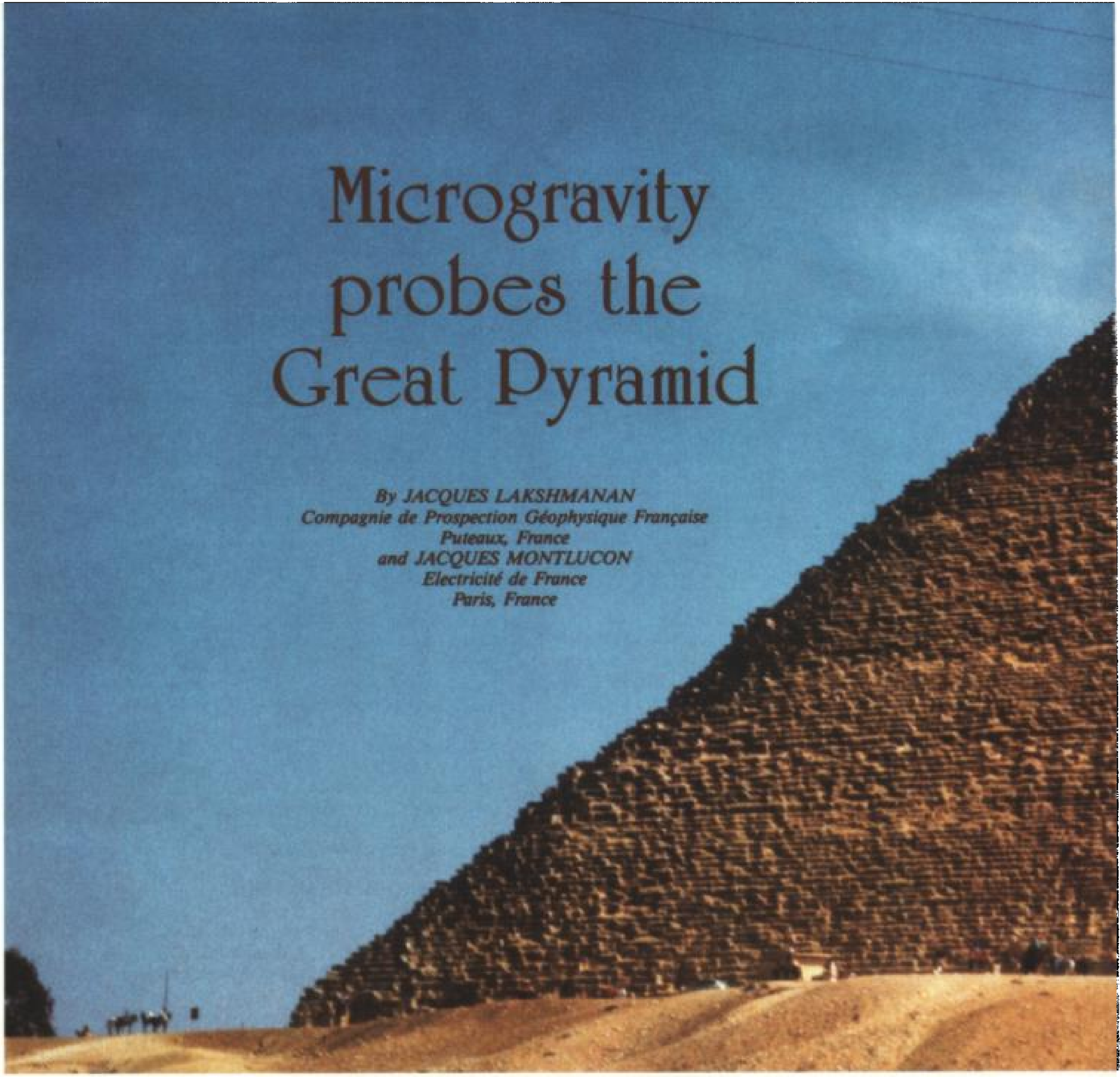

Micrograyity probes the Great Pyramid

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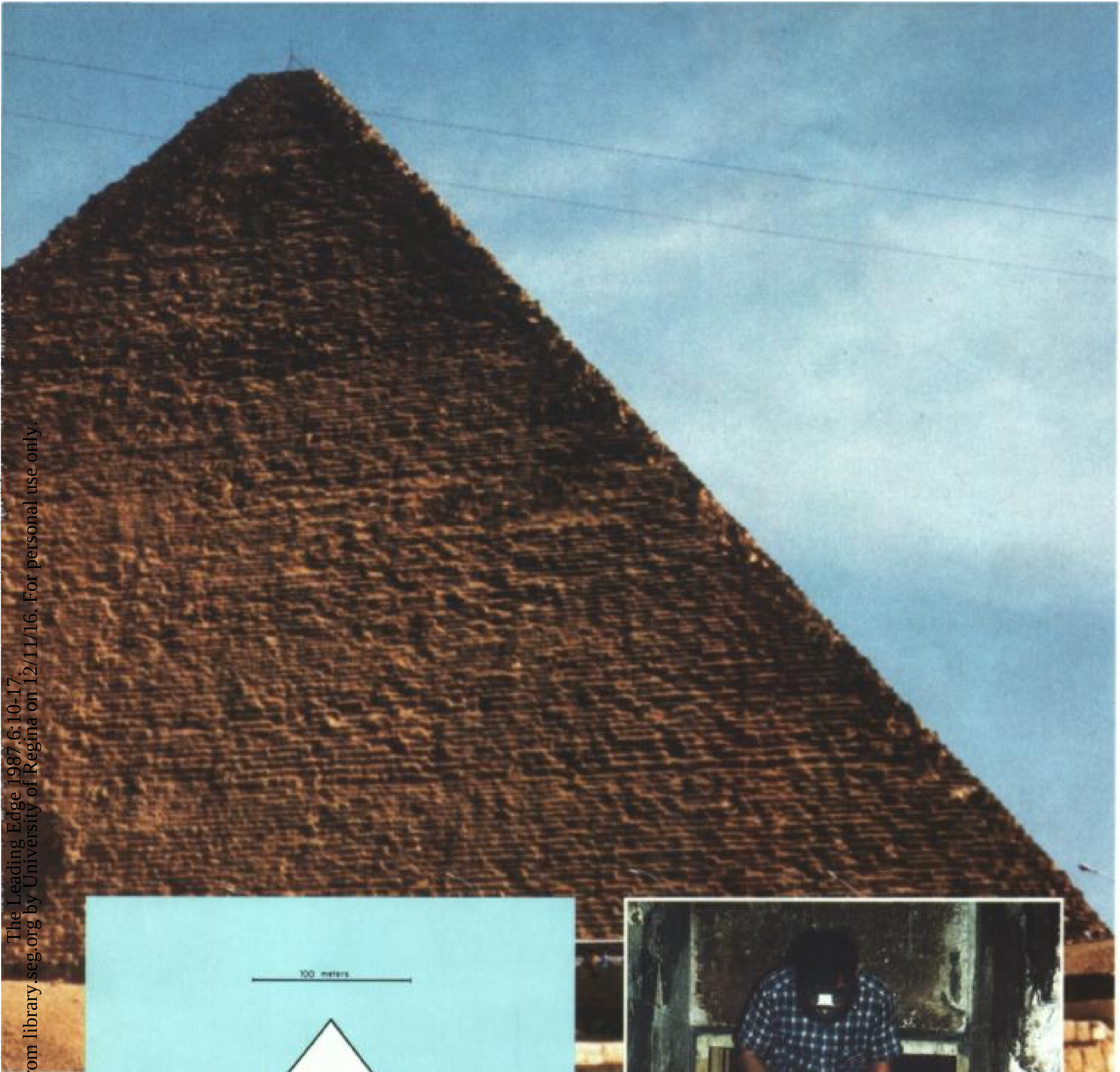
Treasure hunters and some archeologists have been convinced, since at least the 12th century, that mysterious chambers exist in the Great Pyramid which conceal the real tomb and treasures of Cheops. A year ago two French architects, Gilles Dormion and Jean-Patrice Goidin, examined the construction features of the tunnels and chambers inside the Great Pyramid — one of the largest buildings, ancient or modern, ever constructed — from an architectural point of view. They observed several anomalies, particularly:

- The huge vault, much too high, above the entrance of the pyramid.
- The offset of the King's chamber — all other chambers in this and other Giza pyramids are exactly in the pyramid's vertical axis (see Figure 1, inset).
- The abnormal position of the slabs in the Queen's chamber tunnel.
- The abnormally large superstructure (decompression chambers) above the King's chamber.

