*Studia Quaternaria*, vol. 30, no. 2 (2013): 99–108. DOI: 10.2478/squa-2013-0010

# GEOPHYSICAL SURVEY (GPR) IN WEST SAQQARA (EGYPT): PRELIMINARY REMARKS

**Fabian Welc[1], Jerzy Trzciński[2], Sebastian Kowalczyk[2], Radosław Mieszkowski[2]**

[1] *Institute of Archaeology, Cardinal Stefan Wyszynski University, Wóycickiego 1/3, 01-938 Warsaw, Poland, e-mail: f.welc@uksw.edu.pl*

[2] *Institute of Hydrogeology and Engineering Geology, Faculty of Geology, University of Warsaw, Żwirki i Wigury 93, 02-089 Warsaw, Poland*

**Abstract**

Geophysical investigations in West Saqqara area were part of the archaeological fieldwork of the Polish-Egyptian archaeological mission during the campaign in 2012. The main purpose of geophysical prospection using the ground-penetrating radar (GPR) was to determine the location of potential underground sepulchral structures. During the GPR survey, optimal depth penetration was achieved due to dry rocks and monolithic structure of the limestone plateau on which the ancient cemetery was located. Using antenna of 100 MHz, the depth of penetration was up to 45 m and with antenna of 250 MHz, up to 15 meters. Three main groups of archaeological structures were identified: sarcophagi and mummies, burial shafts; mobile objects (solid rock blocks as fragments of tombs). One of the main goal of the GPR survey was to track the route of the western part of the Dry Moat, expressed by a wide and shallow depression spreading towards north-south. The results of geophysical investigations suggest that Saqqara plateau is an ideal site for using GPR surveying technology.

**Key words:** archaeological mission, ground-penetrating radar, Dry Moat, Saqqara, Egypt

## INTRODUCTION

Necropolis in Saqqara is considered as one of the most important archaeological sites in Egypt and in the world. Numerous royal tombs dated to the Old Kingdom period (about 2600–2100 yrs BC) are preserved in the cemetery area with a dominant step pyramid complex built in the 3rd Dynasty by Djoser-Netjerykhet about 2650 yrs BC (Fig. 1).

The area situated immediately to the west of the sepulchral complex of the pharaoh Netjerykhet has been the object of investigations by the Polish-Egyptian archaeological mission headed by Professor Karol Myśliwiec since 1987. The eastern border of the excavations lines up with the enclosure wall of the Step Pyramid and the western one with the western edge of the so-called Dry Moat (cf., Myśliwiec, 2006; Swelim, 1988, 2006; Fig. 2). In the course a dozen of field seasons, the team of Polish and Egyptian scientists has uncovered a section of an extensive necropolis dated to the Old Kingdom period (about 2200 yrs BC), the so-called Lower Necropolis (Myśliwiec et al., 2004) and superimposed on it in the upper layers is a Greco-Roman burial ground (so-called Upper Necropolis: Myśliwiec, 2002; Radomska et al., 2008).

## PREVIOUS GEOPHYSICAL RESEARCHES IN SAQQARA AREA

Geophysical investigations in West Saqqara area have been a part of the archaeological fieldwork ever since their first application during the magnetic survey performed by T. Herbich in 1987 (Myśliwiec & Herbich, 1995). The main purpose of this research was to determine the location of potential underground sepulchral features. The results of this survey allowed to a discovery of the richly decorated tomb of Merefnebef from the late Old Kingdom period (cf., Myśliwiec et al., 2004). Extensive geophysical surveys performed in Saqqara area by J. Mathieson and other researchers should be also mentioned here (Fassbinder et al., 2001; Mathieson, 2007; Price, 2008; 2009; 2012a). These studies resulted in a discovery and localization of hundreds of underground structures from various periods that have improved our knowledge concerning spatial development of the necropolis in Saqqara.

One of the newest methods of geophysical prospection, the ground-penetrating radar (GPR), has been used to surveying Saqqara necropolis lately. This method has been successfully applied by the team of Miller and co-workers (Miller et al., 2005) during examination of a small area located to the north of the tomb of Ptahhotep. GPR was also used to a limited extent during one of the last field seasons of the Saqqara Geophysical Survey Project – SGSP (Price, 2012b).

Geophysical survey using the GPR remote was one of the most important objectives during the campaign in 2012 of the Polish–Egyptian archaeological mission in West Saqqara (Kowalczyk et al., 2012). The main aim of this research was to determine the relationship between the geological structure of the West Saqqara limestone plateau and archaeologi-

