Search for Hidden Chambers in the Pyramids

The structure of the Second Pyramid of Giza is determined by cosmic-ray absorption.

Luis W. Alvarez, Jared A. Anderson, F. El Bedwei, James Burkhard, Ahmed Fakhry, Adib Girgis, Amr Goneid, Fikhry Hassan, Dennis Iverson, Gerald Lynch, Zenab Miligy, Ali Hilmy Moussa, Mohammed-Sharkawi, Lauren Yazolino

The three pyramids of Giza are situated a few miles southwest of Cairo, Egypt. The two largest pyramids stand within a few hundred meters of each other. They were originally of almost exactly the same height (145 meters), but the Great Pyramid of Cheops has a slightly larger square base (230 meters on a side) than the Second Pyramid of Chephren (215.5 meters on a side). A photograph of the pyramids at Giza is shown as Fig. 1. Figure 2 shows the elevation cross sections of the two pyramids and indicates the contrast in architectural design. The simplicity of Chephren's pyramid, compared with the elaborate structure of his father's Great Pyramid, is explained by archeologists in terms of a "period of experimentation," ending with the construction of Cheops's pyramid (*1*). (The complexity of the internal architecture of the pyramids increased during the Fourth Dynasty until the time of Cheops and then gave way to quite simple designs after his time.)

An alternative explanation for the sudden decrease in internal complexity from the Great Pyramid to the Second Pyramid suggested itself to us: perhaps Chephren's architects had been more successful in hiding their upper chambers than were Cheops's. The interior of the Great Pyramid was reached by the tunneling laborers of Caliph Mamun in the 9th century A.D., almost 3400 years after its construction. Of our group only Ahmed Fakhry (author of *The Pyramids*, professor emeritus of archeology, University of Cairo, and member of the Supreme Council of Archeology, Cairo) was trained in archeology. As laymen, we thought it not unlikely that unknown chambers might still be present in the limestone above the "Belzoni Chamber," which is near the center of the base of Chephren's Second Pyramid, and that these chambers had survived undetected for 4500 years. [We learned later that such ideas had occurred to early 19th-century investigators (*2*), who blasted holes in the pyramids with gunpowder in attempts to locate new chambers.]

In 1965 a proposal to probe the Second Pyramid with cosmic rays (*3*) was sent to a representative group of cosmic-ray physicists and archeologists with a request for comments concerning its technical feasibility and archeological interest. The principal novelty of the proposed cosmic-ray detectors involved their ability to measure the angles of arrival of penetrating cosmic-ray muons with great precision, over a large sensitive area. The properties of the penetrating cosmic rays have been sufficiently well known for 30 years to suggest their use in a pyramid-probing experiment, but it was not until the invention of spark chambers with digital read-out features (*4*) that such a use could be considered as a real possibility. [Cosmic-ray detectors with low angular resolution had been used in 1955 to give an independent measure of the thickness of rock overlying an underground powerhouse in Australia's Snowy Mountains Scheme (*5*)].

The favorable response to the proposal led to the establishment by the United Arab Republic and the United States of America of the Joint U.A.R.–U.S.A. Pyramid Project on 14 June 1966. Cosmic-ray detectors were installed in the Belzoni Chamber of the Second Pyramid at Giza in the spring of 1967 by physicists from the Ein Shams University and the University of California, in cooperation with archeologists from the U.A.R. Department of Antiquities. Initial operation had been scheduled for the middle of June 1967, but for reasons beyond our control the schedule was delayed for several months. In early 1968 cosmic-ray data began to be recorded on magnetic tape in our laboratory building, a few hundred meters from the two largest pyramids. Since that time we have accumulated accurate angular measurements on more than a million cosmic-ray muons that have penetrated an average of about 100 meters of limestone on their way to the detectors in the Belzoni Chamber.

Proof of the Method

Before any new technique is used in an exploratory mode, it is essential that the capabilities of the technique be demonstrated on a known system. We gave serious consideration to a proposal that the cosmic-ray detectors be tested first in the Queen's Chamber of the Great Pyramid, to demonstrate that the King's Chamber and the Grand Gallery could be detected. But this suggestion was abandoned because the King's Chamber is so close to the Queen's Chamber and because it subtends such a large solid angle that earlier (low resolution) cosmic-ray experiments had already shown that the upper chamber would give a large signal. It was apparent that the only untested feature of the new technique involved the magnitude of the scattering of high energy muons in solid matter. (An anomalously large scattering would nullify the high angular resolution that had been built into the detectors, in the same way that frosted glass destroys our ability to see distant objects.) We had no reason to doubt the calculated scattering, but we were anxious to be able to demonstrate to our colleagues in the U.A.R. Depart-

The authors are affiliated with the Joint Pyramid Project of the United Arab Republic and the United States of America. They reside either in Cairo, United Arab Republic, or in Berkeley, California. The article is adapted from an address presented by Luis W. Alvarez at the Washington Meeting of the American Physical Society, 30 April 1969.

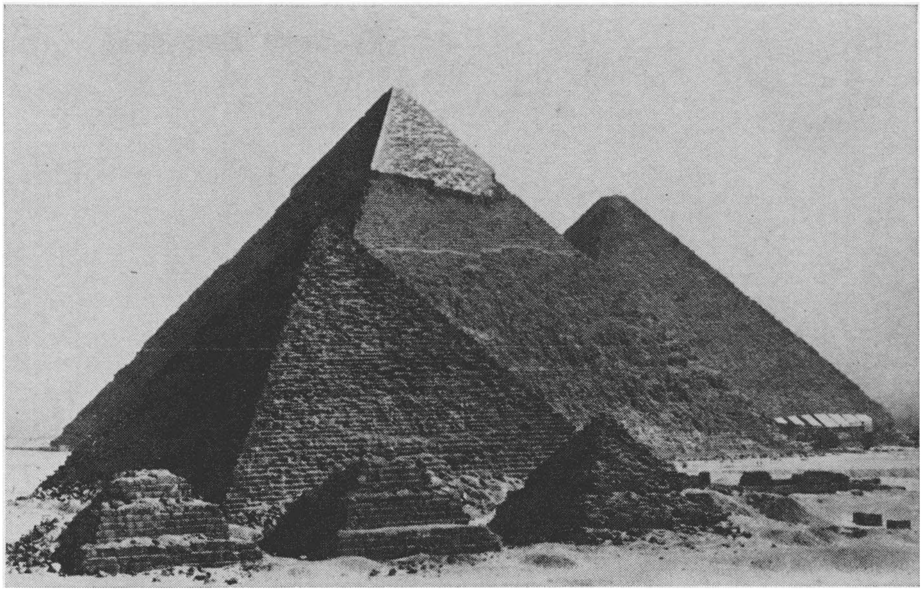


Fig. 1 (top right). The pyramids at Giza. From left to right, the Third Pyramid of Mycerinus, the Second Pyramid of Chephren, the Great Pyramid of Cheops. [© National Geographic Society]

ment of Antiquities in a convincing manner that the technique really worked as we had calculated. For this purpose we required as our test objects not large features that were nearby but, instead, small features separated from the detectors by the greatest possible thickness of limestone. Fortunately, such features are available in the Second Pyramid; the four diagonal ridges that mark the intersections of neighboring plane faces were farther from the detectors than any other points on the individual faces. (From now on, we will refer to these ridges as the "corners.")