Dormion and Goidin accepted these anomalies as proofs that the so-called King's chamber is just a decoy which hides the real King's chamber, and that "stores" should exist close to the Queen's chamber.

Early in 1986, the two French architects convinced the Egyptian Antiquities Department, the French Foreign Ministry and Electricité de France (the French State Power Board) that their theories were sound enough to be tested in the field. Electricité de France, following its policy of technological sponsorship, decided to head the funding of an expedition and start with a geophysical survey. Compagnie de Prospection Géophysique Française was hired as a consultant. Resistivity, electromagnetics and seismic methods were soon rejected. Radar was carefully examined but, in the end, Electricité de France and CPGF selected microgravity as the most efficient technique for cavity detection in the very special conditions existing in the pyramid.



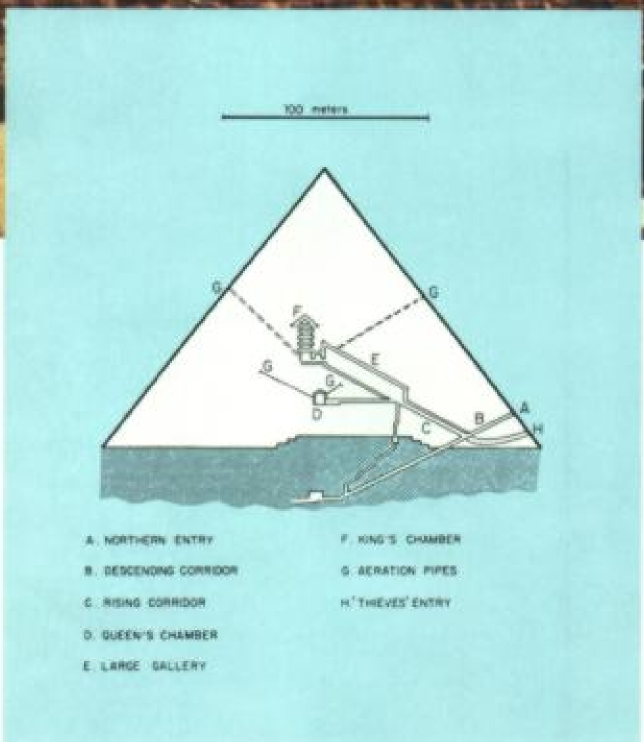


Figure 1.

Vertical gravity gradient measurement (1 m off the ground!)