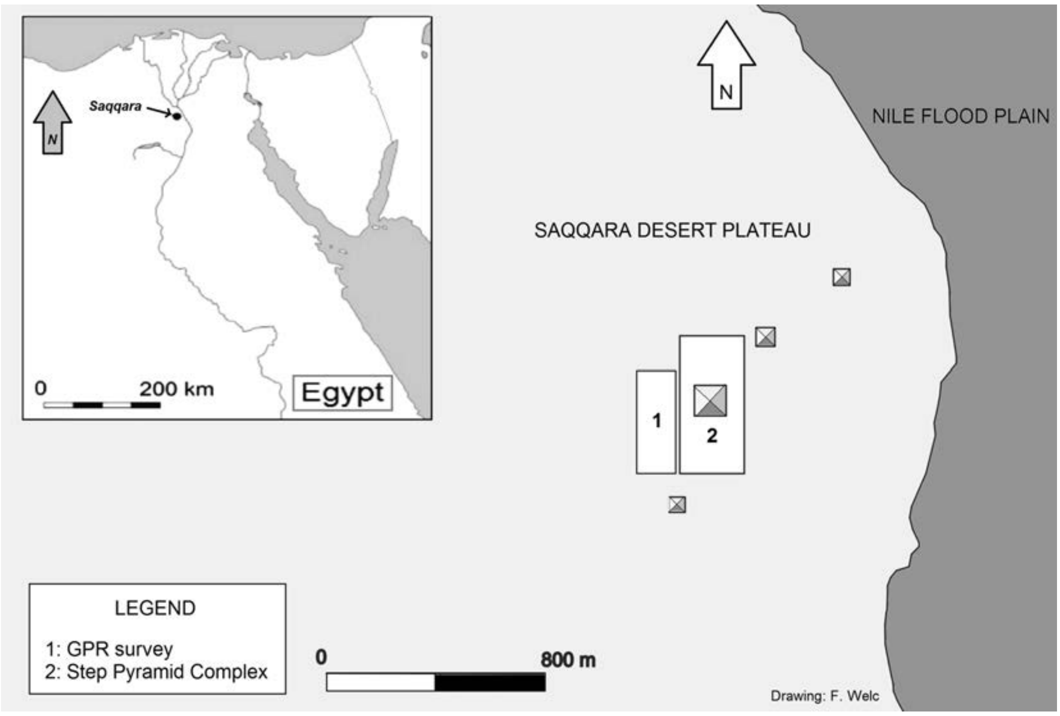


**Fig. 1.** General plan of the necropolis in Saqqara with marked area of geophysical survey conducted on the area of the Polish archeological concession. Drawn by F. Welc

cal features located there, especially those that still remain buried under the sand.

## RESEARCH METHODOLOGY OF GPR SURVEY IN SAQQARA

Ground-penetrating radar is a geophysical method that uses high-frequency radar pulses for creation of images of underground structures. GPR uses electromagnetic radiation in the microwave band (UHF/VHF frequencies) of radio spectrum for detection of signals reflected from underground structures, objects and lithological boundaries. The elapsed time between when the radio pulses are sent and when they are received back is measured (in nanoseconds). It allows precise location of objects buried up to several meters depth.

GPR can be applied to the examination of structures composed of various materials like rocks, soils, ice, water as well as other deposits and constructions. This method is also very useful to locate underground features at archaeological sites (Conyers, 2004).

Though the first GPR devices were constructed at the beginning of 20$^{th}$ century, the period after the Second World War saw their dynamic development and wide application, mainly by geological surveys. Since 1980s it has also been used in non-invasive archaeological prospection, especially to locate underground structures, such as burial shafts and burial chambers (Conyers, 2004). A good example may be the search for modern graves of Basque whalers in the Red Bay on Labrador (Vaughan, 1986) or the attempts to locate the burials and settlements in Gunma prefecture in Japan from the 6$^{th}$ century AD (Imai et al., 1987).

Despite the fact that the functional principles of GPR are relatively simple, the methodology of measurement and data processing is time-consuming and very complicated. This results from complex nature of electromagnetic wave reflection phenomenon, interference (signal enhancement and suppression), very low strength of registered signal and concurrently large number of factors which may potentially disturb it (Karczewski, 2007).

Due to special software, the GPR operator can see on the computer monitor underground structures with approximate depth given. This information is not available in other near-surface geophysical methods. Spreading of electromagnetic waves depends on electric, physical and chemical properties of different material in the ground, which substantially affect the depth of the prospection. For good conductors of electricity, the electromagnetic wave will be subject to a large attenuation and its propagation will be low. So, as conductivity increases, the penetration depth decreases. The depth of me- dium penetration is thus dependent on electrical properties of the medium and applied antenna frequency. Higher frequencies do not penetrate as far as lower frequencies; however, they provide better resolution. The strength of reflexes obtained as a result of GPR survey on the echogram depends on the reflected signal strength from the border of two media. The strength of signal reflection is determined by the contrast of dielectric (relative dielectric permittivity – RDP or dielectric constant – DC) properties. The higher the differences in media dielectric constant, the stronger are the reflexes visible on the echogram.

During the geophysical survey in Saqqara, the Swedish MALÅ GPR ProEx system was used (Fig. 3). Control unit was an integrated ground penetrating remote, fitted directly onto a shielded antenna and powered externally. All GPR profiles were carried out with 100 and 250 MHz shielded antennas and Panasonic CF-19 computer.

