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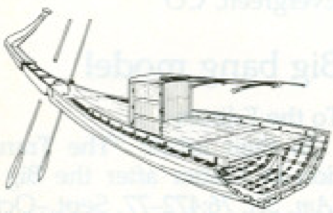
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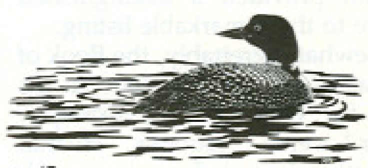
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Cover A Bengal tiger demonstrates the extreme flexibility of the mammalian tongue, one of a number of organs in which muscles use a unique biomechanics to support the movements they produce. See the article by Kathleen K. Smith and William M. Kier on page 28. (Photograph by Animals Animals/Willard Luce.)

Remote Sensing at an Archaeological Site in Egypt

Farouk El-Baz
Bob Moores
Claude E. Petrone

The Great Pyramid of Giza is renowned throughout the world, but little is known about its builder, Pharaoh Khufu of Egypt. Gossip repeated by Herodotus some 2,000 years after the pharaoh's death describes Khufu (or Cheops, as the Greeks rendered his name) as a tyrant who compelled his people to work "for his own advantage." Khufu ruled for 23 years after the death of his father Snefru, the first ruler of the Fourth Dynasty. Khufu's pyramid is the largest ever built, covering over 5 hectares and measuring 230 m along the sides and 147 m high. It is the only known monument of his reign except for a 7.5-cm miniature likeness. Tradition in ancient Egypt, however, held Khufu in great esteem.

The worship of the sun god Ra-Atum figures in the enigmatic "solar boats" depicted in tombs throughout Egypt. Even though boats abound in tomb paintings, and boat pits are considered an integral part of the pyramid complex of the Old Kingdom, Egyptologists are not agreed on the original function of the boats found in such pits. Various theories hold them to have been funerary vessels to carry the body of the pharaoh down the Nile to the burial place, solar barks in which the pharaoh might have visited the sun god Ra, or symbolic boats to accompany Ra on the voyage across the sky *(1)*. In the necropolis of Saqqara, the Pyramid of Unas, who reigned about 200 years after Khufu, hieroglyphs convey the pharaoh's hope to join the sun god in an eternal journey across the sky: "The king comes to Ra and is proclaimed king of the earth. He ascends with Atum, rises and sets with Ra and the solar barges" *(2)*. The journey would be east to west by day and west to east by night. Two pits near the pyramid of Unas may have been used to bury boats for these journeys.

> *Unique equipment and methods developed for use at the Great Pyramid of Giza make it possible to leave delicate sites undisturbed while exploring them by camera, air sampling, and chemical analyses*

Figure 1. Working by night as well as by day, a research team prepares to "investigate" a sealed pit beneath the ground near the pyramids of Khufu and Khafre. Researchers used a specially designed drill, an air sampler, and video and still cameras to examine the contents of the pit—a disassembled ship over 4,500 years old—without excavating it. (Photo by James P. Blair, courtesy of National Geographic Society/Egyptian Antiquities Organization.)

In the 1920s, the American archaeologist George Reisner discovered three boat-shaped pits cut into the rock on the east side of the Great Pyramid *(3)*. In one of them he uncovered minute remains of desiccated wood, which had been gold-plated *(4)*. However, no one expected to find a boat pit with its contents intact at the Giza Necropolis, which had already been thoroughly excavated, and no further excavation was planned. It was not until three decades later that a heap of rock rubble and wind-blown sand was removed, simply to clear the southern side of the pyramid. The clearing uncovered a wall that formed a boundary 2.5 m wide and 1 m high, about 18 m from the pyramid. This boundary appeared to cover two groups of neatly hewn blocks of limestone on either side of the pyramid's axis. In 1954, the Egyptian Antiquities Organization decided to remove the 41 blocks in the eastern group, revealing a cavity 32.5 m long and 2.5 m wide. Markings on the interior wall indicated that the pit had been sealed by Khufu's son Djedef-Ra, who ruled Egypt after his father's death in 2528 B.C. *(5)*; hence, the pit must be over 4,500 years old. Most striking, it was found to contain, in a near-perfect state of preservation, the disassembled remains of the oldest ship in the world.