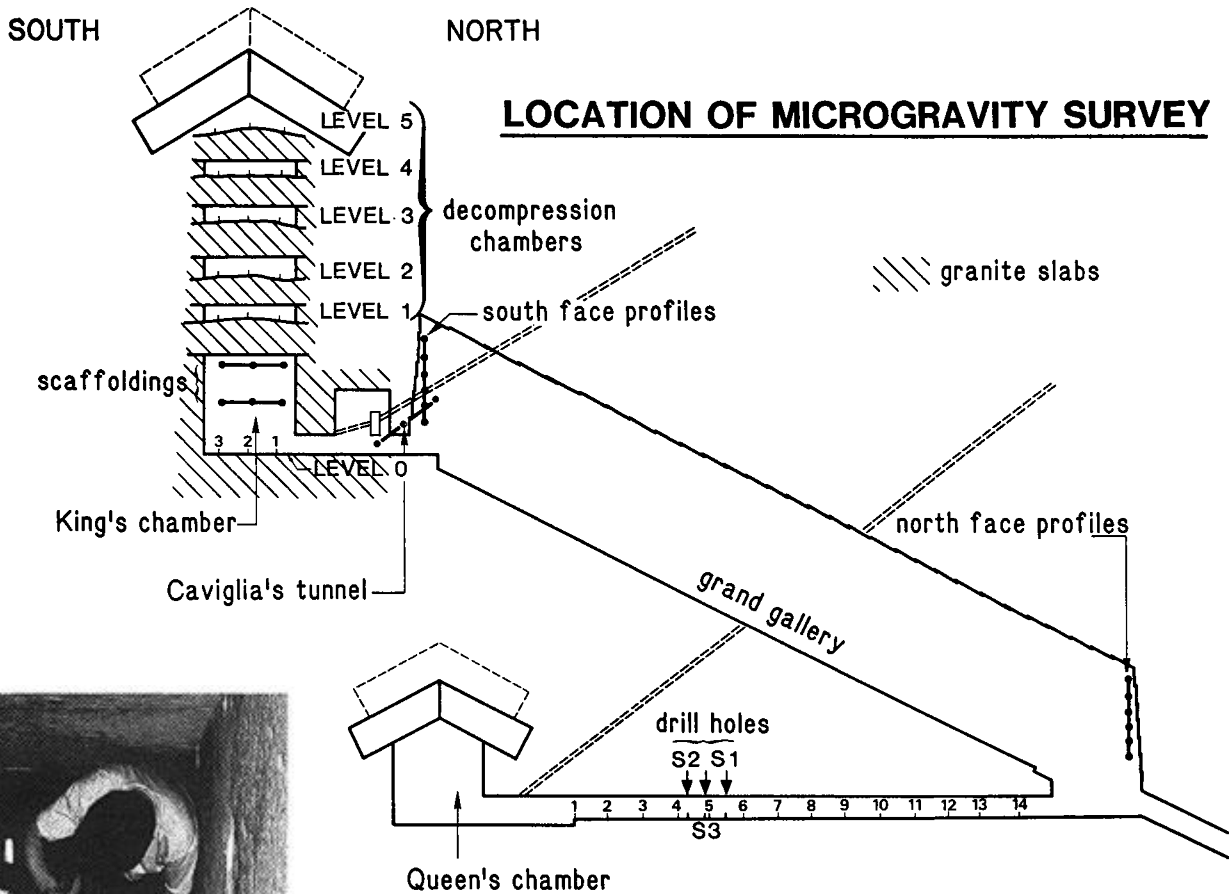
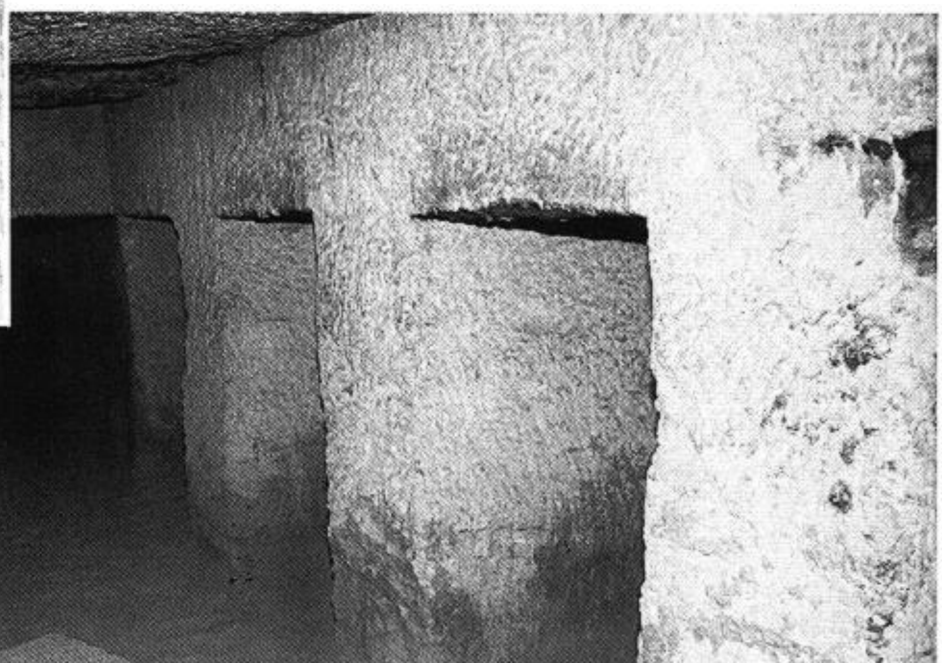


Figure 2.



Above left: Jean-Pierre Baron drilling under supervision of Egyptian Department of Antiquities.
Above: An example from another pyramid of a "store" similar to the one we were looking for along the Queen's chamber access tunnel.

Microgravity surveys for caves. Microgravity surveys have been carried out by CPGF for several years — starting with the Paris-Lyon motorway (detection of karstic cavities) in November 1962 and in the city of Caen in Normandy (underground quarries) in December 1962. CPGF has, subsequently, carried out a number of microgravity surveys, involving a large number of stations. Traditional gravity surveys really became "microgravity" in 1968 when the firm of LaCoste & Romberg brought out the D-meter with a reading accuracy of one microgal. Various field procedures, processing techniques, and interpretation methods have been developed to utilize the higher sensitivity of microgravity surveys and some of them have recently been incorporated into conventional gravity surveys for oil.

Electricité de France is a major user of microgravity surveys — for preliminary site investigation of dams and nuclear power plants, for foundation quality control, and for fine microgravity gridding in the foundation excavation itself. The US Corps of Engineers has recently become interested in microgravity's potential and this year is studying the application of microgravity to the assessment of existing structures and structural foundations.

Station spacing ranges from 2 - 40 m in microgravity surveys. The usual depth of caves is of the same order. The gravity anomalies range from 15-300 μGals. In order to achieve maximum accuracy, field measurements are made with great care, in a semirandom sequence, with returns to base every 20-30 minutes. The instrumental drift curve is adjusted to take into account repeat stations, and to minimize time dependent anomalies. Work is often done at night when ambient noise conditions are quietest.

