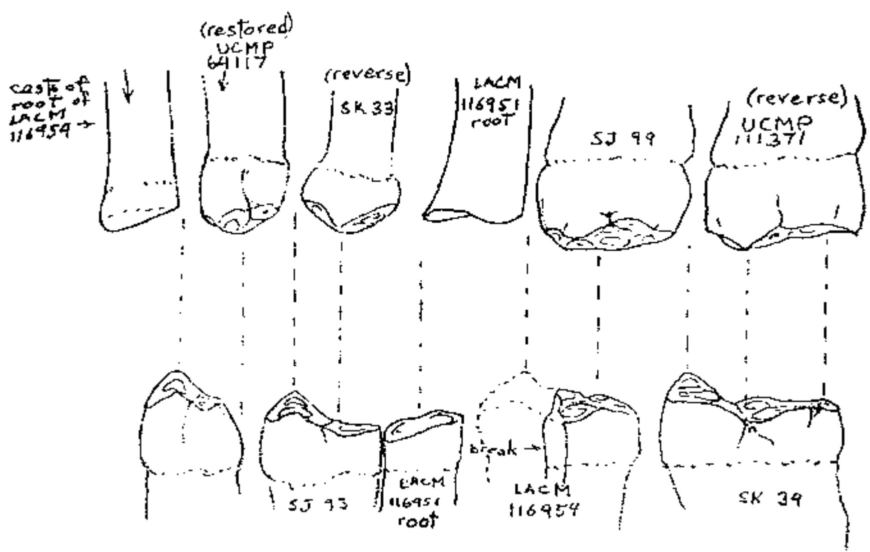

Fig. 51: Diagram showing opposing occlusion of cheek teeth as restored for the Stanford *Paleoparadoxia* mounting. Left buccal view.

The Snagging Tooth, Canine Tusks, and Incisors

The anterior-most premolar in all known *Paleoparadoxia* mandibular specimens is a caniniform tooth that is situated so that a significant diastema exists, both between it and the canine tusk and between it and the third premolar, as mentioned earlier. This tooth is not opposed by any tooth in the upper jaw so it could hardly have been used in the mastication of food. The only purpose that I have been able to conceive for it would be to have served as a convenient hook to help prevent the slippery sea plants from slipping away at every mouthful. For this reason I like to call it the “snagging tooth” (see Fig. 52).

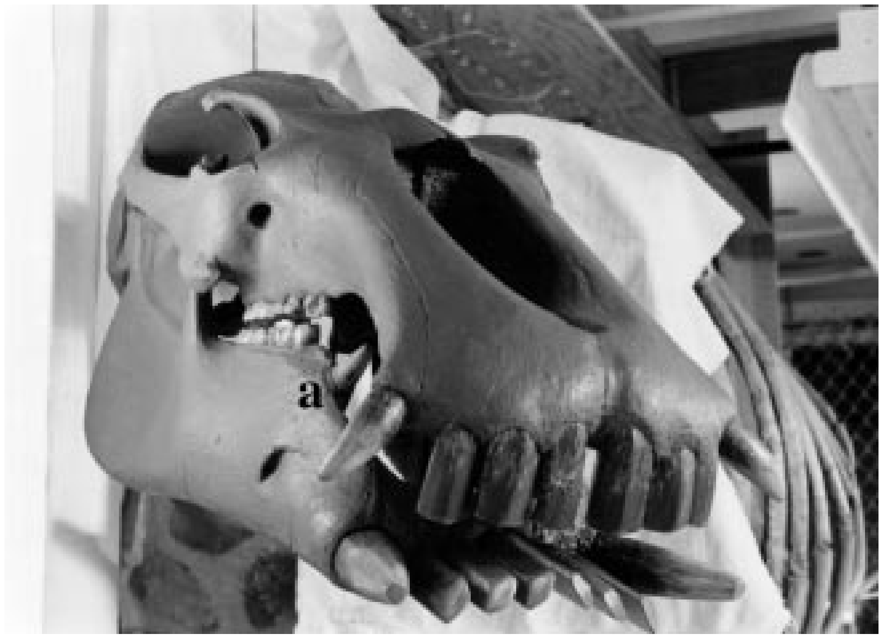

Fig. 52: The “Snagging Tooth”—the right lower P_2 visible at (a).

This tooth is completely preserved in place in the Mission Viejo right mandibular ramus and in both sides of the mandible in the Izumi specimen; its compete root is preserved in our Stanford specimen, and an alveolus for it is preserved in the Point Arena specimen. Because the complete root remains in our specimen, its cross section at the break is visible and measurable, and its position and size are visible and measurable by x ray. The root is quite long, extending down almost to the surface of the horizontally placed tusk root, and is very robust in diameter and curved, with the convexity anteriorly oriented. These features reinforce my opinion that the function of this tooth could have been to serve as a strong hook for an aid in cropping underwater vegetation for feeding.

I ultimately decided to restore the entire crown for the right side of the mandible only and to leave the exposed cross section of the broken tooth on the left as it appears in the actual fossil specimen. The broken surface was painted to the exact appearance of the original. The restoration for the right snagging tooth is designed with an enamel surface that terminates proximally in an indefinite thinning-out manner, exposing some length of root material above the opening of the alveolus. It is inserted at a rather acute angle so that its crown is directed posteriorly and towards the center of the palate. It is given a truncated wear-facet with an open lake at the tip. This facet is presumed to have been formed by repeated contact with the domed roof of the mouth, which may have had a somewhat horny surface such as is developed in extant ruminants, against which their lower incisors occlude.

Contrary to the decision against the restoration of the broken-away crown of the second premolar, it seemed better to restore all four of the canine tusks even though the fossil mandible retains only the butt end of the left lower tusk barely extended beyond the bone of the dentary. It was felt that the general appearance of the completed display would be much more impressive with all four tusks included. The four original plaster blanks that had been cast in the very beginning of the project were used. The primary model used in the designing of the upper tusks was the Santa Barbara skull. Although they are only partially preserved in that specimen, their general size, direction, and curvature can be easily estimated by inspection of the outer surface of the rostrum. Here, enough of the upper tusk root in the bone is visible. The Santa Barbara skull is the closest specimen in size, age, and stage of development to the Stanford specimen, and therefore the most logical one to follow for our restorations.

In the case of the lower tusks there were two good models to use, the complete tusk preserved in place in the Mission Viejo right dentary and also the one preserved in the Reinhart mandible, UCMP 40862. Both of these specimens are of comparable dimensions and evolutionary advancement to our Stanford fossil and therefore serve as good models for our restorations of the lower tusks. In both specimens the tusks are enamel-covered all the way around the tapered shafts, except near the tips where the enamel is broken or worn away. In both cases the very tip ends are truncated by a slightly underslung wear-facet. Even though both are more slender, I was bound to maintain the large diameter of the tusk root preserved in the Stanford specimen.

Thus, the originally cast plaster blanks for the two lower tusks were modified to conform to these models. Their size, amount and orientation of curvature, and direction could be inferred from the Stanford specimen itself. The modifications included reducing the outside diameters to a more slender profile adjusted in such a way as to form an apparent curvature directed laterally so that the two tusks would diverge when mounted in position. The truncated, underslung wear-facets were formed on each tusk tip. The cross section of the preserved tusks and also of the exposed broken stub in the specimen appear somewhat sub-circular, the dorsal perimeter being less curved and the lateral perimeter more curved. These variations in curvature form several slight but visible longitudinal ridges that were also made on the restorations.

