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APPLICATION OF MODERN TECHNOLOGY TO ARCHAEOLOGICAL EXPLORATION AT THE GIZA NECROPOLIS

FIRST RESULTS OF STRUCTURAL ANALYSIS OF THE CHEOPS PYRAMID BY MICROGRAVITY

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I. - INTRODUCTION

In early 1986, the French Ministry of Foreign Affairs and the Egyptian Antiquities Organization, headed by Dr. Ahmed KADRY, asked Electricité de France to find a way of analysing the internal structure of the Grand Pyramid. One of the particular aspects of the request was the control of certain theories which supposed the existence of a set of secret unknown chambers, particularly around the King's chamber (Dormion and Goidin, 1986).

Electricité de France (E.D.F.), after examining the possibilities of other geophysical methods, and taking into account its extensive experience in the use of geophysical techniques for the assessment of foundations of major works such as dams or nuclear power plants decided to use microgravity. This method seemed the most appropriate to help solving this problem, particularly when taking into account the inaccessibility of the discharge chambers

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for many geophysical instruments such as radar. E.D.F. called in Compagnie de Prospection Géophysique Française (C.P.G.F.), who was the world pioneer for the use of microgravity for the location of cavities (Lakshmanan, 1963) and is considered to be a major specialist in this technique (Lakshmanan, 1979 ; Erling and Roques, 1983 ; Lakshmanan, 1987).

C.P.G.F. assisted E.D.F. for 4 field surveys, while for the processing , interpretation and modelling, E.D.F. organized and managed a working group including the following laboratories and research centres :

- Ecole Polytechnique, Massy-Palaiseau, France
- Electricité de France, Direction des Etudes et Recherches, Clamart, France
- Electricité de France, Direction de l'Equipement, Division Techniques d'Exécution, Géologie, Géotechnique, Paris.
- Compagnie de Prospection Géophysique Française, Puteaux, France.

The surveys and their interpretation should be considered to be part of E.D.F.'s general scientific policy, which includes bringing E.D.F.'s high technology towards the cultural, non profitable sector. However, it soon appeared that the investigation of the Grand Pyramid was a formidable challenge, and that new techniques had to be developed partly for the acquisition of data, and mainly for the processing and interpretation of the measurements.

These methods having now acquired an enlarged scope, there has already been a "feed back", i.e., a technology transfer from the methods developed in the cultural sector, for the Cheops Pyramid, back towards the industrial field. During the month of November 1987, a survey was carried out at La Coche hydroelectrical plant and dam (Savoie, France), where a tunnel and a mountain are being surveyed by the now called "Pyramid" technique of endoscopic microgravity.

A review of the principles of gravity interpretation, and those of the first methods specially developed for the Pyramid in 1986, has been made by Montluçon and Lakshmanan (1987) and by Erling and Lakshmanan (1986).

II. - NEW METHOD OF ANALYSIS OF ENDOSCOPIC MICROGRAVITY

II.1 - Basis of the new method

The basis of the method consists in comparing the computed effect of the structure and the surrounding ground (for presupposed densities) at the measurement points, with the measured values. Suitable mathematical procedure allows calculation of the best adjusted densities of the blocks forming the structure.

In October 1986, the method (as described in the appendix) was less sophisticated than today, but had already allowed calculation of a single density (around 2 gm/cc) of the whole pyramid. This density happened to be less than the value expected.

In the present state of the procedure, the Pyramid and the surrounding terrain are divided into a large number of elements (around 2,000) which represent the geometry of the "fulls" and the voids as best as possible. These elements are then assembled into a number of blocks (20 to 40) whose densities (uniform for each block) are the unknowns of the mathematical problem. In turn, these blocks can be considered to be part of large domains :

- the EXOSTRUCTURE, effect of known bodies at kilometric and decakilometric scales, which includes : long distance geological effects and the effect of topography inside a radius of 5 km around the Pyramid,

- the PERISTRUCTURE at decametric and hectometric scales, which includes the effect of known (the subterrean chamber and the descendant gallery) and unknown underground bodies in the rock around and under the Pyramid, e.g. the solar vessels,

- the MACROSTRUCTURE of the Pyramid at a decametric to hectometric scale : after a first analysis with a homogeneous Pyramid, the Pyramid can be divided into quite a large number (20-30) bodies (part "fulls", part known "voids"), each with an unknown density, leaving aside in a single block, the "heart of the Pyramid".

- the MESOSTRUCTURE at a decametric scale, where the "heart" of the Pyramid, which includes all known chambers and where a large data set is available, is subdivided into 20-30 smaller blocks, each also including "full" parts and known voids".

- the MICROSTRUCTURE : in local zones, where enough data are available, certain blocks of the mesostructure can in turn be subdivided again into even smaller blocks, of the metric to decametric range.

II.2 - Application to the pyramid

At the present time, the procedure, as applied to the Pyramid, includes the following steps :

(a) Computation of the gravitational influence of the blocks (for a standard density of 1)

(a.1) Computation of the effect of the EXOSTRUCTURE and the PERISTRUCTURE ; these zones are divided into :

- one large block outside the Pyramid at a distance exceeding 20 m from its foot,
- 6 blocks of the basement under the Pyramid : 5 of these blocks correspond to the divisions of the macrostructure as below ; one was added during the processing, in order to explain an anomaly observed near the north-eastern foot of the Pyramid.

(a.2) *Computation of the effect of the MACROSTRUCTURE*, where the Pyramid, apart from the heart, is divided into :

- 24 blocks (6 horizontal "slices", each divided into 4 quarters)
- 1 block of granite, including all the granite slabs surrounding the King's chamber and the discharge chambers.
- 1 extra block, in order to take into account special phenomena observed during the processing, near the entry (see fig. 2).

(b) Determination of unknown densities and residuals : after comparison between measured values and the effect of all these blocks ; computation (by 3 mathematical techniques) of the 1 + 6 + 1 + 24 + 1 + 1 = 34 unknown densities, and of the "residual" values of gravity at each measurement point.

If σ_i are the best adjusted densities of the 34 groups of blocks, and I(i,j) their influences for a standard density of $\sigma = 1$ on the measurement point "j", and if G(j) are the measured values of gravity (corrected from latitude and free-air effects), then we have :

$$TG(j) = \sum_{i=1}^{i=34} \sigma_i \, . I(i,j)$$

and $RG(j) = G(j) - TG(j)$,

TG(j) being the theoretical value of "gravity" corresponding to the 34 density model, and RG(j) the residual value of "gravity" at each measurement point.

(c) Adjustment of the model :

After analysing the results, the limits of the various blocks are adjusted in order to reduce the difference between the measured and the computed values of gravity. Indeed, we try to minimize the mean square difference MSD :

$$MSD = \sqrt{\sum_{j=1}^{j=n} \frac{(G(j) - TG(j))^2}{n}}$$

considering the measured and computed values at the "n" points obtained during the 4 surveys.

In fact, in the above description, it should be noted that the limits of the "heart" were adjusted several times, and that the extra blocks, near the N-E foot of the Pyramid and around the entry, were added in order to reduce MSD. The best present division of the macrostructure is shown on fig. 6 and 7. In this manner, the analysis of the microgravity measurements is a mean of appreciating different hypotheses on the structural organization of the Pyramid.

Presently, several more sophisticated structural hypotheses of the macrostructure have been drafted, taking into account the results obtained, and their effects are being assested. These hypotheses may include : a spiral structure and a semi-vertical structure with alternating "heavy" and "low" density walls.

(d) Analysis of the mesostructure :

The residual values RG(j) obtained after end of step (d) are then analysed as being the causes of density variations in the "heart" of the Pyramid, in order to study the mesostructure.

Numerous tests have shown us the physical validity of carrying out separately the analysis of the macrostructure and the mesostructure. When trying to invert a more sophisticated model (with 80 blocks including 34 blocks in the macrostructure an 46 blocks in the mesostructure), no significant changes were noticed in the values of the macrostructures density and in the "residuals" obtained on the surface of the Pyramid, as compared to those obtained while processing the MACROSTRUCTURE with the MESOSTRUCTURE reduced to a single block. The suggested procedure facilitates the adjustment of models and reduces processing time. When proceeding in two steps, the second step computes differential

densities, which have to be added to the original density of the "heart" as computed in (b) and then, second degree residuals which are the differences between the measured values of gravity and the field due to the computed model.