Final accuracy on repeats is in the order of 2-10 μGals when field conditions are good. When surveys are made in harsh urban conditions (for example, along the circular Paris freeway), repeat differences vary between 5 and 30 μGals. However, in the middle of large cities, microgravity is practically the only feasible geophysical technique.

The main geological targets in microgravity surveys are ancient underground quarries which occur frequently in chalk and limestone regions in Europe; World War I trenches and tunnels; sink holes and dissolved zones in gypsum, salt or limestone areas; and repeat surveys for controlling grouting operations.

Another novel application of microgravity is the measurement of absolute density of embankments by generalized Nettleton profiles. Conventional microgravity is often completed by vertical gradient profiles across major anomalies for more accurate depth evaluation. Gradient is measured between stations 1-1.5 m apart.

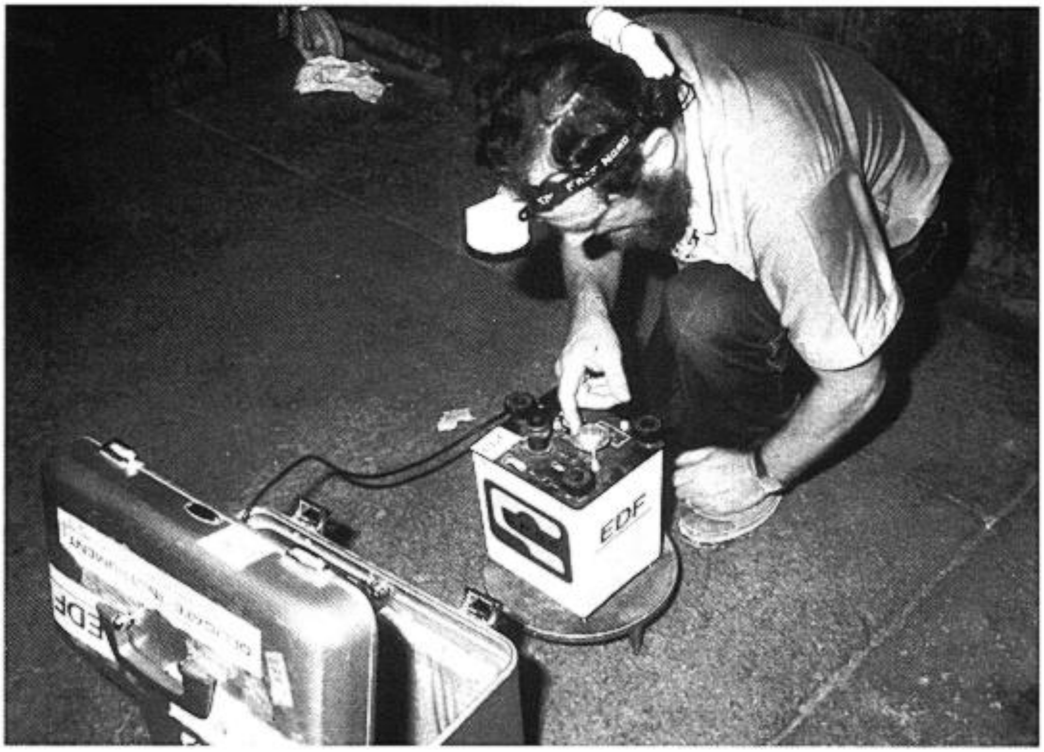
Microgravity survey in the pyramid of Cheops — preliminary modeling. Computer models were run, prior to the survey, in order to evaluate the type and size of cavities detectable by microgravity. These showed that by operating along accessible tunnels and chambers, cavities of around 10 - 40 cu m could be detected at distances reaching 10 m. A complete computer model of the pyramid was then run in order to compute the general effect *(P)* of the pyramid and the corrections *(C)* due to all the known existing chambers and tunnels.

Values of *P* range from $-2{,}500$ μGals in the Queen's chamber tunnel to $+1{,}700$ μGals at the highest decompression chamber with a gradient of around 96 μGals/m (for a density of 2.6 g/cu cm).

Values of *C* range from 0-280 μGals (for the same density) with the maximum values being on the floor of the King's chamber.

All of these corrections were made in advance so that the field crew could compute corrected Bouguer values on the site. Different models of unknown chambers were run in advance so that comparisons leading to immediate decisions could be made during the survey.

Field work in the pyramid (see Figure 2). During the May 1986 survey, a 2.1 × 2.1 m grid of 15 stations was set up on the floor of the King's chamber and on each of the five decompression chambers. In the September survey, scaffolding was put up and two extra levels were surveyed in the 6-m high King's chamber.



Jean-Claude Erling reading LaCoste & Romberg D-meter in the King's chamber.

Three stations were made close to the entry of the King's chamber in Caviglia's tunnel which was dug during the 19th century.

A 27-m profile with 15 stations (spaced 1-2 m) was made in May in the access tunnel to the Queen's chamber. Two other profiles were made in September on each side of the 1.1 × 1.1 m tunnel. Spacing between these three profiles is 0.5 m (which is probably a world record!) These two profiles include a total of 46 stations with spacing ranging from 0.5-2 m.

Interpretation procedure. The Pyramid's density was computed using an interpretation technique similar to that used in borehole gravity surveys. In fact, the measurement of gravity inside a finite body is a generalization of borehole gravity.

Measured free air gravity (*FA*) is the sum of:

- The general attraction *P* of a homogeneous theoretical pyramid, of density σ_p from which the effect *C* of known cavities is subtracted; *P-C* is the effect of the "pyramidoid," by analogy with the geoid.
- Regional effects on the pyramid due to external causes, either linear $(ax + by = C)$ or of the second degree.
- Regional vertical gradient.
- Effect of local inhomogeneities inside the pyramid, such as unknown caves.

After computing *P-C* for an arbitrary density, a multivariable regression between *FA, P-C, x, y* and *z* should yield the correct average density σ_p. In fact, tests show that *P* being very strongly related to *z*, these two parameters cannot be easily separated. The regressions used were therefore based on equations of the type:

$$FA = \sigma_p' \frac{(P-C)}{2.6} + ax + by + c, \text{ or}$$

$$FA = \sigma_p' \frac{(P-C)}{2.6} + ax^2 + a'x + by^2 + b'y + c,$$

σ_p' being an apparent density, as in borehole gravity.

