Tomasz Herbich

Geophysical Research in the Pyramids Area: an Overview of the Application of the Magnetic Method

Abstract: The article discusses research carried out using the magnetic method, in an area of necropolises located between Giza and the Fayum Oasis in Egypt. It describes the enormous progress which took place over the 40 years that have passed since the first magnetic research was conducted there. Progress was made in, among others, the methodology of measurements, processing and visual presentation of data. The method's high efficiency in registering archaeological structures that are invisible on the surface, has been shown by discussing the results from research projects carried out in Giza, Abusir, Saqqara, Dahshur, El-Lahun and Hawara. The method's effectiveness is based on the fact that Nile mud has magnetic properties, and it was used for the production of sun-dried bricks, which was the basic building material in Ancient Egypt. By registering hundreds of structures located beneath the surface, magnetic research not only allows to reconstruct the original layout of, for example, necropolises, but also provides archeologists with useful information for planning future excavations.

1 Introductory Remarks

Geophysical research in the pyramids area – defined as the area between Giza in the north and the Fayoum Oasis in the south – has been carried out since the 1970s. The first surveys took place in locations surrounding the pyramids of Giza. An American-Egyptian team used a variety of methods: radar, electro-resistivity, acoustic sounding and magnetic prospection. This article will focus on the use of the latter method. The reason for only presenting results obtained by the magnetic method has been dictated by two factors. First, it is the interest of Professor Stephan Seidlmayer, to whom this paper is dedicated. Prof. Seidlmayer introduced the magnetic method, with great success, to his research project at Dahshur. The second factor are the interests of the author, who in his research in Egypt mainly uses the magnetic method, while other approaches, such as the electro-resistivity and georadar, were only applied sporadically.

The magnetic method is highly effective in the study of necropolises surrounding the pyramids due to the magnetic properties of Nile mud, which was the basic building material in Ancient Egypt. Iron oxides present in Nile silt are the reason for its magnetic properties. This phenomenon was first used for the purposes of archaeology by Albert Hesse from the Centre d'Études Géophysiques in Garchy-Nièvre, during research carried out at a fortress in Mirgissa, Nubia.[1] The magnetic susceptibility of Nile silt was discovered during an analysis of samples at the Observatoire de Physique du Globe by Émile Thellier. Elizabeth Ralph from the Museum Applied Science Center for Archeology, University of Pennsylvania, was the pioneer in applying the magnetic method in Egypt, conducting research in Malkata in Upper Egypt in 1972–3.[2]

Magnetic surveys were carried out at six sites in the area of the pyramids: Giza, Abusir, Saqqara, Dahshur, El-Lahun and Hawara. More than four decades have elapsed since the first survey in the area was carried out, which took place in Giza in 1977. During this period huge progress was made in magnetic research, thanks to the automation of the measurement process and digital processing of data. It greatly accelerated the field work and made it possible to obtain a much higher number of measurements in a given unit of time, which meant that larger areas could be surveyed. It makes an enormous difference if one measurement takes between 3 to 6 seconds (in the case of proton magnetometers), after which the result has to be recorded manually, or if the instrument takes 10 measurements per second, and the data is recorded digitally by the instrument. The digital techniques used to process the data – and

1 Hesse 1967; Hesse 1970.

2 Ralph 1973.

https://doi.org/10.1515/9783110761665-023

above all to present them graphically – allowed a far more in-depth analysis of the results. The possibility of discerning anomalies of anthropogenic origin when manually drawing maps is incomparably lower than discerning anomalies when using specialized software. Software makes it possible to present results in, for example, specific value ranges, or process data through an algorithm that better defines structures with anomalous values.[3] The gulf separating the 1970s/80s from the 1990s can be seen in the author's research: in 1987 in Saqqara the impassable threshold was taking 1000 measurements per day,[4] compared to 50 thousand per day achieved only a decade later. Automation and speed of measurement, as well as the possibility of digitally processing data, also influenced the density of the measuring grid – from one measurement per square meter to at least eight, which translated into more detailed images of structures that cause disturbances in the magnetic field.[5] The research methodology (measurement methodology and equipment used in the research) will be discussed in the presentation of individual sites. Much of this publication is devoted to early research, which I believe is little known to the community of Egyptologists.

2 Giza

In 1974, a team composed of researchers from the Stanford Research Institute in California and Ain Shams University in Cairo conducted the first test in Egypt of the radar method's effectiveness, mainly in order to find the internal structures of the 4th Dynasty pyramids of Giza.[6] The limited success of the survey prompted researchers to carry out further studies using a number of other geophysical methods: electro-resistivity, thermal photography, acoustic sounding, and magnetic prospection.[7] The following research led to the recognition of the electro-resistivity method's potential. With the help of this method, foundations of stone walls and chambers were recorded. The magnetic method was used in Giza in an area adjacent to the north and west of the Sphinx, on the west and south sides of Chephren's Pyramid and above Chephren's boat pits. Researchers used a G-816 Geometrics portable proton precession magnetometer. In order to obtain an accuracy of 1 gamma (nT), one measurement lasted 5 seconds. To avoid the disruptive influence of daily changes in the value of the magnetic field, measurements were compared to the ones at the base point taken several times a day. Changes in the magnetic field intensity value were observed only along the lines (Fig. 1), as opposed to areas in a regular measurement grid, as was the case in Mirgissa and in Malkata.

Near the Sphinx, only anomalies caused by installations illuminating the monument at night were registered. Measurements taken on the western side of Chephren's pyramid had a similar meagre effect. However, an anomaly registered by the resistivity meter and an acoustic sounder, appeared on the diagram of changes in the magnetic field intensity. This meant that the anomaly was likely caused by an archaeological structure built of limestone, a rock of low magnetic susceptibility, therefore undetectable by the magnetic method, but causing changes in the electrical conductivity of the substrate.

The next magnetic research at Giza took place almost a quarter of a century later. Geophysical methods were used several times as part of the work by the Giza Plateau Mapping Project, headed by Mark Lehner. Among them was the magnetic method, but unfortunately its application did not go beyond tests carried out in a very small area, on the south side of the Wall of the Crow, and at the II Gallery Complex of the workers' settlement of the 4th Dynasty. Results showed a bakery, and also helped determine the course of a destroyed section of a barrack wall. Thanks to a cluster of pottery adjacent to the non-existent wall, it was possible to pinpoint the exact location of the "ghost wall".[8]

3 Herbich 2015a.
4 Myśliwiec/Herbich 1995; Herbich 2003.
5 Herbich 2015a.
6 Dolphin et al. 1975.
7 Dolphin et al. 1977.
8 Dash 2000.

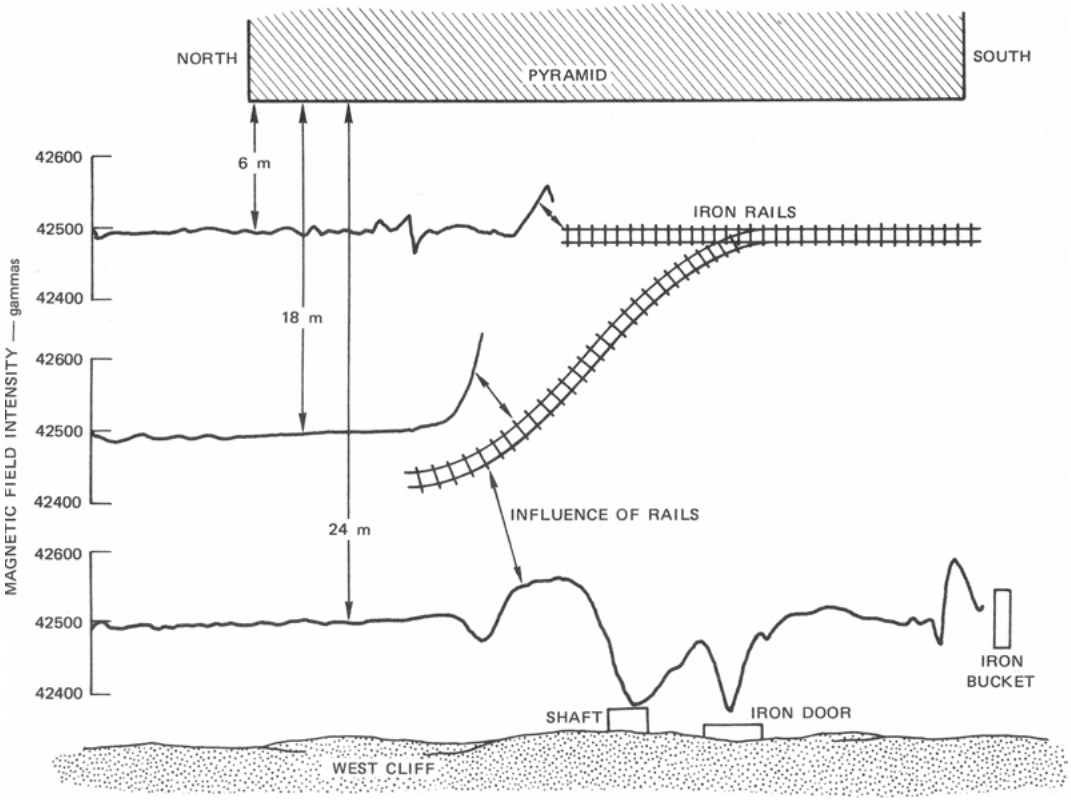

Fig. 1: Giza. Magnetic readings on the west side of Chephren's pyramid.