From the known geometry of the Second Pyramid, the trajectories of cosmic-ray muons that pass through a point on a face 10 meters from a corner and then down to the detectors can be shown to traverse 2.3 fewer meters of limestone than do muons that strike the corner. They should therefore arrive with 5 percent greater intensity than the muons from the corner. Such an increase in intensity, corresponding to such a decrease in path through the limestone, is about half of what would be expected to result from the presence of a chamber of "typical size" (5 meters high) in the pyramid. Since such a chamber would necessarily be closer to the detectors, it would for these two reasons be a much "easier object to see" than the corner.

The detection equipment was therefore installed in the southeast corner of the Belzoni Chamber, with the expectation that it would first show the corners in a convincing manner, so that the presence or absence of unknown chambers could later be demonstrated to the satisfaction of all concerned. In September 1968 the IBM-1130 computer at the Ein Shams University Computing Center produced the data

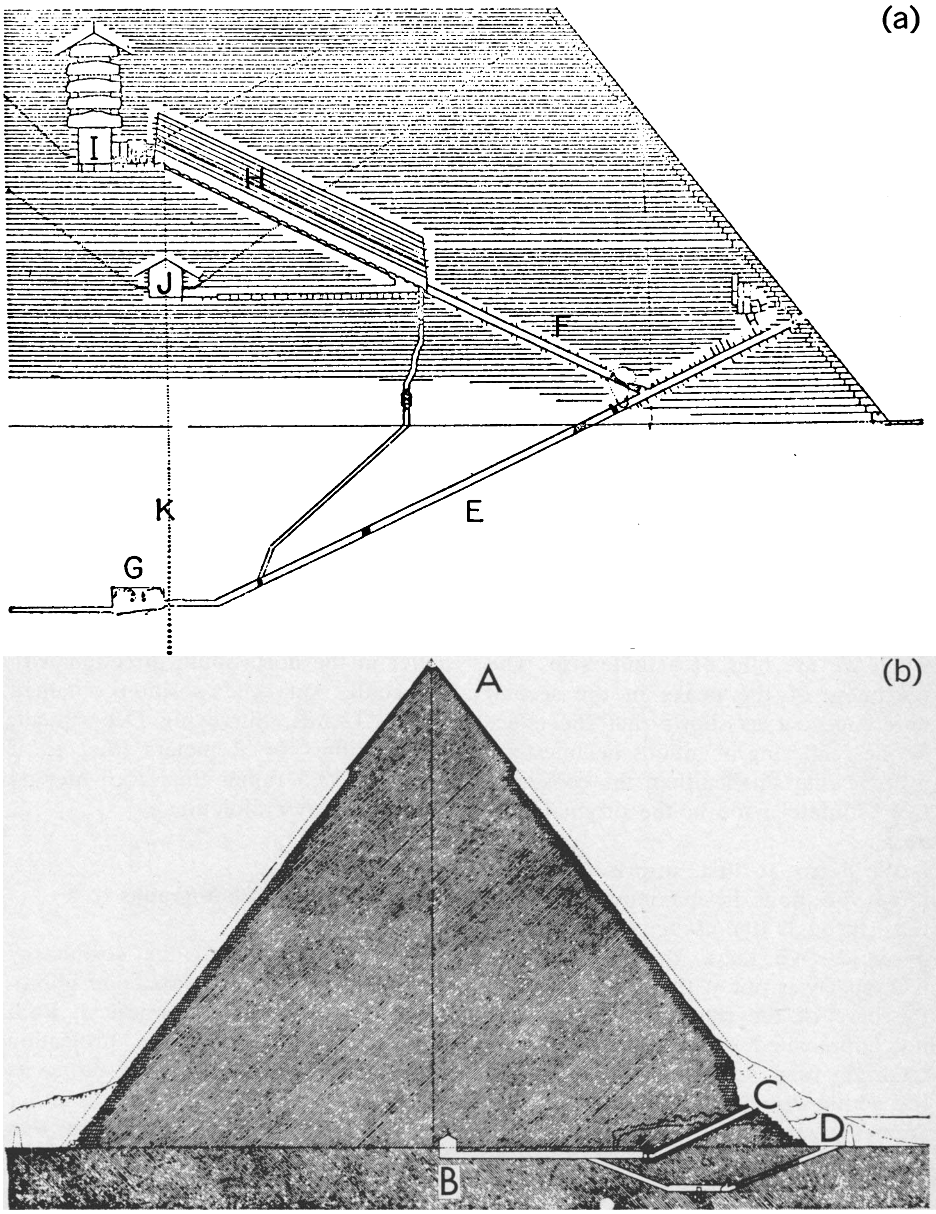
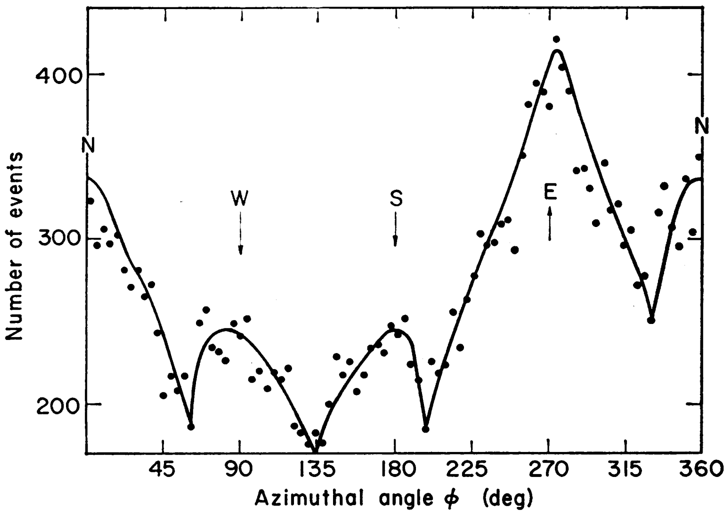


Fig. 2 (bottom right). Cross sections of (a) the Great Pyramid of Cheops and (b) the Pyramid of Chephren, showing the known chambers: (*A*) Smooth limestone cap, (*B*) the Belzoni Chamber, (*C*) Belzoni's entrance, (*D*) Howard-Vyse's entrance, (*E*) descending passageway, (*F*) ascending passageway, (*G*) underground chamber, (*H*) Grand Gallery, (*I*) King's Chamber, (*J*) Queen's Chamber, (*K*) center line of the pyramid.