We also had to take into account the effect of granite slabs (2.65 g/cu cm) surrounding the King's chamber and the decompression chambers. This required an iterative procedure.

Tests were also made using a horizontally stratified, 3-layer pyramid density. Results yielded an average apparent density of the pyramid ranging from 1.88-1.95 g/cu cm (see Figure 3).

After computing σ_p', *a*, *b* and *c*, the theoretical free air gravity (*TFA*) was computed at each point, leading to a residual free air anomaly:

$$RFA = FA - TFA.$$

These residual values were then transformed into differential densities $\Delta\sigma$ by computing the vertical gradient ΔRFA inside a moving window. We (quite arbitrarily) suppose that ΔRFA is due to a local modification of the Pyramid's average density σ_p', inside a cylinder ΔZ meters high, and of a radius *R* meters.

The difference of free air attraction between the top and the bottom of a vertical cylinder is given by:

$$\Delta FA = \frac{80}{3} \cdot \pi \cdot \sigma \left[R + \Delta Z - \sqrt{R^2 + \Delta Z^2} \right],$$

which yields, setting $R = r\Delta Z$,

$$\Delta\sigma = \frac{1}{83.8} \frac{\Delta FA}{\Delta Z} \cdot \frac{1}{1 + r - \sqrt{1 + r^2}}$$

as compared to the usual borehole gravity formula

$$\sigma = \frac{1}{83.8} \frac{\Delta FA}{\Delta Z}.$$

GLOBAL DENSITY OF THE PYRAMID

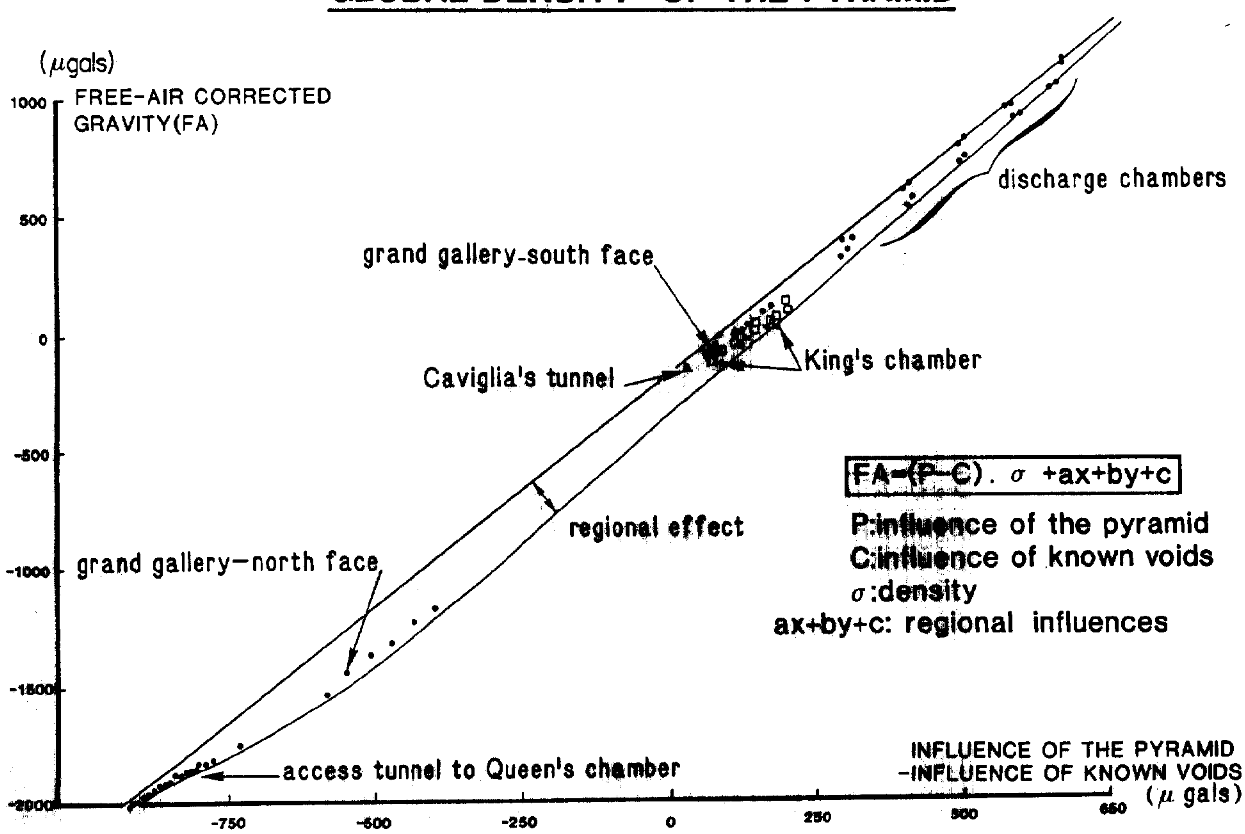


Figure 3. The slanted line represents apparent density of 1.95 g/cu cm. Corrected density is 2.05.

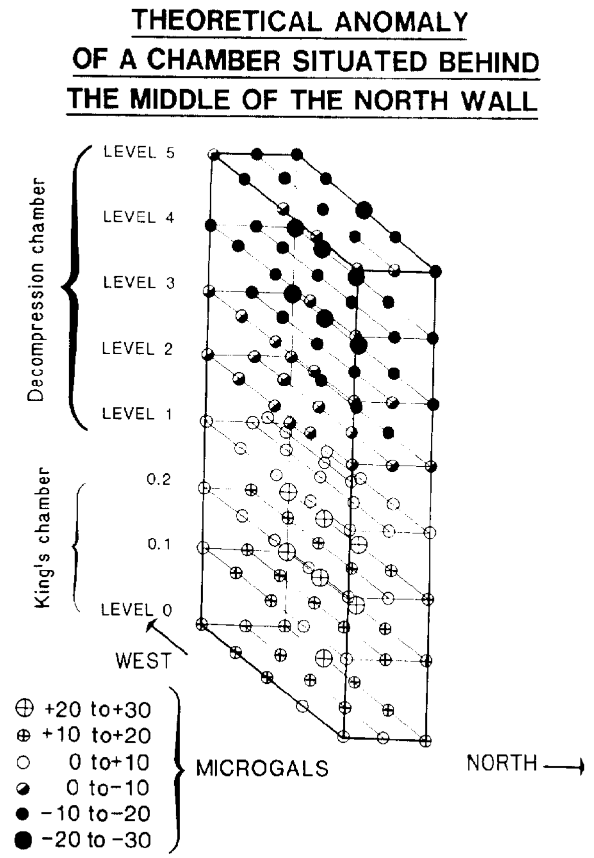


Figure 4.