(e) Analysis of the microstructure :

In a last step, the second degree residuals can be analysed again, in order to determine (at least in certain zones) the characteristics of the microstructure, that is the distribution of densities at a more detailed, metric scale.

III. - MEANS USED

The following geophysical personnel from C.P.G.F. participated in the field surveys :

1st survey : J-C ERLING, Y. LEMOINE, in May 1986
2nd survey : J-P BARON, J-C ERLING, Y. LEMOINE, in August 1986
3rd survey : J-P BARON, J. LAKSHMANAN, in February 1987
4th survey : J-P BARON, Y. LEMOINE, in November 1987

E.D.F.'s experts P. DELETIE and J. MONTLUCON supervised all 4 phases.

The Egyptian Antiquities Organization supplied a very strong and qualified assistance for all phases and without the indefectible support of Dr Ahmed Kadry, this scientific work would never have been done. From a practical point of view, we most appreciated the help of Mrs. Samia El Malar and of Mr. Chawki Nakhla.

The measurements were made with a Lacoste & Romberg model D "microgal" gravity meter. A total of 754 measurements was made during the four surveys.

The preparation of the gravity and topographical data was made by Messrs. J-P BARON and J. LAKSHMANAN. The development of new inter-

pretation techniques, followed by the processing and modelling, was carried out by a crew of mathematicians and computer specialists from E.D.F. (including in particular Messrs. Jacques BATUT, Patrice CORNON and Marc BONNET), headed by Dr. Huy Duong BUI, and advised by J. LAKSHMANAN.

It should be noted that the total means used for the 4 surveys, and for all the calculations, totalize approximately : 3,000 hours of scientists and geophysicists, 300 hours of CPU time on the VAX 11-750 and 50 hours of CPU time on the IBM 3090-400.

IV. - RESULTS

The four microgravity surveys carried out at the Pyramid of Cheops have given the following results:

(a) Development of a new technique of inversion of 3-dimensional gravity surveys in and on a finite structure

Gravity measurements in and on a structure like the Pyramid now allow direct evaluation of the density distribution.

When the data are sufficiently well spread out, the structure can be analyzed in several steps :

- macrostructure (analysis of the structure of the Pyramid itself)
- mesostructure
- microstructure

and in certain cases : exo- and peri-structure (study of local anomalies such as cavities) related to the outskirts of the Pyramid.

(b) The macrostructure

The macrostructure of the Pyramid has been analyzed in detail. The average density of the Pyramid is 2.05 gm/cc. However, it is not homogeneous, as seen by comparing figures 5 (residuals for a homogeneous pyramid) and 8 (residuals for a 34 block model). It appears that the top of the Pyramid, above the top of the highest decompression chamber, has a low density of around 1.8 - 1.9 gm/cc. Below this zone, the Pyramid is heterogenous. We have clearly shown the existence of a large number of light and heavy zones (see figures 6 and 7). These zones, as seen on the slanting edges, do not correlate horizontally. In the light of these results, we are now examining the following structures, both with alternately heavy and light layers :

- a spiral structure
- a semi-vertical structure.

(c) The peristructure around the Pyramid has been studied in 3 zones :

- the second solar vessel, where we clearly confirmed the position of the cavity, and the validity of the method, in May 1986, (see figure 9),
- the S.S.W. "radar" anomaly, where we can see only a very local anomaly (see figure 10),
- the N.N.E. periphery, where we have discovered two particular anomalies, possibly related to fractured zones.

(d) In more detail, the mesostructure shows several anomalies :

- a heavy zone around the entry
- a volume of granite slightly higher than expected

- zones of varied densities in the heart of the Pyramid with, in particular, a light zone in the middle of the Grand Gallery and a small light zone close to the top of the north face of the Grand Gallery (see figure 11).

(e) the microstructure has been studied in detail in several zones :

- the King's and the discharge chambers
- the Queen's chamber
- the access tunnel to the Queen's chamber.

More detailed modelling is presently in progress. After the first 2 surveys, we were already in a position to :

- reject the hypothesis of a large chamber just behind the north wall of the discharge chambers,
- confirm the existence of an anomaly to the west and below the access tunnel to the Queen's chamber whose cause, a sand filled cavity, was soon proved by the 3 drill holes (see figures 12 and 13).

V. - CONCLUSION

The microgravity surveys carried out on, inside and around the Cheops Pyramid were a première in the field of archaelogy. This sophisticated technique now appears as a new tool for the assessment of a structure : it can not only detect cavities, but also appreciate the density distribution of the structure.

Outside the archaelogical world, there has been a "feedback" towards the industrial world : for the first time, microgravity is used for the internal evaluation of a structure : an actual endoscopy. Numerous developments can be foreseen. Very recently this "Pyramid" technique for microgravity interpretation has been used for the assessment of dissolution cavities around a hydroelectrical tunnel in the French Alps.

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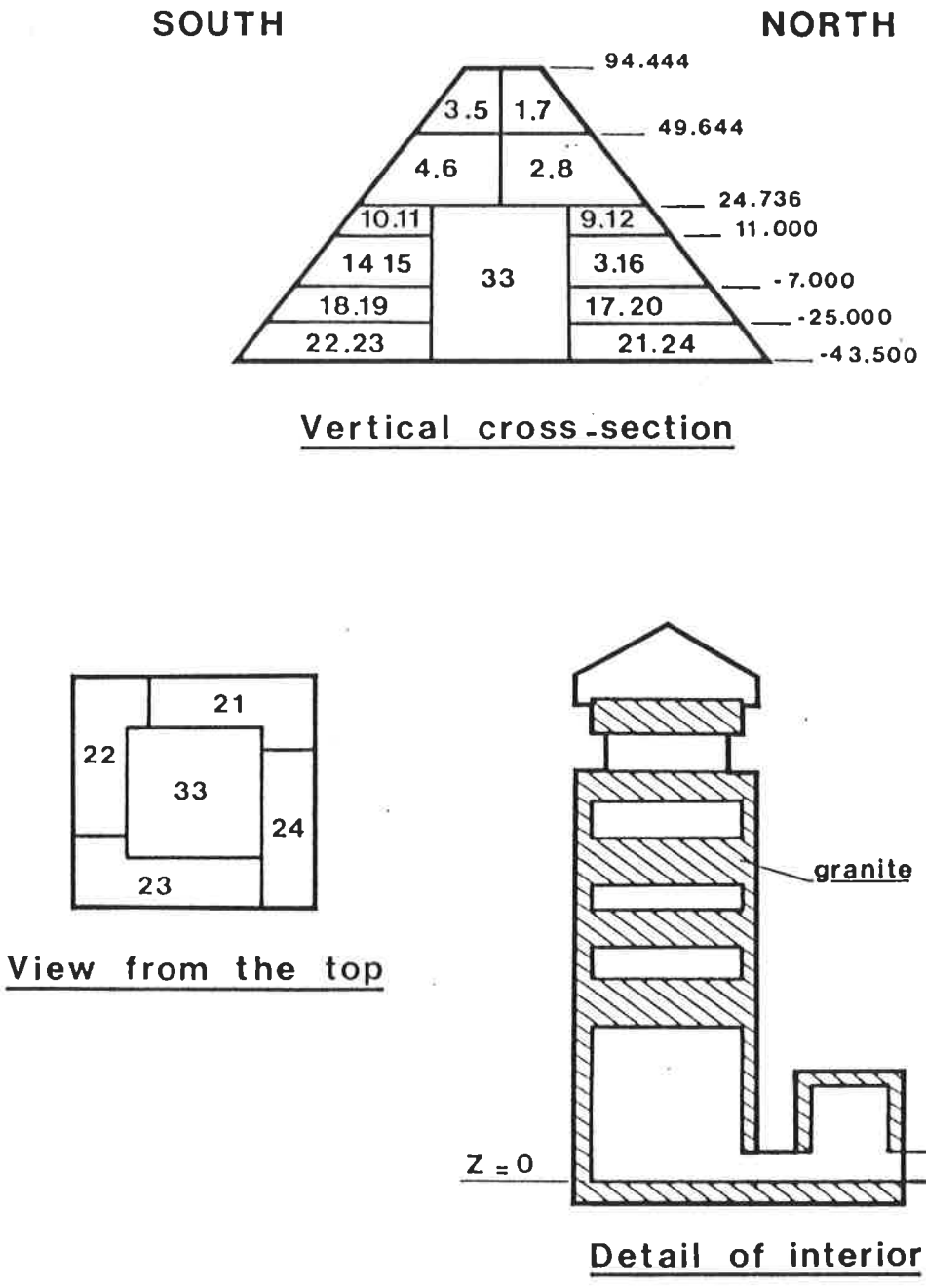