Along each of the outside lateral surfaces another wear-facet was formed to indicate continued abrasion against the opposing upper tusk. These wear-facets are envisioned to have been formed in a similar manner to those seen on the tusks of domestic and wild pigs. Each of these facets was made about 3 inches long, starting at the truncated tusk-tip and continuing along the tusk beyond the base of the enamel, dorso-laterally oriented. An opposing wear-facet was also formed along the inner ventro-medial surface of each upper tusk. The upper tusks being shorter, their facets are only about 2 inches long. Even though such wear-facets formed between opposing tusks are not detectable on the few preserved specimens available to us, Repenning felt strongly that they should be indicated in our mounting.

The Santa Barbara skull being the only available specimen of comparable size and advancement, we could not determine whether or not the upper tusks should also be restored with enamel tips. The preserved skull of the Izumi specimen, NSMT P-5601, is the only one to which we could refer for the upper tusk surface. Ijiri and Kamei[4] describe this tooth as having an

4. See the reference on page 120.

enamel-covered tip. We could not consider this more primitive form to indicate the likely existence of enamel on the upper tusks of the more advanced form; however, a decision was made to indicate an enamel surface for the upper tusks mostly for artistic reasons. It would look nicer.

For incisors we had two good specimens for reference. A worn distal fragment of the first upper right incisor was fortunately preserved and collected at the SLAC locality in 1964. I made the identification myself by reference to the fragmentary remains of I-1 in the Santa Barbara fossil skull. The original plaster casts for all the upper incisors had been modeled after these partially preserved teeth in that same specimen, and our restored skull had been shaped with some rudimentary alveoli to accommodate them. The final wear surfaces at their tips were to be formed when more accurate information might become available.

The second specimen of an incisor that proved to be very important is an undocumented incisor fragment in the possession of an amateur collector, Mike Long, of Santa Cruz, California. I was very fortunate in locating and being allowed to borrow this specimen for our lower incisor restorations, as it consists of the distal approximate 1 inch of shaft, including the terminal wear surface. Detail of both dorsal and ventral surfaces, as well as the truncation at the anterior end, are perfectly preserved. By comparison with the Santa Barbara skull it is easily identifiable as the distal-most section of a right first lower incisor of *Paleoparadoxia*, and I have given it the identification number ML-12. It was collected in one of the Santa Cruz County gravel pits.

There are also several separate incisor specimens that were uncovered in close association with the Mission Viejo specimen and considered to have belonged to it. Four of them are narrow (about 1 inch wide) and straight, indicating them to be mandibular incisors, and three of those have the usual bevelled terminal wear-facets preserved. There is also one strongly curved upper incisor that retains the terminal wear truncation. None of these specimens are as well preserved as the two incisor fragments described previously, but most of the same features are detectable on them. However, the terminal wear-facet on the one upper incisor is quite differently developed from that preserved on the Stanford *Paleoparadoxia* incisor. This facet is formed on the outer anterior surface, rather than the terminal end, making it appear to have been curving back into the mouth when occluded with the opposing lower incisor, whereas the Stanford incisor described above has the occlusal wear on the down-directed distal termination. I have assumed that this unusual upper incisor exhibits another symptom of the pathological condition of the Mission Viejo individual.

None of these Mission Viejo incisors, nor any of the other incisor specimens seen, have any enamel on their surfaces. It is therefore assumed that in at least the more advanced *Paleoparadoxia* species there was no enamel developed on any of the incisor teeth. Therefore, the restorations prepared for the *Paleoparadoxia* mounting are presented without enamel surfaces and are finished according to the appearances of the two specimens described first.

The next step, after having made all the necessary choices, restoration, and modifications for all the tooth casts described above, was the preparation of the skull and dentaries with the required "alveoli" in which the teeth would be finally mounted. To accomplish this task the mandible and the skull were again removed from the display so that the alveolar surfaces would be available. It was decided that all the cheek teeth, both upper and lower, could be sufficiently held in place with uncolored Guck as long as the insertion holes were well fitted. These holes were formed along the maxillary alveolar surfaces with the skull resting upside down on a rolling cart. To test the fit with the mandibles, it would be easier to mount the latter unit upside down on the skull than the other way around because of the extreme weight of the skull. It was some disadvantage to assess the appearance of the fit between upper and lower teeth in this reversed orientation, but it was deemed preferable to lifting the heavy skull for each test.

First, some modifications to all the alveolar surfaces for the cheek teeth were necessary; in particular, quite a lot of material had to be trimmed from the right mandibular restoration along the alveolar section because it was somewhat thicker and higher than the left original cast. Each of the right cheek tooth casts had been prepared with about 1/2 inch more or less of root for insertion into the dentary, so holes were then made in the right side of the mandible, right side up, to accommodate them. The holes were begun with steel router points used in the flexible shaft rotary tool. They were then carefully fitted to each tooth by hand, using the pocketknife, small screwdriver, and other small tools. To accommodate the fit between the cast tooth and its intended hole, a suitably trimmed small piece of carbon paper would be placed in the hole to mark high spots or conflicts. The carbon paper could be turned either way to mark either the tooth or the hole until a perfect fit would be achieved. This process was not necessary for the left dentary because the original alveoli were available in the casting. The roots of the teeth chosen for each position were modified to fit into the original alveoli. When all of these preparations were completed, a way of temporarily holding the tooth casts in position, even when the mandible would be turned upside down for testing the occlusion with the skull, was needed. This was accomplished with the use of a plastic adhesive intended for mounting posters on painted walls or other similar uses. This product is called UHU Holdit and is available in stationery and hardware stores. It can be applied and subsequently removed without marring the surfaces.

The maxillary surfaces and alveoli were prepared in a similar manner except with the skull upside down. All of the work of fitting and preparation for insertion of the teeth was completed before the tooth casts were painted. It then became desirable to remount the skull onto the skeleton, so the upper cheek teeth were finalized and painted, and then installed in place before the mandible was completed. However, in case the mandible would need to be returned to its final position, the unpainted lower cheek teeth could be placed in their prepared alveoli because they would hold in position by gravity.

A more complicated system was resorted to for safely anchoring the larger, heavier, and more vulnerable tusks and incisor teeth. It was felt that each of these joinings should be reinforced with a sturdy metal bar inserted up into the bone cast and down into the tooth cast, and square or rectangular material should be used to prevent rotation. So that the final position of each tooth could be viewed, estimated, and judged in each case, and also in comparison to each other, the work was done with the head pieces in place on the mounting.

Before beginning, a “safety net” was devised and installed below the anterior part of the head to minimize the danger of breakage to any tooth cast that might accidentally drop. This was a “Mickey Mouse” arrangement that used an old sweater, tied from the waist to one side and below the rostrum, and tied from the sleeves below the other side of the rostrum. Paper clips, “alligator” clamps, and string were used, and the device was held open laterally with paper towel rollers that would not cause damage to a falling cast. This inelegant device served its purpose.

The alveoli for all of these teeth needed some advance preparation, routing and shaping for the desirable fit, and also some careful trimming was needed on the inserting “root” ends. These processes were accomplished with colored chalk, as previously described. Assessment of the results was made frequently by the use of UHU Holdit.

Square reinforcing rods of 1/2-by-1/2 inch aluminum stock were used in the two upper tusks and the right lower tusk. The holes for them were originally drilled with a small round drill and then enlarged to square by hand for a good fit. Because the left lower tusk was to be attached to the smaller butt end of the broken-off preserved tusk, a rectangular-shaped rod was used in it. The tusk restoration had been fashioned to fit around and over the original butt end. This strut was cut from the end of an aluminum sheet 3/8 inch thick. The cross section then measured about 3/8-by-5/8 inch. All four of these reinforcing bars extend more than 1 inch of depth into each of the adjoined pieces. Before permanently installing them, small nicks were made at random along their 90° edges on the end sections that would be inserted into the prepared holes, to provide added grasping power by the Guck adhesive, as was described previously. Similarly, 1/4-by-1/8 inch steel bars were used to reinforce the attachment of all the upper and lower incisors [see Fig. 53 (a) and (b)].