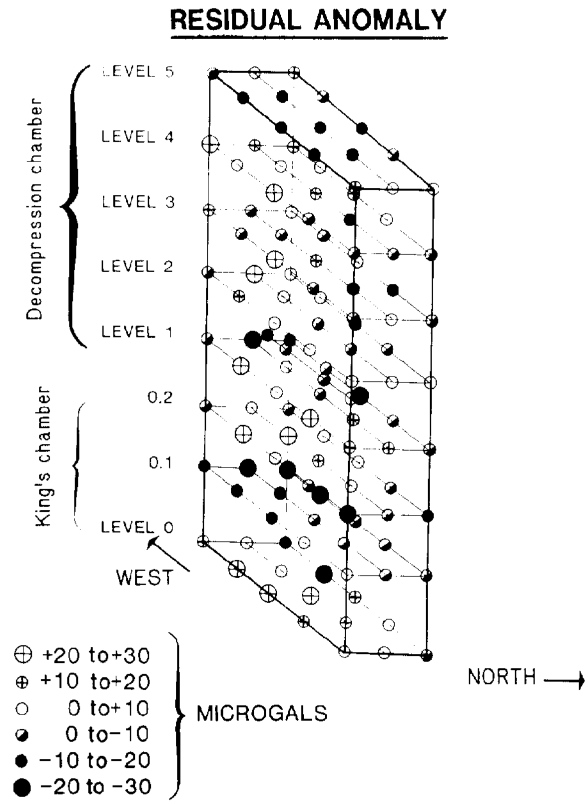


Figure 5.

When r = 5, we obtain $\triangle\sigma = \frac{1}{75.5}\frac{\triangle FA}{\triangle Z}$.

We can then compute an apparent density σ' at each point

$$\sigma' = \sigma_p' + \triangle\sigma.$$

Vertical gradients due to regional effects were then computed. The correction of the effect of a large gravity feature located 25 km NW of the pyramid increases the apparent density by 0.15 percent. The correction of the topographic effect of the Nile valley and of the effect of lower density quaternary sediments increases the apparent density by about 5 to 7 percent.

Average density and structure of the pyramid. Taking into account these corrections, the average density of the pyramid is very close to 2 g/cu cm. This figure should be compared to the known density of the materials of which the pyramid is (or could be) formed:

- TURA limestone, which covers all the access tunnels is 2.6 g/cu cm.
- Local paleogenic limestone is an average of 2.07 g/cu cm.
- Fill seen in Meidun Pyramid, but not yet seen in Cheops is 1.8 g/cu cm.

Pending further debates, we consider the hypothesis of a massive pyramid, mainly made of local limestone, without (or with very little) fill, to be the most coherent.

The results of more intricate models (3-layer, or with a second degree regional) make us suspect that this density of 2 g/cu cm is just an average. We feel that the lower southwest part of the pyramid could be heavier, but further measurements on the surface of the pyramid would be necessary.

Results in the King's chamber. The residual values range from

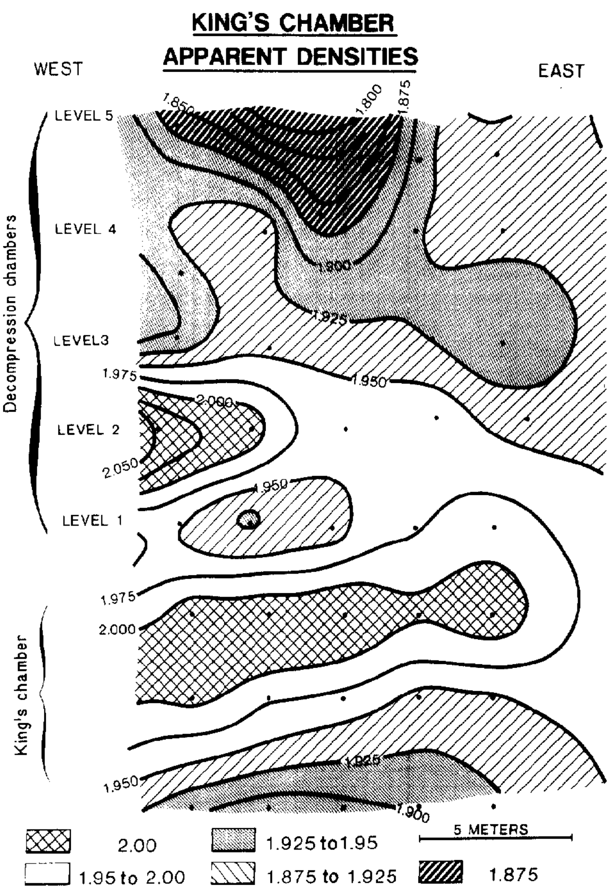


Figure 6.

−25 to +33 μGals. The main negative anomaly is located at the northwest corner of the King's chamber's floor. It corresponds to a small old investigation tunnel, leading out from below the stone coffin. A couple of small high frequency local anomalies show up and will be investigated later, but they have nothing to do with the anomaly computed from the presumed unknown tomb, which should have given a 5 m wide negative anomaly at decompression chambers 2 and 3 and a symmetrical positive anomaly of the two reading levels on the scaffoldings.

Figures 4 and 5 compare the theoretical gravity due to the suspected chamber and the real residuals and Figure 6 shows the apparent densities computed from these residuals corrected by 7 percent of the effect of regional vertical gradient.

