Shallow Geophysical Techniques to Investigate the Groundwater Table at the Giza Pyramids Area, Giza, Egypt

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ABSTRACT

The near surface groundwater aquifer that threatened the Great Giza Pyramids of Egypt, was investigated using integrated geophysical surveys. Ten Electrical Resistivity Imaging, 26 Shallow Seismic Refraction and 19 Ground Penetrating Radar surveys were conducted in the Giza Pyramids Plateau. Collected data of each method evaluated by the state- of- the art processing and modeling techniques. A three-layer model depicts the subsurface layers and better delineates the groundwater aquifer and water table elevation. The aquifer layer resistivity and seismic velocity vary between 40-80 Ωm and 1500-1800 m/s. The average water table elevation is about +15 meters which is safe for Sphinx Statue, and still subjected to potential hazards from Nazlet Elsamman Suburban where a water table elevation attains 17 m. Shallower water table in Valley Temple and Tomb of Queen Khentkawes of low topographic relief represent a sever hazards. It can be concluded that perched ground water table detected in elevated topography to the west and southwest might be due to runoff and capillary seepage.

Keywords: Giza Pyramids, Groundwater, Electrical Resistivity, Seismic refraction, GPR.

I. INDRDUCTION

In recent years, the 4500 years old Giza Great Pyramids (GGP) of Egypt; Cheops (Khufu), Chephren (Khafre), Menkaure and Sphinx statue; threatened from the rising groundwater table resulted from the water leakage of the suburban, irrigation canals and mass urbanization surrounding the GGP. This problem promoted the need to use non-destructive near surface geophysical techniques integrated with available borehole hydrogeological data to investigate and characterize the groundwater occurrences in the GGP. The GGP located in the southwestern part of the Greater Cairo Region (Fig. 1). Geologically, the Giza Pyramids Plateau composes mainly of white limestone, cream and yellow argillaceous limestone and dark grey dolomitic limestone of Middle-Upper Eocene age. The plateau rocks are commonly interbedded with thin marl layers in their upper part, which dips with about 5-10° to the Southeast (SE) direction. Steep escarpments border the plateau to the north and east directions as shown in Fig. 2 (Yehia, 1985; Mahmoud and Hamdan, 2002). Two regional groundwater aquifers underlie the

Sphinx (Fig. 3), the Quaternary aquifer of the Nile alluvium, consists of graded sand and gravel with intercalations of clay lenses at different depths exhibit water table at depth ranges between 1.5 to 4 meters below ground surface (bgs). The second aquifer is fissured carbonate aquifer that covers the area below the Pyramids Plateau and the Sphinx, where water table ranges in depth of 4 – 7 m bgs. The recharge of the aquifer below Sphinx area occurred mainly through water system leakage, Irrigation and massive urbanization (AECOM, 2010; and El-Arabi et al., 2013).

Many geophysical studies carried out in the GGP mostly for archaeological exploration and investigations (e.g., Dobecki, T. L., 2005; Abbas et al., 2009 and 2012). Geophysical studies have an effective contribution in characterizing groundwater aquifers especially geoelectrical resistivity, seismic refraction and ground penetrating radar techniques. Sharafeldin et al. (2017) studied the occurrence of the ground water table in GGP using combined VES, ERI and GPR to investigate the groundwater table in the area. The present work implemented an integration of Electrical Resistivity Imaging (ERI), Shallow Seismic Refraction (SSR), and Ground Penetrating Radar (GPR) techniques to depict the groundwater table and characterize the aquifer in the Giza Pyramids area. The locations of different surveys conducted in the GGP are illustrated in Fig. 4.

II. Method

II.1 Electrical Resistivity Imaging (ERI) Surveys

Two-dimensional electrical resistivity imaging (tomography) surveys are usually carried out, using a multi-electrode system with, 24 electrodes or more, connected to a multi-core cable (Griffiths and King, 1965). Syscal-Pro resistivity meter, IRIS Instruments, France, was deployed at the site of the GGP using 24 multi-electrode dipole-dipole array configuration with 5m electrode spacing. The length of spread is 115m for each profile and attains 23.5 m maximum depth of investigation. Ten ERI profiles were performed to characterize the resistivity of subsurface layers to delineate the groundwater aquifer (Fig. 4). The topographic elevation of each electrode is considered along ERI profile and linked to the Res2Dinv program. The acquired ERT data were processed using, Prosys II software of IRIS Instruments, to filter and exterminate bad and noisy data acquired in the field and produced the pseudo resistivity sections. The Res2Dinv software implemented to invert the collected data along conducted ERT profiles (Loke, and Barker, 1996; Loke, 2012). This software works based upon automatically subdividing the subsurface of desired profile into several rectangular prisms and then applies an iterative least-squares inversion algorithm for solving a non-linear set of equations to determine apparent resistivity values of the assumed prisms while decreasing the misfit values between the predicted and the measured data. Samples of interpreted data are shown in Figures 5 to 10.

II.2 Shallow Seismic Refraction (SSR)

Seismic refraction is widely used in determining the velocity and depth of weathering layer, static corrections for the deeper reflection data. It is also employed in civil engineering for the bedrock investigations and large scale building construction. It is also used in groundwater investigations, detection of fracture zones in hard rocks, examining stratigraphy and sedimentology, detecting geologic faults, evaluating karst conditions and for hazardous waste disposal delineation (Steeples, 2005; Stipe, 2015). A refraction technique is widely developed for characterizing the groundwater table (Grelle and Guadagno, 2009). Particularly, the unsaturated soil followed by saturated soil can be separated by a refracting interface (Haeni, 1988). The seismic velocity values for the depth estimation of the groundwater can be used as an indicator for water saturation. The values of P-wave velocity are not uniquely correlated to the aquifer layer, but many authors related the P-wave velocities around 1500 m/s to represent a saturated layer (Grelle and Guadagno, 2009). The tomographic studies view that the water table corresponds to a P-wave velocity values of 1100 to1200 m/s (Azaria et al., 2003; Zelt et al., 2006).

Twenty-six SSR profiles were acquired at GGP (Fig. 4). OYO McSEIS-SX seismograph with 24 geophones and channels, was deployed in the GGP site to collect the seismic refraction data with geophone spacing of 5m. Sledge hammer with 10Kg and an iron-steel plate are used to generate seismic P-wave. Five shots per spread were gathered, two off-set forward and reverse, and a split spread shot. The spread length covers 115m. Due to the historical and touristic nature of the site, a considerable amount of noise is imposing to the recorded data. These noises were minimized as possible by using the internal frequency domain filter and vertical stacking of several shots during data acquisition. The first arrival times were picked using SeisImager software version 4.2 of Geometrics. Tomographic inversion; generate initial model from the velocity model obtained by the time-term inversion, then applying the inversion, which iteratively traces rays through the model with the goal of minimizing the RMS error between the observed and calculated travel-times curves (Schuster, 1998). SeisImager utilize a least squares approach for the inversion step (Zhang and Toksoz, 1998; Sheehan et al., 2005; Valenta, 2007). A three layers model assumed to represent the subsurface succession with the inverted velocities and thicknesses. The top most layer exhibits a velocity range of 400-900 m/s, and thickness of 2 and 5 meters, is correlated with loose dry sand, fill and debris. The second layer shows a velocity range between 1200 and 2400 m/s with 10 to 20 m thick. This layer is correlated with wet and saturated sand and fractured limestone. The third layer shows a higher domain of velocity, where it ranges between 2800 and 3800 m/s, which can be correlated to marly limestone and limestone. The calculated arrival time for the resulted model is compared with the measured arrival time and RMS error is calculated and illustrated on modeled seismic profiles. Samples of interpreted data are shown in Figures 5 to 10.