3 Abusir

Researchers from the Charles University in Prague, who have been conducting research at the Old Kingdom necropolis at Abusir since 1960, started in 1976 concentrating their activities on the southern part of the burial ground, thanks to a newly obtained archaeological concession. In the late 1970s, Czechoslovakia was one of the leading countries in the implementation of geophysical methods in archeology, and the magnetic method was a frequently used tool in the study of sites in the Czechia, Slovakia and Moravia.[9] It is not surprising, therefore, that when planning research on the little explored site, archeologists reached for geophysical methods as a supporting tool when planning excavations. They applied magnetic and electro-resistivity methods, and the magnetic susceptibility of materials used in structures located beneath the surface, as well as their surroundings, were investigated. The results of the research were reported on an ongoing basis in far-reaching periodicals.[10]

The geophysical survey was carried out in 1978–81. Magnetic measurements were taken in six sectors, covering an area of approx. 7 ha (Fig. 2).[11] Vladimir Hašek of the Geofyzika Brno company (Fig. 3), who led the research, used proton magnetometers, manufactured by Geometrics, type G816. Measurements were carried out in a grid divided into various sizes: from 1 m × 1 m to 5 m × 1 m. Tests for the effectiveness of the measurements were also carried out at a variable height of the sensor above the ground (from 0 to 120 cm). Magnetic field variations were recorded every 2 minutes at the base-point. The results were presented in the form of manually drawn maps showing the changes in the intensity of the magnetic field (Fig. 4). Magnetic susceptibility was measured using the KT-5 kappameter manufactured by Geofyzika Brno.

Among the main goals of the survey was to determine the location of mastabas and plans of structures identified (but not excavated) by researchers studying the site earlier. Innovative – at the time – issues were also considered,

9 Hašek 1979.

10 E.g. Verner/Hašek 1981.

11 Verner/Hašek 1981, 69; Hašek et al. 1988, 3 and 21.

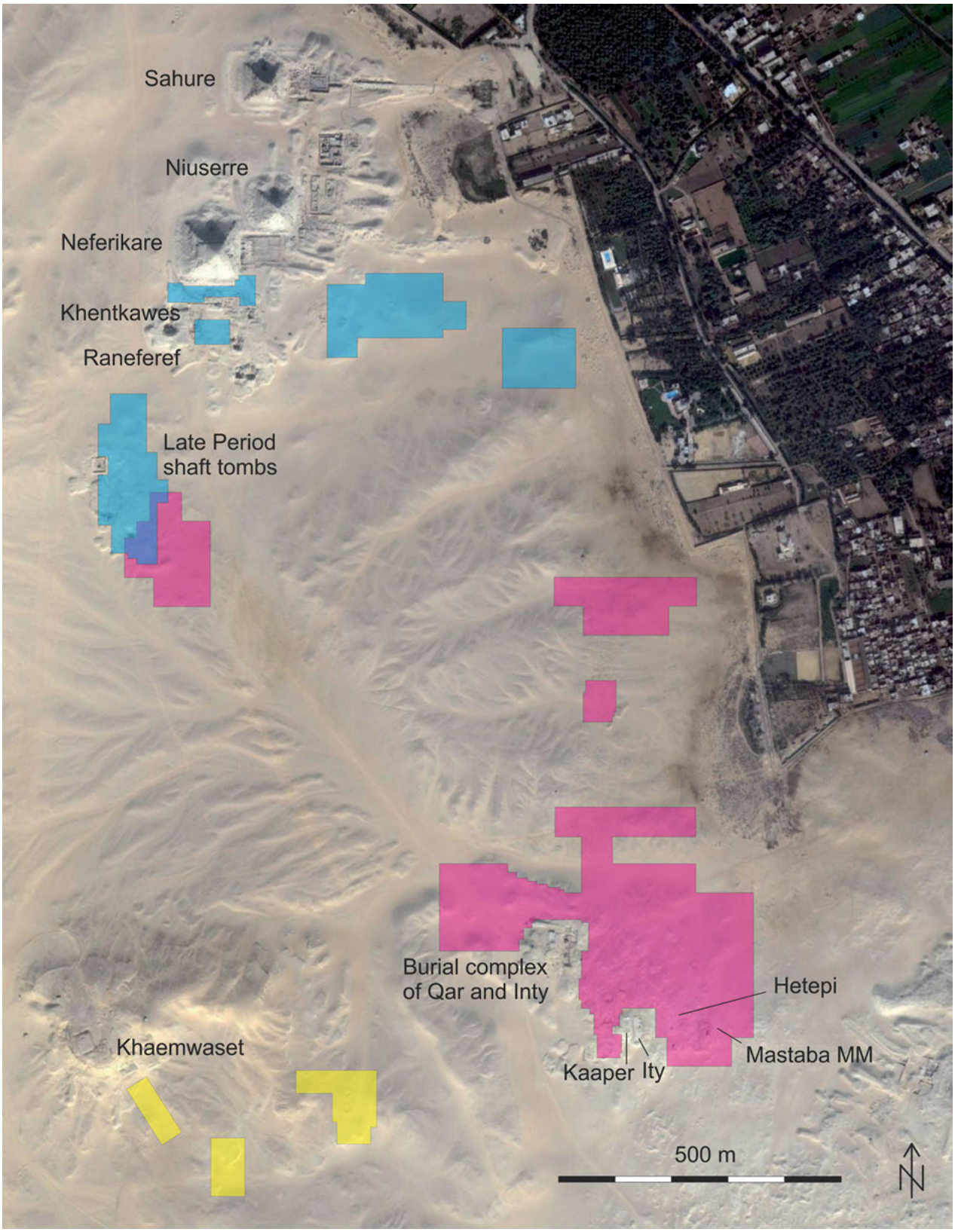

Fig. 2: Abusir/Saqqara North. Location of magnetic surveys on a Google Earth image. In blue – survey of the Charles University with the use of a proton magnetometer (1978–81); in violet – survey of the Charles University and the Institute of Archeology of the Academy of Sciences of the Czech Republic with the use of a caesium gradiometer (CG) (2002); in yellow – survey of Waseda University with the use of a fluxgate gradiometer (FM) (2008).

Fig. 3: Abusir. Vladimír Hašek taking measurements with a proton magnetometer.

such as determining the type of building material and constructional phases of some structures excavated during former exploration seasons.[12] An additional application of the electro-resistivity method confirmed the stated hypotheses, which were based on an analysis of the results of the magnetic method.

The study on the eastern side of a pyramid, marked by Lepsius as the XXIV Pyramid (later identified by the Czech team as Raneferef's burial site), was to determine the building plan of the mortuary temple. Results of magnetic measurements provided a basis for the reconstruction of the size of the temple and its internal structure. Positive anomalies were considered to reflect dried mud-brick walls, and negative anomalies to show the presence of stone structures. This interpretation of negative anomalies was supported by the results of the following resistivity survey: in places where these anomalies occurred, the results showed an increase of resistivity typical for stone structures. These observations were later confirmed during excavations carried out in 1982–1984.[13] Strong positive anomalies corresponded to dried mud-brick walls of magnetic susceptibility in the range of 0.7–1.3^{-3}SI. Negative anomalies corresponded to the remains of stone walls and to areas covered by stone slabs.

Research in the area referred to as the Eastern Sector, on the south side of the causeway of the Niuserre pyramid, allowed to identify a number of structures, of which those with positive values have been interpreted as the remains of tomb architecture built from sun-dried mud-brick (or as clusters of pottery), and negative anomalies as the remains of stone architecture. The connection between the presence of anomalies and mastabas was also confirmed by the results of the electro-resistivity survey, as well as an analysis of the surface relief. Some of the detected structures were also verified by test pits.[14] The research showed that the whole area is covered by mastabas, and their characteristic features and date (late 5th Dynasty) were already indicated by earlier studies of the stone and brick tomb sepulcher of princess Khekerebnebty, and other tombs of significant dignitaries located next to it.