Fig. 1. Modelisation of the pyramid

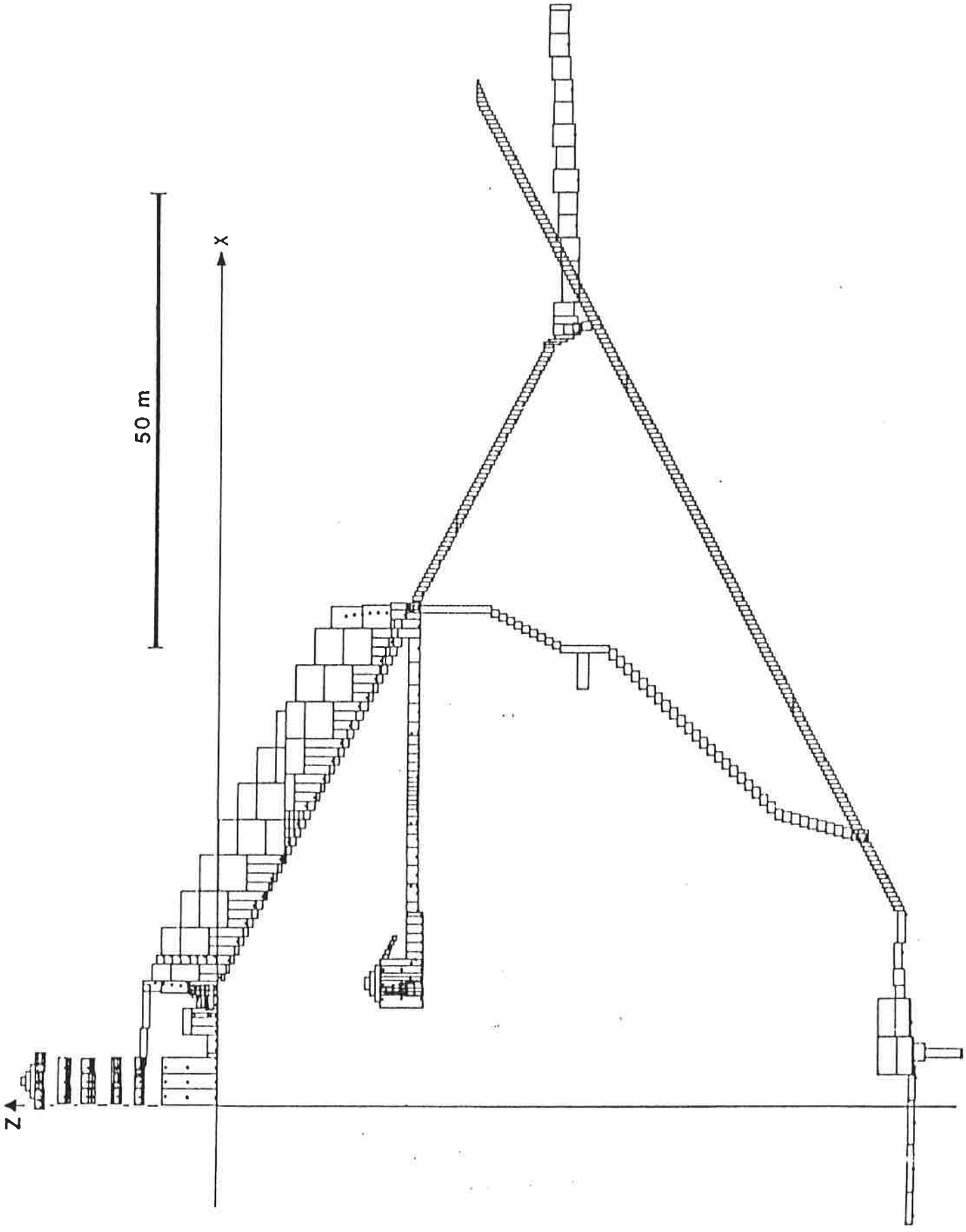


Fig. 2. Digitization of underground chambers

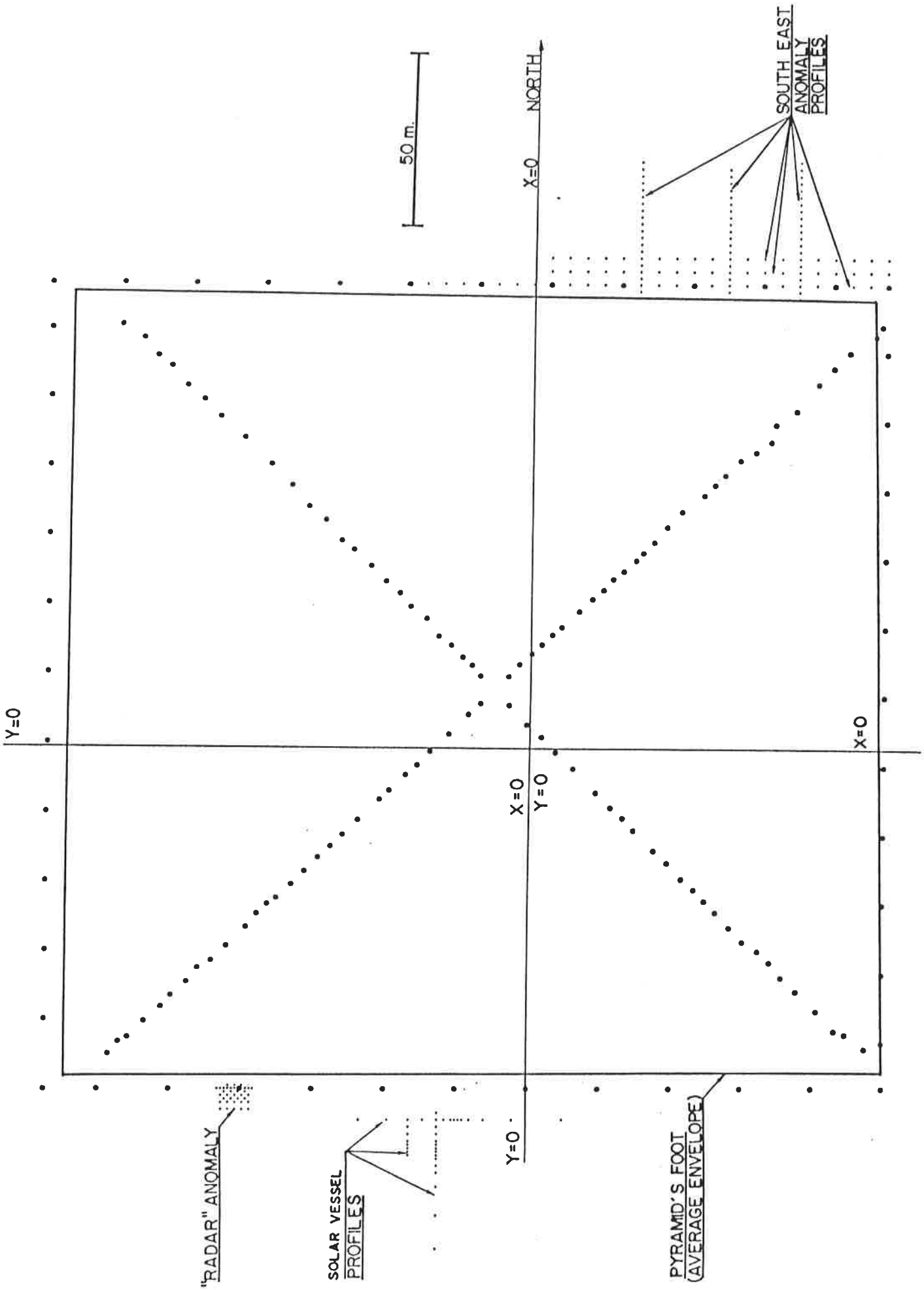


FIG. 3. Vertical view of measurement