The disassembled boat was composed of 1,224 pieces, ranging in size from 10 cm to 23 m; the pieces were arranged in a sequence related to construction, and the topmost layer was covered by reed mats *(6)*. The excavation, preservation, and reconstruction of this royal bark required 18 years: 3 years to excavate the contents of the pit completely and 15 more to preserve the wood and reconstruct the boat. Polymerized polyvinyl acetate and an animal hide glue were used as preservative and adhesive, respectively *(7)*. When reassembled, the ship measured 43.4 m long and 5.9 m wide at the beam. It was housed in a specially designed "Boat Museum" built on the site of discovery and opened to tourists in 1982 *(4)*. Because of its great age and its imposing size—one and a half times that of the largest Viking ship—the boat created an international stir.

The design of the boat is unusual, with the prow, about 6 m high, in the shape of a papyrus-bundle. The

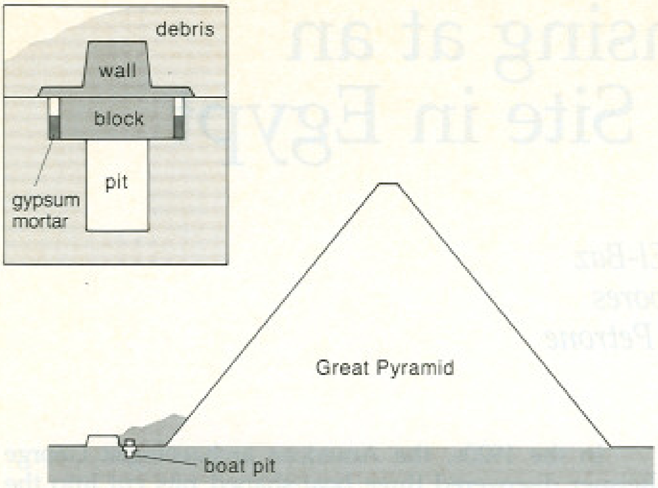


Figure 2. The disassembled boats of Pharaoh Khufu were hidden in pits beneath blocks of stone and a mound of debris just south of the Great Pyramid of Giza. The first such pit was excavated and its boat reconstructed for permanent exhibit; the second pit, shown schematically here, was not excavated but was explored by special techniques of remote sensing and photography to leave its seal of gypsum mortar intact. (After Jenkins, ref. *6*.)

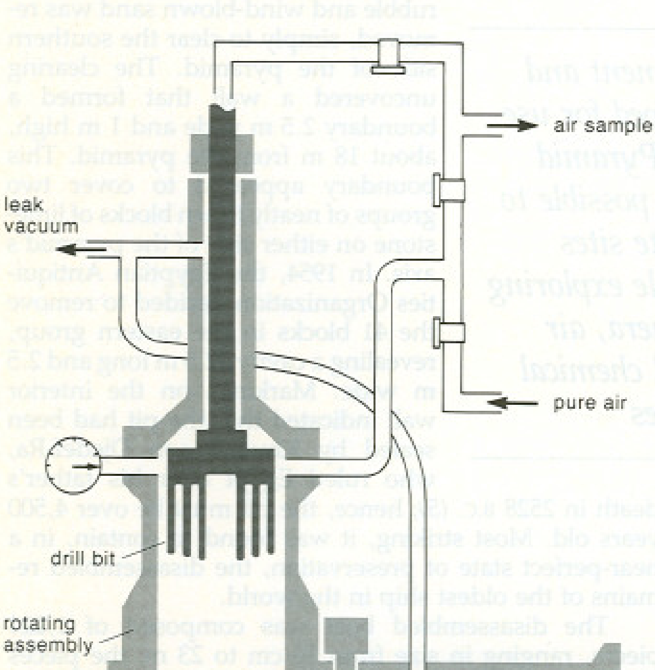


Figure 3. Because there was a possibility that the second boat pit had been hermetically sealed since its construction, sampling the air inside it offered a chance to gather information about the air of northern Egypt some 4,500 years ago. The air lock used was specially designed to avoid introducing any gases or particles from the air outside into the pit during drilling, air sampling, enviromental monitoring, and photography. The leak vacuum, in which the volume between two seals is evacuated to 0.5 atmosphere, acts as an extra precaution against introducing contaminants into the pit.

stern rises to 7 m high and the rudder consists of two massive oars. On the deck is a main cabin consisting of two rooms, a smaller room (2 m long) in the front separated from the larger (7 m long) by a door. Forward of these rooms lies the captain's canopy. Ten oars, five on either side, vary in height from 6.5 to 8.5 m.