Measurements were also taken in a large area near the Late Period tomb of Udjahorresnet (Fig. 4). Some groups of anomalies were interpreted as the remains of burial architecture. The map showed locations of seven differently sized structures. Archeological excavations of five of those anomalies led to the discovery of the tombs of Iufaa, Menekhibnekau, Padihor, and two tombs marked, respectively, AW 4 and AW 6. The study of the latter, which began

12 Hašek et al. 1988, 20.
13 Hašek et al. 1988, 28–33; Verner 1994, 137.
14 Hašek et al. 1988, 25–28, 36.

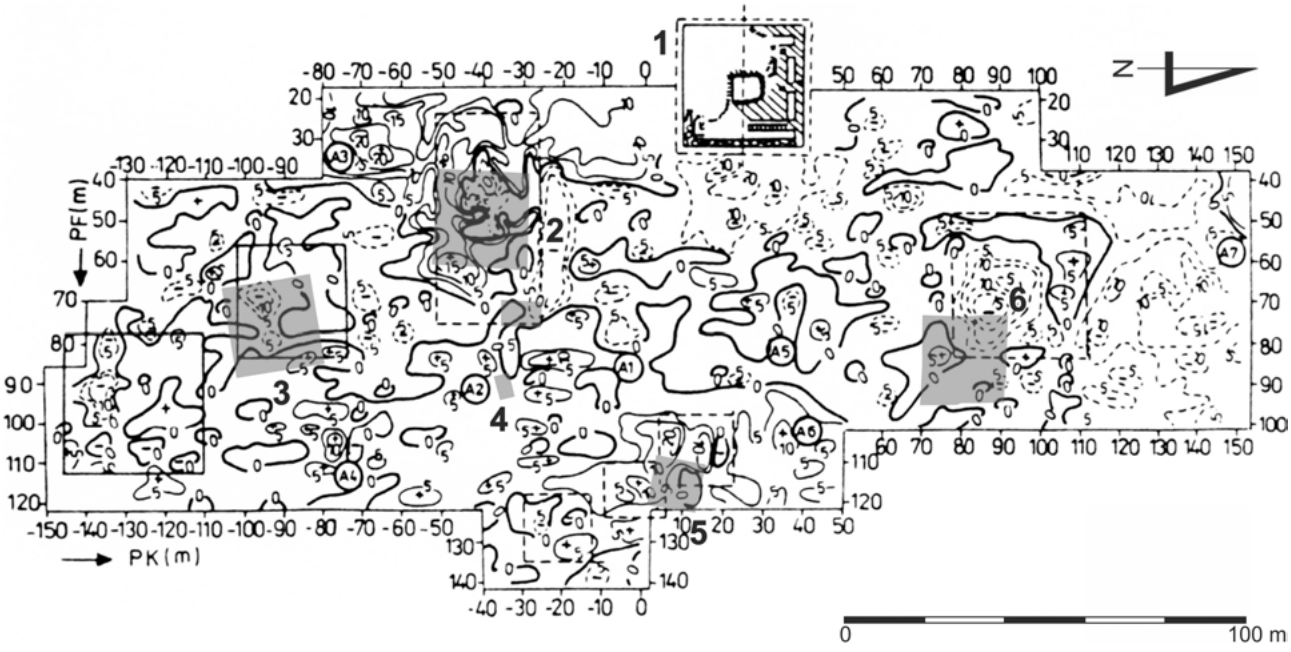

Fig. 4: Abusir. Magnetic map of the area with shaft tombs from the Late Period. Measurements taken with a proton magnetometer. Squares and rectangles in continuous and dashed lines mark positions of tombs discovered thanks to the survey. Grey squares mark the locations of tombs excavated following the findings of the magnetic survey. 1 – Udjahorresnet; 2 – Iuffa; 3 – Menekhibenekau; 4 – Padhor; 5 – AW 4; 6 – AW 6.

in 2016, did not as of yet clarify the identity of the person buried inside it.[15] The opening of the tomb of Iufaa in 1996 was of particular value to the researchers, as it was not robbed in antiquity. Verification tests of the structure described by Lepsius as Pyramid XXVIII showed that there are no remains of buildings at that location.

At the time a completely innovative aspect of the research process was to analyze construction phases of structures by observing their magnetic susceptibility. A temple erected in the pyramid complex of queen Khentkaus was chosen for the study. In order to separate the different phases and alternations of the temple's layout, magnetic susceptibility of mud bricks was measured, and then divided into groups of similar susceptibility values (in the range of 0.67 to 1.3 x10–3SI). The obtained data was consistent with an independently conducted survey by an architect.[16]

The final results of geophysical studies in Abusir[17] are unfortunately omitted in publications on archaeological geophysics. Meanwhile, they are an excellent and innovative example of a comprehensive approach to that topic. The research carried out by the Czechs was preceded by theoretical studies – an analysis of the physical properties of building materials used in antiquity (including a detailed study of what causes magnetic susceptibility in Nile mud bricks), and theoretical work on the modeling of magnetic and electric fields**.** The research assumed close cooperation with archaeologists – to be able to verify the accuracy of obtained geophysical results. From the beginning, researchers decided that the simultaneous use of different geophysical methods to study physical characteristics of the substrate would bring better results, and increased the likelihood of discovering more objects underneath the surface. It also enabled some pioneering observations as to the type of building materials used in structures, and, thanks to the idea of analyzing magnetic susceptibility, allowed to distinguish construction phases.

Magnetic methods were used again in Abusir in 2002 as part of a collaboration between Charles University and the Institute of Archeology of the Academy of Sciences of the Czech Republic. The study was carried out in three areas in the southern part of the site (15.4 ha in total) and in a necropolis dating to the times of the Persian Saite Period, in the south-eastern part of the area studied in 1979 (2.2 ha) (Fig. 2). The research was carried out by Roman

15 Verner 2017, 338–370; Bareš et al. 2018.
16 Verner 1982, 165.
17 Hašek et al. 1988.

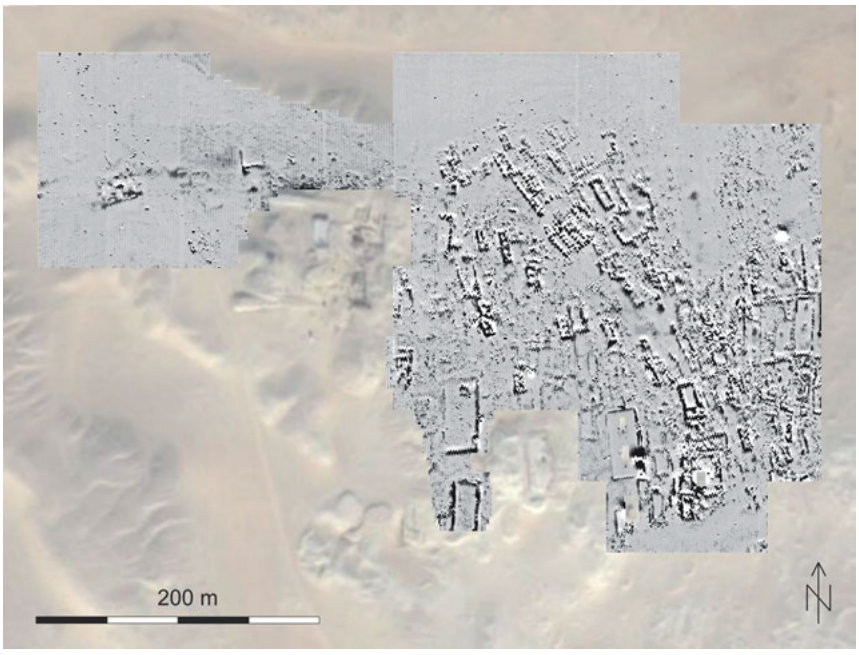

Fig. 5: Abusir South/Saqqara North. Magnetic map/ Google Earth image. Caesium gradiometer, dynamics –5.9/9.9 nT.

Krivanek, who used a caesium magnetometer Scintrex Smartmag SM 4G with two probes positioned to measure the vertical gradient of the magnetic field strength with a resolution of 0.01 nT. The distance between the measurement lines was 1 m, and sporadically, for better resolution of the magnetic images, the profiles were placed every 0.5 m. The aim of the research was to identify structures invisible on the surface, and therefore to indicate prospective archaeological zones. Another reason for locating possible research zones in Abusir South was to create a general archaeological landscape by showing areas with the remains of anthropogenic activities and places without them.[18]

Publications included results of a study of an area adjacent to the already excavated Kar and Inty burial complex and the Kaaper and Hetepi mastabas, dating to the 3rd–6th Dynasty (Fig. 5). The images show several dozen structures built on a rectangular plan, undoubtedly reflecting tomb architecture. The magnetic map provides such an accurate picture of individual structures that they can be classified according to their building plan and size.[19] The map also shows that the orientation of tombs was adjusted to the terrain they were built on: on flat areas – in the highest and lowest parts – they are oriented in the direction of the north-south line. There is a gradual change of orientation of the mastabas located on a slope; their longer sides are parallel to contour lines running NW-SE. Some anomalies have a shape of zig-zag curves – they in fact correspond to structures running along straight lines, but this effect was caused by taking measurements in zig-zag mode, i.e. walking in two directions while taking measurements. This mode, when used in difficult surface conditions such as uneven terrain and slopes, does not allow to maintain an even pace of walking. Magnetic maps of the remaining sectors surveyed in Abusir South have not been published.