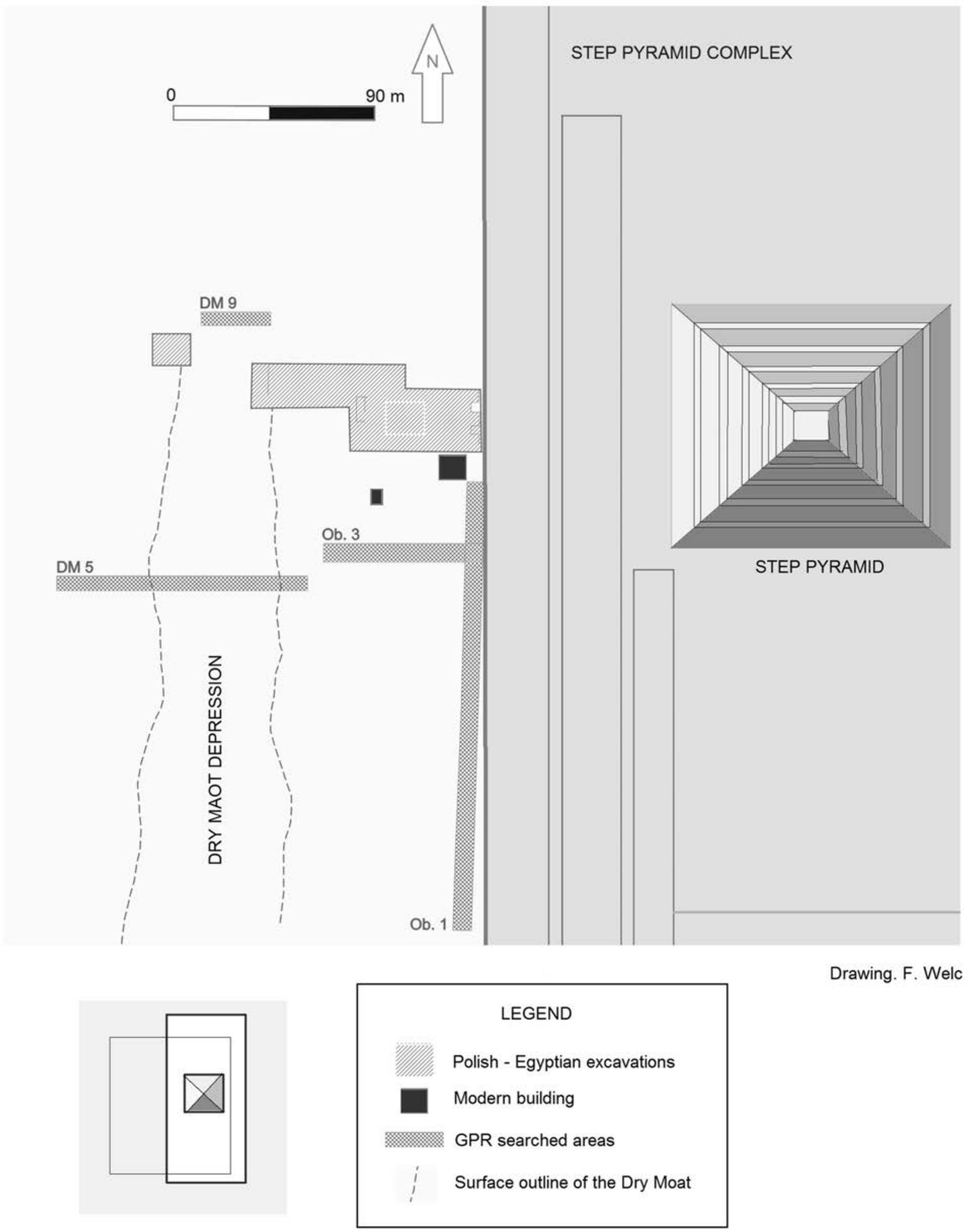


**Fig. 2.** Detailed plan of the areas examined using GPR on the Polish archaeological concession located directly to the west of Djoser from the period of 3rd Dynasty (ca. 4600 B.P.). Drawn by F. Welc

**Fig. 3.** Performance of the profiles using GPR on the OB 1 area, view from south – west. Phot. F. Welc

**Table 1**
The values of dielectric constant for selected geological layers (Jol, 2009) observed in the examined area

| Rock \ medium | Atenna frequency (MHz) | Dielectric constant $\varepsilon_r$ (-) | Vertical resolution (m/ns) |
|---|---|---|---|
| limestone (dry) | 100 | 4-8 | 0.27-0.38 |
| | 250 | 4-8 | 0.11-0.15 |
| sands (dry) | 100 | 3-6 | 0.31-0.43 |
| | 250 | 3-6 | 0.12-0.17 |

In terms of methodology, more than 30 areas were selected for geophysical survey in West Saqqara, all of them within the boundary of the Polish archaeological concession. A total of 25 areas were located in the southern part of the concession and the remainder in northern one. Most of the areas were straight strips of approximately 75 meters in length and 7 meters in width, oriented in accordance to the cardinal directions (Fig. 4).

During the field survey the GPR antennas were generally in contact with the ground for the strongest signal strength. All obtained electromagnetic profiles were initially archived by using special software, Ground Vision pro- gramme. In the next stage, all profiles were processed into professional GPR software, ReflexW View of the Sandmeier company.

All individual GPR profiles (depth sections) collected over the surveyed area in Saqqara can be used in future to construct quasi three-dimensional or tomographic images. The data may be presented as three-dimensional blocks or as horizontal or vertical slices. Horizontal slices (known as "depth slices" or "time slices") are essentially plain view maps isolating specific depths. Time slicing has become standard practice in archaeological applications, as horizontal patterning is often the most important indicator of cultural activities.

For comparative purposes, the same parameters of reflected waves registration and so-called signal assembly were used in order to strengthen weak amplitudes of useful reflexes and limitation of the possibility of registration of coincidental and low-amplitude noises. Registration of the routes was conducted in a few time windows depending on the frequency of antenna used. The examined media, usually loose sands and carbonate rocks, were characterized by differentiated values of dielectric constant and soil electric conductivity which substantially affected the depth of prospection (Table 1).