Figure 53(a)

Fig. 53: Method used to attach lower incisors and tusks: (a) Mandible in lower view showing prepared alveoli and (b) array of incisors and tusks with prepared slots cut, metal reinforcing bars, and tools.

Before any of the teeth could be permanently mounted in place, they needed to be painted. The upper cheek teeth were completed and installed some weeks in advance of the remaining teeth, so it was necessary to again use a color system that could be satisfactorily reproduced for a perfect match from batch to batch. Different colors would be needed for indicating enamel surfaces, dentine surfaces, root surfaces, and cementum. The enamel surfaces of fossil teeth vary greatly in color according to the chemical make-up of the surrounding matrix in which they were deposited. Even the small selection of fossil *Paleoparadoxia* teeth available to us vary in color from white to black and various shades of tan and brown. To simplify color matching and mixing, I made the practical decision to mix various amounts of black acrylic paint with white to give a selection of grey tints. Perhaps a more realistic coloration would have been achieved by the addition of some brown, but that would have required a more complicated formula. The grey colors have resulted in a somewhat unnatural silvery look, but I am not dissatisfied because these colors increase the contrast between teeth and bones, serving to rather dramatically highlight the bizarre dentition of these animals.

Four tints of grey were used on the enamel surfaces to replicate the mottled colorations, highlighted sparingly with white and black. The root color was mixed to a yellowish tan undercoating that would be lightly rubbed over with a very thin solution of brown paint to accentuate the surface sculpturing. The open lakes on the occlusal surfaces were painted with these same root colors. The cementum, which appears to be preserved on some of the collection of fossil teeth, is represented in a dark brown color. All of the paints used are water-based acrylic, and a water-based acrylic glossy varnish was used only on the enamel surfaces. It was applied in two coats after the grey colors would be quite dry.

As mentioned earlier, it was decided to represent all four tusks as having enamel-covered tips. These four teeth were made having a longitudinally grooved surface as they erupt from the bone. The grooves can be seen on the remaining exposures of surface detail of the tusk preserved in the Stanford *Paleoparadoxia* mandible, and they are closely spaced, very narrow, shallow, and somewhat irregular. Such grooves were sculpted on all four plaster tusks, starting from the bases in the bone and gradually wearing to smooth along the length of the tusk shafts. This is intended to indicate that the grooves would wear off smooth in time. The grey paints used to indicate these enamel surfaces were applied by alternating darker with lighter shades in delicate streaks to highlight these striations. The base sections without enamel are painted dark brown with light brown highlights on the striations. The description of the preserved tusk in the *Behemotops emlongi* specimen, USNM 186889, published by Domning, Ray, and McKenna, 1986, provided the basis for this appearance of the tusks. To quote:

> "The exact proximal limit of the enamel crown is difficult to define because the deposition of enamel apparently terminated irregularly in streaky continuations of longitudinal ribs and wrinkles, which are apparent on the crown wherever wear facets or polishing have not removed them."[5]

The terminal and lateral wear facets on the tusks are painted a rusty brown with yellowish highlights, as are the terminal wear facets and dorsal surfaces of the lower incisors. The lower incisor teeth were painted to conform with the coloration of specimen number ML-12, after which they have been patterned. This specimen has a lighter-colored ventral surface, somewhat streaked with dark specks and blotches. The dorsal surface is a darker brown color with some lighter-colored streaking. All of these streaks have a longitudinal trend. The terminal facet gives a view of the internal structure. There appears to be a thick horizontal core in the center of the shaft, and the tooth material is deposited in delicate thin layers over this core which gradually builds up to complete the thickness of the tooth. These layers can be seen something like tree-rings in the surface of the wear-facet. It is also possible to make out some of these details in the broken incisors that remain in the Santa Barbara specimen, and also on some of the other fragmentary incisor specimens collected from the Santa Cruz County gravel pits. These details were indicated with some difficulty on the lower incisor restorations. The colors used were some that had already been mixed for other parts of the display for consistency. On the undersides, the ventral surfaces, the light brown highlighting color was applied in an even coat; then, delicate longitudinal streaks were rather randomly painted on, using a rusty-brown color. The terminal facets and dorsal surfaces are coated evenly with the rusty-brown paint, which is gradually blended to dark brown at the base in the same manner as on the four tusks. And like the tusks, the dark brown parts are delicately streaked with the light brown highlighting color. The growth rings at the terminal truncation are indicated with the yellowish highlighting color. The narrow central core of the incisors appears as a wavy line that is drawn across the facet with black India ink.

Considering that a terminal fragment of one upper first incisor was discovered in association with the Stanford *Paleoparadoxia* specimen, the upper incisors needed to be painted according to its preserved coloration. The specimen is dark brown on all its surfaces with delicate longitudinal striations discernible on the outside surface, and similar wavy striations latitudinally developed across the inner surface. The anterior grooved surface has yellowish rusty highlights and the posterior surface is highlighted in whitish wavy streaks. As closely as possible, the cast of the preserved section of the tooth was painted as the original, using the dark brown color as the overall base color. The anterior surface is highlighted with the yellowish and light brown streaks, and the inner surface markings are all executed with the light brown color. The terminal wear facet also

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5. Daryl P. Domning, Clayton E. Ray, and Malcolm C. McKenna, "Two new Oligocene Desmostylians and a discussion of Tethytherian systematics," *Smithsonian Contributions to Paleobiology*, No. 59 (1986).

has barely visible laminations in evidence, and these are indicated with the yellow color as was done on the lower incisors. This cast of the distal incisor fragment had previously been permanently plastered to the restoration made for the proximal part of the tooth, rendering a complete tooth for mounting in the display. The restored part, as well as the other five restorations of upper incisors, were all painted in a similar manner as that described for the fragment. Even though the coloration of the upper incisor fragment that we necessarily had to follow seemed at first very different from the coloration of our only lower incisor specimens, by using the same palette of colors sufficient homogeneity of appearance was achieved (see Fig. 54).

The mandible was again removed for the permanent installation of all the teeth (see Fig. 55). After the cheek teeth were cemented in place, using Guck as before, touch-ups were made to the seams around the alveolar edges. These narrow areas were painted dark brown in simulation of cementum holding the teeth in place. Such touch-ups had previously been made around the upper cheek teeth. The incisor and tusk casts were first reinforced by the permanent insertion of their prepared reinforcing bars, cemented in place with Guck. The upper tusks and incisors were installed in place on the mounting, but their lower equivalents were mounted in the mandible on the worktable. Because the insertion of the incisors into the left dentary would require quite a lot of additional restoration of the broken-away sections of the ventral alveolar borders, it was necessary to have these areas available to hands and eyes. It was also necessary to be able to build up the thickness of the Guck gradually to prevent it from sagging out of place while still soft. When completed, the restored surfaces were suitably ornamented with cracks, roughness, pores, etc., to simulate the bony surface and painted with the plain brown base color without rusty highlights.

Fig. 54: Upper incisors and tusks—posterior view (viewed from the interior of the mouth).

Fig. 55: Mandible in ventral view with incisors and tusks. Photo also shows restoration of the incisor alveoli on the left side and of the sympheseal region.

With all mandibular teeth permanently in place, the mandible unit was replaced under the skull and the two screws tightened to complete the *Paleoparadoxia* skeleton mounting, on May 14, 1993, after 24 years of effort.