The Queen's chamber access tunnel. This zone was only surveyed as a secondary target; however it was here that we had the most significant results.

Figure 7 is a residual anomaly map, showing the results of the three profiles after all corrections. Towards the entry of the tunnel, a positive zone (+20 μGals) shows up, while towards the Queen's chamber, a strong negative feature (−25 μGals) is visible, mainly on the western profile. The difference between the two zones, around −45 μGals, is a very significant, non-ambiguous anomaly.

Quantitative analysis is very difficult because data are only available along the three tightly spaced profiles. We made various interpretations with different hypotheses, supposing various positions and amplitudes of the maximum anomaly. The most prudent hypothesis supposes that the maximum is reached at the west profile, while one could suppose that this profile is in fact just on the edge of a larger anomaly (see Figure 8).

The different proposals yield various interpretations (either

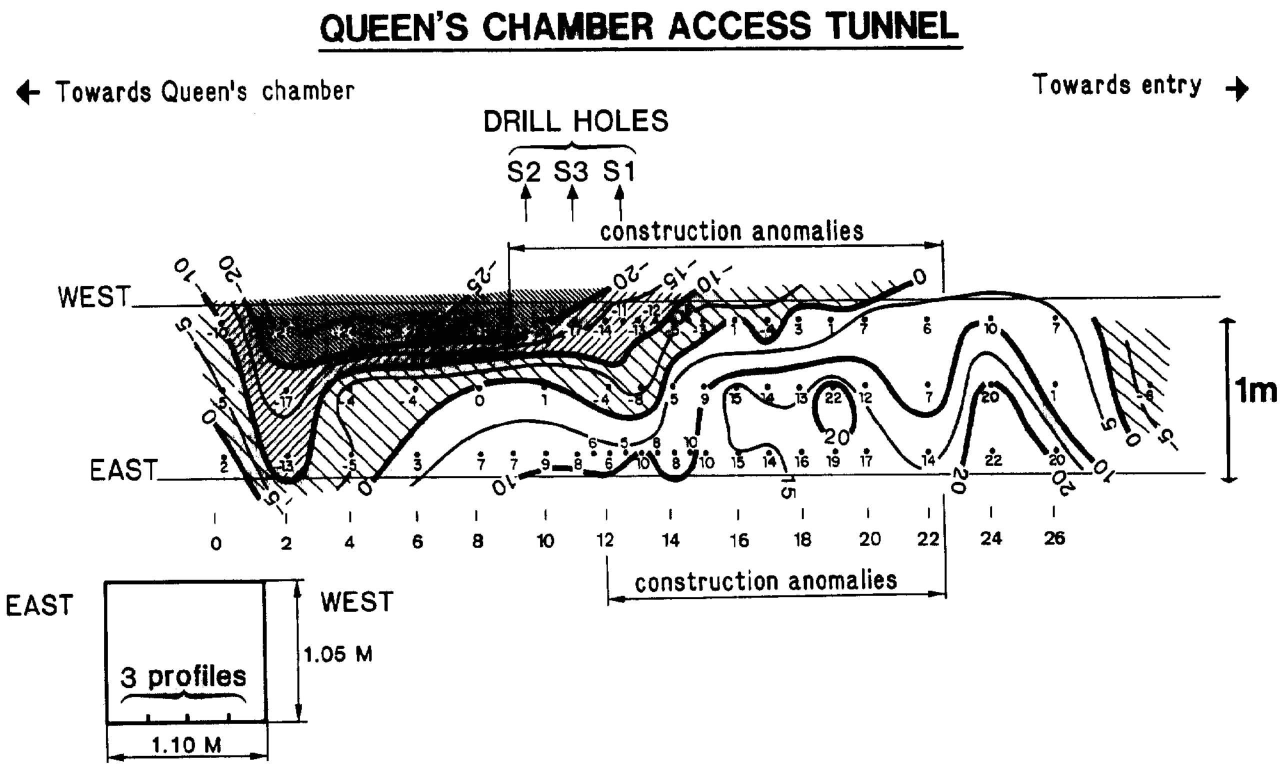


Figure 7.

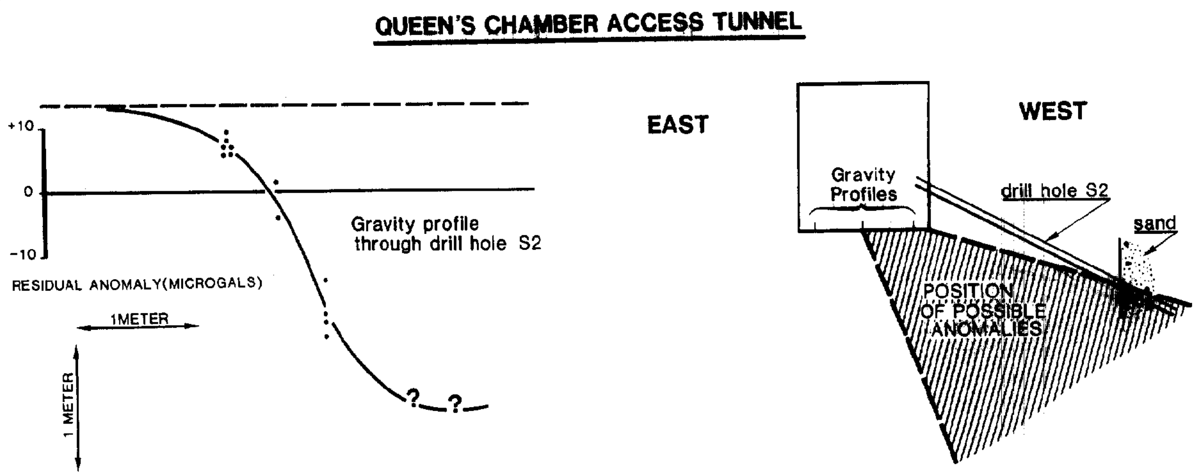


Figure 8.