points on and outside the pyramid

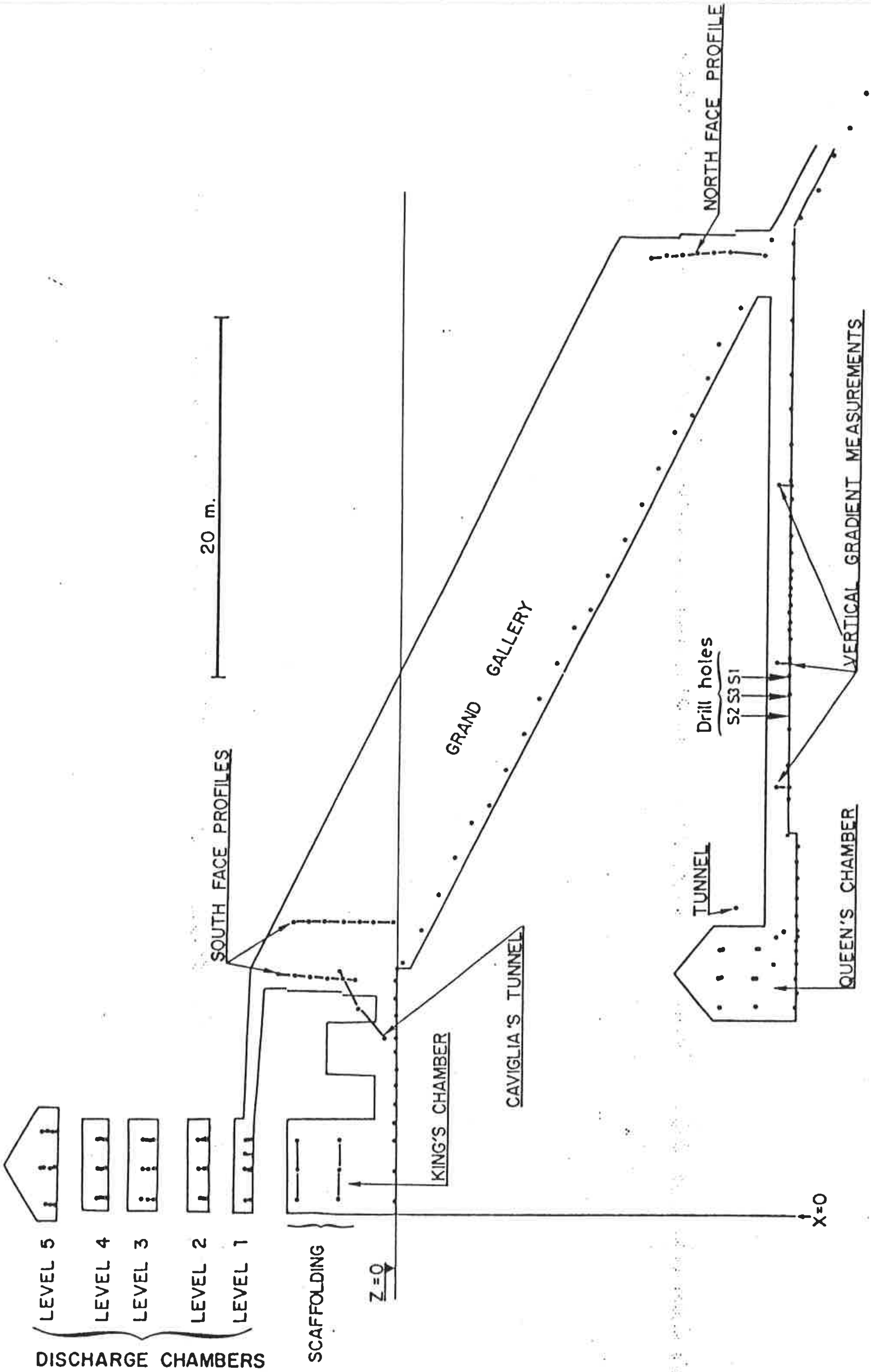


Fig. 4. Enlarged view of the measurement points in the King's chamber, the Queen's chamber and the Grand Gallery, seen from the East