Moving and Final Assembly

Among the complications inherent to the construction of this fossil skeleton mounting was the engineering necessary to provide for moving the structure from the basement workroom, where it was originally created, into its final display case to be constructed in another building about 1/4 mile distant. It was decided that it would be foolhardy to try to move it as a complete unit, for the vibrations of the suspended limbs would surely result in some damage. For this reason each of the four limbs, the skull and jaws, tail, hyoid arch, etc., were designed to be removable and replaceable with one or several screws in each case. Two large packing crates built of wood for another SLAC project were reserved for this.

The plan was carried out as follows:

1. The two large wooden crates were prepared with a generous supply of styrofoam “popcorn” packing bits, covering the bottom surfaces well.

2. The hyoid arch was removed and carefully packed in a small cardboard box with a sufficient amount of styrofoam bits to protect it well. The screws and other hardware were packed in a small zip-lock bag and placed in the same box that held the hyoid arch. This box was then put into one of the two large crates.

3. The mandible was removed from below the skull and placed in the smaller of the wooden crates, along with its two screws in a marked zip-lock bag. The skull was then removed and also packed in the smaller crate, as well as the first five cervical vertebrae and their cork separators.

4. The tail unit was removed next and packed in a smaller cardboard box first so that all the loose pieces were kept together. This, too, was then packed in one of the two wooden crates.

5. The four limbs were removed, one at a time, with several people working together. Each one needed to be carefully handled because the small amount of flexibility that remained in the steel support structure might have twisted the pieces sufficiently to crack out some of the plaster material that surrounds the locking pins. The four limbs were placed individually in the larger crate, for these units with bent joints needed the most space. All four limbs fitted into the box with a sufficiently large amount of styrofoam bits to completely protect each unit from the others.

6. The two pelvic units were removed by pulling the two locking pins from each one. At this point new locking pins were cut from 1/8 inch steel stock, such that each one was short enough to be concealed in its proper position when the skeleton would be reassembled. Each of these pins was packed in a separately marked bag and included with the pelvic units. These last two pieces were packed into the larger wooden crate over the four limbs that had been well buried below with styrofoam bits.

7. The crates were completely filled with more packing material and covered with heavy paper in preparation for the move.

8. The basic remaining unit, consisting of the spinal column and rib cage that had been permanently mounted on the square steel beam, was all that was left hanging by the two supporting aircraft cables. A specially prepared rack of aluminum scaffolding fixtures and pipes that had been made over from the original supporting rack for the rib cage construction stood ready. The basic skeleton unit, that is the backbone and rib cage, was then transferred from the original supporting rack to this temporary rack and supported by the same aircraft cables with the clamps moved down very close to the spinal column. It was necessary to accomplish this move in such a way that the 8 foot long cables did not mar the painted bony surfaces of the skeleton casts. Because there is a large square pillar in the room near the temporary support rack, it would have been difficult to use a fork-lift or other machine, so it was deemed preferable to make the transfer to the smaller rack by three or four strong persons carrying it.

9. The rib cage unit was stabilized on the small rack with ropes and covered with soft blankets to prevent damage during the move. All three packed units were then trucked over to the display hall.

10. Reassembly in place was performed in reverse order before the glass panes were installed on the display case, which had already been constructed. A glass door at one end had been incorporated, and two smaller cabinet doors opening into the upper concealed region were provided for access to the interior of the display case after the skeleton would be in place within. An earthquake stabilizing mechanism consisting of three hydraulic stabilizer cylinders, concealed high above the skeleton directly under the ceiling, was installed simultaneously with

the installation of the skeleton mounting. This stabilizing system was designed and built by the engineer, John Flynn, and consists of two such mechanisms positioned at right angles to and one lengthwise along the axis of the spinal column. All three systems tie into the two aircraft cable supports very closely fitted between the adjacent vertebral spines, the shortest possible distance above the square central support beam. The wires used in these connections are music wire that combines great strength with narrow gauge. They can be seen in Fig. 56, a photograph of the completed display taken by Pete Nuding.

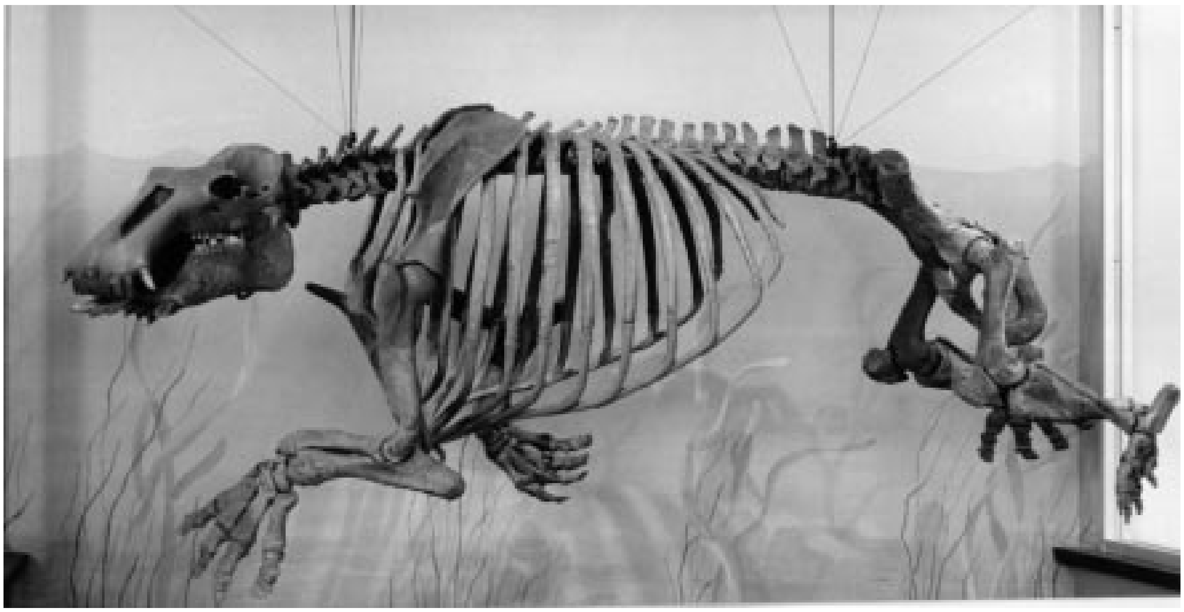

Fig. 56: The completed *Paleoparadoxia*.

Appendix A: Weight Chart — *Paleoparadoxia* Casts

Pieces	Weights		Sub-Totals		Totals
I Head	lbs.	oz.	lbs.	oz.	lbs.
1. Skull	49				
2. Upper tusks and incisors sub-total 1 and 2	1	13	50	13	
3. Mandible — left	11	4			
4. Mandible — right	13	8			
5. Lower tusks and incisors sub-total 3, 4, and 5	1		25	12	
6. Hyoid bones (5 pieces) Entire Head		9 1/2	9	1/2	77 1/4
II Neck					
1. Atlas	1	12			
2. Axis	2	5			
3. Third cervical	1	13 1/2			
4. Fourth cervical	2	3 1/2			
5. Fifth cervical	2	5			
6. Sixth cervical	2	6			
7. Seventh cervical sub-total — cervicals	1	15	14	12	
III Thoracic vertebrae					
T-1	2	1			
T-2	1	14 1/2			
T-3	1	9 1/2			
T-4	1	9			
T-5	1	7			
T-6	1	5 1/2			
T-7	1	7			
T-8	1	10			
T-9	1	8 1/2			
T-10	1	9 1/2			
T-11	1	9 1/2			