A magnetic survey in Abusir was also conducted by Egyptian geophysicists from the National Institute of Astronomy and Geophysics (NIARG) in Helwan. They conducted a survey on the northwest side of the sun temple of Niuserre, on an area of 1.44 ha (Fig. 6). The Geoscan Research fluxgate gradiometer with a resolution of 0.1 nT was used. Measurements were taken every 0.5 m along lines set 0.5 m apart.[20] At the northwest edge of the map, in an approx. 20 m wide strip, the remains of at least 5 square or rectangular structures were registered. The side of the largest structure is 15 m, however the lengths of the sides of structures which have been registered do not exceed 10 m. The characteristic features of the anomalies indicate that the structures have been built from dried mud bricks. The

18 Křivánek/Bárta 2003; Bárta et al. 2003; Křivánek 2009.
19 Křivánek 2009, 24–25.
20 Abdallatif et al. 2005.

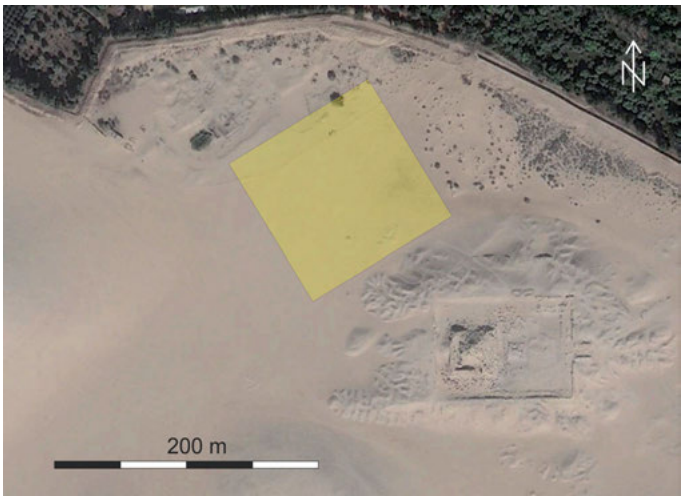

Fig. 6: Abusir North. Approximate location of the magnetic survey near The Sun Temple of Niuserre (Google Earth image).

magnetic map also shows anomalies which suggest the presence of two parallel walls made of mud brick, situated at a distance of about 10 m apart, at least 60 m long. Measurements of magnetic susceptibility of the surface were also taken. Increased values of susceptibility approximately corresponded to the areas where mud structures occurred. The authors did not provide information as to whether the results of their research were later verified by archeological excavation.

4 Saqqara

The same American-Egyptian team which carried out research in Giza also conducted a magnetic survey in Saqqara. The research was carried out in the northern part of the site, in the area of the Late Period Sacred Animal Necropolis. Unfortunately, results came out negative when attempts were made to register chambers and ceramic clusters in the galleries. Measurements were limited to observing changes along single lines. The method was found to be useful only in registering Nile mud-brick structures, confirming the conclusions from the research carried out by Ralph in Malkata.[21]

Further research was carried out in 1987 when the Polish Center of Mediterranean Archeology was granted a concession to conduct research in the area to the west of the Djoser pyramid. This area, in the shape of an elongated depression covered by aeolian sand, in the eastern part adjacent to the enclosure wall of the Djoser complex, had never been explored before, and there were no traces of archaeological structures on its surface. The head of the mission, Karol Myśliwiec, from the Department of Mediterranean Archeology of the Polish Academy of Sciences, already had some experience with non invasive methods at Tell Atrib,[22] and decided that the sites would be selected for preliminary excavation based on the results provided by geophysical research. Although Myśliwiec was aware that this method would not be able to detect stone buildings, he also knew that they were often accompanied by mud-brick structures – and it was the registration of the latter that was the aim of the study. An area of 1 ha was surveyed (Fig. 7). Measurements were taken using two PMP4 proton magnetometers of Polish production with a resolution of 1 gamma (one measurement lasting 6 seconds) in the differential mode, i.e. two instruments simultaneously, one of which was moved along the measurement lines, and the other was at a constant base point for all measurements.

At the time, measurements were recorded manually. The difference values between measurements taken by the traversing probe, and the probe at the base point, were written down on graph paper, on which, proportionally to the value of the anomalies, points were either marked in red (for positive anomalies) or blue (for negative anomalies).

21 Dolphin et al. 1977, 33–35.
22 Myśliwiec/Herbich 1988.

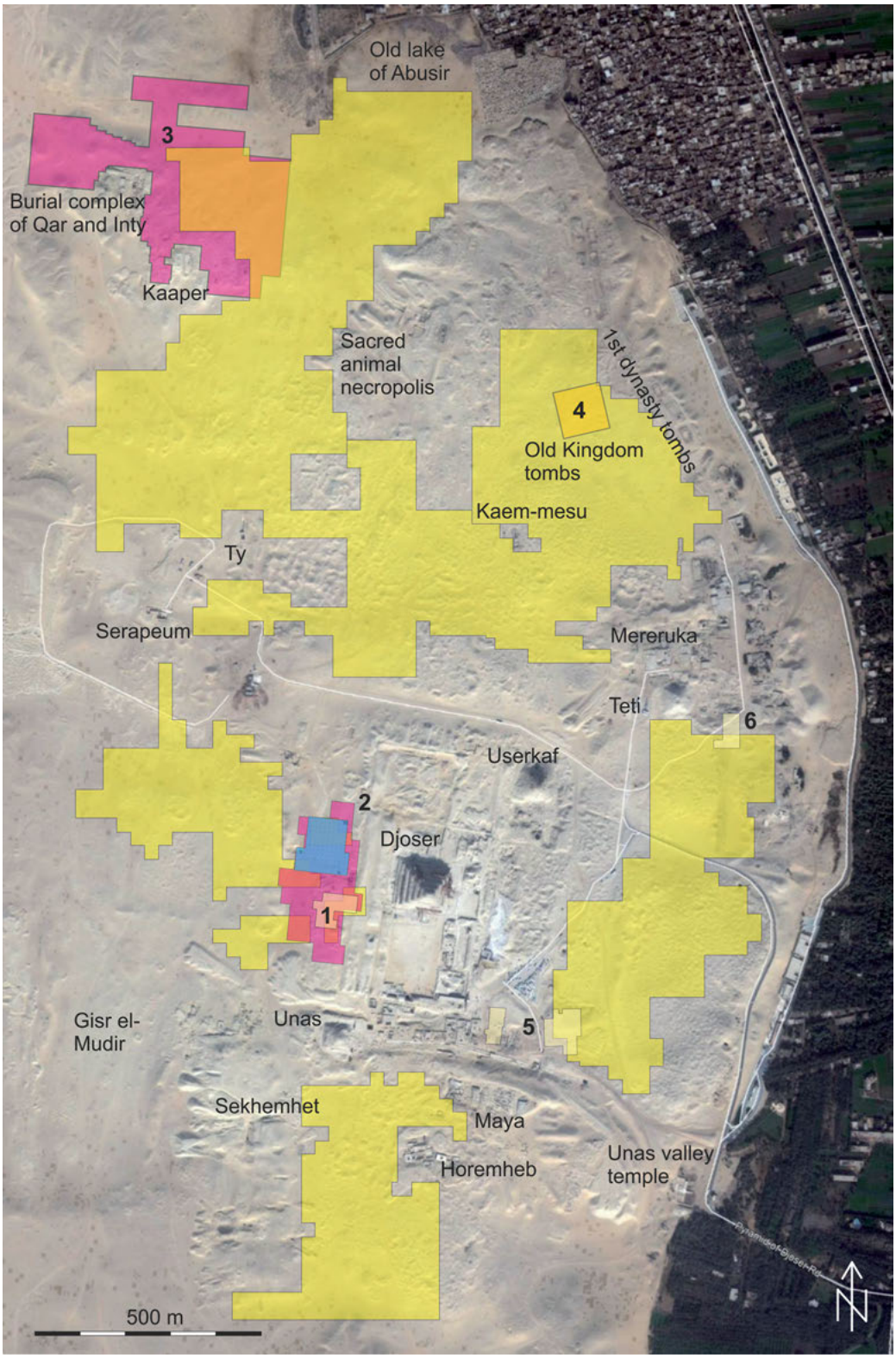

Fig. 7: Saqqara/Abusir South. Location of magnetic surveys on Google Earth image. In blue – survey of PCMA with proton magnetometers (1987); in yellow, marked 1 – survey of the PCMA with a fluxgate gradiometer (FM) (1996); in violet, marked 2 – survey of the PCMA/Bavarian State Dept. for Monuments and Sites with caesium magnetometers (1996); in yellow, not marked with numbers – Saqqara Geophysical Survey Project with the use of FM (2001–2008); in violet, marked 3 – Czech survey in Abusir South with a caesium gradiometer (see Fig. 2); in dark yellow, marked 4 – survey of NIARG with the use of FM; in light yellow, marked 5 – survey of the Louvre Museum mission, with use of FM; In light yellow, marked 6 – survey of Pennsylvania University with the use of FM.

Fig. 8: Saqqara. Helmut Becker with a double sensor caesium magnetometer, 1996.

The map made it possible to register three areas with disturbed values of the magnetic field intensity, and test trenches were made in these locations. During the excavation phase of the research project, a wall of limestone blocks was found at the site which registered as the largest anomaly. The reason of the anomaly's existence was explained almost a decade later, when research was resumed in 1996. The anomaly was caused by a cluster of mud bricks by the wall in the rock threshold of the ground, at the entrance to the burial chamber of the tomb of Merebnebef, a dignitary from the 5th Dynasty.[23]

The area of the Polish concession was also examined by Helmut Becker and Jörg Fassbinder from the Bavarian State Department for Monuments and Sites, who used Scinterx Smartmag SM 4G caesium magnetometers. The measurements were taken in a mode developed by Helmut Becker: simultaneous measurement of the total magnetic field with two probes connected to one console, placed 1 m apart (Fig. 8).[24] This system allowed the two researchers to cover an area of up to 1.5–2 ha per day (with a distance of 0.5 m between the measurement lines). The survey registered two square structures – the nature of the anomalies was typical of mud bricks.[25] The structures turned out to be walls, typical for the Late Period, surrounding a tomb shaft similar to the one uncovered in Abusir.[26] Helmut Becker's system, first used in Egypt in Saqqara, also turned out to be very effective in recreating a plan of a city

23 Herbich 2003, 16–17.
24 Becker 1999.
25 Fassbinder et al. 1999.
26 Verner 2017.

Fig. 9: Saqqara. Ian Mathieson taking measurements in Gisr el-Mudir, 2003.

complex from the New Kingdom in Qantir.[27] The area where the square structures were detected was also examined using the FM36 Geoscan Research fluxgate gradiometer.[28] A comparison of the image taken by the gradiometer and the image taken by the caesium instrument measuring the total field intensity showed that the image made by the former gives a much better picture of the structures.