MICROGRAVITY TEST ABOVE THE SOLAR VESSEL CHAMBER

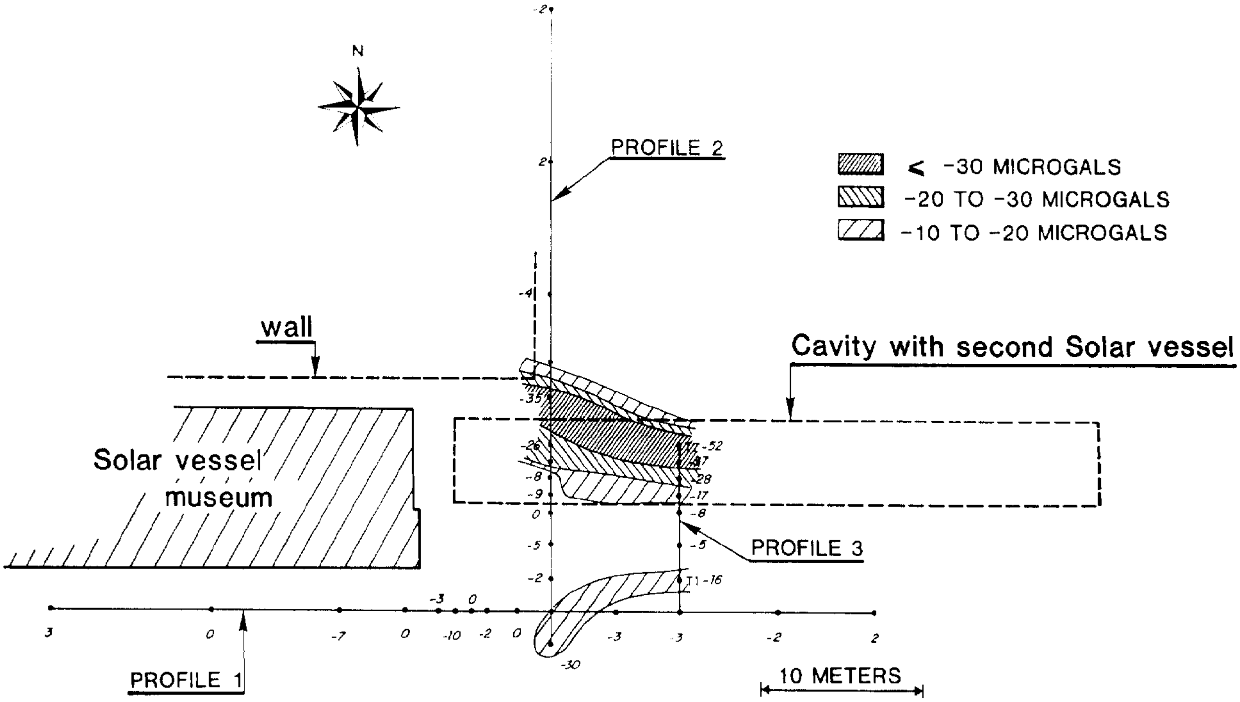


Figure 9.

for a horizontal cylinder or for a horizontal strip) all located in the hatched zone.

Of course, if one of these sources extended upward towards the side of the tunnel, the upper part (located on the same horizontal level as the measurements) would not create any anomaly at all on the vertical component of g, measured by the meter.

The position of this anomaly along the tunnel and its location on the west side coincide with a certain number of observations made by the architects. It was therefore decided to drill sideways, with holes tilted 30 degrees from the horizon, in order to locate possible "stores" as have been found in other pyramids.

The drill used was a small electric rotary drill with a 35-mm diameter. The Egyptian authorities made us carry out a preliminary test on large blocks outside the pyramid to avoid all risk of destroying valuable objects. The pyramid's building blocks are limestone and 53 cm thick. We were allowed to use water injection to flush out the sediments for the first 45 cm of drilling but we had to end the drilling in each block with dry diamond drilling.

Three holes, 2.6 m long, were drilled 1.5 m apart. After crossing about 2.1 m of limestone (four blocks), they all struck loose sand with pieces of mortar. The three holes were visually inspected using a Bodson endoscope. The edge of the sand was seen to be vertical in all three holes. This sand is very loose and we air-flushed out several liters with a small compressor. The architectural purpose of this sand is not known; however, the Egyptian Antiquities Department agrees that this discovery is a definite indication of an organized structure, probably related to new and unknown chambers.

Reverting to gravity interpretation, it is clear that if the anomaly was only due to sand, its volume would have to be very large — around 40 cu m for anomaly 4, for example.

Gravity test over the buried vessel chamber. A short gravity test was also carried out outside the pyramid, over a chamber where a buried vessel is suspected. A similar vessel has previously been discovered and reassembled in an adjacent museum.

The survey included 35 stations with spacings ranging from 1-6 m. The two profiles which cross the presumed vessel clearly show anomalies reaching −30 to −50 μGals. This short test showed how easily fine microgravity could be used for locating small underground chambers. Of course, all the sophisticated corrections made inside the pyramid were not necessary here.

We wish to put aside the "treasure hunt" and "curse of the Pharaoh" sides of the survey, which attracted 40 international journalists to the pyramid. We do not wish either to intervene in the present controversy between schools of Egyptologists as to the nature of the sand-filled cavities we have detected. However, the techniques used: microgravity with advanced correction and interpretation techniques, and microdrilling with endoscope visualization, are considered by all involved to be the best combination for surveying underground chambers, particularly when surveying inside structures like the pyramid.

Egyptian and French authorities are now discussing the best follow-up courses. One debate is between the use of a larger, more powerful drill or the construction of an investigation tunnel.

More gravity surveys are anticipated along uninvestigated tunnels (particularly the Grand Gallery) and on the outside faces of the pyramid. A complete 3-D gravity model "weighing" the pyramid could yield more information on both the possibility of other chambers and on the geotechnical features of the pyramid itself. Several observations (particularly in the decompression chambers) suggest that stability problems exist in the pyramid. Such an investigation could be a useful test for developing techniques for the assessment of other larger existing structures, such as earth dams. LE

(Oral versions of this article were presented at a seminar at the Colorado School of Mines in September and at SEG's Annual International Meeting in November 1986.)