Pieces	Weights		Sub-Totals		Totals
	lbs.	oz.	lbs.	oz.	lbs.
T-12	1	10			
T-13 sub-total — thoracics	1	10 1/2	21	—	
IV Lumber vertebrae					
1. first lumbar	1	9 1/2			
2. second lumbar	1	10			
3. third lumbar	1	10			
4. fourth lumbar	1	14			
5. fifth lumbar	2	2			
6. sixth lumbar	2	1 1/2			
7. seventh lumbar sub total — all lumbars	1	12	12	11	
V Remaining vertebrae					
1. first sacral element	2	8			
2. second sacral element	3	13			
3. caudal vertebrae, seven elements sub-total 1, 2, 3		8	6	13	
Entire Spinal Column II, III, IV, V					55 1/4
VI Right front limb					
1. scapula	11	12			
2. humerus	15	10			
3. radius	4	8			
4. ulna sub-total 1, 2, 3, and 4	8	2	40	—	
5. carpal bones — 6 elements	2	5	2	5	
6. first metacarpal (II)		13 1/2			
7. second metacarpal (III)	1	7			
8. third metacarpal (IV)		15 1/2			
9. fourth metacarpal (V) sub-total 6, 7, 8, 9		14	4	2	
10. toes — three phalanges for first digit (II)		7			

Pieces	Weights		Sub-Totals		Totals
	lbs.	oz.	lbs.	oz.	lbs.
11. second digit (III)		6			
12. third digit (IV)		7			
13. fourth digit (V) sub-total 10, 11, 12, 13		7	1	11	
14. sesamoids (missing)	0				
Entire right front paddle			8	2	
Entire right front limb — VI					48 1/8
VII Left front limb					
1. scapula	9				
2. humerus — proximal section	6	10			
3. humerus — distal section	9	8			
4. radius	4	14			
5. ulna sub-total 1, 2, 3, 4, 5	6	4	36	4	
6. carpal bones — six elements	2	1 1/2	2	1 1/2	
7. metacarpal II		13 1/2			
8. metacarpal III	1	6			
9. metacarpal IV	1	—			
10. metacarpal V sub-total 7, 8, 9, 10		12 1/2	4		
11. three phalanges for digit II		5			
12. three phalanges for digit III		7			
13. three phalanges for digit IV		6			
14. three phalanges for digit V sub-total — toes 11, 12, 13, 14		6	1	8	
15. sesamoids		1 1/2		1 1/2	
Entire left front paddle			7	11	
Entire Left Front Limb — VIII					44
Total weight of pectoral girdle VI and VIII					92
VIII Sternum plates (front to back — 1 to 4)					

Pieces	Weights		Sub-Totals		Totals
1. First right	1	8			
	lbs.	oz.	lbs.	oz.	lbs.
2. first left	1	15			
3. second right	1	5 1/2			
4. second left	1	12 1/2			
5. third right	1	2 1/2			
6. fourth right		12			
7. fourth left sub-total entire sternum	1	6 1/2	9	14	
IX Ribs — 14 pairs — one to 14, anterior first					
1. first pair	4	12			
2. second pair	3	12			
3. third pair	4	12			
4. fourth pair	5	—			
5. fifth pair	5	4			
6. sixth pair	5	—			
7. seventh pair	5	—			
8. eighth pair	4	12			
9. ninth pair	4	14			
10. tenth pair	4	4			
11. eleventh pair	4	—			
12. twelfth pair	3	8			
13. thirteenth pair	3	—			
14. fourteenth pair sub-total — all ribs	1	12	60	—	
Total rib cage — ribs and sternum					69 7/8
X Pelvis					
1. right pelvic element	18	4			
2. left pelvic element sub-total — entire pelvis	18	8	36	12	36 3/4

Pieces	Weights		Sub-Totals		Totals
	lbs.	oz.	lbs.	oz.	lbs.
XI Right rear limb (excluding pelvis)					
1. femur	15	12			
2. tibia	9	4			
3. fibula		11			
4. patella sub-total 1, 2, 3, 4	2	14	28	5	
5. Tarsal bones — astragalus	1	6			
6. calcaneum	1	13			
7. remaining three tarsals	1	4			
8. metatarsal II		5			
9. metatarsal III		6 1/2			
10. metatarsal IV		11			
11. metatarsal V sub-total 5 through 11		11	6	8 1/2	
12. three phalanges for digit II		6 1/2			
13. three phalanges for digit III		8 1/2			
14. three phalanges for digit IV		9 1/2			
15. three phalanges for digit V		7 1/2			
16. sesamoids (8 pieces)		4			
Entire right rear paddle			8	12 1/2	
Entire Right Rear Limb					37 1/4
XII Left Rear Limb (excluding pelvis)					
1. femur	13	4			
2. tibia and fibula	11	—			
3. patella sub-total — 1, 2, 3	2	12	27	—	
4. tarsal bones — astragulus	1	5			
5. calcaneum	1	14			
6. remaining four tarsals	1	4 1/2			

Pieces	Weights		Sub-Totals		Totals
	lbs.	oz.	lbs.	oz.	lbs.
7. metatarsal II		5 1/2			
8. metatarsal III		9			
9. metatarsal IV		10 1/2			
10. metatarsal V sub-total — 4 through 10		11 1/2	6	12	
11. three phalanges — digit II		6			
12. three phalanges — digit III		9			
13. three phalanges — digit IV		9			
14. three phalanges — digit V		8			
15. sesamoids		5			
Entire left rear paddle			8	1	
Entire Left Rear Limb					35 1/8
Total weight of pelvic girdle — X, XI, XII					109 1/8
Total weight of complete skeleton					403 1/2

Appendix B: Modifications Made on the Cast Restorations

I. Right Forelimb

1. *Manus* — modified restored carpal elements to allow more flexure in wrist. Removed material from most articular surfaces of: *unciform*, *trapezoid*, *trapezium*, the proximal articulation of *metacarpal V*, and the articular surfaces of the *magnum* section of metacarpal III.
   In detail:

   a. *Unciform* — modified on proximal and distal surfaces by removal of some thickness of plaster to conform to the shape of left preserved unciform, and to allow greater rotation of wrist into a more flexed position.

   b. *Trapezoid* — proximal articulation deepened.

   c. *Magnum part of metacarpal III* — also reduced.

2. *Manus, second phalange* — articular surfaces of all three segments of this toe were somewhat modified to improve the articulation of the joints (removal of plaster with sandpaper); also, the proximal articulation of the first segment was trimmed to allow this toe to lie closer and more parallel to Phalange III.

3. *Ulna* — distal articulation slightly reduced to allow rotation of the cuneiform to the posterior-most region of the joint surface for a more flexed position. Further modified along the contact surface with the preserved radius to provide an improved fit (some material removed, some added).

4. *Humerus* — distal joint surfaces were modified to allow smooth rotation of the elbow joint (material removed).

5. *Scapula* — some thickness of plaster was added to the under-surface at both the proximal and distal edges, worked into a roughened texture with brush bristles. This was needed to increase the concave curvature of this inside surface in accordance with the preserved left scapula.

6. *Shoulder joint* — also removed some thickness from ventral (underside) and medial edges of the glenoid cavity of the scapula for a more spherical shape (to correct distortion that occurred to the clay restoration before casting). Also removed some material from the corresponding surface of the humerus head.

II. Right Rear Limb

1. *Femur* — head of the femoral joint rounded to fit preserved acetabulum, particularly the ventral and dorsal areas of the spherical surface. Also, refined the shape and surface decoration to approximate contours of the preserved left femur, particularly around the

epicondyles and the lesser trochanter. Some material later removed from patellar articulation surface to improve fit with preserved patella.

III. Cervicals

1. *Atlas* — articular surfaces for the occipital condyles were deepened by removal of some material (flattening of this part must have happened to the clay restoration before casting).