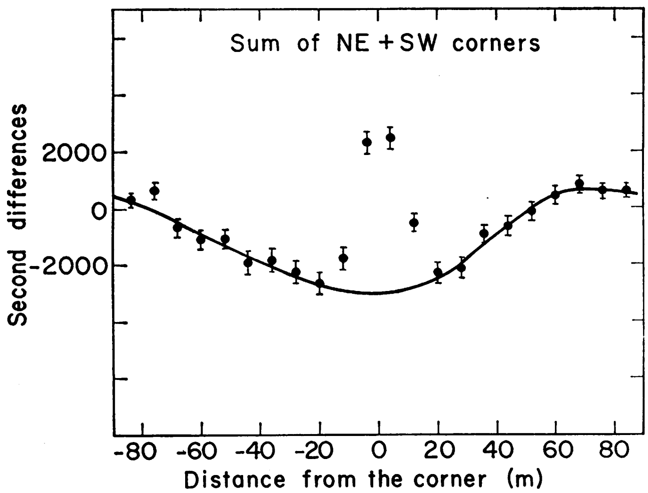


Fig. 3 (left). The initial measurement (with zenith angle of counts from 20 to 40 degrees) of the variation of cosmic-ray intensity with azimuthal angle, as observed from the Belzoni Chamber underneath the Second Pyramid of Chephren. Fig. 4 (right). Detection of the northeast and southwest corners of the pyramid obtained by plotting the second differences of the counting rate on the planes tangent to the corners as a function of distance from the corners.

for Fig. 3, which shows the variation of cosmic-ray intensity with azimuthal angle (compass direction). The expected rapid changes in cosmic-ray intensity in the vicinity of the corners were clearly shown, and the capability of the method could no longer be doubted. An analysis of more data was later made on the Lawrence Radiation Laboratory's CDC-6600 computer and is shown in Fig. 4. Here the "second differences" of the counting rate with distance from each corner are plotted on planes that are located symmetrically with respect to adjacent faces and that are tangent to the corner. Mathematically, we would expect to see a sharp spike at the corner of a sharply defined pyramid in the plot of the second derivative of counting rate with respect to distance. The second derivative becomes a second difference curve when we use bins of a finite size. The sharpness of the peaks in the second difference curves shows that the effect of the scattering of muons in limestone is somewhat smaller than the conservative estimate made in the original proposal.

We were at first surprised by the large variations in maximum counting rate through the four faces of the pyramid. We knew that the Belzoni Chamber was not at the exact center of the base of the pyramid, but we had not appreciated what large changes in counting rate would be occasioned by the actual displacement of the detector from the center of the base; the equipment is 15.5 meters east and 4 meters north of the center. There are two independent ways to use cosmic-ray data to determine the location of the detector with respect to the exterior features of the pyramid.

1) The difference in the maximum counting rate through the east and west faces gives the displacement of the detector toward the east, and similar measurements in the north-south directions give the displacement to the north.

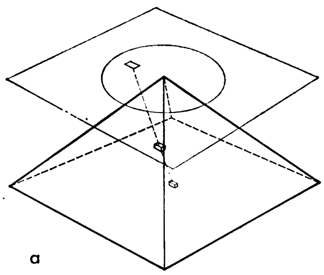
2) The azimuthal angles of the dips corresponding to the corners give a second, quite independent, and more sensitive measure of the displacements. We can report that from cosmic-ray observations alone, "looking through" 100 meters of limestone, we can locate the position of our detectors to within 1 meter. To the best of our knowledge, no such measurement has ever been made before. Our cosmic-ray-derived position agrees to within less than 1 meter in the north-south direction with a recently surveyed position obtained by the U.A.R. Surveying Department, but it differs by 2 meters (that is, it indicates 13.5 rather than 15.6 meters) in the east-west direction.

Simulated X-ray Photographs

We have presented the cosmic-ray data in two different ways, one photographic and the other numerical. Both these methods involve the projection of each recorded muon back along its trajectory to its intersection with either a horizontal plane or a sphere that touches the peak of the pyramid. Figure 5a is a diagram representing the Second Pyramid with the horizontal "film plane" touching the peak of the pyramid and with a dashed line (representing the path of a cosmic ray) passing from the detector through a hypothetical chamber to the image of the chamber on the "film plane." (The mapping of the pyramid structure by this technique is identical to what we would obtain by x-raying a small model of the pyramid, with an x-ray source in the Belzoni Chamber and with an x-ray film touching the peak of the model pyramid.) Figure 5b represents the spherical shell onto which cosmic rays were projected for numerical analysis.

Figure 6 is a view of all the equipment, which occupied most of the southeastern part of the Belzoni Chamber. Figure 7 is a closer view of the detector. The two spark chambers, each 6 feet (1.8 meters) square, are separated vertically by a distance of 1 foot (0.3 meter). Above and below the spark chambers and just above the floor level were scintillation counters, which triggered the spark chambers when all three counters signaled the passage of a penetrating muon. The 4 feet (1.2 meters) of iron between the bottom two scintillators was installed to minimize the effects of muon-scattering in the limestone.