## GPR SURVEY IN WEST SAQQARA

The area searched by the Polish-Egyptian archaeological mission in West Saqqara is a limestone slope partly transformed by human activity (an ancient quarry operated there during the Third Dynasty, in effect a series of rock terraces were created, – cf., Welc, 2011, sloping at an angle of approximately 5–7 degrees down to the west (Youssef et al., 1984). The altitude is between 48 and 53 m above sea level. Natural and anthropogenic deposits accumulated on the slope are differentiated both in thickness and lithological composition. In the central part of the site, that is, directly to the south and east of the tomb of Merefnebef, sand and rubble layers reached 2 m in thickness. The thickness by the enclosure wall did not exceed 2.5 m. At the western edge of the site, which is also the lowest part of it, by the edge of the Dry Moat, the lay-

**Fig. 4.** Performance of the profiles using GPR on the Dry Moat area, view from the south-west. Phot. F. Welc

ers measured no more than 0.5 m in thickness (Myśliwiec et al., 2012).

During the GPR survey, optimal depth penetration was achieved due to the dry sandy layers and monolithic structure of the limestone outcrop on which the ancient cemetery was located. Using antenna of 100 MHz, the depth of penetration was up to 45 m and with antenna of 250 MHz, up to 15 meters. It suggests that Saqqara limestone plateau is almost an ideal site for using GPR surveying technology.

It may be noted that comparing the echograms obtained using both antennas from the same profile, the images received using the antenna of 250 MHz are characterized by considerably better signal resolution. The outline of reflection surfaces is reflected more precisely compared to echograms obtained from the 100 MHz antenna. Higher number of visible details in the ground was obtained as a result of prospection using an antenna of frequency of 250 MHz. This allowed more detailed interpretation of underground geological and archaeological structures up to 15 m in depth.

Better profiling results received using 250 MHz antenna are mainly due to the fact that the examined tomb structures were localized at a considerably low depth, maximally up to 5 m. These structures (burial shafts, chambers) were partially immersed in a compact limestone, which is the medium that absorbs electromagnetic waves only to a low degree. In contrast to the shafts, burial chambers are usually and only in part filled with rock debris as was noted during excavations. Therefore, they emit strong reflexes on echograms due to considerable contrast of dielectric constant between compact rock and rock rubble and air that usually partially fills these structures. Dielectric constant and electrical conductivity for limestone are 4–8 and 0.5–2 ms/m, respectively, while these values for air are 1 and 0 ms/m (Davis & Annan, 1989). This is confirmed in the study conducted by Chamberlain et al. (2000) performed using a 100 MHz antenna and by prospections of El-Qady et al. (2005) obtained using a 200 MHz antenna (both prospections concerned localization of the caves hewn in limestone and their 3D projection).

The obtained GPR examination results in Saqqara confirm the high usefulness of 250 MHz antenna in localization of shallow buried archaeological objects and in reconstruction of the examined area paleogeomorphology. It should be also emphasized that it is possible to obtain 3D models of underground geological and archaeological structures for the areas where profiles were concentrated in sufficient numbers and with appropriate interspaces (not less than 0.25 m).

## RESULTS AND INTERPRETATION FOR SELECTED FRAGMENTS OF RESEARCH AREA

Selected echograms from some areas examined by GPR in Western Saqqara are discussed below. These allow us to present the possibilities of an application of the discussed method on typically desert archaeological sites. Moreover, the echograms present various underground anthropogenic structures, which may be marked and interpreted (Fig. 2).

The echograms interpretation was strongly facilitated by the results of excavation works and geoarchaeological survey carried out in the area in question. These works allowed elaborating a synthetic lithostratigraphic profile of the West Saqqara archaeological site which is as follows (Welc, Trzciński, 2013):

1. layers of marly and pelite limestone, dated to early Paleogene – Upper Eocene age,

2. layers of rubble-muddy flows of thickness varying from 0.5 to 3 m, dated to the late Holocene – Old Kingdom period,