The most ambitious magnetic research in Saqqara was undertaken by Ian Mathieson. His Saqqara Geophysical Survey Project, initially on behalf of the National Museums of Scotland, then the Glasgow National Museum, began in 1990. Mathieson, who in his earlier work in Egypt focused mainly on the use of the electro-resistivity method,[29] started the project by taking multi-level resistivity measurements along a line running from the remnant lake in Abusir, located north-west of the Sacred Animals Necropolis, across Old Kingom mastaba fields, the Serapeum area, and towards the early Old Kingdom enclosure Gisr el-Mudir. The measurements, useful for identifying the geological structure of the subsoil, also showed the presence of structures in areas that had not been previously explored archaeologically.[30] Next, the team tested various geophysical methods at Gisr el-Mudir, while excavating the site (Fig. 9).[31] At the end of the 1990s, the research extended beyond the area of Gisr el-Mudir. Archeologists focused on using the magnetic method, and at the same time verified some of the detected structures by excavation.[32] A team, led by Jon Dittmer, took measurements using Geoscan Research fluxgate gradiometers. A unified system defining the measurement grid using GPS was used for the entire site. This system was supposed to make it possible to locate structures with an accuracy of up to 5 cm, and to correctly locate the structures discovered in previous decades.[33]

Moving north of Gisr el-Mudir, on the west side of Ptahhotep's tomb, a group of seven structures was registered, which appeared to be foundations of a mud-brick temple complex. Excavations showed a staircase, made of Tura limestone, leading to the entrance of one of the structures. All the entrances pointed towards the main Serapeum temple, and an analysis of the pottery indicated that the structures date to the Late Period and the Ptolemaic Period.[34] On the northern side of the Serapeum, another group of temple foundations was discovered, again with entrances facing the Serapeum ("The North Temples", Fig. 10). Excavations indicated that they date back to the same period as the group discovered earlier. Moving further north, the 2003–4 survey covered the wadi area leading to the rem-

27 Pusch/Becker 2017.
28 Herbich 2003, 32–33.
29 Mathieson 1984.
30 Mathieson/Tavares 1993.
31 Mathieson et al. 1997.
32 Mathieson/Dittmer 2007.
33 Mathieson/Dittmer 2007, 79–80.
34 Lines 2007.

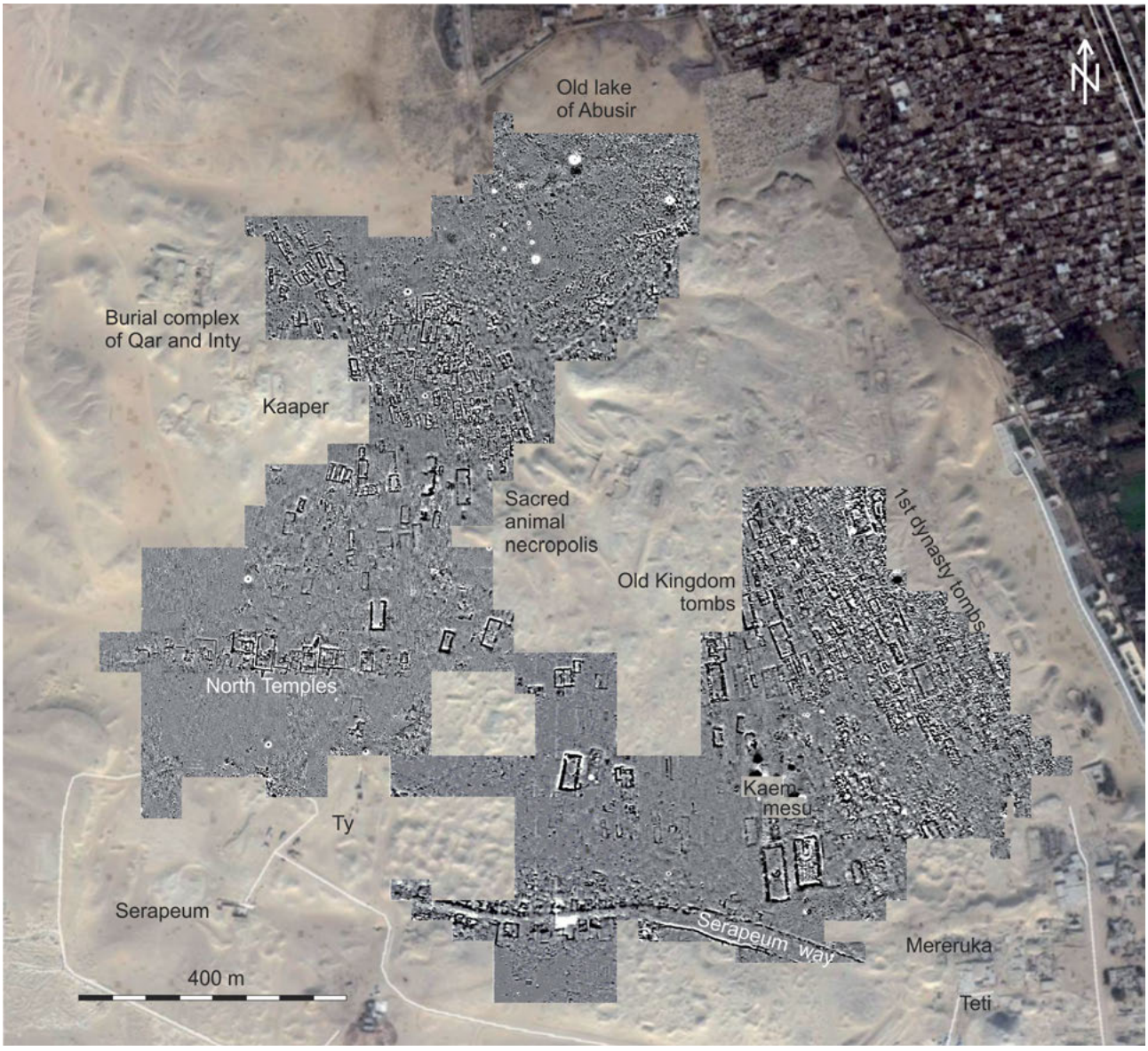

Fig. 10: Saqqara North, Saqqara Geophysical Survey Project. Magnetic map of the northern part of the site.

nant lake of Abusir, partly repeating the 2002 study conducted by the Czech team (Fig. 7: 3). The magnetic map showed a large group of structures in this area, interpreted to comprise tombs, houses, and workshops. The presence of houses and workshops seems logical, as the wadi was a natural communication route leading to the center of the necropolis. The linear layout visible especially on the slopes above the south side of the lake, suggests that the structures were built along streets. The magnetic map image showing a few mastabas was so clear that even individual architectural features of the structures could be distinguished, such as offering niches and cell-like chambers.[35]

In 2005–6, measurements were taken in the area of the Saqqara plateau, limited in the east by tombs of the 1st Dynasty. The results provided exact locations of mastabas which had been unearthed in earlier years, as well as previously unknown structures – doubling the number of tombs known in the area according to Campbell Price, who took part in the research.[36] An analysis of the layout of the necropolis shows that the tombs tended to be built

35 Mathieson/Dittmer 2007, 84.
36 Price 2013, 84.

towards the edge of the escarpment, where they would have been clearly visible from the settlements in the area.[37] In the southern part, the magnetic map showed the largest two mastabas so far discovered in this necropolis. Their shapes are the same as tomb S9801 of the 1st Dynasty and the tomb of Kaem-mesu, which is adjacent to the north of the site (Fig. 10). Further south, research results gave a very precise image of the Serapeum Way, beforehand only roughly known from a map created by August Mariette in the mid-19th century. Test pits on the northern wall of the way exposed a structure of mud wall and mud pavement.[38]

In the final years of the project's field work (2007–2009), areas on the eastern side of the Djoser complex and an area in a New Kingdom necropolis on the southern side of the Unas causeway were examined by researchers, who also returned to the area where they had begun their investigations: Gisr el-Mudir. However, results from the eastern side were not as satisfying as in previous years – they were less readable, hindered by disturbances caused by spoil heaps from many legal (and illegal) excavations, and by metal objects left behind by tourists over the years. Structures detected in the area of a modern car park – excluded from archaeological research – have been linked to structures found within the enclosure wall of the Bubasteion, and are likely the remains of a temple. Its layout associates it with temple platforms from the Late Period discovered at the Serapeum.[39] Next, research in the area of a necropolis from the New Kingdom led to the discovery of several dozen structures in the shape of similarly oriented rectangles in the immediate vicinity of Horemheb's tomb – undoubtedly tomb architecture (Dittmer – personal communication). The aim of the research carried out at Gisr el-Mudir was to establish the presence of a gateway in the eastern wall. However, the results turned out negative – which of course does not mean that the gate does not exist, but that the material used for its construction does not alter the magnetic field intensity, as is for example the case with limestone.[40]

Although the map showing locations where magnetic research was conducted in Saqqara is dominated by SGSP research, it is worth mentioning other projects carried out in the necropolis area. A small part of the SGSP study in northern Saqqara had already been examined earlier by a team from NIARG (Fig. 7: 4).[41] The SGSP research partially overlaps with a survey conducted by the Pennsylvania University archeological team at the Teti pyramid, and by the Louvre Museum on the north side of the Unas causeway (Fig. 7: 5 and 6). The results of the two surveys (both carried out by the author of this paper) have not been published, but in both cases they did not provide any significant information about the presence of unknown structures in those areas. Geophysical surveys were conducted (also by the author) in three locations on the south-eastern side of the Palace of Khaemwaset from the New Kingdom, as part of the Waseda University mission (Fig. 2). Research in the easternmost area led to the discovery of a number of anomalies, which, following excavation, turned out to be rock-carved graves.[42]

5 Dahshur

The first magnetic survey in Dahshur took place in 1999, near the Middle Kingdom pyramid of Senwosret III, as part of the Metropolitan Museum of Art project. The research, led by Dieter Arnold, was carried out by the author of this paper, who used the chance to test the effectiveness of the method in the study of the surroundings of the mud-brick pyramid. However, measurements were carried out on a very small area, as the head of the project was interested in registering structures only in a strip 40 m long and 5 m wide. An area this size could not give the test a chance of success, and therefore no further research was carried out.