The simulated x-ray photograph of the pyramid shown in Fig. 13a is an uncorrected (raw data) scatter plot of 700,000 recorded cosmic-ray muons as they passed through the "film plane." The four corners of the pyramid are very clearly indicated. If a Grand Gallery and a King's Chamber were located in the Second Pyramid as they are in the Great Pyramid, the Grand Gallery



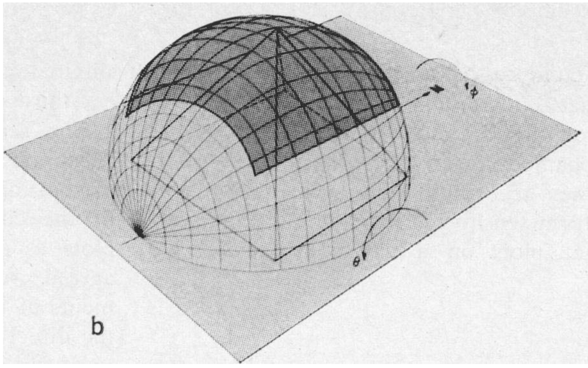


Fig. 5. (a) Geometry of the Second Pyramid, showing the projection technique used to produce a simulated x-ray photograph. The plane on the top of the pyramid can be thought of as the "film plane." (b) The spherical surface on which the events were projected for the numerical analysis of the data.

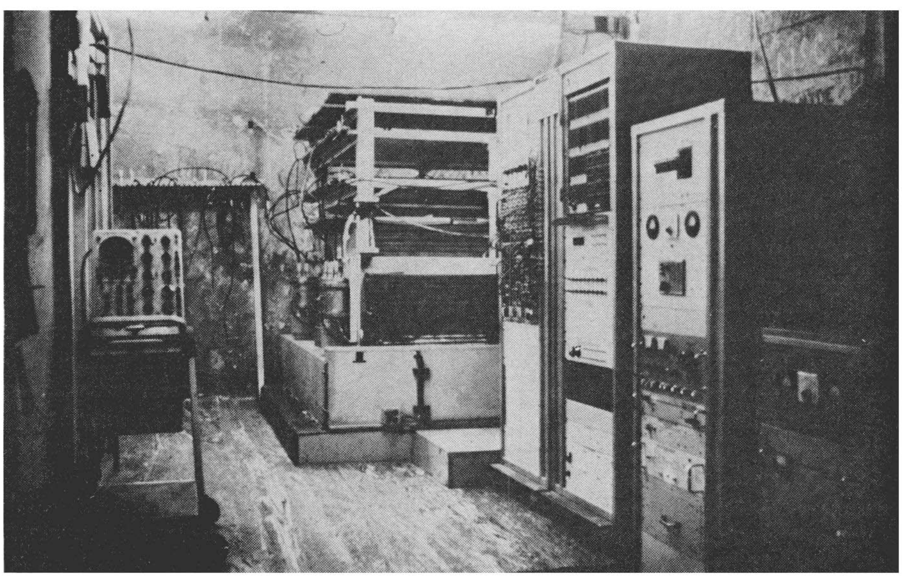
would have shown up clearly but the King's Chamber would probably have required some computer assistance to be made visible. There is one unexpected feature in Fig. 13a: on the north face, there appears to be a narrow north-south-oriented region that has a lower cosmic-ray intensity than is found in surrounding areas. We were at first hopeful that the north-south streak indicated the presence of a Grand Gallery above and north of the Belzoni Chamber, just as the Grand Gallery is above and north of the Queen's Chamber in the Great Pyramid. But we later found a satisfactory explanation of this feature in the picture that did not involve any interior structure in the pyramid. The region of lower cosmic-ray intensity resulted from the construction of the spark chambers. Since we could not transport square chambers 6 feet (1.8 meters) on a side through the small passageways of the pyramid, each square chamber comprised two chambers 3 by 6 feet (0.9 by 1.8 meters) in area. Also, each of the large scintillation counters was divided into sections. The inactive areas between the two pairs of spark chambers and between the sections of the counters led in a predictable way to the unexpected signal shown in Fig. 13a.

Numerical Analysis

We concluded from our study of the simulated x-ray picture that no unexpected features were discernible. But since we had been looking for an increase in intensity of approximately 10 percent over a region larger than that to which the eye responds easily, we then turned to a more detailed numerical analysis of the data. (The reason for expecting a 10 percent increase in intensity in the direction of a new chamber is simply that the integral range spectrum of the muons is represented by a power law with an exponent equal to -2. Therefore, if the rock thickness is changed by an amount ΔX, out of an original thickness X, the relative change in intensity is $\Delta I/I = -2\Delta X/X$. The four known chambers in the two large pyramids have an average height of about 5 meters. Therefore $\Delta X/X$ should be -5 percent, and the corresponding value of $\Delta I/I$ should be $+10$ percent.)

Since the counting equipment was sensitive out to approximately ± 45 degrees from the vertical, our data were plotted in a matrix with 900 entries, 30×30 bins, each 3 by 3 degrees. Figure 5b illustrates this system of binning on a sphere that encircles the pyramid. We wrote a computer program to simulate the counting rate expected in each of these bins. As the simulation program became more sophisticated with time, it took into account the most detailed features of the measured exterior surface of the pyramid, including the "cap" of original limestone casing blocks near the top, the surveyed position of the detectors in the Belzoni Chamber, the positions of the walls and ceiling of the Belzoni Chamber, and the sizes and positions of each of the four spark chambers and the fourteen scintillation counters.

An important control on the quality of the experimental data being compared with the simulated data came from scatter plots showing the exact x and y coordinates of each recorded



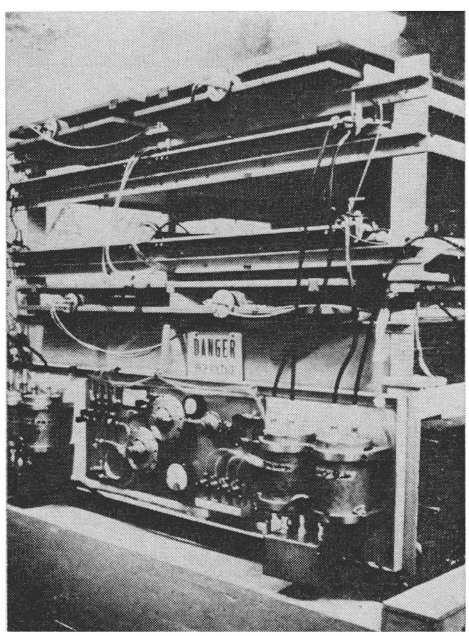


Fig. 6 (left). The equipment in place in the Belzoni Chamber under the pyramid.
Fig. 7 (right). The detection apparatus containing the spark chambers.

muon as it passed through each of the five planes containing scintillators or spark chambers. Unsatisfactory operation of the spark chambers showed up as small blank areas in the scatter plots of muons passing through the chambers. Such unsatisfactory operation was found to be correlated with contaminated neon in the spark chambers; the log books show that whenever the chambers were flushed with fresh neon they recovered their substantially uniform sensitivity. By examining the scatter plots on a day-by-day basis, we eliminated from the data base about one-third of the measured muons.