2. *Axis* — a number of modifications were made to this piece, as listed below:

   a. Posterior articular surface, left side, was reduced in thickness by at least 1/16 of an inch and smoothened to permit closer articulation with the third cervical in required left-facing position of the skull. As originally sculpted there was insufficient allowance made on the cervical restorations for turning the head from side to side.

   b. Left transverse process modified to improve its articulation with C-3, and to increase the appearance of an osteoarthritic condition.

   c. The neural opening was filled with plaster to accommodate the square hole for the central support beam.

   d. Left posterior surface reduced by at least 1/16 inch of material and smoothened.

3. *Third cervical* — centrum was modified in several ways: by beveling the ventral parts of both anterior and posterior edges, along with removal of nearly 1/2 inch of thickness from the lower anterior face to make it appear more parallel to the posterior face. All four upper articular surfaces, cranial and caudal, were smoothened for better fit.

4. *Cervicals 4, 5, and 6* — up to 1/4 inch of thickness was removed from the centra of all three of these pieces to give the neck a more appressed appearance, such as I had noted on the Point Arena specimen, then readjusted the positions of all cervicals accordingly.

5. *Fourth cervical* — in addition to the same modifications as were made on the third cervical, noted above, a small lump on the anterior edge of the left transverse process was removed to eliminate conflict with C-3 in the looking-to-the-left position.

6. *Fifth cervical* — as with C-3 and C-4, both anterior and posterior centrum faces were modified to be approximately parallel and bevelled at their extreme edges. Both posterior articulations were reduced and smoothened and the left transverse process reduced by at least 1/2 inch both posteriorly and anteriorly to prevent conflicts with C-4 and C-6.

7. *Sixth cervical* — received similar modifications as the previous cervicals.

8. *Seventh cervical* — the anterior articular surfaces were slightly deepened and smoothened.

IV. Thoracic vertebrae

1. *First thoracic vertebra* — was modified by the beveling of the ventral part of the anterior edge of the anterior centrum face and reduction of the right posterior articular surface. Further reduction was made to shorten both posterior articular processes, and also to the pillars of the neural arch to allow closer assembly with T-2 and its cranial articular surfaces. This modification appears to lengthen the neural spine.

2. *Second thoracic vertebra*, a restoration except for the neural. Reduced thicknesses and widths of both anterior articular processes to improve fit with T-1.

3. *C-7 and T-1* — further modifications were made to improve the fit between these two vertebrae:

    a. Reduced the thicknesses of their mutual articular surfaces and both centra.

    b. Carved away some thickness around the bodies of both centra for improved fit. The centrum of T-1 was thicker on the right than on the left, which was corrected by this adjustment.

    c. Other minor adjustments were made to the articular surfaces, neural arches, and rib facets on both of these restorations.

V. Ribs

1. *All incomplete ribs* — mostly from the right side, needed to be plastered together with their respective restored parts, which all had to be modified by a greater or lesser degree for a perfect fit.

2. *Left second rib* — the restored distal half of this rib received some additional plaster along the medial edge in accordance with the flaring preserved on the two second ribs of the Japanese Izumi specimen. This flare is thin and somewhat concave to the anterior.

    a. Also reduced the restored head of the rib for an improved fit with the vertebral articulation.

3. *Right second rib* — modified similarly to the left second rib.

4. *Right third rib* — modified restored distal section for less curvature and overall shape to better conform to the preserved complete left third rib.

5. *Right rib number 12* — is almost entirely reconstructed, having only a small bit of the rib head cast from a preserved bone. After assembly, this rib was removed from the mock-up and plaster was added along the upper central part of its curvature to render a similar curvature and cross section as its neighboring ribs, R-11 and R-13.

VI. Right Mandibular Ramus

1. Deepened the *mental foramen* sculpted on the lateral surface to better match that structure on the preserved left half of the mandible.

2. *Symphyseal region* — modified by removal of material along the surface of the seam, most towards the posterior inter-ramal area and gradually less toward the first incisor alveolus anteriorly. The effect of the trimming brought the mandibular condyles and cornoid processes closer together and more upright to fit under the glenoid fossae of the skull.

3. *Alveolar surface for cheek teeth* — was trimmed lower by 1/4 inch or more to widen the gap between the upper and lower tooth rows. The inner and outer lateral surfaces were refinished for a more bone-like appearance and better agreement with the left side.

4. *Incisor alveoli* — had originally been incorrectly oriented and therefore needed to be re-directed to hold these teeth dipping laterally to their horizontal axes as in the preserved left side. To accomplish this reorientation the new angles were carved out of the solid plaster and the original angles filled in with Guck. These holes could then be accurately fitted to the root-stub ends of their respective incisor restorations by using blue chalk, as previously described in the text. The lateral edges of these long, flat lower incisors dip downward and their medial edges tip upward so that the aspect from the front view of the incisor row is as shingles over a hip-roof.

5. *Head of condyle* — needed to be reduced in size and height and sculpted to better conform to the shape of the preserved left mandibular condyle. The posterior margin and posterior surfaces of the ramus just below it were reduced somewhat to relieve conflict with the massive mastoid processes of the skull.

VII. Skull

1. *Right mastoid process* — was also somewhat reduced and the bony-looking surface restored. This modification was restricted to the vertical ridge along the inner (anteriorly facing) surface.

2. Both *glenoid fossae* slightly deepened and sanded smooth for an improved fit with the mandibular condyles.

3. Shallow *alveoli* were cut into the alveolar surfaces to accommodate the previously prepared cheek-tooth casts. Also, some modifications to the detail shapes and bony appearances of the outer lateral alveolar surfaces were made at this time.

4. The *alveoli* for the prepared tusk and upper incisor casts modified by removal or addition of material to permit the insertion of these teeth to their most desirable appearance. This fitting was accomplished as before, with colored chalk or small circles of carbon paper between the adjoining surfaces.

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Instructions for the Dismantling of The SLAC Paleoparadoxia Skeleton Display

Adele Panofsky

If it should ever become necessary to dismantle the Paleoparadoxia skeleton display, preparations must be made in advance to prevent serious damage.

Before beginning, a good supply of sturdy, large, and smaller packing boxes and packing materials should be at hand.

First - the real fossil specimens that are displayed on the sand below the skeleton must be removed, and each one packed in a separate box. Do this with care because they are fragile and easily damaged. Be sure to include the paper identification number with each specimen. These numbers refer to the identifications given on the outside front of the display case.

To take the skeleton apart it would be helpful to first read the assembly process described in the SLAC-PUB-7829 report "Stanford Paleoparadoxia Fossil Skeleton Mounting" by Adele Panofsky, Sept. 1998, on page 130 to have a better understanding of the structure. Taking it apart will be the reverse process.

1. First remove the Hyoid Arch by finding the two 6-32 machine screws

under the back end of the skull – one right, one left, that hold the arch in place below the skull. Pack the two screws along with the arch in its own separate box.

2. Now the mandible can be removed by unscrewing the two 1/4 x 20 bolts that hold the mandible unit under the skull. The bolts are screwed into the central square support beam. One person must hold the mandible securely while a second person removes the screws because it is very heavy. Be sure to include the two screws in the same packing box with the mandible.

3. Now the skull can be removed by sliding it forward off the square central support beam and placed in a well-padded packing box. CAUTION: The skull weighs 50 pounds! This step requires 2 persons, at least! Also, be aware that once the mandible is removed, the skull could slide off by its own weight, and be severely damaged!

4. Next the cervical vertebrae, the neck bones, can be removed, one by one, starting with the Atlas that fits up against the skull, then the cork separator; the second one is the Axis,

and the five remaining cervical vertebrae, along with the cork separators of each. It would be best to pack these seven pieces in an oblong box in their sequential order, along with their cork separators.