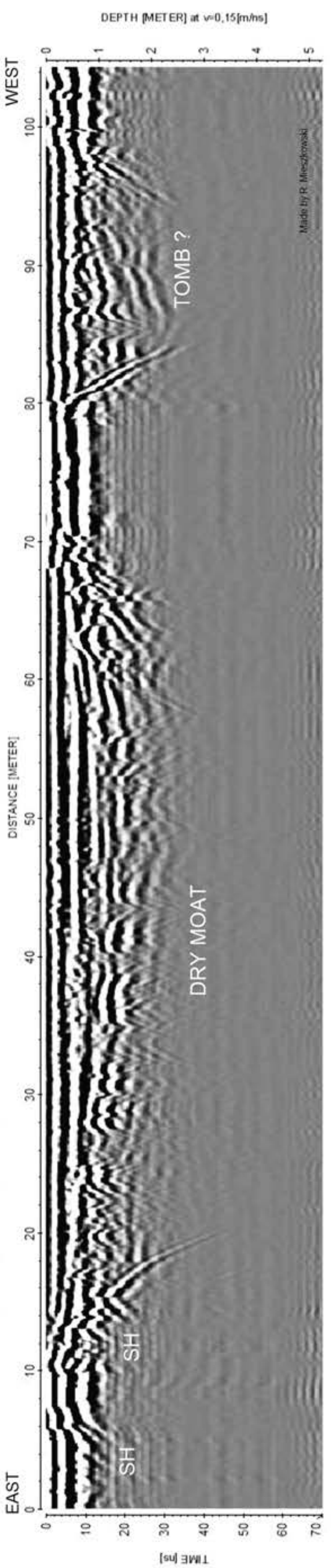


**Fig. 5.** Echogram from area DM 5, profile 11, orientation E-W, antenna 250 MHz, SH – shaft.

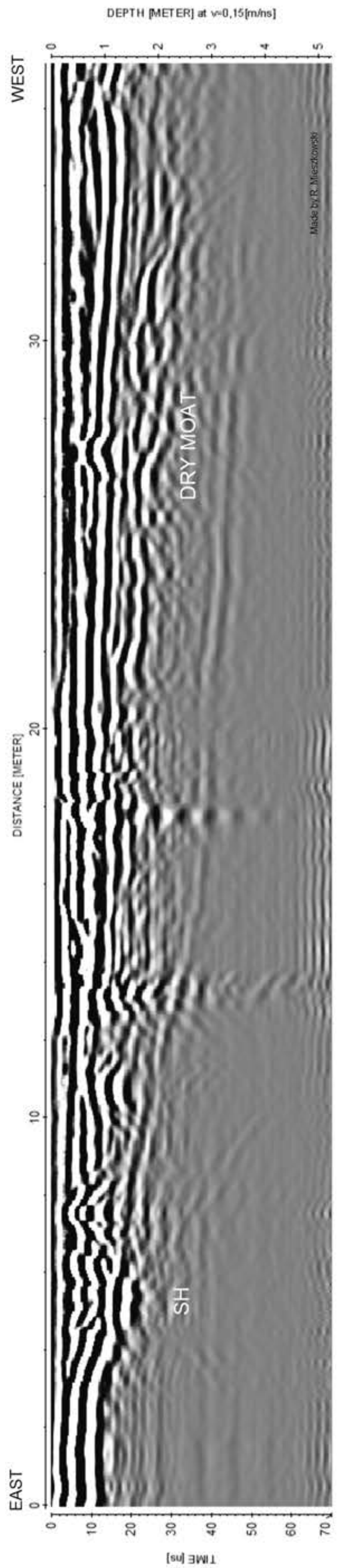


**Fig. 6.** Echogram from area DM 9, profile 9, orientation E-W, antenna 250 MHz, SH – shaft.

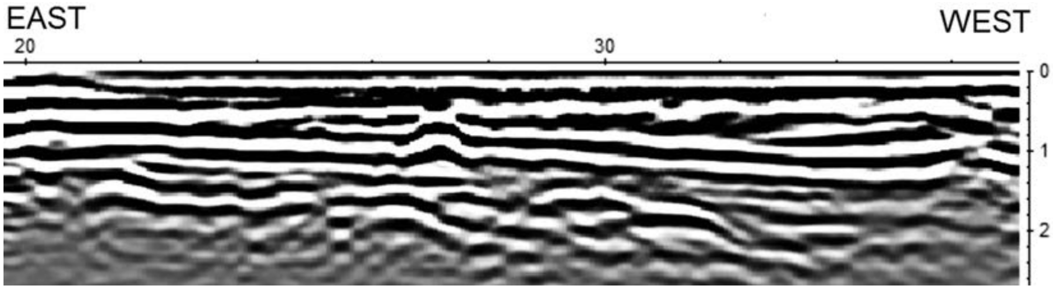


**Fig. 7.** Fragment of echogram of profile 9 from area DM 9: lamination of aeolian sands is very well visible.

3. layers of aeolian laminated and massive sands of thickness from 30 cm to a few meters, dated to the late Holocene – from First Intermediate Period to the Greco-Roman time.

Archaeological structures in the examined area of the necropolis may be divided into three main groups, and the most abundant are:

1. Greco-Roman burials – sarcophagi, mummies buried directly in the layers of aeolian sands, in sparse cases deposited in hollows cut directly in limestone bedrock – they give strong reflexes (mostly characteristic hyperboles) on the echograms,

2. Brick-stone remains of cult chapels and accompanying burial shafts cut in rock of different depth (from a few to over 20 m) dated to the late Old Kingdom period – they generate differentiated kind reflexes on the echograms,

3. Mobile objects such as solid limestone blocks, parts of tomb equipment – due to their small size, it is not possible to distinguish them from the objects gathered in point 1.

As stated above, the searched area in West Saqqara is varied morphologically. The difference in the altitude between particular parts of the area reaches a few meters and increases towards the top of the slope where the archaeological site is located. The echograms presented do not take into account the so-called topographic adjustment despite often considerable drops, because area topography consideration considerably impedes an interpretation and legibility of the echograms.

As it was mentioned above, one of the main goal of the GPR survey in 2012 was to track the route of the western part of the Dry Moat, which is manifested as a longitudinal wide and shallow depression, concurrently constituting the western border of the Polish archaeological concession in Saqqara (Fig. 2).