The scatter plots also served as a check on the resolution and accuracy of the angle measurements. The edges of the counters showed up on these plots as sharp lines at positions that agreed well with the direct measurements of the counter locations. Neither the direct measurements of the counter positions nor the inferred positions of these counters as obtained from the data themselves were good enough to permit the program to make sufficiently accurate calculations. In a typical 3- by 3-degree bin there are 1600 events. The statistical uncertainty in this number of events is 2.5 percent. It was necessary to make calculations to at least such an accuracy to make full use of the data. We first varied the assumed positions of the scintillators by small amounts in an effort to fit the expected counts to the measured counts. This approach was unsatisfactory. Calculations of the desired accuracy were obtained only after we eliminated the events that passed near the edge of at least one of the counters. In effect, each counter was defined to be slightly smaller than it actually was, and only the recorded muons that passed through these defined counter positions were accepted. This method eliminated the problems associated with small displacements of the counters during the experiment, with small-angle scattering of muons in the iron, and with decreased sensitivity of the counters near their edges. About 15 percent of the events were eliminated in this way. We believe that the 650,000 muons in the final selected sample are free of important biases resulting from improper functioning of the equipment.

In the course of the computer analysis, about 40 fits were made to minimize the difference between the matrices of actual and simulated counts. Although the matrices contain 30×30 bins each, some of the bins at the edges contain so few counts (or none at all) that the effective number of bins is close to 750. If we knew all the physi-

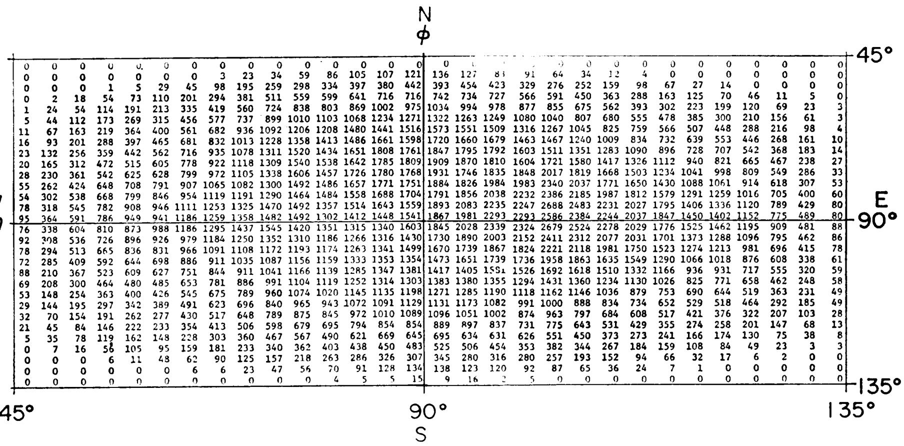


Fig. 8. An array containing the numbers of events (uncorrected) observed during several months of operation in each 3- by 3-degree bin.

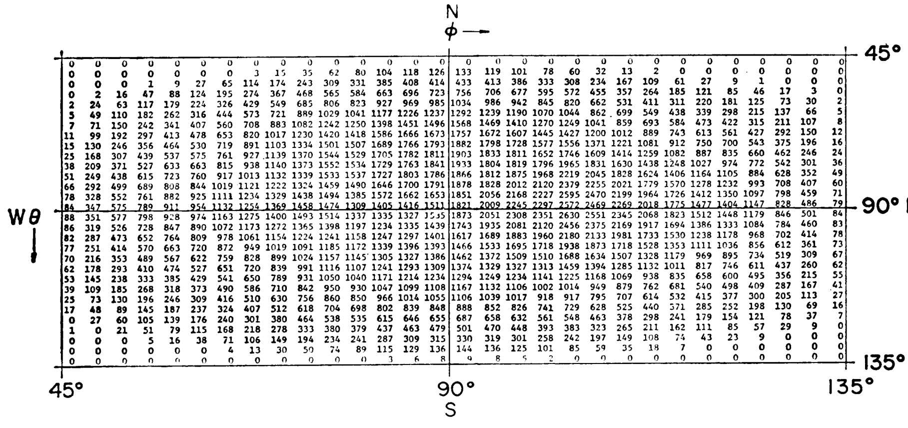


Fig. 9. An array containing the predicted number of events in each 3- by 3-degree bin for the best fit to the data.

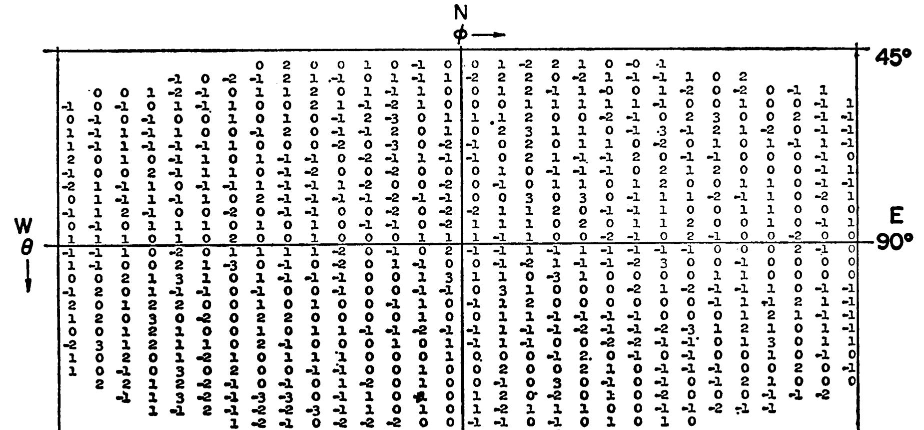


Fig. 10 (bottom left). The differences between the numbers of events measured and predicted expressed in integral numbers of standard deviations for the best fit to the data for which the χ^2 was 905. (The bins for which the predicted number of events was less than 30 were not used in calculating the χ^2.)

cal parameters of our detection equipment, if we were equally sure of the equations describing the cosmic-ray spectrum, and if we were, in addition, sure that the pyramid was made of solid limestone, then we would expect the χ^2 of the fit between the actual and the simulated data to be about 750. The earliest fits had χ^2's of close to 3000, but this important parameter dropped to approximately 1400 by the time the stereophotographically determined contours of the pyramid exterior were made available to us through the courtesy of the U.A.R. Surveying Department.