II.3 Ground Penetrating Radar (GPR) techniques

GPR is a non-invasive and effective geophysical technique to visualize the near surface structure of the shallow subsurface and widely used to solve the environmental and engineering problems (Jol and Bristow, 2003; Comas et al., 2004; Neal, 2004). GPR is a site-specific technique that imposed a vital limitation of the quality and resolution of the acquired data (Daniels, 2004). The GPR surveys were carried out using 100 MHz shielded antenna of MALA ProEx GPR. A total of 19 GPR profiles were performed along selected locations in the study area (Figure 4). The GPR profiles range in lengths from 40 to 200 m, according to the space availability, with a total GPR surveys of about 2.5 kilometer. Wheel calibration was carried out near the Great Sphinx along 30 m in distance, the velocity used in calibration is 100 m/μs resulted from WAAR test using 100 MHz unshielded antenna of Puls-Echo GPR. Harari (1996) showed that the groundwater table can be detected easily with a discerning selection of the antenna frequency and he observed that the lower frequency antenna (e.g.100 MHz) was more effective for locating the groundwater table depth. Several basic processing techniques can be applied to GPR raw data stating from DC-shift to migration (Annan, 2005; Benedetto et al., 2017). All 19 GPR profiles were processed to delineate subsurface layering and ground water elevation in the study area. Appropriate processing sequence for GPR data was applied to facilitate interpretation of radargram sections using REFLEXWIN V. 6.0.9 software (Sandmeier, 2012). Firstly time-zero correction, and then dewow filters to remove DC component and very low frequency components were applied to all GPR data. Then, a band-pass filter was used to improve the visual quality of the GPR data, gain recovery was applied to enhance the appearance of later arrivals because the effect of signal attenuation and geometrical spreading losses (Cassidy, 2009). Running average filters was the last filter applied. Some sections of interpreted data are shown in Figures 5 to 10.

III. Results and discussion

The integrated interpretation of the SSR, ERI and GPR surveys supports a three layers model assumed to represent the subsurface succession with the inverted velocities, resistivities and thicknesses. The top most layer exhibits a velocity range of 400-900 m/s and a resistivity values varies between 10’s to 100’s Ohm.m and is correlated with heterogeneous loose dry fill and debris of thickness ranges between 2 and 5 meters. The second layer shows a velocity range between 1200 and 2400 m/s and a resistivity values varies between 40 to 80 Ohm.m, this layer is correlated with wet and saturated sand and fractured limestone and the thickness varies between 10 to 15 meters. The third layer shows a high velocity ranges between 2800 to 3800 m/s and a resistivity values varies by changing the topographic elevation and marl intercalation in the limestone layer. GPR data delineated the subsurface succession and accurate detection of the water table in area near Sphinx, Valley Temple, Mastaba and Tombs. The interpreted ground water table elevation ranges between 14-16 meters in these locations. As the ground relief increases toward the Mankaura Pyramids the water table is deeper and a perched water table detected in elevations between 22 to 45 meters.

Groundwater rise was detected in some locations which have an archaeological importance, these locations are Nazlet El-samman Village, Sphinx, Sphinx Temple, Valley Temple of Khafre, Central Field of Mastaba and Khafre Cause Way.

a- ***Nazlet El-samman Village*** is a suburban area located outside the core of the archeological site. The geophysical surveys SSR-3 & 4 and GPR-2 conducted in the area show a velocities of 1600-1800 m/s and interpreted water table at elevation of 16-17 m. This elevation is fairly matched with a nearest piezometers-6 and 7 in the area where the ground water elevation is 16-17 m. The aquifer in this part is belonging to the Nile Alluvium Aquifer. This shallow water table might rise the water table level below Sphinx area (Fig. 5), causing a sever hazards.

b- ***Sphinx, Sphinx Temple, Valley Temple of Khafre, Central Field of Mastaba and Khafre Cause Way,*** this is the most important part of the study where the water appear on the surface at the Valley temple and surrounding area of the Sphinx. The locations of the surveys were chosen according to the limited space approved by the Pyramid Archaeological Authority. The locations of the conducted data are shown in (Fig.4). Survey shows a good matching between the different techniques, where the correlation between different surveys results, revealed that groundwater elevation between 14-15 m. The base level elevation of the Sphinx Status is 20 m, and safe water table elevation should be at elevation of 15 or less. This level is lower than the suburban area of Nazlet El-samman, which might indicate a recharge of the aquifer below Sphinx and increase capillary water rise.

Sphinx and Sphinx Temple, GPR-9, SSR-13 and ERI-1 conducted in front of Sphinx and Sphinx Temple. The integration of these surveys in front of Sphinx Temple, the groundwater elevation is about 14.5-15.5 m, as shown in Figure 6.

Valley Temple of Khafre and central field of Mastaba, GPR profiles 3, 4, 5, 10 and 11; SSR profiles 5, 6, 7, 8 and 14; and ERI 2. The integration of this surveys in front of Valley Temple of Khafre and central field of Mastaba, the groundwater elevation is about 14-15 m as shown in Figure 7.

Tomb of queen Khentkawes, GPR-11; SSR-15; and ERI-3 conducted near the Tomb. Figure 7 shows the surveys conduct near the site. The integration of this surveys in front of Valley Tomb of queen Khentkawes, the groundwater elevation is about 14.5-15 m.

Valley Temple of Menkaure, GPR-12; SSR-16; and ERI-4 conducted near the Temple. The integration of these surveys in front of Valley Temple of Menkaure, the groundwater elevation is about 16.5-17 m. GPR profiles might detect the perched ground water table at shallower depth from ground level (Fig. 8).

Cause way to Menkaure Pyramid, show high resistivity value near the surface, and water table located at elevation ranges from 22 to 24 m. ***Menkaure Queens Pyramids and Menkaure Quarry,*** where the surveys in this part conducted at higher topographic relief, the correlation of the different techniques revealed that the water table might be interpreted at elevations 45-58 m. This might detect the perched ground water table at shallower depth from ground level (Figs. 9 and 10).

Table 1, shows a comparison of the ground water table elevation data recorded in some piezometers illustrated in (Fig 12), installed by Cairo University in Wdi Temple and Sphinx area (AECOM, 2010), and the interpreted water table elevation resulted from nearest conducted geophysical surveys. There is a relatively good agreement between the results and differences might be related to the tolerance in the geophysical data and exact physical properties surface between the wet and saturated media. Moreover, the pumping stations discharge might lower the water table in the site.

Figure 11 represents a cross-section, using the ERT and GPR data, to illustrate the difference of groundwater table elevation between the Great Sphinx to the small pyramids of Menkaure that indicates the increase of groundwater elevation from west to east. As the average water table elevation to be about 15 m, the water table to the west might be considered as perched water table due to leakage, surface runoff and capillary and fracture seepage. Figure 12 represents the compiled groundwater table elevation contour map from the geophysical surveys, overlay the groundwater table levels measured from some of the piezometers installed by Cairo University (AECOM 2010). The present geophysical surveys proved that, the pumping system installed by

AECOM 2010 lowering the groundwater levels in some piezometer and a need of more pumping to compensate the recharge of the water leakage resulted from surrounding area of Sphinx. Figure 13 shows a 3D representation of the groundwater system in Great Giza Pyramids Plateau and surrounding area.