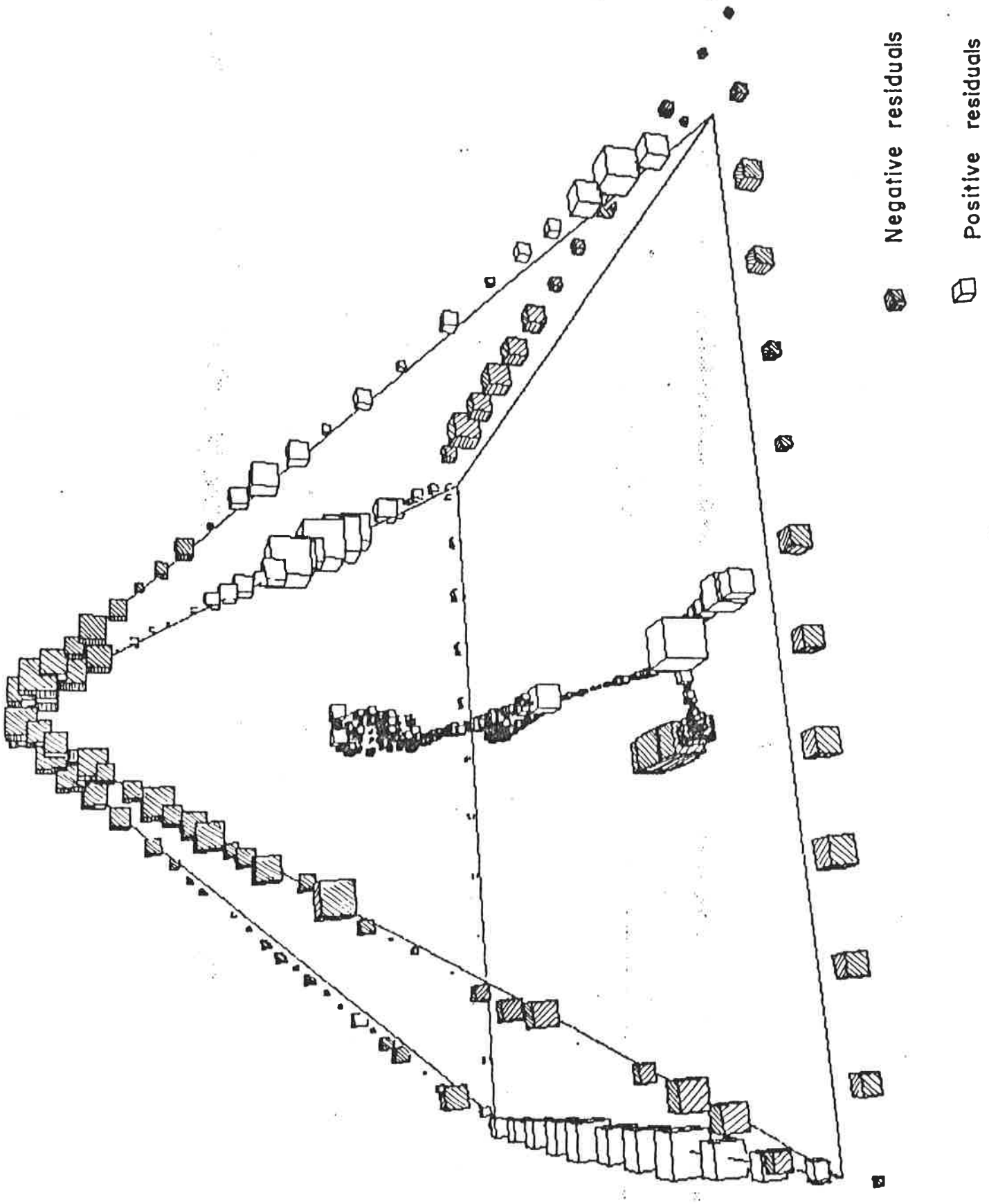


Fig. 5. General perspective view of the residuals with a 3-density model

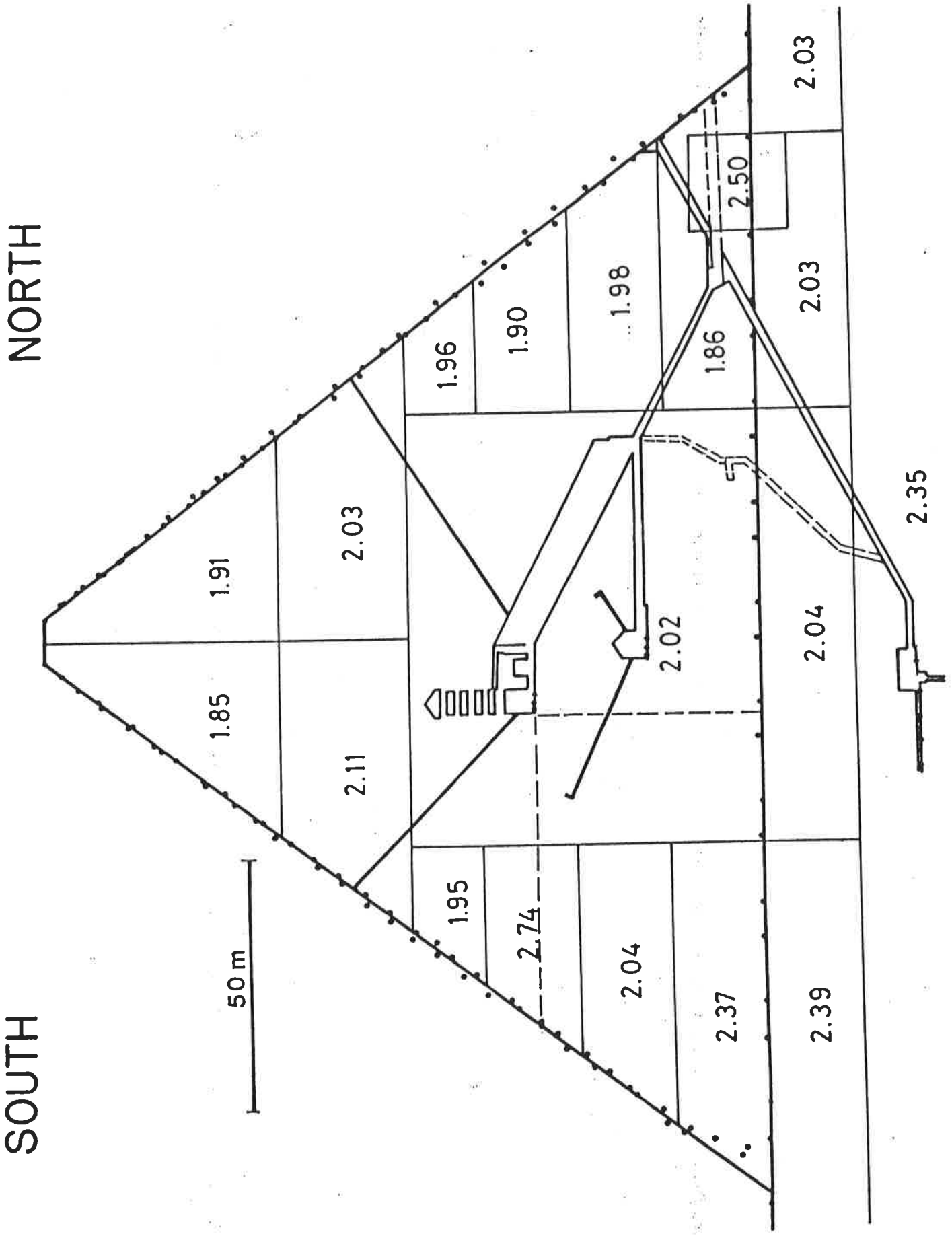
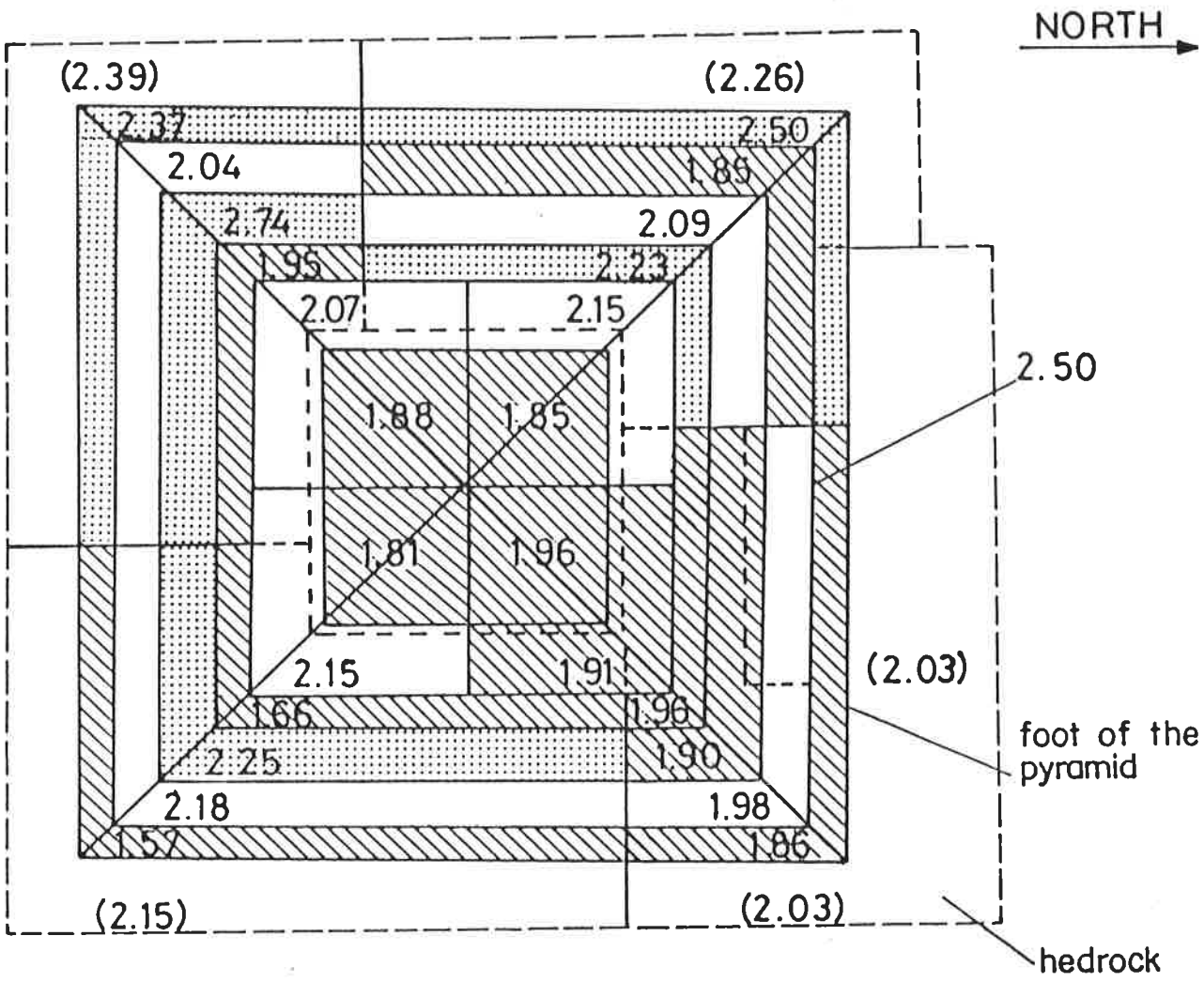