Figure 8 is a matrix showing the total number of real counts recorded in each of the 900 3- by 3-degree bins. Figure 9 is one of the final simulation runs, and Fig. 10 is the difference between Figs. 8 and 9 expressed as the closest integral number of standard deviations. [For a bin in which the number of counts was 2500, an entry for +2 standard deviations means that the actual count exceeded the expected count by $2(2500)^{1/2} = 100$.]

If these deviations are only statistical in nature, one expects about 87 percent of the bins to have contents of −1, 0, or +1, about 12 percent of the bins to have ±2, and 1 percent of the bins to have ±3. There is one chance in three of finding one bin having ±4, one chance in 200 of finding one bin with ±5, and only one chance in 3×10^4 of finding one bin with ±6, if the deviations are due only to statistical fluctuations. Thus no single bin has a significant effect unless its contents are at least ±4. Figure 10 contains no bins showing ±4.

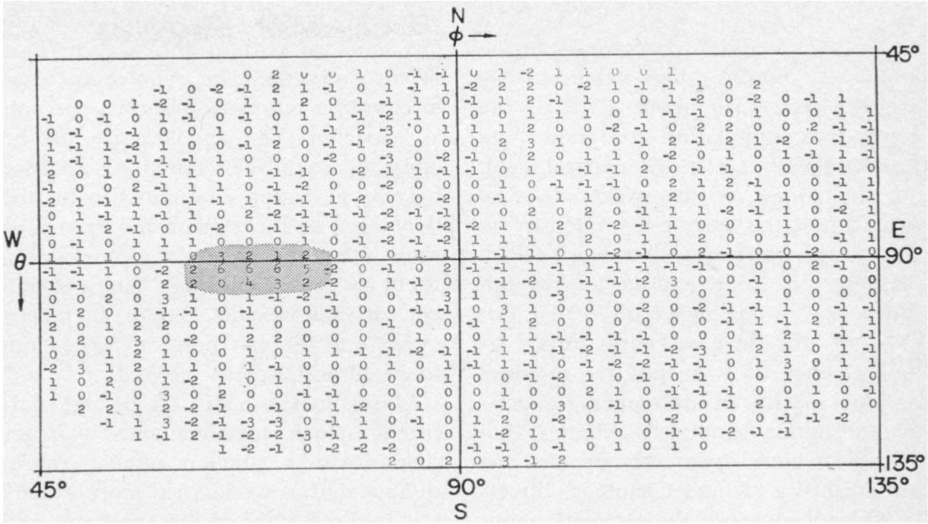


Fig. 11. The display of Fig. 10 as it would have appeared had there been a "King's Chamber" in the pyramid 40 meters above the apparatus. The group of numbers larger than 3 at the center-left (shaded area) indicates the chamber's position.

Detection of the Cap

The most distinctive feature of the Second Pyramid is the cap of original limestone casing blocks near the top. All the casing was removed from the Great Pyramid in the Middle Ages, but the builders of Cairo, who "quarried" the pyramids at that time, stopped before completely stripping the Second Pyramid.

Before the simulation program in the computer took account of the presence of the cap of limestone casing blocks on the pyramid, the difference plots (like the plot given in Fig. 11) always contained a central region with a preponderance of negative entries. When the cap was properly allowed for in the simulation, the actual counts in this region were no longer systematically lower than predicted by the computer, and the value of χ^2 dropped accordingly.

Although the χ^2 of the fit between the actual and simulated data was lowered when the features of the cap were introduced into the simulation, this drop does not constitute the strongest proof that we were in fact detecting the cap. Figure 12 compares the measured and cosmic-ray-determined variation in thickness of the limestone cap in two 24-degree-wide strips that run over the top of the pyramid in the north-south and east-west directions. In the absence of a cap both on the real pyramid and in the simulation, we would expect the experimental points to lie along the zero lines of deviation. The smooth curved lines are obtained from the simulation program by utilizing the recently determined contours of the pyramid. The generally good agreement of the data points with the prediction (Fig. 12) shows clearly that we have detected the presence of the cap through more than 100 meters of limestone.

The detection of the cap was much more difficult than detection of the corners; together, these two "proofs of the method" convinced us that we could have seen any previously unknown chamber that might exist in our "field of view."

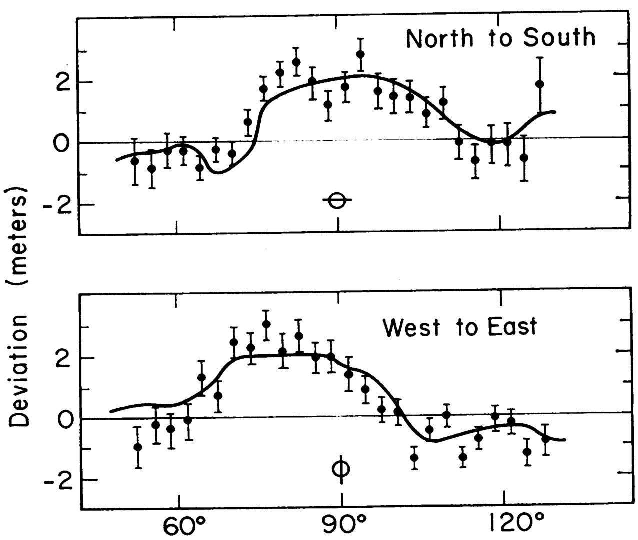


Fig. 12. This graph shows that the cap on the top of Chephren's Pyramid is observed in this experiment. The quantity plotted is the difference between the measured distance from the detector to the surface of the pyramid and the distance calculated under the assumption that the pyramid has no surface irregularities. The data points represent the distances indicated by the cosmic rays and are to be compared with the solid line, which represents the same distance measured by the aerial survey. These distances have been averaged over 24-degree-wide bands centered on the middle of the pyramid, one running north-south, the other east-west.