V. Conclusions

The integrated interpretation of ERT, SSR and GPR surveys was performed in Great Giza Pyramids site successfully investigate the groundwater aquifer and water table elevation in Great Giza Pyramid and assist the hazards mitigation. An interpreted model consists of three layers assumed to depict the subsurface layers and better delineation of the aquifer layer associated with resistivity range of 40-80 Ωm and seismic velocity of 1500-1800 m/s. The average water table depth is about 15m, which is safe for the Sphinx status where the base foot at elevation of 20 m. The water table elevation increases in Nazlet Elsamman Village to 16-17m and might recharge the aquifer below Sphinx and Valley Temple which considered a sever hazard on the site. Tomb of Queen Khentkawes threatened by water leakage resulted from vegetation in old cemetery and nearby football field. A parched groundwater table might exist in elevated area toward west and southwest. A great care should be taken to the effect of massive urbanization to the west of the Great Giza Pyramids which might affect the groundwater model of the area. The dewatering system should be accomplished to avoid such hazards.

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Table 1: Average interpreted Groundwater elevations to the nearest 8 piezometers, installed piezometers (modified after EACOM 2010)

Piezom. No.	Surveyed Area	Geophysical Data	Piezom.GWT (m)	Interpreted GWT (m)
PZ-6 & 7	*Nazlet Elsaman*	SSR3 & 4 GPR2, 5	15.9-17.4	16-17
PZ-8	*Sphinx Temple*	SSR3& 4, GPR2 ,5 ERI1	15.7	14.5-15.5
PZ-11 & 14	*Valley Temple*	SSR14,GPR10 & ERI2	14.4 – 14.1	14-15
PZ-12, 15 &16	*Sphinx*	SSR13, GPR9 & ERI1	15.3- 15.6	15-15.5

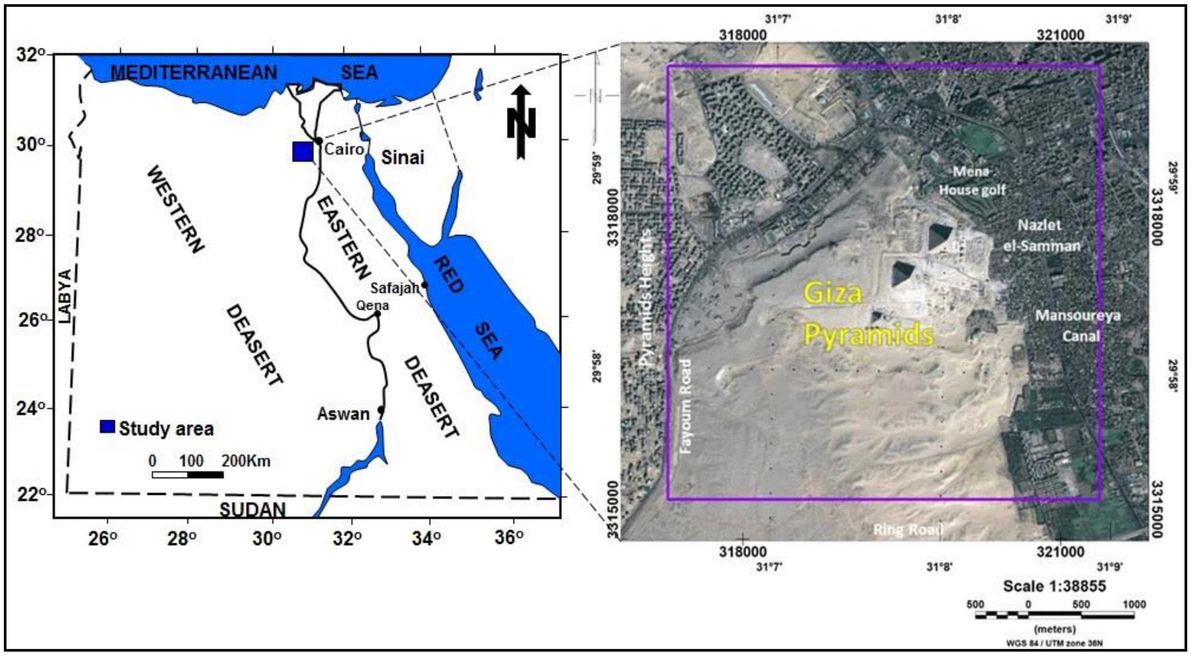

Fig. 1: Location map of the study area of Pyramids Plateau.

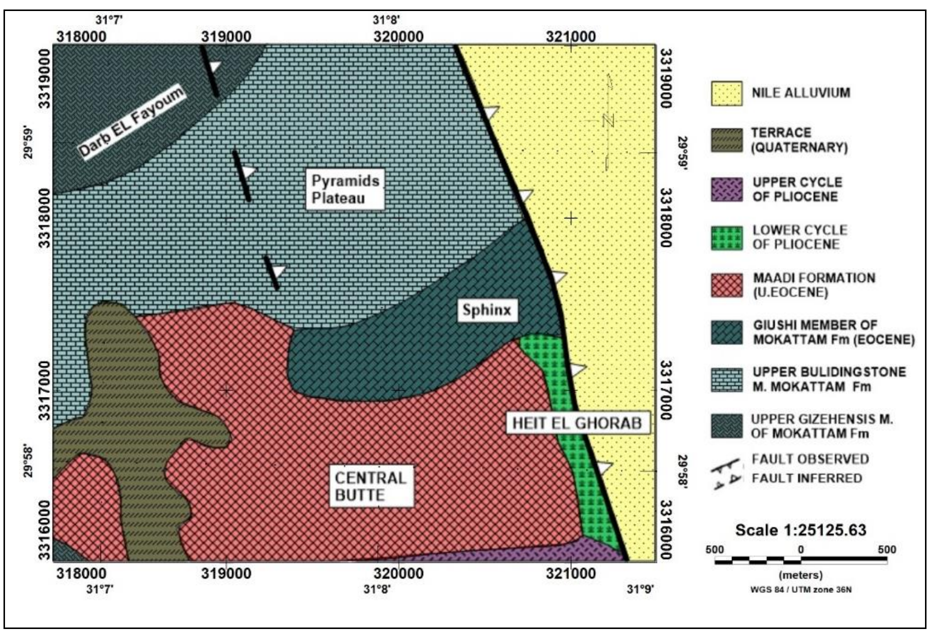

Fig. 2: Geologic map of the Giza Pyramid Plateau, Egypt. (Modified after Yehia, 1985).

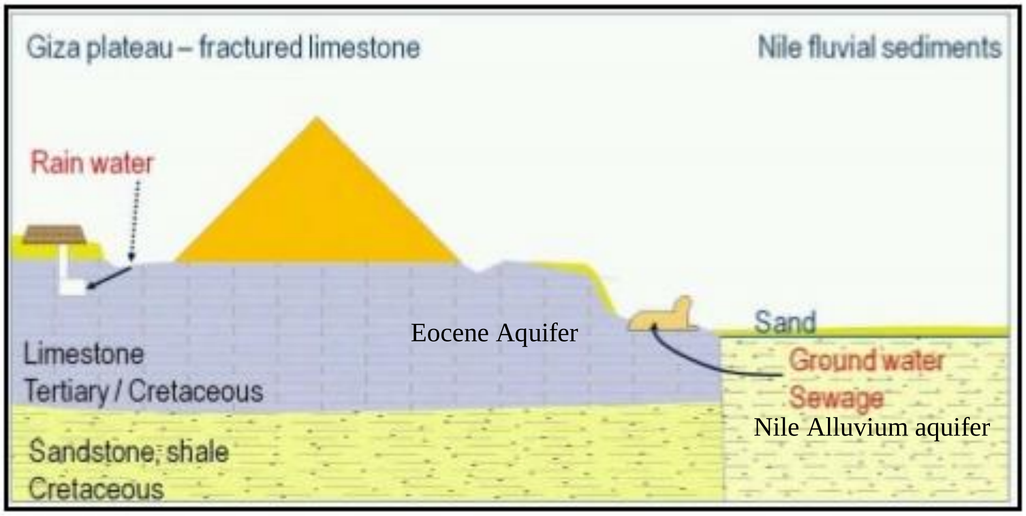

Fig. 3 Ground water aquifers affected the Giza Pyramids Plateau (El-Arabi et al., 2013).