Fig. 6. Densities of a 34 block model : vertical south-north section



Density of the heart of the pyramid: 2.02

Density of the heart of the basement: 2.04

Density of the long distance terrain: 2.35

>2.20 1.95 to 2.20 1.57 to 1.97

Fig. 7. Densities of a 34 block model : view from the top

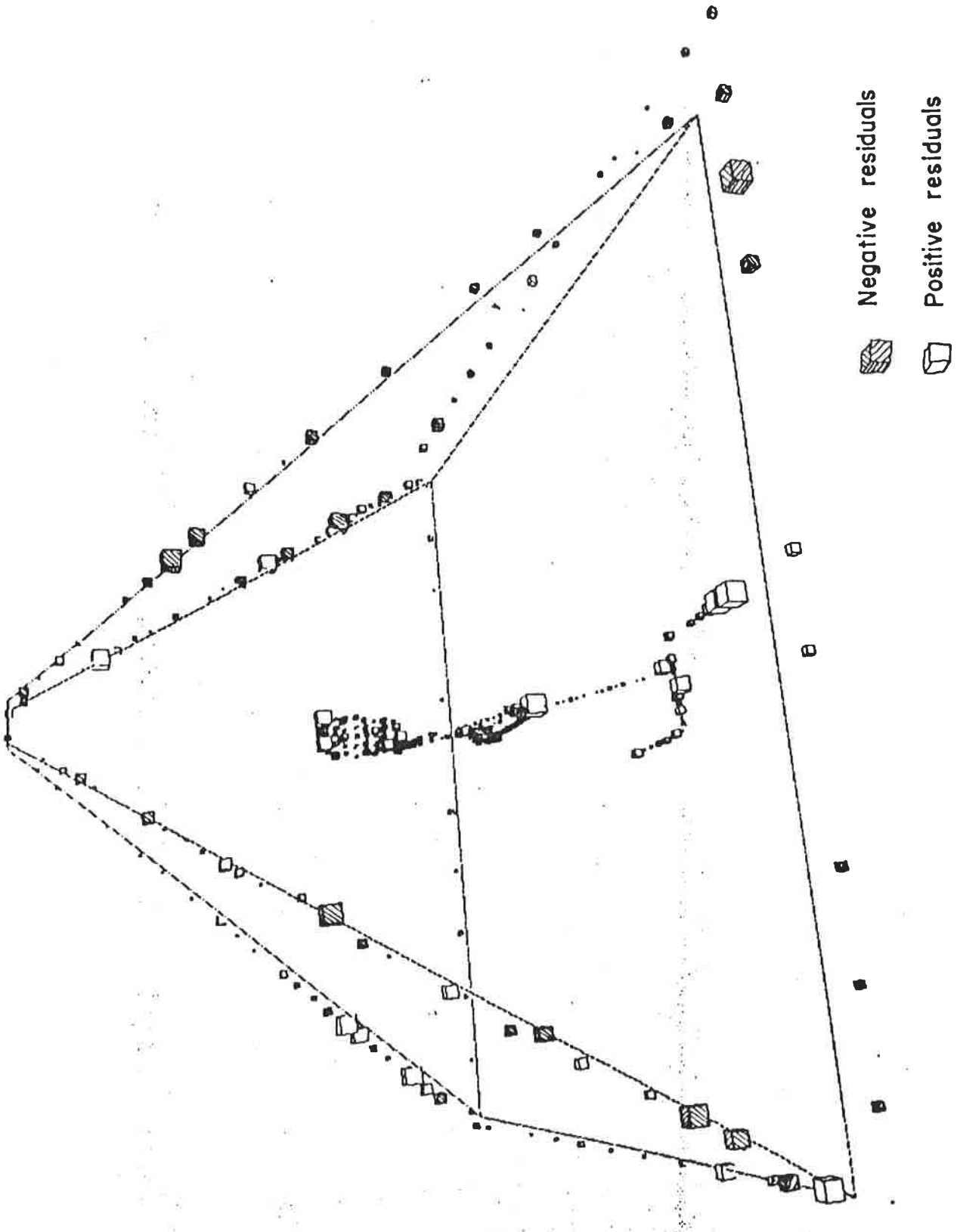