Search for Cavities

As the analysis proceeded during about 2 months, the value of χ^2 dropped slowly to about 1200 as the computer's simulation program was provided with better geometrical data. [In the course of this work we confirmed that the cosmic-ray intensity in the momentum range of concern (40 to 70 Gev) is isotropic and has an integral-range power law index of -2.1.] For most of this time we were excited by the presence of two "positive regions" on our matrix of differences (experimental minus simulated counts). One of these regions apparently signaled the presence of a "King's Chamber" directly under the apex of the pyramid, about 30 meters above the Belzoni Chamber. Because of the displacement of the Belzoni Chamber to the north and east of the center of the pyramid's base, the apparent chamber mapped itself onto the southern part of the western face of the pyramid. The relative increase in counting rate was about 10 percent, as expected. The angular size of the anomaly could be related to distance only by assuming a certain size for the floor area of the "chamber." If we assumed that the anomaly came from a room the size of Cheops's King's Chamber, it had to be about 30 meters away, and its plan position turned out to be almost exactly central.

Unfortunately, this large and persistent signal, together with a larger signal over a smaller angular range, disappeared as we learned more exactly all the dimensions of the apparatus and of the pyramid that were important in the simulation program. (We had not anticipated the need for such accurate data.) The artifacts we observed are mentioned only to show that far from "seeing nothing" throughout the analysis period, we had three very exciting signals that disappeared only after the greatest care had been taken to make the simulation program correspond exactly to the geometry of both the apparatus and the pyramid.

When the simulation program was as complete and as correct as we could make it, the fit between the recorded and the simulated counts was described by a χ^2 of about 1100. The formal rules of statistical analysis say quite unequivocally that such a fit is very unsatisfactory. But a careful look at the matrix of differences showed that the increase in χ^2 (over the expected value of about 750) came primarily from a rather uniform increase in difference values from south to north. If we assumed that the cosmic-ray intensity varied as $1 + d \cos \theta$, where θ is 90 degrees in a vertically oriented east-west plane, and 0 degree for rays approaching horizontally from the north, the χ^2 dropped to 905 when d had the value of 0.15 (Fig. 10). Such a value of d would correspond to a smooth variation in cosmic-ray intensity, from 30 degrees north to 30 degrees south, of ± 7 percent. We do not believe, of course, that the cosmic-ray intensity changes in such a manner, but it is quite reasonable to assume that our spark chamber systems had such a small and systematic change in sensitivity.

Our confidence in such an explanation was increased when we found that the required value of the constant d was different when we analyzed the data in two separate samples, one measured by each pair of 3- by 6-foot (0.9- by 1.8-meter) spark chambers. We know that the spark chambers were not uniformly sensitive over their whole areas, and we discarded all data from runs in which there were gross changes in sensitivity from point to point in the chambers. But we have no technique available to compensate for slow variations in sensitivity with position. (In our next operations, the apparatus will be arranged so that it rotates about a vertical axis; the linear variation in sensitivity that we have just postulated will average out in the improved apparatus.)

We made several attempts to simulate the $1 + d \sin \theta$ behavior of the apparent cosmic-ray intensity by the presence of a chamber above and very close to the apparatus. But the more

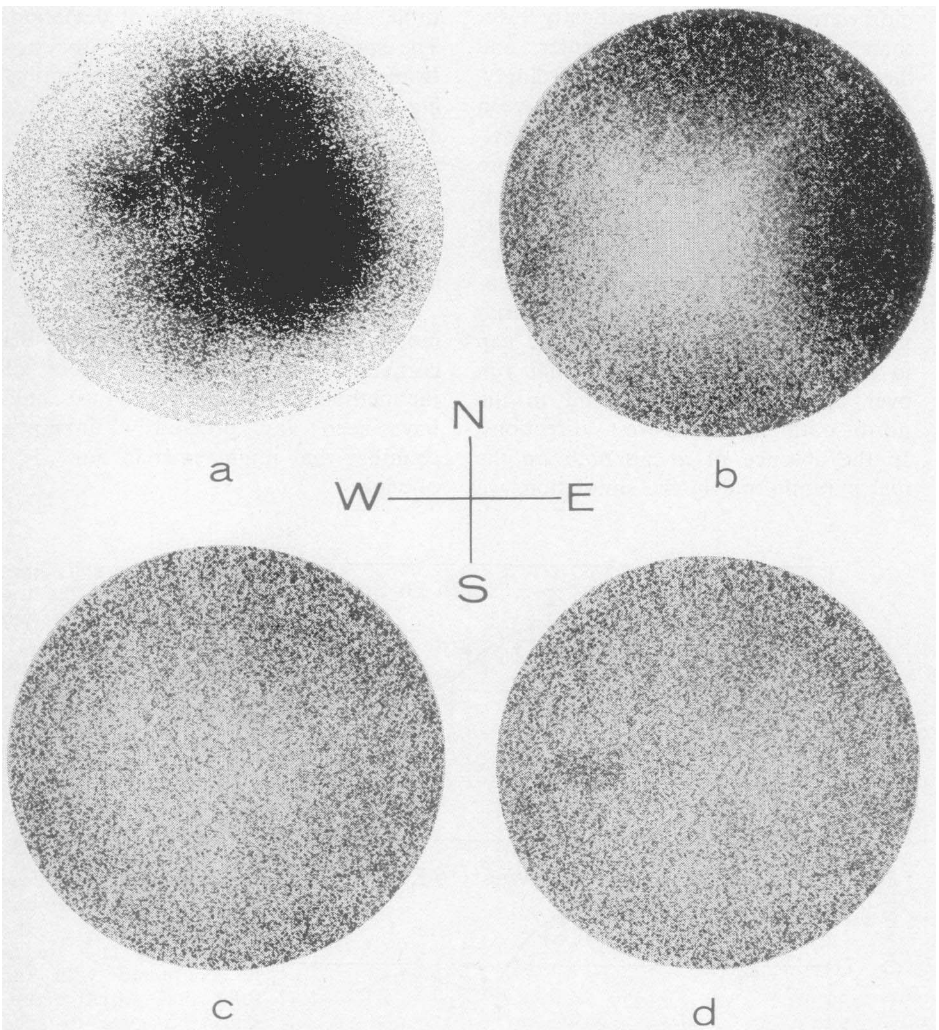


Fig. 13. Scatter plots showing the three stages in the combined analytic and visual analysis of the data and a plot with a simulated chamber. (a) Simulated "x-ray photograph" of uncorrected data. (b) Data corrected for the geometrical acceptance of the apparatus. (c) Data corrected for pyramid structure as well as geometrical acceptance. (d) Same as (c) but with simulated chamber, as in Fig. 12.

we tried, the more evident it became that the slow north-south variation was an instrumental effect, unrelated to any cavities in the pyramid rock. The fit obtained by using this slow north-south variation shows no statistically significant deviations from a solid pyramid.