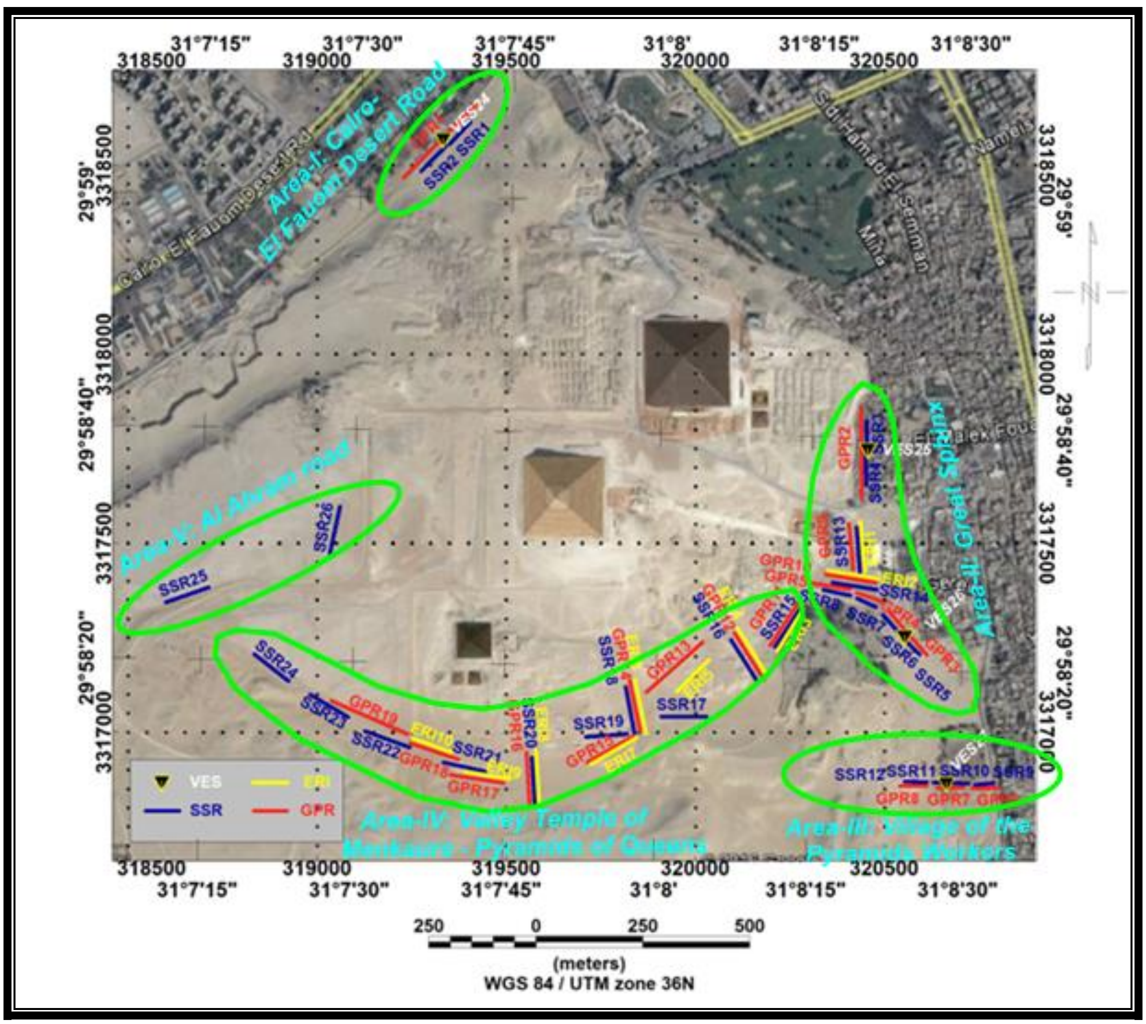

Fig. 4: locations for the profiles and techniques used along the different parts of the Giza Pyramids plateau.