With its papyrus-shaped prow, this royal ship looks very different from the other boats depicted on wall paintings, which the Egyptians used to ferry along the Nile and the many canals that crisscross the countryside. It is also very different from the wooden vessels that carried passengers up and down the river and the cargo ships that look like today's feluccas on the Nile.

The historical record shows that Old Kingdom pharaohs sought special wood from countries to the north of their arid environment. According to engravings on the Palermo stone, a slab of diorite rock listing the kings of ancient Egypt (the largest piece of the slab is now in Palermo, Italy), Khufu's father Snefru sent his navy to Lebanon to seek cedar. Such vessels returned with enough logs to construct large ships and barges. The royal bark of Khufu could have been built from such a special cargo.

In the first five years of its exhibition, the boat began to show signs of wear. Conservators believed that the signs of deterioration were due to unacceptable environmental conditions inside the museum. Meanwhile, a second group of blocks nearby was thought also to conceal a pit containing a boat, much like the first. It was believed that an investigation of its environment would lead to a better understanding of how to preserve the wood of the boat on exhibit in the museum. This was the driving force behind the project to study the second boat pit; one phase of the investigation is shown in Figure 1. Furthermore, there was a chance that the first pit, before its excavation, had been hermetically sealed. Kamal El-Mallakh, the architect from the Egyptian Antiquities Organization who was responsible for site work, maintained that a smell of cedar wood had emanated from the pit when it was first opened; moreover, the wooden parts of the ship looked to him "as hard and as new as if they had been placed there but a year ago" *(8)*. If the second pit was similarly sealed (see Fig. 2), then sampling of the air inside it might possibly uncover important data on the composition of the earth's atmosphere 4.5 millennia ago.

Unique equipment needed

In 1985 the Egyptian Antiquities Organization and the National Geographic Society launched a project called the Nondestructive Investigation of the Second Boat Pit of Pharaoh Khufu. A group of scientists with expertise in archaeology, chemistry, geophysics, imaging technology, and remote sensing conceived a research plan *(9)*, which called for surveying the shape of the chamber and of its contents by remote sensing techniques to select a proper drilling site *(10)*; drilling a vertical hole in a block of chalky limestone up to 2 m thick without using any lubricants or cooling fluids that might contaminate the pit's environment, and with assurance that no air or other gases would be transferred into the pit; and sampling the air inside the cavity at different levels while making sure that no chlorofluorocarbons were introduced into the sample and while passing the air through filters to separate any pollen grains or other microorganisms for analysis. In addition, the pressure, temperature, and relative humidity inside the chamber were to be measured, and the interior was to be photographed with a video system and a 35-mm still camera without raising the temperature inside. Finally, the drill hole was to be resealed, with sensors left inside the pit to measure the temperature and humidity periodically.

To accommodate these stringent requirements, a unique rotary air lock was developed. As illustrated in Figure 3, only two elements form the basis of the air lock:

In the 1920s, the excavation of a pit at the Great Pyramid revealed the remains of gold-plated, desiccated wood

a circular steel plate, and a rotating assembly attached on a pivot. The steel plate is fixed and sealed to the material being drilled, whereas the assembly can be rotated 90° in order either to align holes in both elements for drilling and probing, or to cover the hole in the fixed plate, sealing the work surface. When the lock is sealed, various drills or probing heads can be safely exchanged by means of a bolted connection at the upper part of the rotating assembly. Figure 4 shows the air sampling probe in use.