Fig. 8. General perspective view of the residuals with a 34-density model

MICROGRAVITY TEST ABOVE THE SOLAR VESSEL CHAMBER

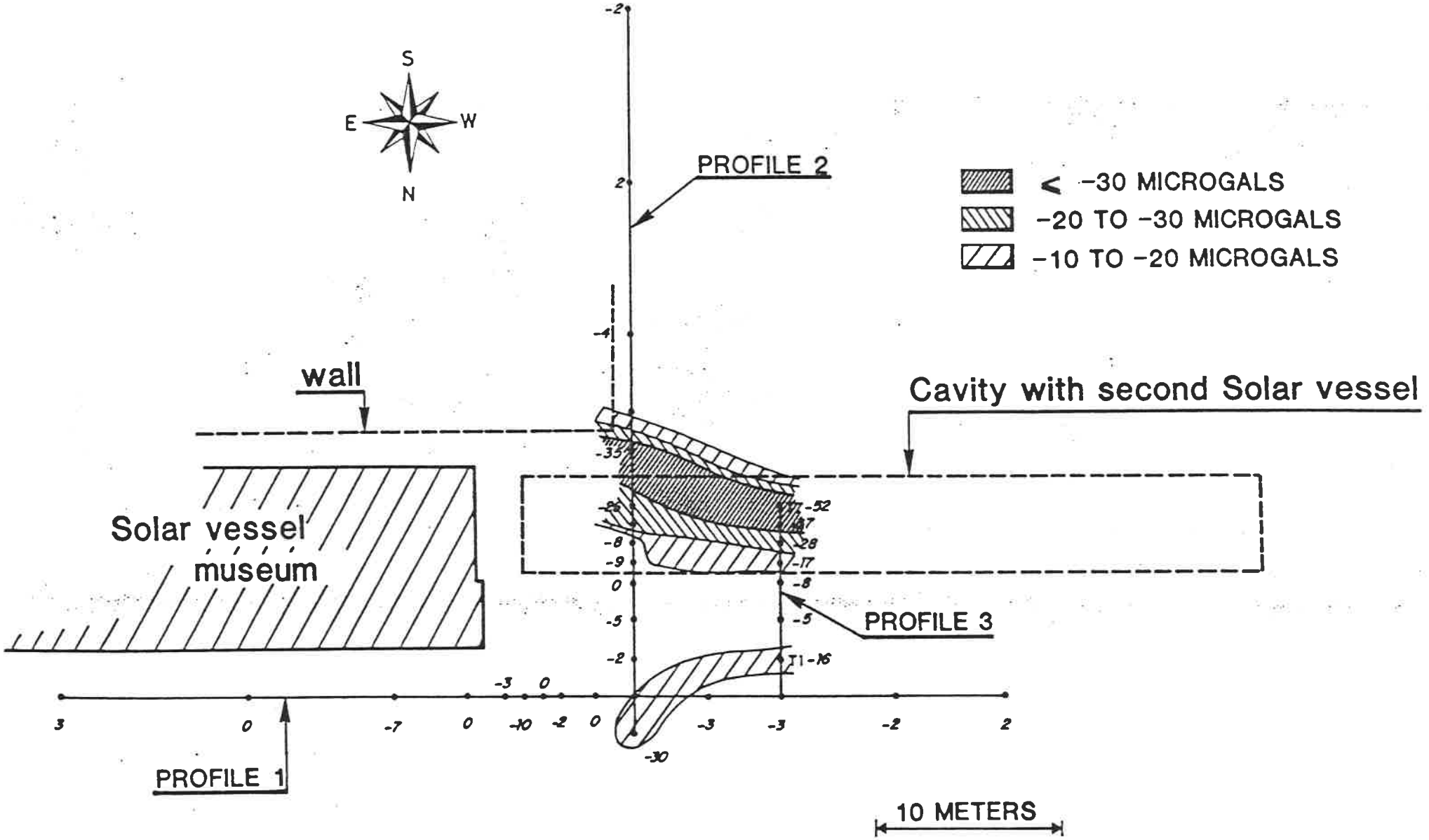


Fig. 9. Peristructure : second solar vessel profiles

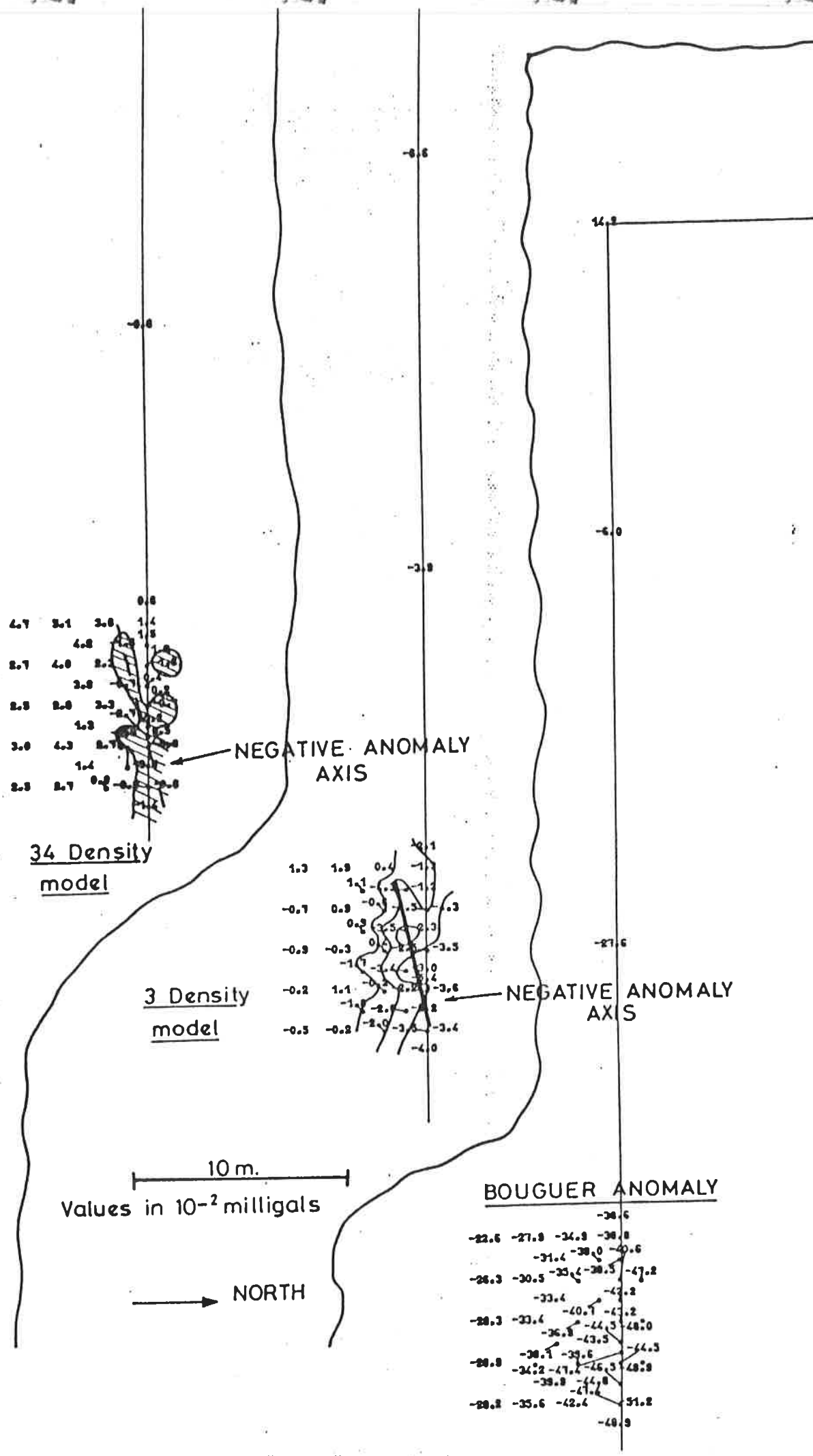


Fig. 10. Peristructure : S.S.W. "radar" anomaly microgravity gridding