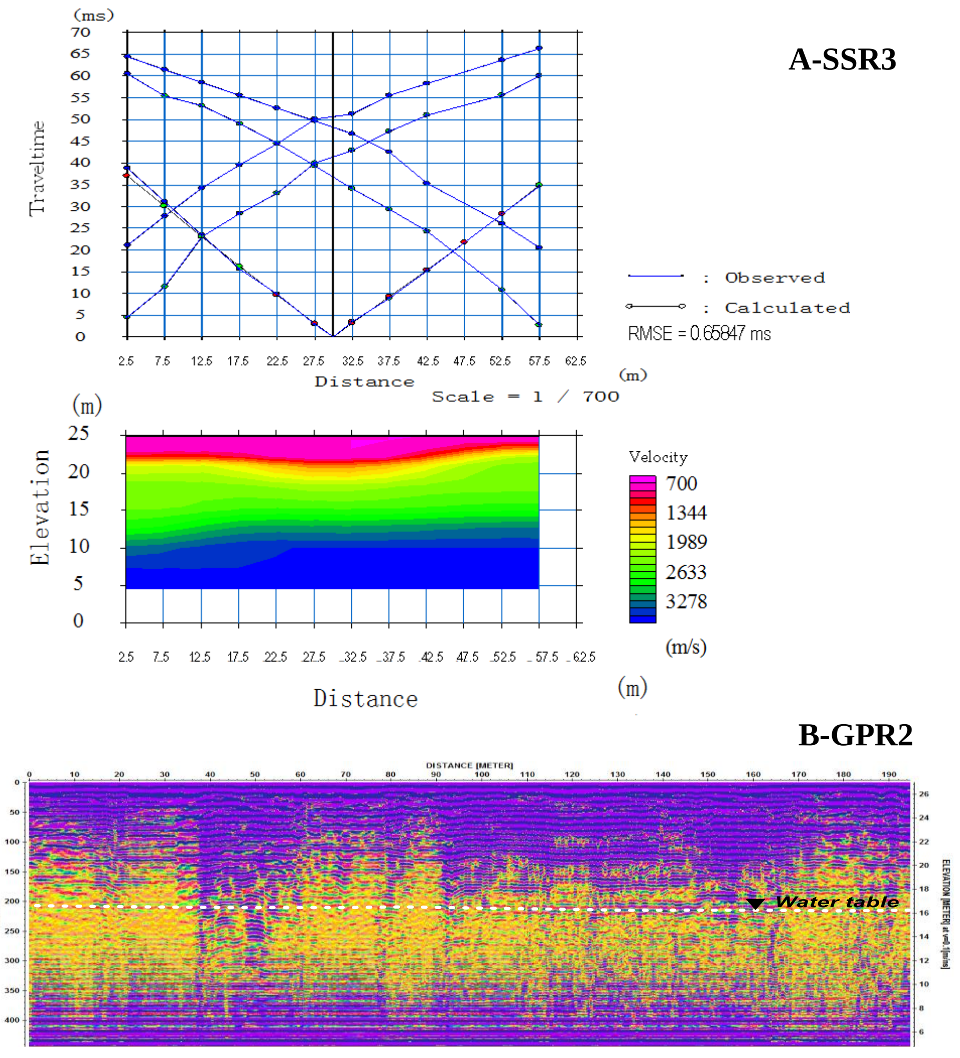

Fig. 5. SSR and GPR profiles in Nazlet El-semman Village

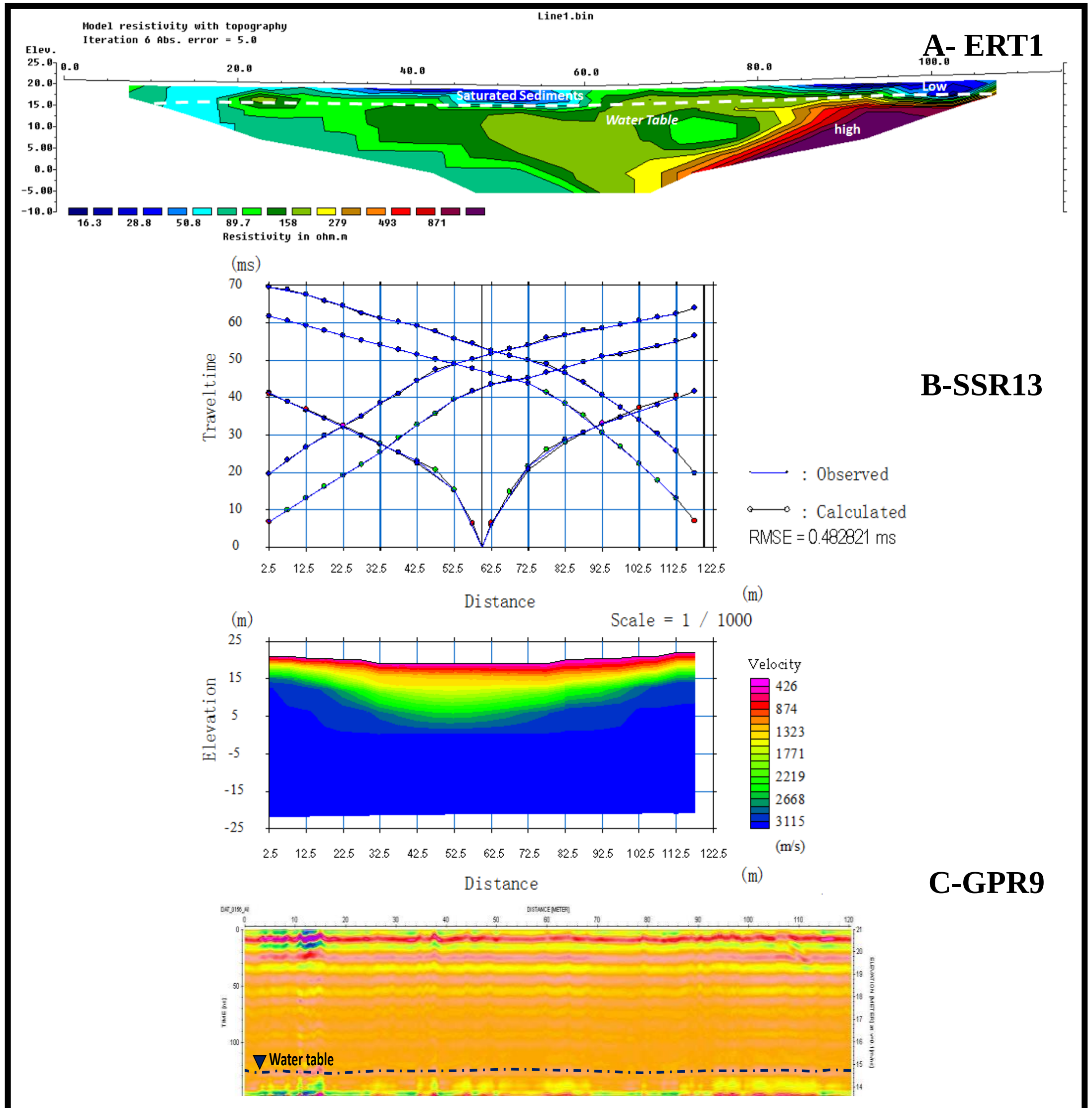

Fig. 6. ERI, SSR and GPR profiles in Sphinx and sphinx Temple

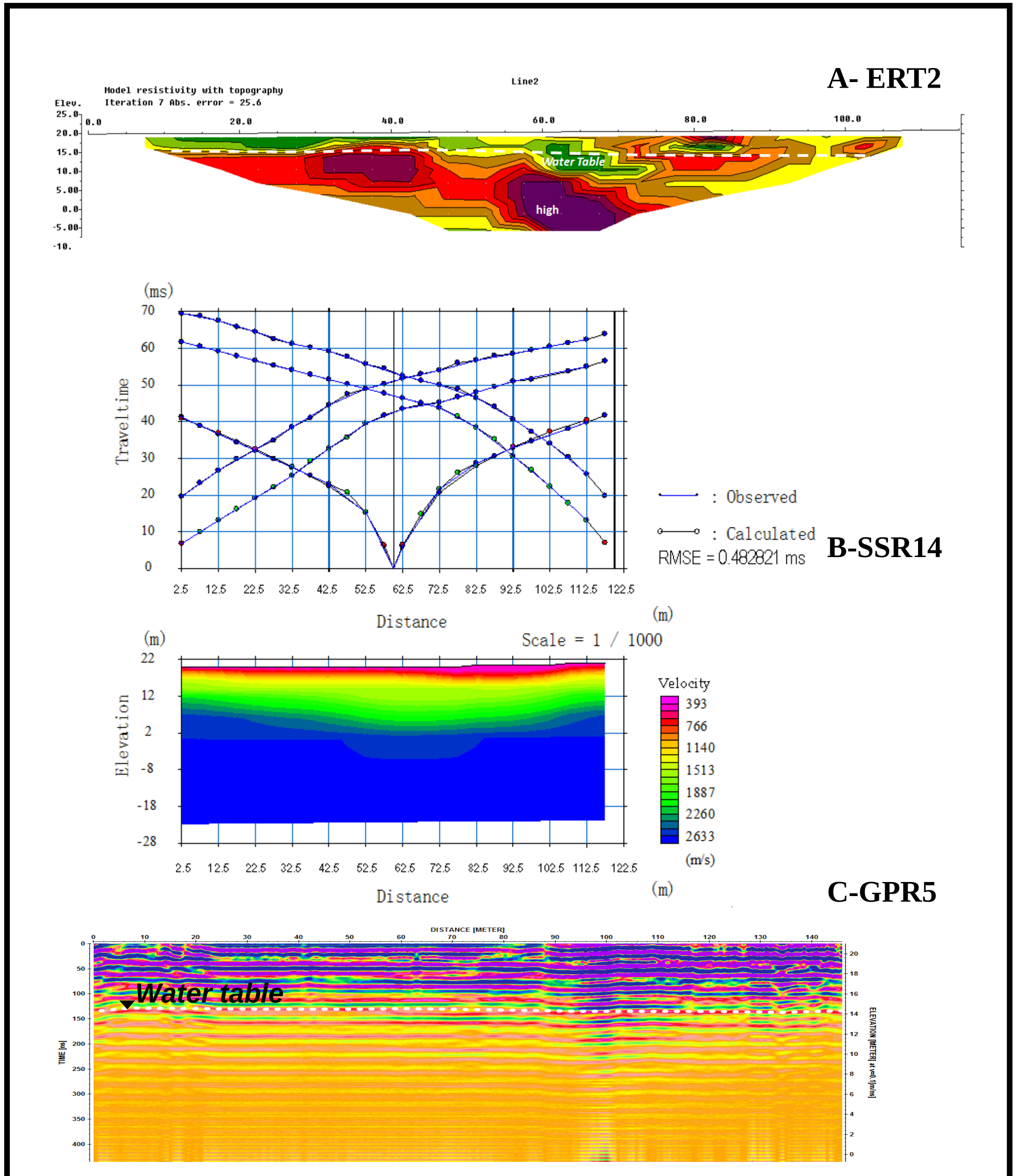

Fig. 7. ERT, SSR and GPR profiles in Valley Temple of Khafre and central field of Mastaba