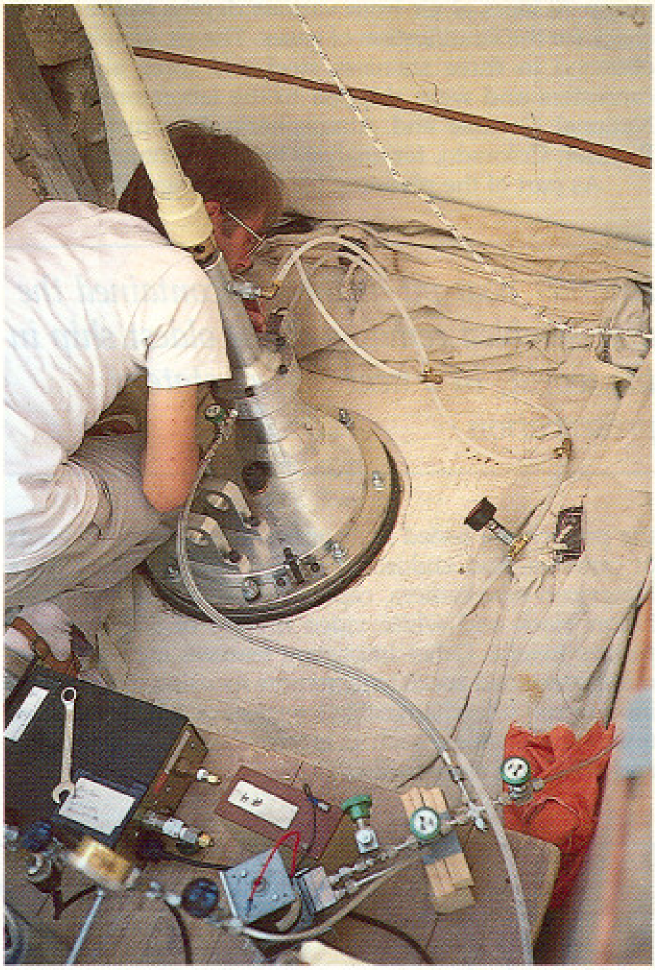


Figure 4. Once the interior of the pit had been reached by drilling through a limestone block, it was possible to sample the air inside. The air sampling probe, 3.7 m long, collected specimens into six cannisters, three of polished stainless steel and three of deactivated aluminum; the specimens were later analyzed by gas chromatography. (Photo by F. El-Baz.)

Specialized drilling and photography

Work at the site began on a block near the eastern end of the pit. The block, made of chalky limestone with no visible flaws, measured about 4 m long and about 90 cm wide. Only part of the wall was cleared to expose the block, on top of which a scaffold was erected to hoist the equipment, as shown in Figure 1. A tent was set up to protect the photographic equipment and video monitors. An area in the center of the block was made perfectly level, and a location for the hole was marked 2 m from its north edge. The surface of the stone was sealed with a thin layer of epoxy resin, which was allowed to cure overnight. With the fixed plate as a template, eight 12.7-mm-diameter holes were drilled into the block to bolt the masonry anchors.

A neoprene gasket was placed over the masonry anchors to form a perimeter seal for the fixed plate, and a lead gasket was positioned around the main drill hole. The lead gasket formed an inner barrier to the possible emission of freons from the neoprene perimeter seal. As a further precaution against the introduction of contaminants to the air in the pit, the volume between the primary lead seal and its surrounding neoprene secondary seal was evacuated to about 0.5 atmosphere. This "leak-scavenging" partial vacuum was also maintained between other seals in the assembly.

The special design of the drill bit (three concentric masonry core drills with tungsten-carbide tips) precluded the need to remove a large core segment from the bottom of the hole. The 90-mm-diameter drill bit was driven at the reasonably slow speed of 375 rpm to minimize heating of the rock, and, therefore, the environment inside the pit. Only 2.5 cm was drilled at a time, and before each cycle the drill chamber was pumped and charged with freon-free air to 10–30 mm of mercury less than the barometric pressure.

A special core-breaking tool was used to snap off the two standing rings and central core of material produced by the triple core bit. The broken fragments and remaining dust were easily retrieved with a vacuum cleaner. The drill head was then reassembled to the air lock, the drill chamber was purged of outside air, and another drilling cycle commenced. After two days, the drill assembly suddenly fell 15 mm, signalling breakthrough. Allowing for a certain portion of the core segment that split from the block and fell into the pit, the total thickness of the block was 159 cm.

The drill bit was withdrawn into the airlock, which was turned 90° to seal the hole. Now the drill head was replaced with the air-sampling probe, which appears in Figure 4. A stainless steel tube 12.7 mm in diameter and 3.7 mm long was pushed through two O-ring seals to pump 70 liters of air from various depths in the pit, to check for the stratification of gases. The air samples were obtained in three stainless steel and three aluminum cannisters and were shipped to the laboratories of the National Oceanic and Atmospheric Administration in Boulder, Colorado, for analysis by gas chromatography.