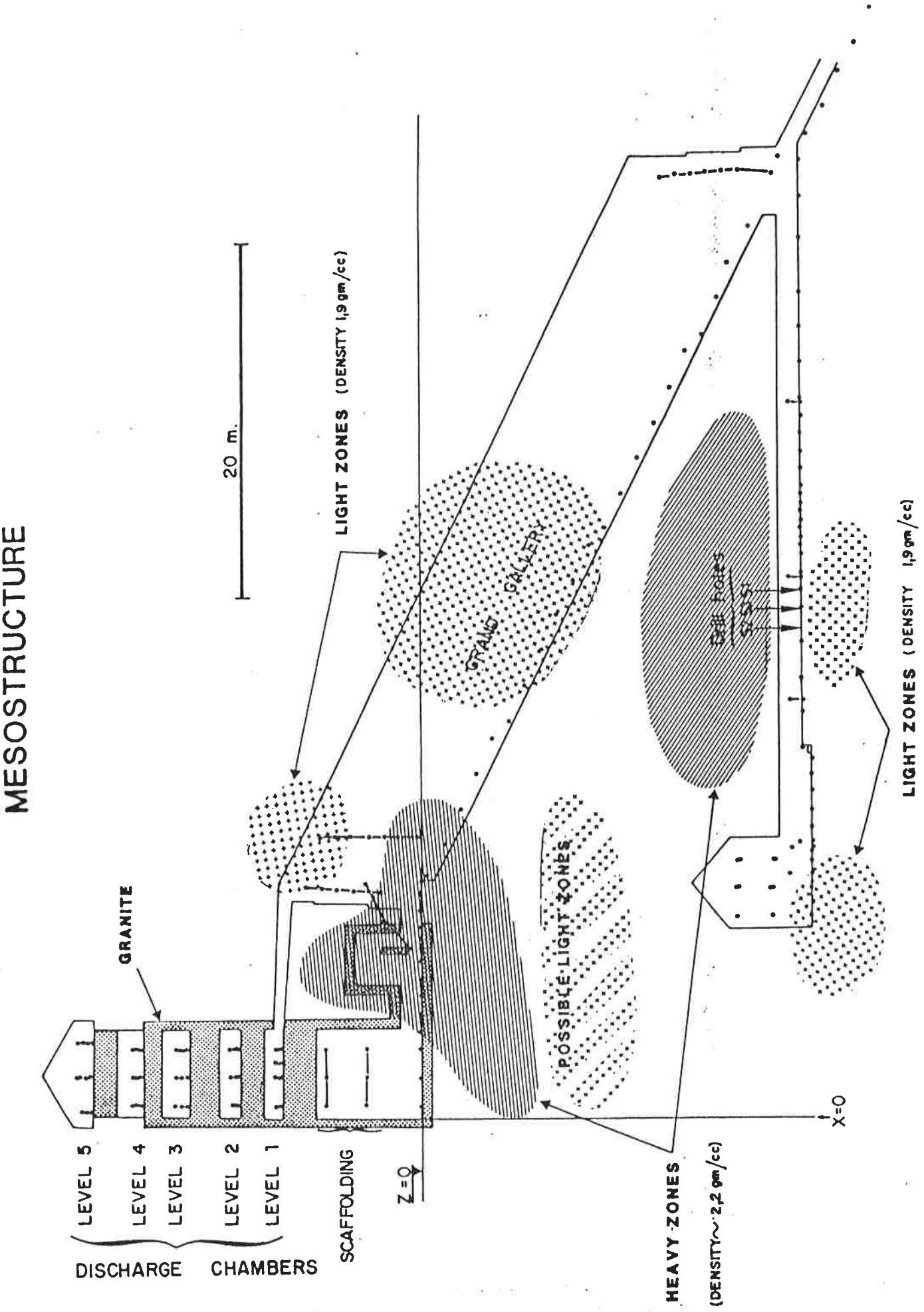


Fig. 11. Densities of the mesostructure after division into 18 blocks

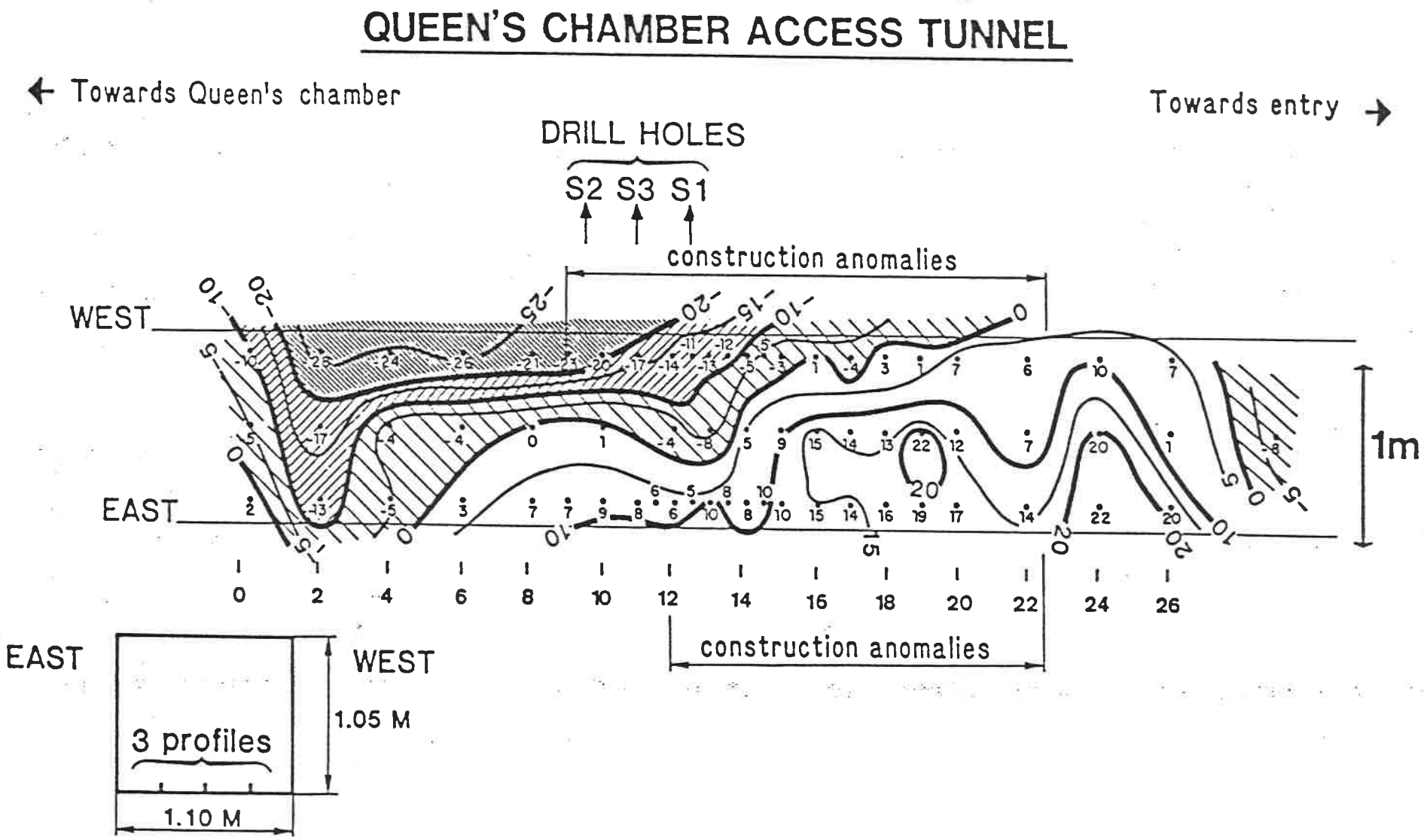


Fig. 12. Queen's chamber access tunnel, residual anomaly map

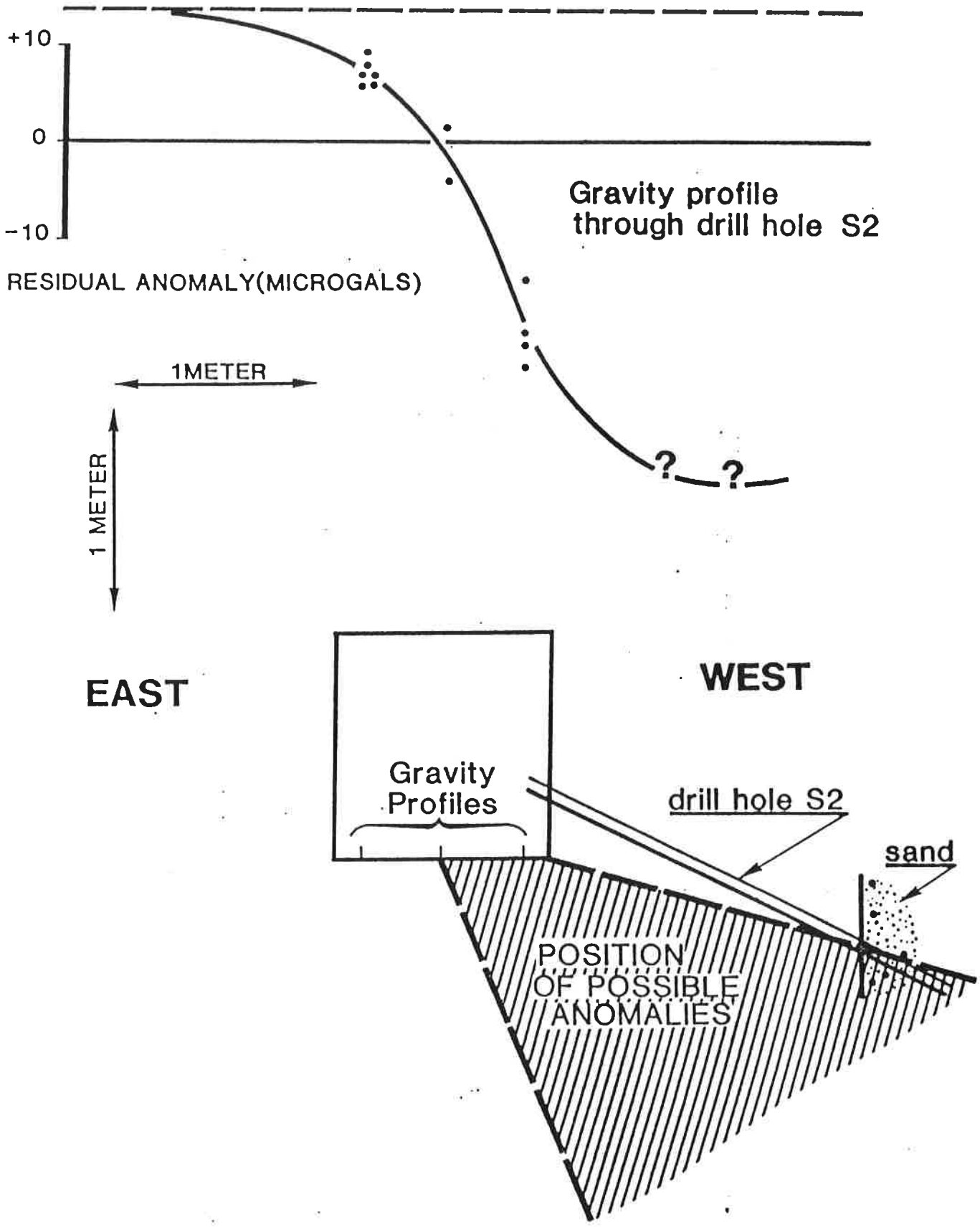


Fig. 13. Queen's chamber access tunnel, gravity profile and drill hole results