Luckily, a different approach to magnetic research was presented by the project of the Free University of Berlin and the German Archaeological Institute in Cairo – the latter having experience in applying the magnetic method in large areas, e.g. in Buto.[43] Helmut Becker, who was invited to conduct the geophysical survey in the years 2003–

37 Price 2015, 423–425.
38 Mathieson/Dittmer 2007.
39 Price 2015, 425–426.
40 Price 2015, 428.
41 Odah et al. 2005.
42 Herbich 2011a; Yoshimura et al. 2013.
43 Hartung et al. 2003.

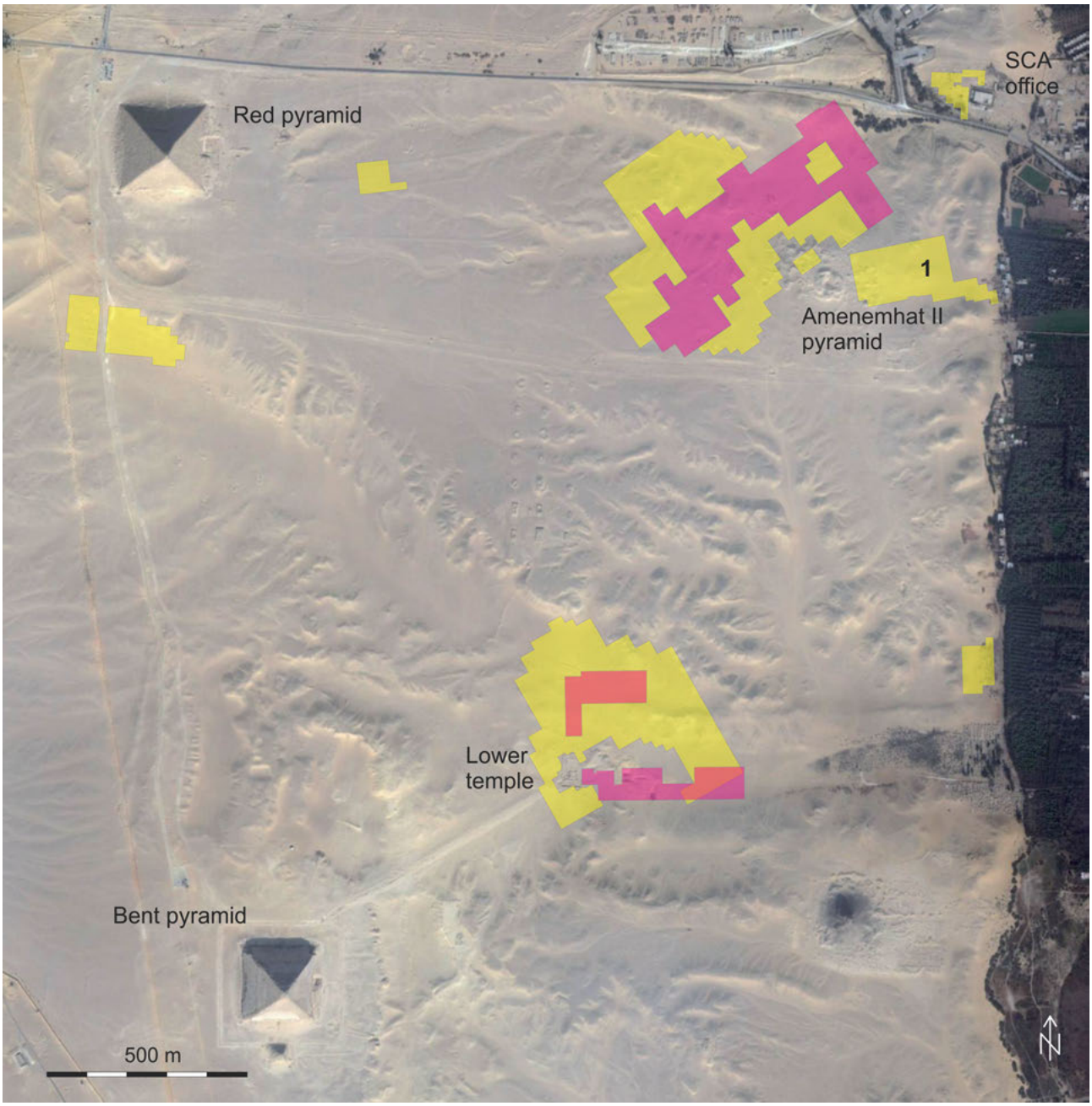

Fig. 11: Dahshur. Location of magnetic surveys on Google Earth image. In yellow – survey with the use of FM (2006; 2012–2019); in violet – survey using caesium magnetometers (CM) (2002–2008); in yellow, marked 1 – survey of NIARG with the use of FM (2008).

2008, used the caesium system which he had applied earlier in Saqqara, as well as the fluxgate gradiometer. The measurements covered two areas: the Old Kingdom cemetery located in the wadi on the eastern side of the Red Pyramid, and the surroundings of the lower temple of the Bent Pyramid – both pyramids built by the same ruler of the 4th Dynasty, pharaoh Snofru (Fig. 11).

Research in the cemetery showed the layout to be densely organized, with large and middle sized family tombs with several (up to 10) square shafts, visible mainly as negative anomalies on the magnetic map, due to their fillings composed of sand of low magnetic susceptibility.[44] The results also showed that the necropolis covers the southern

44 Alexanian et al. 2006, 25–27.

slopes of the wadi, adjoining the site of the Middle Kingdom pyramid complex of Amenemhat II, and indicated the precise locations of mastabas excavated by Jacques de Morgan in 1895. A simultaneous study of the pottery allowed to date the necropolis to the mid 4th–6th Dynasty.[45] In 2007, a previously unknown necropolis was discovered on the eastern side of the pyramid complex. Results showed that the burial ground is organized into two groups of rows of shafts, parallel or perpendicular to the pyramid. Such a plan indicates that the shafts were planned and built in direct relation to the pyramid complex. Excavations confirmed that the shafts date to the Middle Kingdom.[46]

A survey in the area of a cemetery dating to the Old Kingdom was conducted by Becker using the Geoscan Research fluxgate gradiometer. Measurements using this tool gave a much clearer picture of the structures than the image which was provided when observing the total intensity of the magnetic field.[47] However, having a choice between better quality images (obtained by using the gradiometer), and at least 3 times higher measurement speed when using the other method, and assuming that the measurement of the total magnetic field intensity provides a greater in-depth range, Becker decided to carry out further measurements using the two probe caesium system, similar to the one used in his earlier research in Saqqara, but this time he used the Geometrix G-858 instrument.

Research in the area of the lower temple of the Bent Pyramid, on its eastern side, led to the discovery of the lower causeway leading from the temple towards the Nile valley, and a wall, which in the course of further excavations and drillings, turned out to be the southern wall of a U-shaped structure, with dimensions of 145 × 90 m, its short side adjacent to the lower end of the causeway (Fig. 12 B). The structure is thought to be a harbor basin.[48] Measurements on the northern side of the temple, at the bottom of a wide wadi, showed the presence of an area of anomalous values, but their arrangement was too unclear to interpret their function.