Results of the GPR research of the Dry Moat are presented on echogram DM 5 (Fig. 5) which was made, like all other echograms presented in the article, using 250 MHz antenna. This is the profile of a length of about 120 m, oriented west-east which perpendicularly crosses the Dry Moat structure (Fig. 2). The outline of side edges of this huge hollow is clearly visible on the current profile between $10^{th}$ and $70^{th}$ m. Upper aeolian layers of a thickness of about 1–1.5 m may be distinguished within the Dry Moat. Below the sands, the hollow is presumably filled with rubble-muddy (slope deluvial series) layers strongly cemented with calcium carbonate (on these layers cf. Trzciński et al., 2010; Welc & Trzciński, 2013). Numerous Greco-Roman burials are dug into this layer which are marked on the echogram as small characteristic hyperboles. Since slope deluvial layers contain considerable amounts of clay fraction with predominant clay minerals, this causes considerable suppression of electromagnetic waves resulting in a lowering of the depth of signal prospections from GPR antenna. Therefore, it is difficult to determine the total depth of the Dry Moat in the examined site. There is no doubt however that it is deeper than 5 m and in other places the depth is (see below) more than 10 m. Fine bedded layers of local marly and sandy limestone are visible between $70^{th}$ and $80^{th}$ linear meter of the profile. In turn, the anomaly which may be interpreted as a kind of regular, presumably anthropogenic hollow cut (probably tomb courtyard) in the rock of a width of ca. 30 m and depth of ca. 3 m, is clearly visible in the western part of the profile, i.e. between $80^{th}$ and $100^{th}$ linear meter. Numerous reflexes within the area are generated by the borders between subsequent alternate layers of sand and rubble filling the described structure completely, which is probably a cult courtyard cut in the rock related to an unidentified tomb complex.

The cross-section of the Dry Moat was also displayed on the echogram of DM 9. This east-west oriented profile is about 40 m long (Fig. 6). Eastern part of the Dry Moat is clearly visible, with its rocky bottom falls systematically towards the west at a small angle. In the central part of the echogram, the bottom is set at depth of over 10 m. The discussed section of Dry Moat is completely filled with rubble-muddy layers (slope deposits), and from a depth of about 2 m up to the top with a series of bedded aeolian sands (Fig. 7). The same stratigraphic arrangement of the layers was registered in a deep excavation trench made during the archaeological sexcavations in the close vicinity. During this recent exploration work the western edge of Dry Moat was cleaned. Some of late Old Kingdom (about 4200 yrs BC) chapels were hewn in to it. About 3 meters thick layer of aeolian sands, clearly bedded, was documented inter alia above the thick rubble-muddy sets filling of the discovered archaeological structures (Fig. 8). Like in the case of the echogram discussed above, small hyperboles reveal the burials from Greco-Roman period dug directly into the layers of aeolian sand and into slope rubble-muddy layers. Attention should also be paid to the distinctly manifested rubble-sandy fill of the burial shaft situated between $4^{th}$ and $6^{th}$ meter of the GPR profile.

Area of the eastern part of the Polish archaeological concession in Saqqara appears a bit different on the obtained GPR echograms. The main purpose of profiling performed in this place was to establish the depth of the rock bedding and localization of most important underground burial structures. For this purpose, a strip of a total length of 200 m that

**Fig. 8.** Southern wall of the excavation in the vicinity of DM 9 area: laminated aeolian sands in the upper part are well visible. Phot. F. Welc

ran north-south, directly adhered the damaged monumental enclosure wall surrounding the complex of the step pyramid was examined inter alia. Echogram no 20 (Fig. 9) of south-north orientation on the discussed area revealed a distinct border between massive limestone bedrock and above laying rubble-muddy layers of about 3 m thickness. Attention should be paid to the strong secondary reflexes that concurrently disturb the measurement, with the source set just under the surface. The geoarchaeological survey conducted at this site reveald the presence of numerous blocks of white limestone of different size lying both on the surface and just below it, at a relatively small depth. This material originates from partially pulled down enclosure wall. These blocks probably constitute the main source of strong anomalies reaching ca. 1 m in depth. A clear discontinuity in the top of Eocene limestone outcrop is visible between 165$^{th}$ and 185$^{th}$ meter of the profile, which was presumably formed as a result of anthropogenic activity. It may be considered with a high probability as an anomaly generated by a relatively large burial structure, probably a burial shaft of considerable dimensions. It seems that it is justified to relate the anomaly described above to a clear outline of a burial structure, i.e. shaft mouth which was localized in the same place during the survey conducted by Mathieson (Mathieson, 2008). A similar anomaly, however, less unequivocal in interpretation, is visible between the 95$^{th}$ and 110$^{th}$ linear meter of the profile described.

Above-discussed profile no. 20 crosses other GPR profile no. 17 of a total length ca. 70 m, so-called area OB 3 (Fig. 10). The echogram obtained there demonstrates very significant results concerning the arrangement of the top surface of the limestone outcrop. It presents differentiated roof of Eocene rocky formation with hollows reaching, at some places, a depth of about 4–5 meters. It is noteworthy that the surface of limestone rock falls toward the east, i.e. goes deep directly under the enclosure wall of the step pyramid complex. It may be interpreted as a kind of entrance ramp to an unknown tomb or more plausibly as an effect of quarrying activity. This issue is difficult to determine without archaeological excavations conducted at this site, which would verify the results obtained during GPR survey. In the eastern part of the analysed echogram there is very clearly visible pre-Quaternary top surface of limestone outcrop and above it are particular sequences of layers and deposits overlaid by laminated aeolian sands lying just under surface. Particularly high concentration of anomalies is visible between the 35$^{th}$ and 65$^{th}$ meter of the profile. Numerous burials and larger fragments of debris and stone blocks probably generate these anomalies. In addition, the presence of burial shafts is suggested to occur between the 40$^{th}$ and 50$^{th}$ meters.