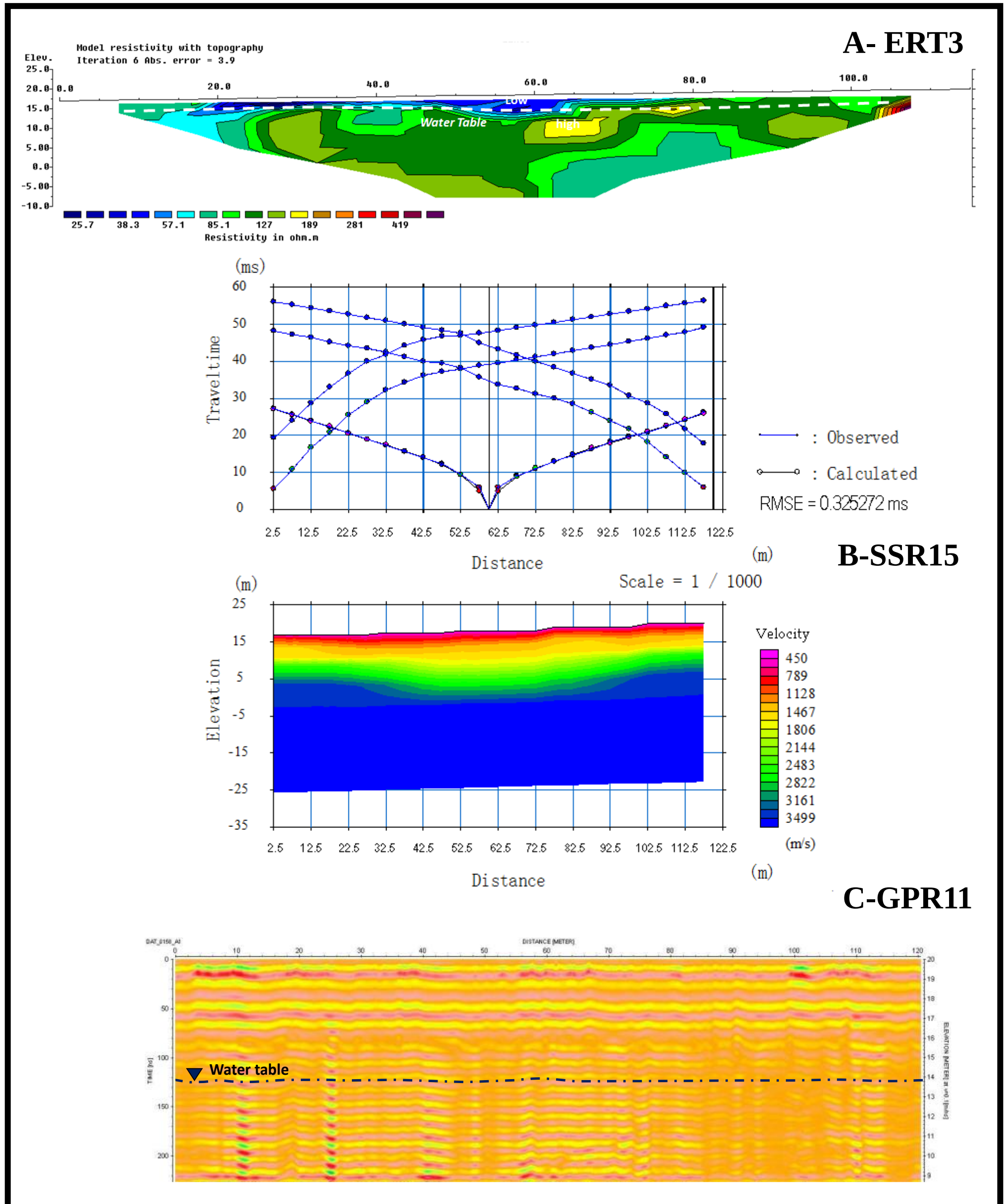

Fig. 8. ERT, SSR and GPR profiles in Tomb of queen Khentkawes

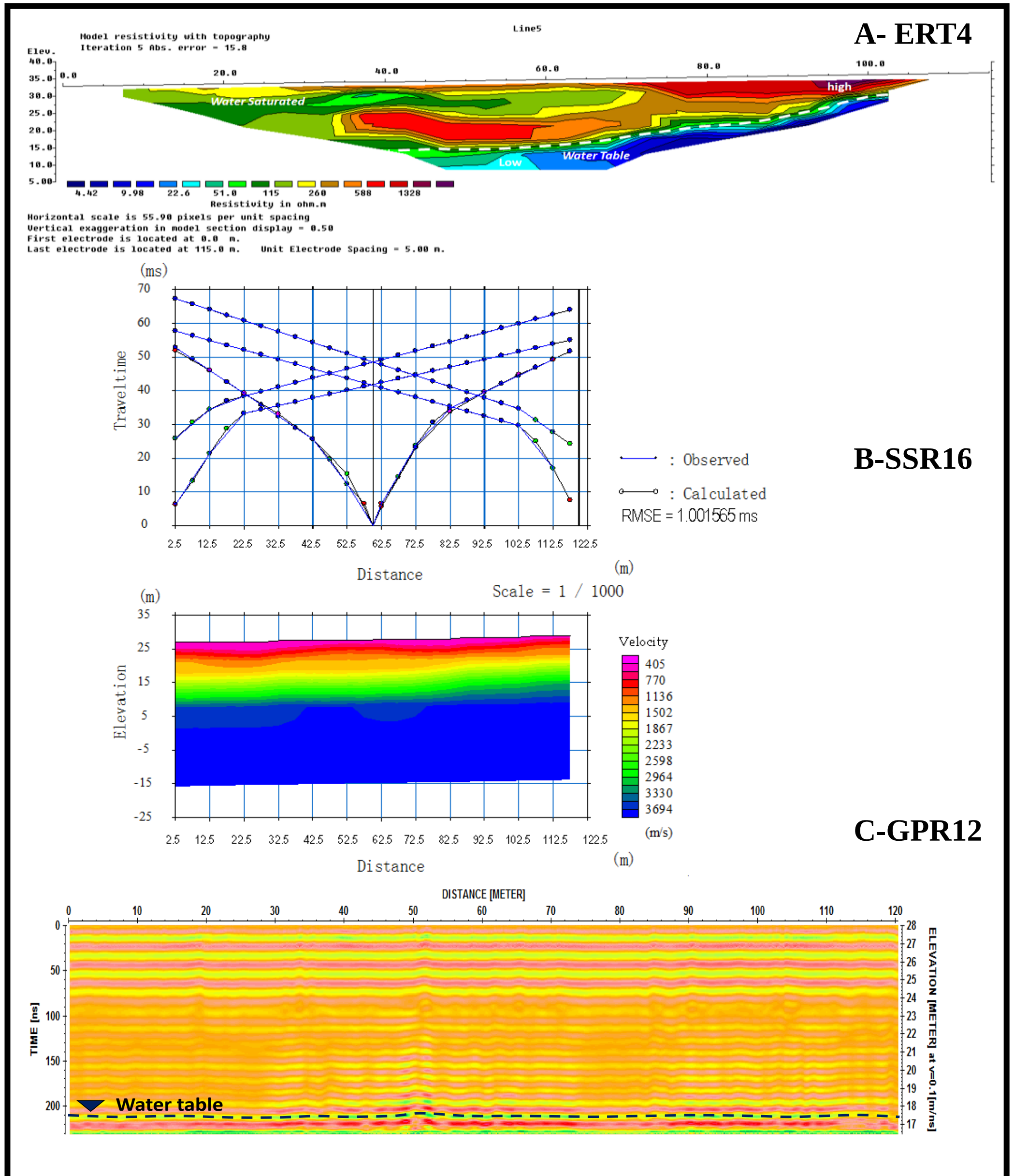

Fig. 9. ERT, SSR and GPR profiles in Valley Temple of Menkaure.