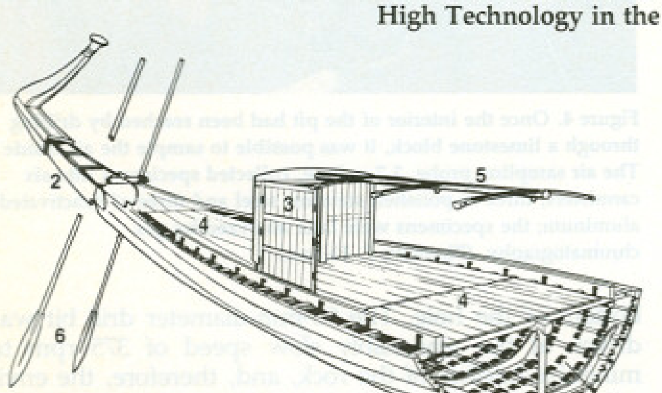
As part of the planning for the photographic part of the project, we tested fiber optics, borescopes, all kinds of cameras, and endoscopes. We chose the Rees 93, a Newvicon tube camera, capable of producing high-resolution black and white video images of 550 lines per picture height. Other important features included a remote-controlled zoom lens, remote focusing, and remote iris control. Interchangeable lenses gave a wide range of unique capabilities, such as extreme wide-angle viewing and 90° prism close-focusing.

Another boat pit at the site contained the disassembled remains of the oldest ship in the world, in a near-perfect state of preservation

We had decided on a 90-mm drill hole because this was the smallest size through which we could get a "fast" zoom lens, whose light-gathering capacity would give high resolution under low-light conditions. The video camera itself did not provide sufficient light; an additional light source was needed, but it must emit little or no heat and little or no infrared radiation. A Diaguide 300-watt xenon source was selected to provide illumination through a fiber-optic light, whose heat was dissipated above ground. With the camera's resolving capability, it was established that the light could reach 15 m within the pit. A redesigned aluminum outer housing provided interior space for the light guide, and a mechanical cable and rod assembly provided a 95° lift movement, with a gravity-assisted return to the vertical. Real-time images were recorded on a JVC 2-cm VCR tape, with a Sony Mavica disk recorder providing still video images.

A second arm contained a modified Canon MC still 35-mm film camera. In addition, a Sony SC-117 color CCD chip and lens were extended by 46 cm of flat cable from the body of the camera to allow more freedom of movement and less weight on the pivoting arm. This video camera's sole purpose was to provide eyes for the still camera. A small projector bulb operated at 24 volts provided adequate illumination with a minimum of heat in the pit.

High Technology in the Old Kingdom, 2500 B.C.



Drawing by Peter A. Schmid
courtesy of National Geographic Society

Both the reconstructed royal ship of Pharaoh Khufu and the timbers stored in the second boat pit give evidence (shown here in a schematic diagram) of remarkable engineering and artisanship. Sewn shipbuilding has occurred throughout the world from antiquity to the modern age, but the transverse methodology used at Giza (1) differs from the longitudinal stitching seen in every other period and provenance. Although it is weaker, transverse lashing uses fewer hard-to-untie knots and is easier to pass from one hole to the next because the holes are much larger. This unusual technique may have developed from the need to transport dismantled ships from one area to another—for example, around the cataracts of the Nile at times of low water.

The deckhouse panels of the second boat (3) were found in the pit as assembled units, unlike every other visible element except some decking (4). They are held together not by lashings but by fixed mortise and tenon joints, dados, and dowels. Identical prefabricated panels in the first ship were attached to the deck beams in such a way as to make changes in deckhouse configuration (or even removal) as easy as possible.

By using the known widths of the pit's 40 ceiling blocks as a rough scale, it is possible to estimate the length of the deckhouse from its central carrying beam (5) and its width from the prefabricated panels. A 20% difference between these figures and those of the first ship, combined with observations that the second pit held less material overall, leads to the conclusion that the second ship is smaller.

Oar blades (6) appear to be intentionally broken off from their shafts, but the reason for such a step is unclear.