Conclusions

To be sure that we could have detected a chamber of "average size" above the Belzoni Chamber, we programmed the computer to believe that its simulated pyramid had such a chamber filled with material whose density was twice that of limestone. The program then predicted that fewer muons than usual would come from the direction of the "chamber," so that the difference matrix showed positive numbers, as expected for a hollow chamber in the real pyramid and a pyramid of uniform density in the simulator. Figure 11 shows what we would have seen had there been a King's Chamber 40 meters above the Belzoni Chamber. (The scattering of muons in the rock is simulated by the computer.) If the King's Chamber were moved farther away, the angular width of the region having an excess of counts would drop inversely with distance. We have no doubt that we could detect a King's Chamber anywhere above the Belzoni Chamber within a cone of half-angle 35 degrees from the vertical. If the Second Pyramid architects had placed a Grand Gallery, King's Chamber, and Queen's Chamber in the same location as they did in Cheops's Pyramid, the signals from each of these three cavities would have been enormous. We therefore conclude that no chambers of the size seen in the four large pyramids of the Fourth Dynasty are in our "field of view" above the Belzoni Chamber.

We started by using two methods of analysis, one photographic and the other analytic. By itself the photographic method was unsatisfactory, because effects due to the apparatus itself were so large that they obscured any effects from the pyramid. Although the analytic method could succeed because it was able to take these instrumental effects into account, it was necessary to "invent" a north-south variation in sensitivity to obtain success. By combining the two methods of analysis, it is possible to obtain the sensitivity of the analytic method in a photographic simulation. The combined method consists of plotting the ratio of the observed number of events to the predicted number, using bins that are about 0.15 by 0.15 degrees. Figure 13 shows three such scatter plots for the data in the cone of 35-degree half-angle centered on the vertical. Plot 13b corrects for instrumental effects but does not take into account the fact that the instrument is covered by a pyramid. The corners of the pyramid are clearly indicated in it. The next scatter plot (Fig. 13c) further corrects for the presence of the pyramid with all its surface irregularities. Figure 13d shows what we would have seen if a "King's Chamber" had been in the pyramid, a chamber the same in size and location as that used to obtain Fig. 11. It is evident that no effect in the data approaches the magnitude of the effect produced by a King's Chamber.

We have explored 19 percent of the volume of the Second Pyramid. We now hope to rearrange the equipment so that we can look through the remaining 81 percent of the volume of the pyramid. This operation will be greatly simplified by our new understanding of the effects of muon scattering on angular resolution. It is now apparent that the iron absorber was not necessary for the success of the experiment, and we will omit it in the rebuilt apparatus. Rotation of the detectors about the vertical will thus be facilitated, and the possibility of "x-raying" some of the other large pyramids will be enhanced.

Summary

Because there are two chambers in the pyramid of Chephren's father (Cheops) and the same number in the pyramid of his grandfather (Sneferu), the absence of any known chambers in the stonework of Chephren's Second Pyramid at Giza suggests that unknown chambers might exist in this apparently solid structure. Cosmic-ray detectors with active areas of 4 square meters and high angular resolution have been installed in the Belzoni Chamber of the Second Pyramid; the chamber is just below the base of the pyramid, near its center. Cosmic-ray measurements extending over several months of operation clearly show the four diagonal ridges of the pyramid and also outline the shape of the cap of original limestone facing blocks, which gives the pyramid its distinctive appearance. We can say with confidence that no chambers with volumes similar to the four known chambers in Cheops's and Sneferu's pyramids exist in the mass of limestone investigated by cosmic-ray absorption. The volume of the pyramid probed in this manner is defined by a vertically oriented cone, of half-angle 35 degrees, with its point resting in the Belzoni Chamber. The explored volume is 19 percent of the pyramid's volume. We hope that with minor modifications to the apparatus the complete mass of limestone can be searched for chambers.

References and Notes

1. A. Fakhry, *The Pyramids* (Univ. of Chicago Press, Chicago, 1961).
2. R. Howard-Vyse and J. S. Perring, *Operations Carried On at the Pyramids of Gizeh* (London, 1840–42), 3 vols.
3. L. W. Alvarez, *Lawrence Radiation Laboratory Physics Note 544* (1 March 1965).
4. V. Perez-Mendez and J. M. Pfab, *Nucl. Instr. Methods* **33**, 141 (1965).
5. E. P. George, *Commonw. Eng.* (July 1955).
6. The Joint U.A.R.–U.S.A. Pyramid Project has been fortunate in the strong support it has received from many individuals and organizations on two continents. The initial and continuing interest of Dr. Glenn T. Seaborg was reflected in the financial support of the project by the U.S. Atomic Energy Commission during the period when the detection equipment was designed and built at the University of California's Lawrence Radiation Laboratory. The U.A.R. Department of Antiquities extended every courtesy to members of the project, and, in addition to inviting us to install our equipment in the Second Pyramid, they put at our disposal an attractive and conveniently located building which served as our laboratory and general headquarters. The Smithsonian Institution was generous in its support of the project, particularly in making available travel funds that permitted project members from our two countries to work together both in Berkeley and in Cairo. The Ein Shams University and the University of California both supported the project in many ways, and we give special thanks to Vice Rector Salah Kotb and Chancellor Roger Heyns. The IBM Corporation, the National Geographic Society, the Hewlett-Packard Company, and Mr. William T. Golden made important contributions to the project for which we will always be grateful. The U.A.R. Surveying Department made accurate measurements of all external and internal features of the Second Pyramid, without which we would have been severely handicapped. The overall guidance of the project was vested by our two governments in a "Committee of the Pyramids," under the chairmanship of Dr. Salah Kotb. We are indebted to the distinguished members of this committee for the warmth and understanding they displayed in the exercise of their responsibilities. All of us take pride in the fact that the friendly spirit in which we started the project survived not only the perils that confront any interdisciplinary or intergovernmental effort but also a break in diplomatic relations between our two countries. In conclusion, we acknowledge important assistance from Raymond Edwards, Sharon Buckingham, Fred Kreiss, William E. Nolan, Kamal Arafa, Sayed Abdel Wahab, Mohamed Tolba, Aly Hassan, August Manza, and Vice Chancellor Loy Sammet.