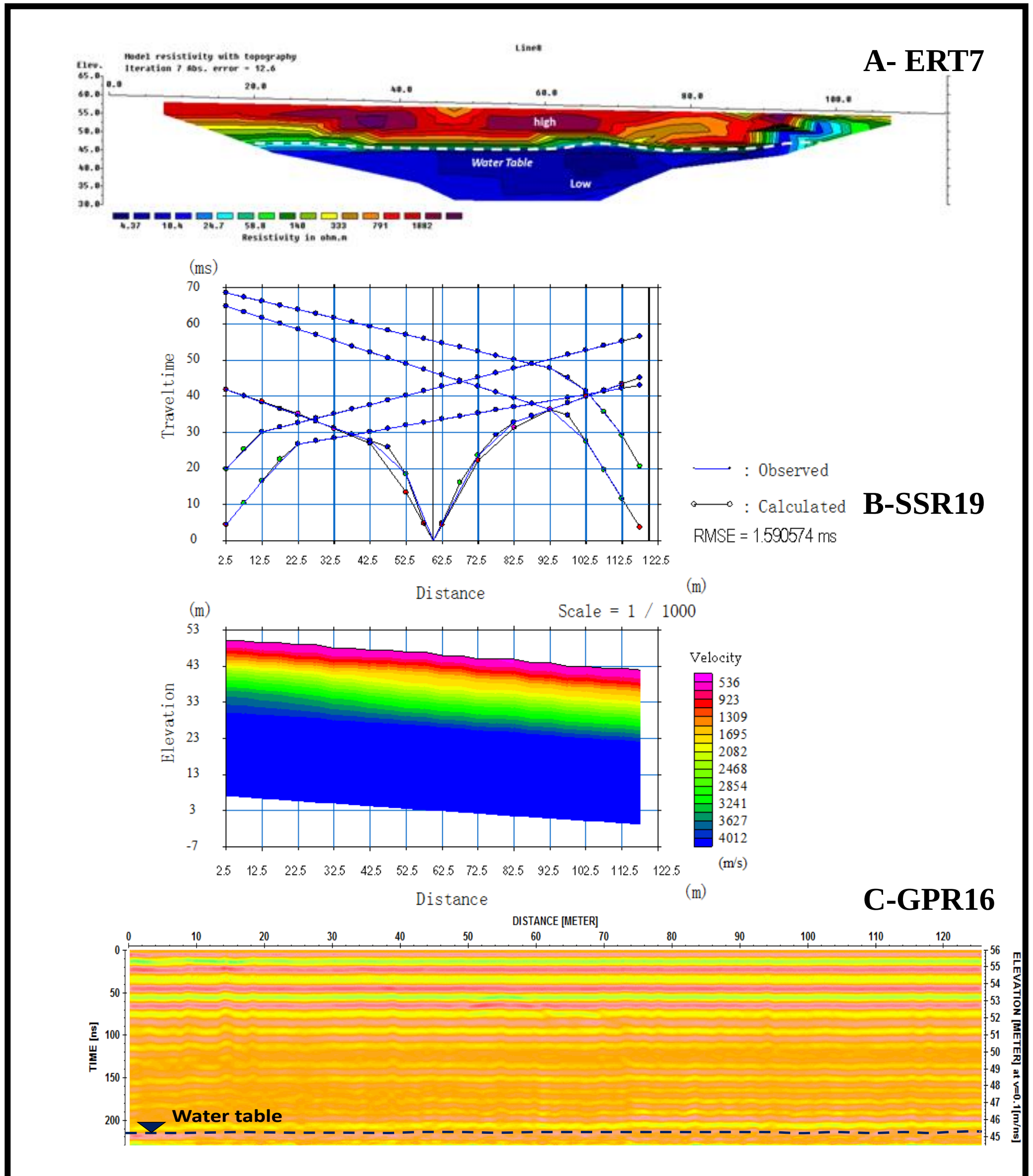

Fig. 10. ERT, SSR and GPR profiles in Cause way to Menkaure Pyramid.

Fig. 9. ERT, SSR and GPR profiles in Valley Temple of Menkaure.

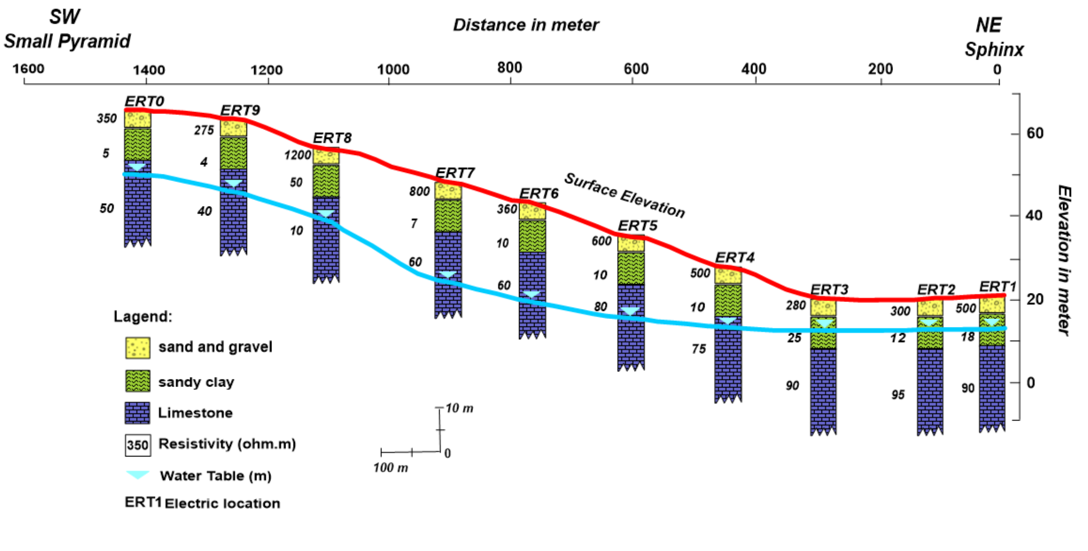

Figure 11 Cross-section using the ERT data shows how the groundwater elevation change from Sphinx to Menkaure Pyramid.