Great skill in engineering is demonstrated in the way deck-level tension and lower-hull compression are controlled by means of longitudinal girders both above and below the deck beam, highly shaped bow and stern timbers (2), sophisticated lashings, and complex, locking plank scarfs (not shown). Petroglyphs dating from approximately 500 years before Pharaoh Khufu's reign show a ship with a similar hull profile and arrangement of the deckhouse, indicating that these problems were not new to the 4th-Dynasty Egyptian shipwrights. In fact, the nature of ship evolution and the superb marriage of aesthetic detail and structural integrity displayed in Khufu's ships prove that we are seeing two polished examples of the highest technology available in the Old Kingdom.—*Paul Lipke, principal consultant for image analysis, National Geographic Society, Plymouth, MA*

A modified Vivitar 283 strobe flash was used as illumination for the still photos. The flash tube was separated from the condenser and the power boards to place less weight on the pivoting arm. This allowed a 24-volt motor to move the arm holding the video lens, still camera, viewing light, strobe, and strobe sensor a full 180° vertically. Color temperature was a constant 5,500 K, and with the addition of an ultraviolet barrier filter over the strobe light lens, hazardous heat rays were all but eliminated.

After five days of documentation, the investigation crew prepared to seal the pit. An aluminum plug with three nitrile O-ring seals was inserted through the air lock to a depth of 75 mm below the top surface of the block. This plug contained a split flange through which a cable passed to the temperature and humidity sensor that would remain inside the pit. After placement of the aluminum stopper, the air lock was safely removed from the block. The 75-mm space above the plug was filled with pure gypsum plaster, much like the material that the original builders had used to seal the pit.

A beginning for remote sensing

When the drill bit reached the ceiling of the pit, we noted with some disappointment that there was no change in pressure, as would have been expected if the cavity were hermetically sealed. This was the first indication that there had been communication between the air inside the pit and outside. However, the investigation continued as if the seal were intact *(11)*, in order to prove the methodology and to test the technology completely.

Imaging of the interior of the chamber showed that the cavity was partly filled with stacks of a disassembled boat. Deckhouse panels were clearly visible on top, and three slender oar blades were revealed in the eastern end of the pit, with a fourth in the western end. The cameras also revealed notations, much like the quarry marks discovered in the first pit, which gave measurements beneath hieroglyphs for the height, width, and length of the ceiling blocks. A remote photograph of the chamber is reproduced in Figure 5; Figure 6 shows the reconstructed boat that had been excavated from the first pit.

The photographs revealed additional evidence that the pristine environment of the chamber had at some point been violated. Dark-colored streaks on the wall emanating from between the cap blocks suggested that there had been water seepage down the sides; the bundles of wood appeared to be at least 10 cm below their original level in the pit, as indicated by scratch marks on the wall; and, completely convincing in itself, a live black desert beetle was seen crawling on the wood. We learned that the seal of the porous limestone chamber may have been made more leaky by disturbances at the surface; during construction of the boat museum in 1966, a cement mixer and brick-making machine had been positioned directly over the pit *(12)*.

At the laboratories of the National Oceanic and Atmospheric Administration, the samples of air were

Figure 5. A remote photograph of the inside of the chamber shows the stacked timber of a disassembled boat. The white patches are pieces of gypsum mortar that have fallen from the ceiling. (Photo by Claude E. Petrone, courtesy of National Geographic Society/ Egyptian Antiquities Organization.)