The Limbs

Each of the four limbs is a complete unit. As they are quite long they will require large boxes for sufficiently careful packing. They also may flex a little when being moved which could crack the plaster surfaces around the concealed pins that keep the plaster casts from sliding off the metal support rods. (See figure 14, page 33 in the SLAC-PUB-7829 report.) Two or three people will be needed for their removal, to prevent twisting as much as possible.

5. To detach the front legs, a socket wrench is needed for removal of the 1/4 x 28 button-head socket-cap screws that secure the fore-limbs to the shoulder bracket supporting device. To clearly understand these fixtures, refer to the text and illustrations on pages 70, 71, and 72 of the SLAC-PUB-7829.

These mounted limbs must be held by several persons during their removal and packing to prevent damage as stated above. If a little of the surface chips out, the white plaster will be visible, necessitating small repairs and repainting to match the surface colors.

6. Moving now to the rear of the display, first the tail should be removed. Refering to the method by which the tail is constructed, see the description on page 75 of SLAC-PUB-7829. The complete tail unit can be removed by unscrewing it from the sacrum between the pelvic bones. The support rod for the tail is threaded for more than one inch of its length, so the tail unit must be rotated counter-clockwise through many turns for removal. Note that the first caudal vertebra is loose on the rod, so it and its cork separators must be kept together with the tail unit so they will not get lost.

7. Rear Limbs.

Each rear leg can be removed as a single unit. Viewed from behind, the steel support bars from the pelvic bones can be seen extending from the pelvic joints across the top of the femur casts. The support rods that extend up through the leg mountings are each secured by 2 Allen-head bolts to the horizontal support bar. To remove the limb it must be firmly held in position by one or two persons while another worker removes the bolts. Then slide the limb <u>horizontally</u> off the support bar, avoiding twisting of the separate elements as much as possible.

8. Now the support fixtures for the two pelvic units can be seen inside the hollow of the joint where the leg units were removed. To permit the remoral of the two pelvic bones, the L-shaped support bars can be unscrewed and stored each with its leg unit --- left bracket with the left limb, and right bracket with the right limb, and including the bolts for each fixture.

9. The two pelvic elements are secured to the supporting bracket by locking pins, two in each. The supporting bracket can be seen in Figure 21 on page 45 of SLAC-PUB-7829. If these two elements are to be removed, the locking pins must be located and pushed out. Accompanying photographs showing surface details of the pin positions are to be used in locating the exact positions of these pins. They are cut from 1/8 inch steel rod. Preserve these pins.

10. The remaining spinal column and rib-cage cannot be taken apart. It is the basic element of the display. If it must be

removed from the display window, a support device needs to be constructed for it. The supporting rack that was used for the transport of the skeleton to the final showcase is shown in the two accompanying photographs. It was constructed of aluminum pipe and an assortment of aluminum fixtures available for assembling temporary scaffolding.

11. The skeleton display hangs from the overhead structure of the display case by two lengths of sturdy aircraft cable that are permanently attached in two points of the central steel supporting beam; see fig. 37, page 77 of SLAC-PUB-7829. Above the display and cocealed among the rafters are the two devices that secure the upper ends of the air-craft cables. Then a three-way stabalizing system was installed to prevent the skeleton from developing a swinging motion during an earthquake or similar disturbance. These features can be seen in the photo of the completed display on page 1 of SLAC-PUB 7829. If all of these supporting cables and wires are disconnected from above the display, they will hang down over the skeleton and could mar the surface paint. A layer of old blankets or quilts spread over the skeleton would protect

the painted plaster surfaces.

12. <u>CAUTION</u> The basic unit of the rib cage and spinal column will not fit through the glass door entrance to the display, located in left side panel. One larger glass pane would need to be removed from the frame if the entire skeleton display must be taken out. The final assembly of the skeleton mounting was completed before the glass panes were installed.