## FINAL REMARKS

The conducted GPR prospection in the area of the Polish-Egyptian archaeological mission in West Saqqara confirmed high usefulness of this modern end effective method of non-invasive research of the cemetery located in the desert area, especially when using 250 MHz antenna. It should be however emphasized that the large depth range and high resolution, obtained during the survey, resulted to a high degree due to favourable geological conditions, i.e. strong contrast of dielectric properties between limestones and lithologically differentiated Quaternary overlying rubble and sandy

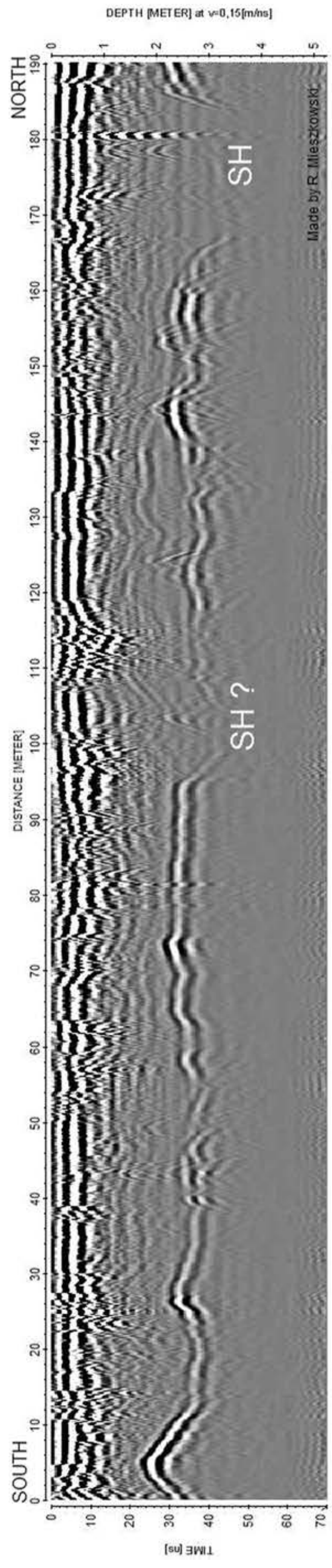


**Fig. 9.** Echogram from area OB 1, profile 20, orientation SN, antenna 250 MHz, SH – shaft.

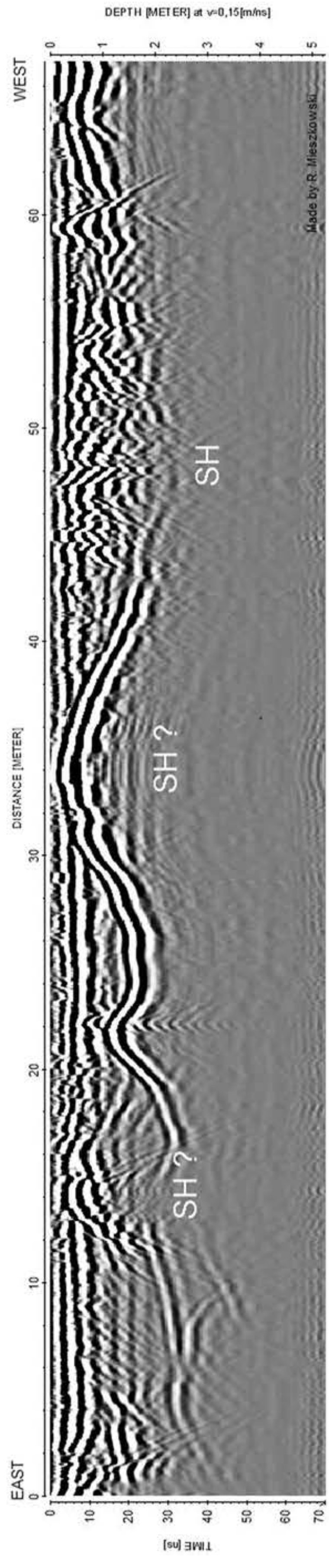


**Fig. 10.** Echogram from area OB 3, profile 20, orientation EW, antenna 250 MHz, SH – shaft.

sediments. Very dry conditions, and thus low water content in the searched sediments were also significant.

It may be thus concluded that currently applied GPR systems, however complicated and relatively expensive, belong to one of the most common and concurrently the most perspective methods of non-invasive archaeological prospection. It should however be emphasized that the above presented preliminary results should be verified using archaeological probing research.

## REFERENCES

Chamberlain, A.T., Andrew, T.C., William, S., Chis, P., Roslyn, C. 2000. Cave detection in limestone using ground penetrating radar. *Journal of Archaeological Science* 27: 957–964.

Conyers, L.B. 2004. Ground-penetrating Radar for Archaeology. Altamira Press, Walnut Creek, California.

Davis, J., Annan A.P. 1989. Ground penetrating radar for high – resolution mapping of soil and rock stratygraphy. Geophysics 37: 531–551.

El-Qady, G., Hafez, M., Abdalla, M.A., Ushijima, K. 2005. Imaging subsurface cavities using geoelectric tomography and ground-penetrating radar. Journal of Cave and Karst Studies 67: 174–181.

Fassbinder, J.W.E., Becker, H., Herbich, T. 2001. Magnetometry in the desert area west of the Zoser's Pyramid, Saqqara, Egypt. In: Hemmeter, K., Fassbinder, J.W.E., Irlinger, W.E., Petzet, M., Ziesemer, J. (eds.), Magnetic prospecting in archaeological sites. Monuments and Sites 6: 64–65.