Magnetic research in Dahshur, interrupted for several years, was resumed in 2012, by a team led by the author. This time only the Geoscan Research fluxgate gradiometers were used. Research carried out in the immediate vicinity of the lower temple of the Bent Pyramid was supposed to help register mud-brick architecture studied by Felix Arnold, which chronologically preceded the construction of the stone structure (although both were erected during the reign of the same ruler).[49] The measurements detected the remains of mud-brick walls, related to the so-called funeral enclosures built for early dynastic rulers in Abydos (Fig. 12).[50] The research also helped clarify the nature of the anomalous area Becker had been investigating on the north side of the lower temple (Fig. 12 A). Gradiometer measurements provided a clear image of a regular plan of buildings along the streets. Excavations undertaken in this location by Daniela Rosenow led to the discovery of a settlement dating to the early 4th Dynasty.[51] The rich furnishings of the houses suggest that they were occupied by representatives of higher-ranking social classes, perhaps specialists involved in the construction of the pyramids erected for pharaoh Snofru. The nature of oval anomalies visible on the map in many areas, with increased field intensity, about 1–2 m in diameter and arranged in rows, was later explained by excavations conducted in the mud-brick complex which chronologically preceded the stone building of the temple: the anomalies correspond to silt-filled pits dug in the sand, in which trees and shrubs had been planted.[52]

Interesting results were obtained from the study of a complex of structures on the south side of the Red Pyramid, interpreted during earlier excavations as barracks for the workers who built the pyramid.[53] The set of linear anomalies of lower magnetic values made it possible to accurately reconstruct the plans of two stone barracks with elongated rooms, in shape and size similar to the workshop barracks uncovered in Giza (Fig. 13). The almost complete absence of disturbances caused by modern garbage (the area was inaccessible to tourists until the end of the 1990s) made it possible to locate furnaces inside the buildings and at their entrances.[54]

45 Alexanian et al. 2009.
46 Alexanian et al 2012/13a.
47 Becker 2009, 132.
48 Alexanian et al. 2012/13c.
49 Alexanian et al. 2012/13e.
50 Arnold 2018.
51 Rosenow 2019. See also paper by Daniela Rosenow in this volume.
52 Arnold 2018.
53 Alexanian et al. 2012/13d.
54 Alexanian/Herbich 2014/15.

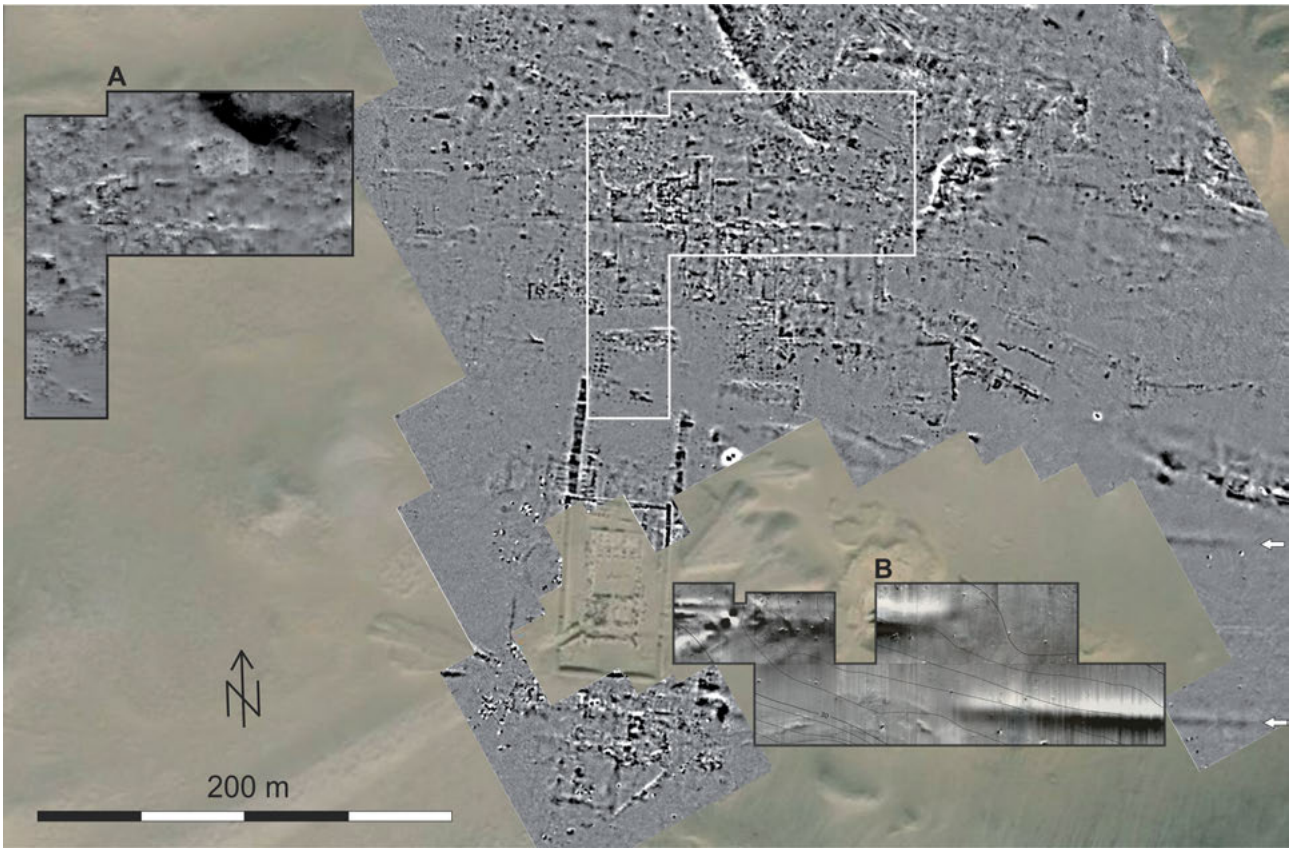

Fig. 12: Dahshur. Magnetic map of the the 4th Dynasty settlement and the harbor area. FM; dynamics −8/+8 nT. White line marks the location of the area surveyed with CM (map created by data from CM shown as box A). B – magnetic map (CM) of lower causeway and harbor area. White arrows marking north and south walls of the harbor basin.

Further geophysical research in the area of the Old Kingdom cemetery in the wadi on the eastern side of the Red Pyramid led to the discovery of other burials, and helped to locate structures excavated by de Morgan on the northern side of the pyramid of Amenemhat II. On the south-western side of the pyramid, results showed (as point anomalies caused by ceramic coffins) the location of a cemetery dating to the Greco-Roman period already examined earlier.[55]

Some interesting observations regarding the depth range of fluxgate gradiometers were made as a result of research carried out in the area of the harbor basin. According to Becker, it was only possible to detect structures underneath a 4 m thick layer of sand thanks to the measurement of the total magnetic field intensity, in the resolution obtained by caesium instruments (personal comm.). As it turned out, fluxgate gradiometers were also able to register walls (Fig. 12). This result was undoubtedly achieved by the fact that the walls were in an environment completely devoid of magnetic properties. The measurements also recorded a wall on the northern side of the basin, which, according to drilling results, is located at the same depth below the surface.[56]

Further studies in the area to the east of the pyramid complex of Amenemhat II were carried out by researchers from NIARG. Results confirmed the location of the eastern enclosure wall of the complex and provided a precise location and the dimensions of the causeway. On the basis of the types of disturbances, researchers attempted to determine the functions of individual areas shown on the map (e.g. workshops).[57]

55 Alexanian et al. 2012/13b.
56 Herbich 2015b.
57 Abdallatif et al. 2010.

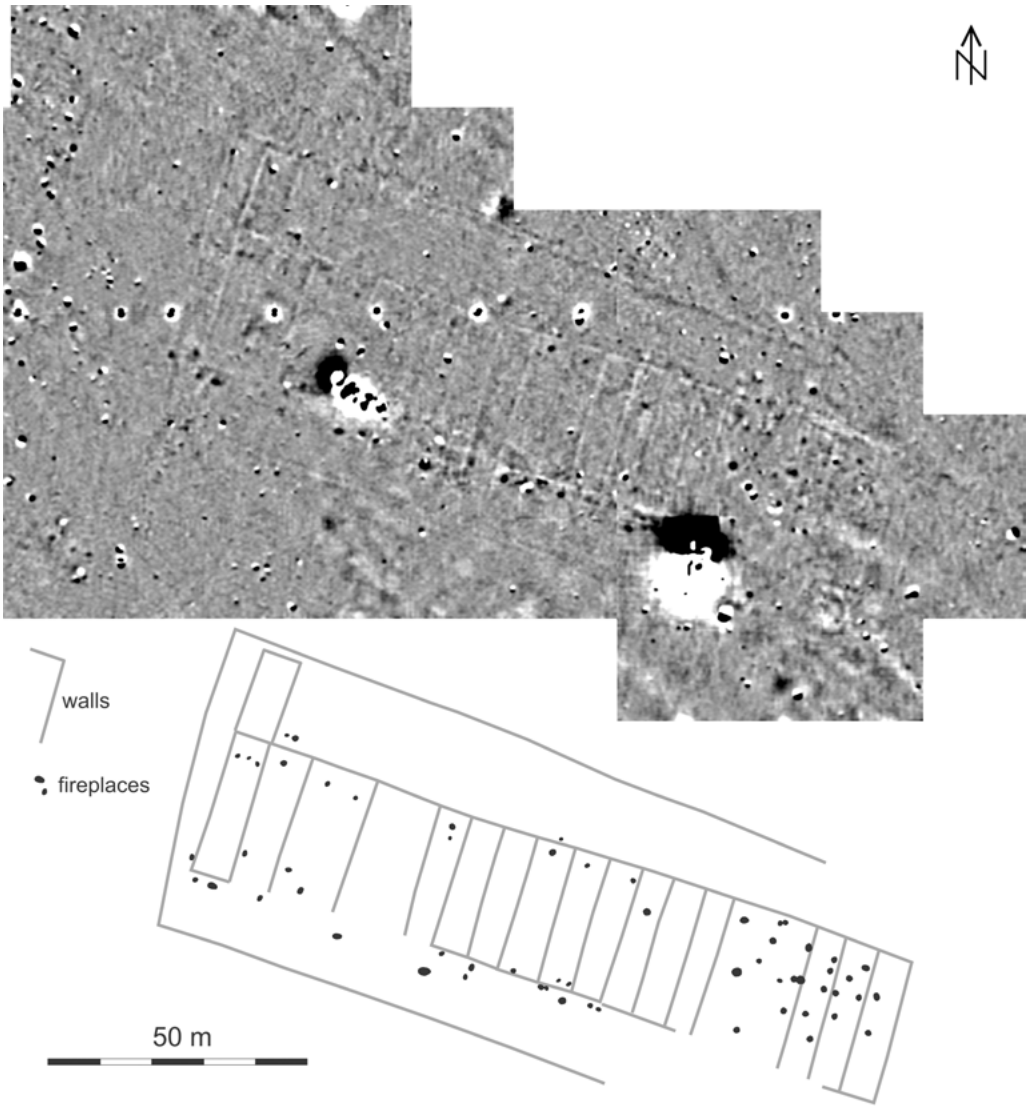

Fig. 13: Dahshur. Eastern complex of the 4th Dynasty workers' barracks located south of the Red Pyramid. Above: magnetic map (FM), dynamics –2/+2 nT. Below – reconstruction of the barracks based on the magnetic map.