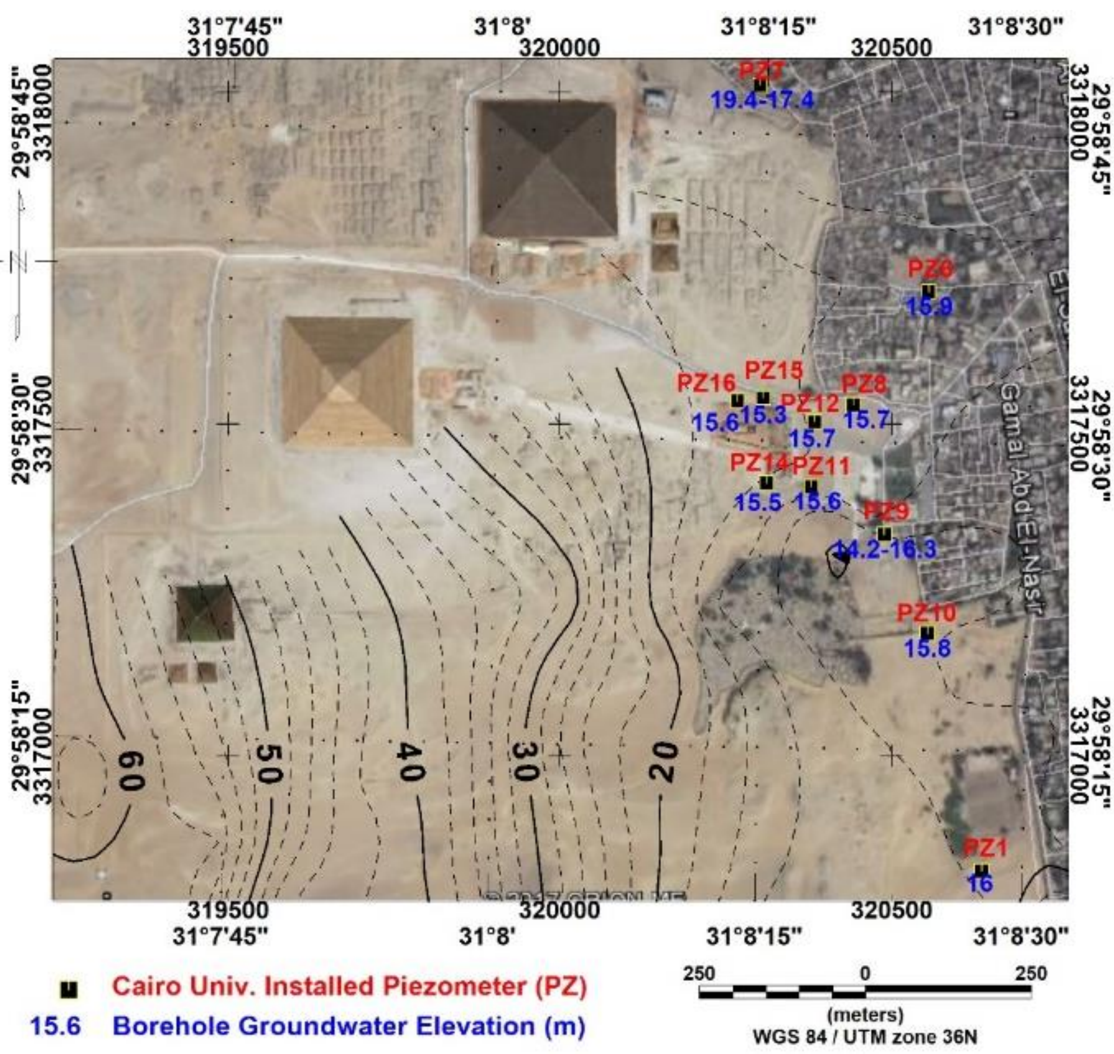

Fig. 12: Groundwater elevations map from the ERI, SSR and GPR data taken across the study area of the Giza Pyramids plateau, including the installed piezometers and their groundwater levels by Cairo University 2008.

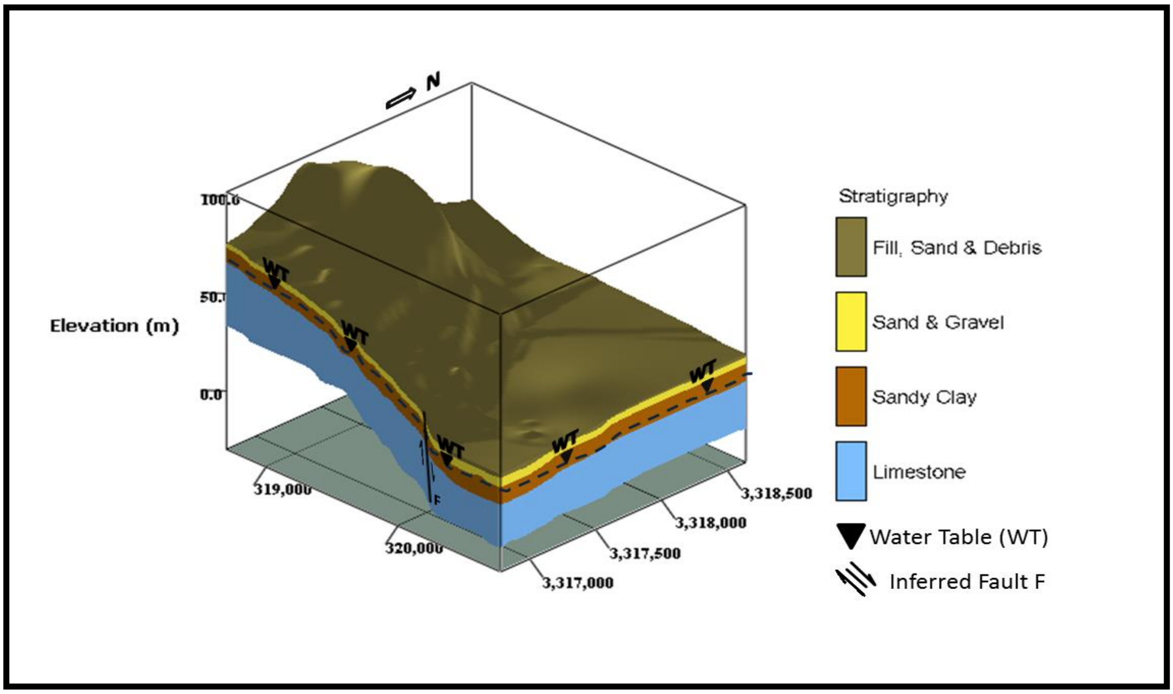

Fig. 13: 3D model of the Giza Pyramids Plateau, illustrating the groundwater table.

Authors' response to the Associate Editor comment on the paper entitled "Shallow Geophysical Techniques to Investigate the Groundwater Table at the Giza Pyramids Area, Giza, Egypt" gi-2017-48

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We would like to to thank Prof. Jothiram Vivekanandan, Chief-Executive Editor, Prof. Andrea Benedetto, the Associate Editor, and the reviewer for their constructive comments for improving our manuscript.

Replies to the comments of the reviewer

Comment #1:-

"Authors present a case study dealing with a multi sensor approach in the assessment of the water table level in the Giza Plateau. The field data were collected by using 3 different geophysical techniques: ERI, SSR, GPR. Field setups and measurements procedures are quite well described".

Reply:

Thank you very much for your valuable and helpful comments. We have gone through the manuscript taken into your considerations (corrected, modified and added the missing figures).

Comment #2:-

"I suggest the authors to introduce additional information about the gauges calibration."

Reply:

We have done this in the text in GPR by measuring the velocity by using Unshielded Pulss-Ekho GPR as stated in the text.

Comment #3:-

"The data processing and analysis is performed through existing software. It is not clear in the text the use of the boreholes data. The paper does not present novel tools or analysis techniques; furthermore the integration of data, collected through different instruments, is quite common. Despite this, the study can be interesting for the specific investigation site and for a cost-effective planning of future measurement campaigns."

Reply:

We have added a new table to compare the WT elevation results between piezometers and geophysical surveys results.

Comment #4:-

"A more interesting data presentation could be obtained by introducing the uncertainty in the analysis."

Reply:

This was done by calculating the RMS errors between measured and calculated arrival time. Also, in the models of ERI, the RMS illustrated on the figures.

Comment #5:-

"The text is generally well written, but sometimes it is redundant. As noticed by the SC1, figures are not in the pdf."

Reply:

Thank you very much for your valuable and helpful comments. We have modified the text to avoid the redundant sentences. Also, we have added the missing Figures.

Thank you