Imai, T., Toshihiko, S., Takashi, K. 1987. Use of ground-probing radar and resistivity survey for archaeological investigations. Geophysics 52: 137–150.

Jol H. M. 2009. Ground Penetrating Radar: Theory and Applications. Elsevier Science: 524.

Karczewski, J. 2007. Zarys Metody georadarowej. Kraków.

Kowalczyk, S., Welc, F., Trzciński, J., Mieszkowski, R. 2012. Geophysical researches (Ground Penetrating Radar) on the Polish archaeological concession in West Saqqara. In: Welc, F. (ed.), Memphite Necropolis (Egypt) in the light of geoarchaeological and environmental research, 13–15. Second Geoarchaeological Conference in Warsaw, 7-8 December. Abstract of the papers, Warsaw.

Mathieson, I.J. 2007. Recent Results of a Geophysical Survey in the Saqqara Necropolis. In: Schneider, T. & Szpakowska, K. (eds.) Egyptian Stories, 155–167. A British Egyptological Tribute to Alan B. Lloyd on the Occasion of his Retirement, Münster.

Mathieson, I.J. 2008. The Search for Imhotep. Ancient Egypt Magazine 8 (5): 34–36.

Miller, C., Allen, A., Speece, M., El-Werr, A., Link, C. 2005. Land Streamer Aided Geophysical Studies at Saqqara, Egypt. Journal of Environmental and Engineering Geophysics 10: 371–380.

Myśliwiec, K. 2002. The Ptolemaic Period Cemetery in West Saqqara. In: Bács, T. A. (ed.), A Tribute to Excellence, Studies offered in honour of E. Gaál, U. Luft, L. Török, StudAeg 17: 349–359.

Myśliwiec, K. 2006. "Dry Moat" west of the Netjerykhet enclosure. In: Barta, M. (ed.), The Old Kingdom Art and Archaeology, 233–237. Proceedings of the conference held in Prague, May 31-June 4, Prague.

Myśliwiec, K., Herbich, T. 1995. Polish Research at Saqqara in 1987. Études et Travaux 17: 186–195.

Myśliwiec, K., Kuraszkiewicz, K., Czerwik, D., Rzeuska, T.I., Kaczmarek, M., Kowalska, A., Radomska, M., Godziejewski, Z. 2004. The Tomb of Merefnebef, Saqqara I. Warsaw, Neriton.

Myśliwiec, K., Welc, F., Trzciński, J. 2012. Geoarchaeological and Paleoclimatic research by Polish Archaeological Mission in Saqqara, an updated overview. Études et Travaux 25: 276–296.

Price, C. 2008. East of Djoser: Preliminary Report of the Saqqara Geophysical Survey Project, 2007 Season. In: Kousoulis, P., Lazaridis, N. (eds.), Proceedings of the Tenth International Congress of Egyptologists, Rhodes, Greece 17-24th May. Peeters, Leuven, (in press).

Price, C. 2009. Geophysical survey east of the Saqqara Step Pyramid. Egyptian Archaeology 34: 38–39.

Price, C. 2012a. Scotland at Saqqara. The Work of the Saqqara Geophysical Survey Project, 1990-present. Friends of Saqqara Foundation Newsletter 10, Leiden: 49–53.

Price, C. 2012b. Recent Results of the Saqqara Geophysical Survey Project. In: Welc F. (ed.) Memphite Necropolis (Egypt) in the light of geoarchaeological and environmental research, 16–17. Second Geoarchaeological Conference in Warsaw, 7-8 December. Abstract of the papers, Warsaw.

Radomska, M., Kowalska, A., Kaczmarek, M., Rzeuska, T.I., Kopp, E., Kuraszkiewicz, K.O., Winnicki, J.K., Myśliwiec, K. (ed.). 2008. Saqqara III. The Upper Necropolis, Part I. Warsaw, Neriton.

Swelim, N. 1988. The Dry Moat of the Netjerykhet complex. In: Baines, J., James, T.G.H., Leahy, A., Shore, A.F. (eds.). Pyramid Studies and Other Essays Presented to I. E. S. Edwards, 12–22. London, Egypt Exploration Society.

Swelim, N. 2006. Dry Moat. The south rock wall of the Inner South Channel. In: Czerny, E., Hein, I., Hunger, H., Melman, D., Schwab, A. (eds.). Timelines: Studies in Honour of Manfred Bietak, 363–376. Louvain-la-Neuve: Peeters.

Trzciński, J., Kuraszkiewcz, K.O., Welc, F. 2010. Preliminary report on geoarchaeological research in West Saqqara. Polish Archaeology in the Mediterranean 19: Reports 2007: 194–208.

Vaughan, C.J. 1986. Ground – penetrating radar surveys used in archaeological investigations. Geophysics 51: 595–604.

Welc, F. 2011. The Third Dynasty open quarry west of the Netjerykhet pyramid complex. Études et Travaux 24: 272–304.

Welc, F., Trzciński, J. 2013. Geology of the Site. In: Myśliwiec, K. (ed.), Saqqara V, Varsovie, V.2, 323–343. Editions Neriton.

Youssef, M., Cherif, M.O., Boukhary, M., Mohamed, A. 1984. Geological Studies on the Saqqara Area, Egypt, Neues Jahrbuch für Geologie und Paläontologie Abhandlungen 168: 125–144.