September 16, 2006

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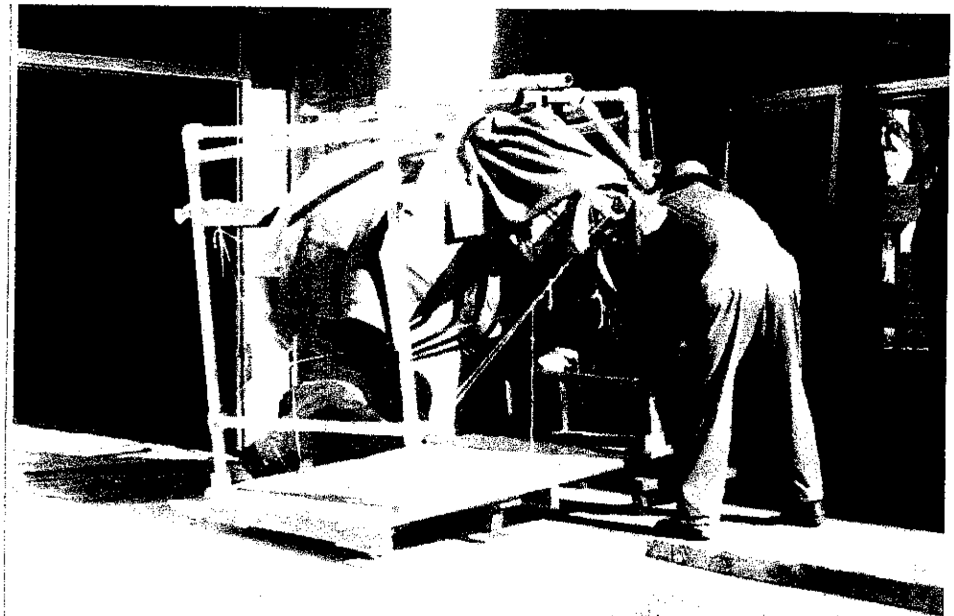
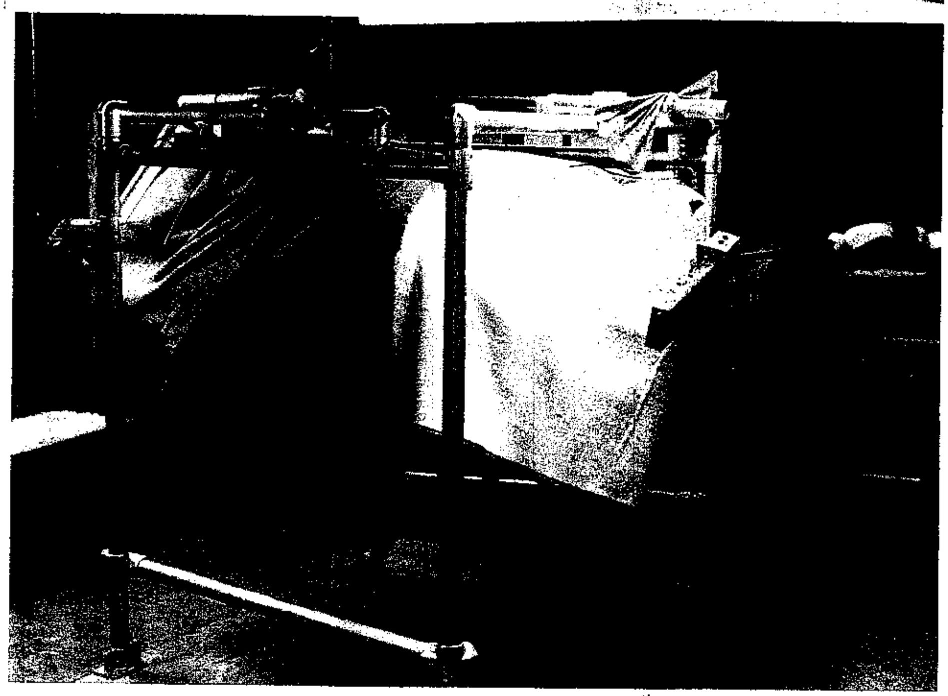
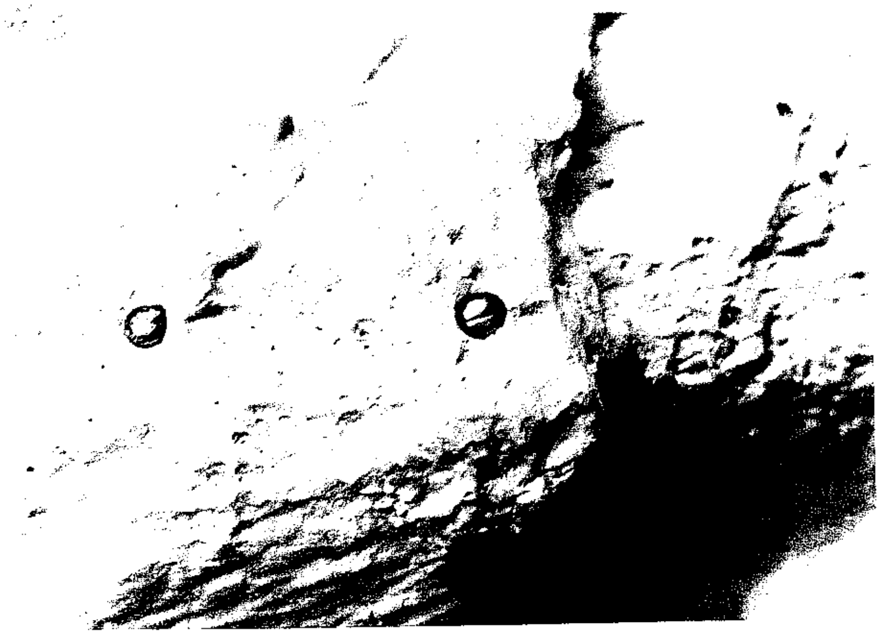
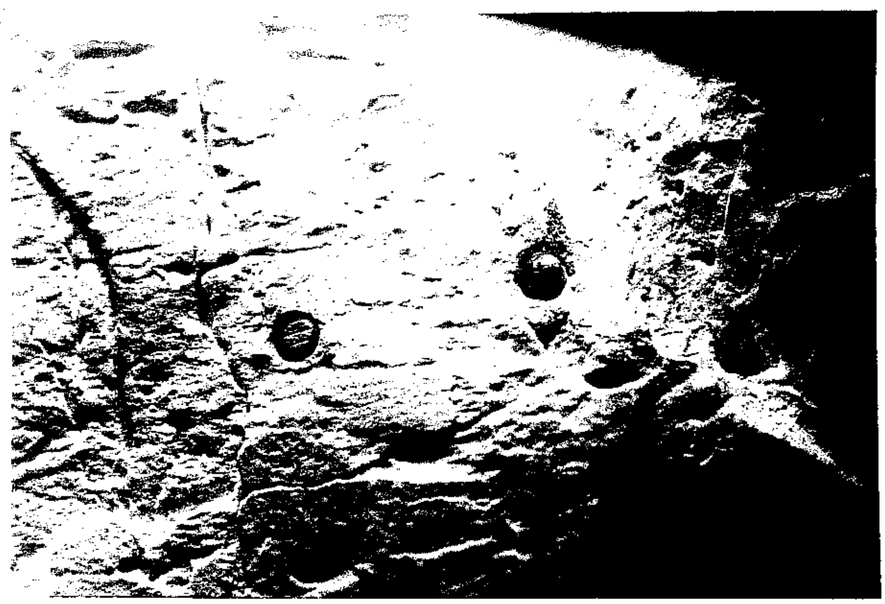




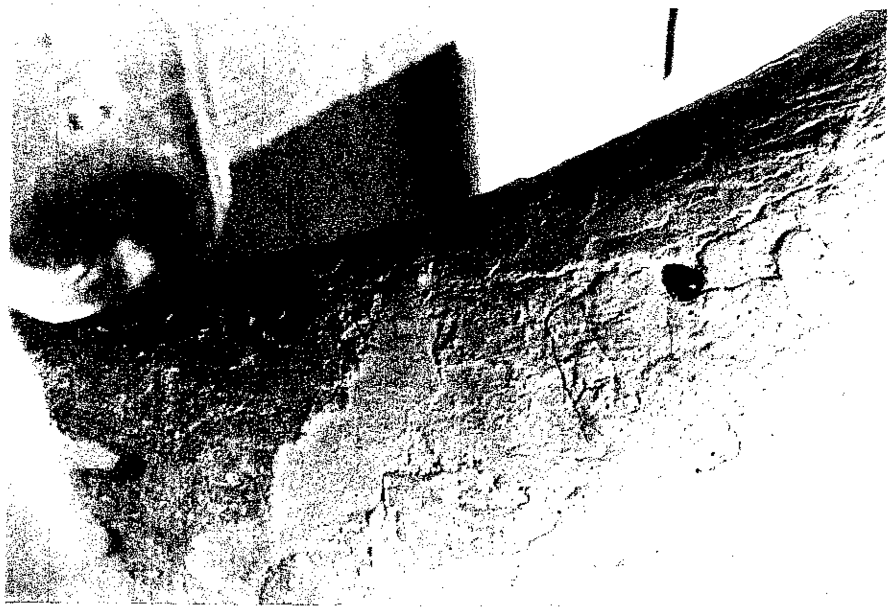
The rib-cage and spinal colunn wrapped in blankets was transported to the Visitor Center on this devise constructed of temporary scaffolding fixtures.

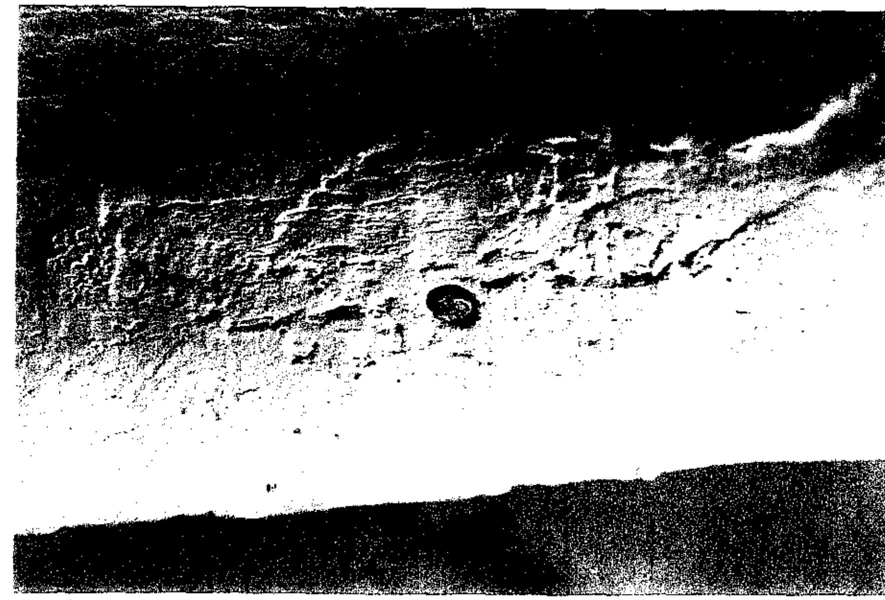




Photos to be used

to locate 2 locking pins that hold LEFT Pelvic unit on the support rod.





Photos to be used to locate 2 locking pins that hold the RIGHT Pelvic unit on the support rod.