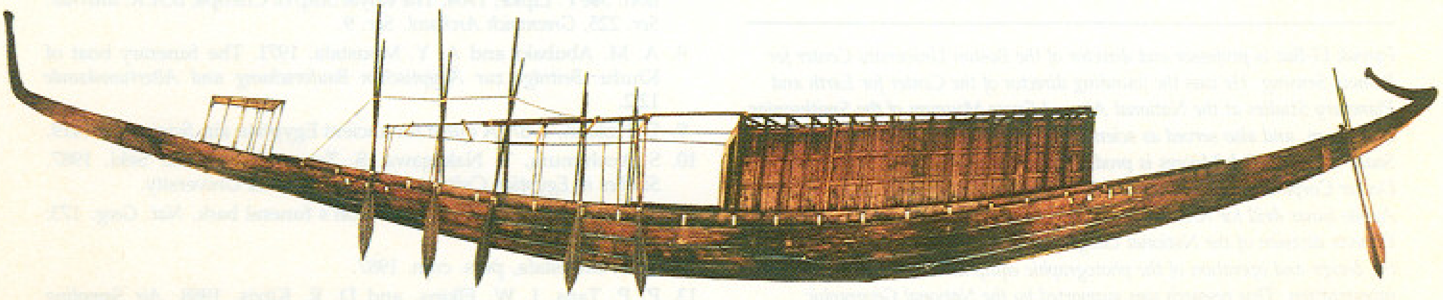


Figure 6. The first boat discovered was excavated from its pit and reconstructed for permanent exhibit in an on-site museum. The oldest ship ever found, it measures 43.4 m long and 5.9 m wide. It is because this ship has deteriorated seriously since its excavation that the second "boat pit" discovered nearby has been studied by remote sensing instead of by excavation. (Photo by Victor J. Boswell, Jr., courtesy of National Geographic Society/Egyptian Antiquities Organization.)

examined for the presence of various gases. Freons, or fluorinated hydrocarbons used in refrigeration and as a propellant in aerosols, occurred in two isotopes: freon 11 measured 300 parts per trillion (ppt), and freon 12 about 540 ppt. As might be expected near the large city of Cairo, these values were about 25% higher than those of ambient air. Samples of the air outside the pit gave similar results, confirming that there had been communication between the two environments. The content of CO_2 in dry air, after the freezing out of water, measured 720 parts per million (ppm), exactly double the amount in the ambient atmosphere. Carbon dioxide may have been produced by degassing from the organics inside the pit or may even have been driven off the limestone walls *(13)*. Dating of the CO_2 by the tandem accelerator at the University of Arizona gave an age of 2,000 years *(14)*, which suggests a mixture between ancient air and a modern counterpart. In addition, low values of hydrogen and carbon monoxide suggest the presence of bacteria.

Figure 7. This statuette of Khufu, 7.5 cm high, is one of the few surviving likenesses of the pharaoh. (Photo by Victor J. Boswell, Jr., courtesy of National Geographic Society/Cairo Museum.)

The pressure inside the chamber was identical to that outside. The temperature measured 27.2 C ± 0.3. The relative humidity was 84.9%. It is noteworthy that the humidity measured in the first boat pit a few days after it had been opened was 88%. This high humidity perhaps originated from moisture seeping through the surrounding rock, and if kept constant may have helped to preserve the wood.

A sample of mud-brick was retrieved from the base of the wall above the pit, to be tested for age. Some archaeologists believed that the wall was ancient, built to surround the pyramid complex. Others had thought it was much younger, perhaps Roman in age, because of the mix of rubble it contained, its width, and its probable original height. The carbon date of 2300 B.C., obtained by the tandem accelerator *(14)*, resolved the issue.

Several attempts were made to capture organic particles from the air for the identification of any microorganisms. Samples were analyzed at the Al-Azhar University, Suez Canal University, and the Egyptian Atomic Energy Establishment, but nothing was found to grow in the cultures that had been prepared *(15)*. This may have been because the air was pumped from nearly one meter above the wood, whereas bacteria or other organisms may have settled to the bottom of the pit or the upper surface of the wood. Filters through which the air had been pumped proved to contain mineral particles, but no evidence of pollen or bacteria.

This demonstration of remote sensing technology in archaeological research may open new opportunities for the nondestructive study of similar sites throughout the world. Although the second boat pit of Pharaoh Khufu was not a sealed, intact environment, the specialized equipment developed for its investigation may be capable of retrieving samples of gases, fluids, or solids from other remote locations without tainting the environment under study, and with photographic documentation of every step. With suitable modifications, a system such as the one outlined here may have broad applications not only in archaeology but in other exploratory investigations, such as rescue from submarines or mines, the remote probing of nuclear reactors, and the close study of resources within the earth.

Farouk El-Baz is professor and director of the Boston University Center for Remote Sensing. He was the founding director of the Center for Earth and Planetary Studies at the National Air and Space Museum of the Smithsonian Institution, and also served as science advisor to the late President Anwar Sadat of Egypt. Bob Moores is product development manager for Black & Decker Corporation in Towson, MD, and participated in the design of the Apollo lunar drill for NASA. Claude Petrone is with the Photographic Special Projects division of the National Geographic Society and was responsible for the design and operation of the photographic equipment used in this investigation. This research was supported by the National Geographic Society and the W. M. Keck Foundation; the Egyptian Antiquities Organization participated in the planning and provided logistical support. Address for Professor El-Baz: Center for Remote Sensing, Boston University, Boston, MA 02215-1401.

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