6 El-Lahun and Hawara

Magnetic research in El-Lahun, in the Middle Kingdom mortuary complex of Senwosret II, was carried out as part of a project initiated in 2008 by the Museum of Fine Arts in Budapest. One of the main goals of the project was to document previously excavated structures using modern methods and technology – necessary, because of rapidly progressing degradation of structures discovered over a hundred years ago, which had been left uncovered.[58] The survey, conducted by the author, covered an area of the south-western part of the temple-town complex and the valley temple (Fig. 14). Research allowed to establish correct locations of several structures in the southern section of the enclosure wall bordering town on the west side, and registered some unknown features in the temple area. However, the prospection showed above all the unfortunate degree of destruction both of the temple and the town area, and left no illusion as to the preservation of any substantial architectural remains in the town.[59]

58 Horváth 2009.
59 Herbich 2011b.

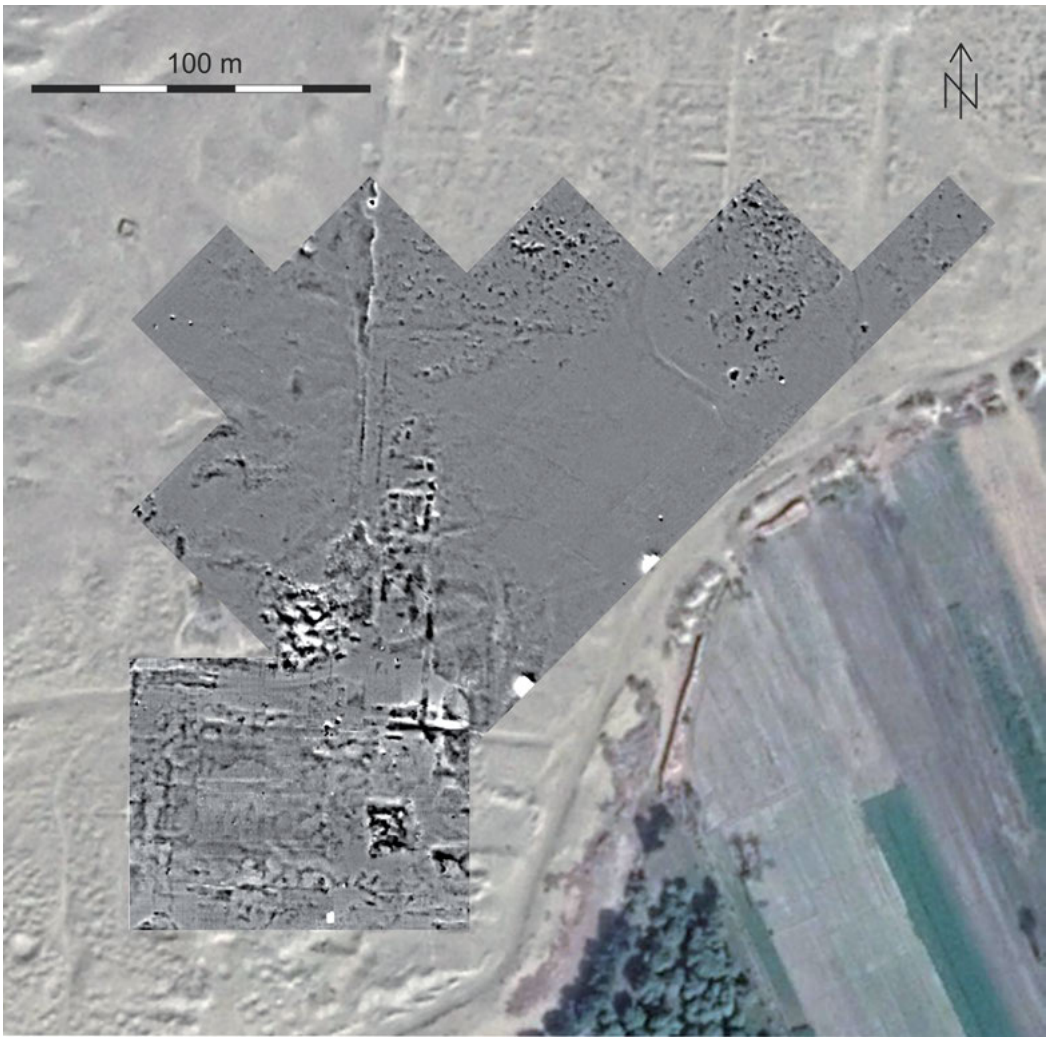

Fig. 14: El-Lahun. Magnetic map (FM) on Google Earth image. Dynamic –6/+6 nT.

The research in the vicinity of the Middle Kingdom pyramid complex of Amenemhat III in Hawara was carried out by the NIARG team. Measurements, taken with a Geoscan Research fluxgate gradiometer, covered an area of 1.2 ha, 300 m east of the pyramid,[60] in a location which had never been excavated before. The results showed a series of irregularly shaped disturbances. They may correspond to unrecognized mud structures destroyed during illegal excavations, or – what is more likely – the disturbances were caused by these illegal excavations, as can be assumed by comparing the result with satellite images.

7 Conclusions

The research presented in this article clearly proves that the magnetic method is highly efficient in registering burial architecture, invisible on the surface. The high clarity of magnetic images of mud-brick structures is the result of their geological context, which is responsible for a contrast between the high magnetic values of structures and low values of the desert surrounding, composed of rocks of very low magnetic susceptibility.[61]

60 Abdallatif et al. 2019.
61 Herbich 2019.

Even a quick glance at a juxtaposition of maps of the sites covered by magnetic measurements, allows to observe that the most researched site is Saqqara. The prospection carried out there covered more than 130 ha, which makes it the third largest site in Egypt, in terms of researched area, after Qantir and Tell el-Dabᶜa.[62] A comparison of results of surveys carried out using different instruments shows that measurements of the vertical gradient of the magnetic field give much better results than measurements of the total field intensity. The most striking example of this is the comparison of the results obtained from a settlement area near the lower temple at Dahshur (Fig. 12). Research has also shown that, in these particular conditions of the desert, the depth range of fluxgate gradiometers is much greater than expected. Additionally, results indicate that the distance between profile lines should not be greater than 50 cm. Such a distance (when measurements are taken at least 0.25 m apart on the profile line) guarantees high resolution magnetic images.

Of the three geophysical methods commonly used in archeology: magnetic, resistivity and georadar, the former – owing to the speed of taking measurements, and the lack of contact between the instrument and the surface during the survey – is the easiest method to use (the resistivity method requires inserting electrodes into the ground, the radar method – moving the antenna over the surface). However, recent experience from research conducted in Sudan shows that the radar method could also be very useful when searching for mud architecture in a sandy environment.[63] The advantage of the radar method over the magnetic one is the fact that it can quite accurately indicate the depth at which the structure is located, and register structures with low magnetization, unreadable for the magnetic method (e.g. limestone walls).

It was mentioned in the introduction that the research conducted by the American-Egyptian team in Giza and Saqqara is the one with the earliest publication regarding magnetic measurements taken in this area. Doubts about the accuracy of this belief have arisen on account of the contents of Elizabeth Ralph's archive, kept at the Penn Museum, University of Pennsylvania. There is a folder under the date 1966 in the register of contents (thus far earlier than the date of the described research in Giza and Saqqara), titled "Egypt-Memphis – magnetometer" – according to the name of the site and the method used, similarly to other files containing research documentation from field work led by Ralph. The documents only testify to Ralphs's theoretical interest in the model of changes in the magnetic field intensity above mud-brick structures – tomb shafts surrounded by mud-brick walls, known from necropolises adjacent to Memphis. This folder, however, contains documents that may indicate that magnetic research was carried out in the area of the pyramids already in 1966 by Fondazione Lerici from Rome. A confirmation of this theory, however, requires a perusal of the Foundation's archive, which was impossible at the time of writing this article.

Magnetic research near the pyramids by registering hundreds of previously unknown structures below the surface has given the basis to reconstruct the landscape of the pyramids area, to the extent which would normally require many decades of work if classic excavation methods were used. As a participant of this research, I must admit that this can be a source of great satisfaction. An expression of this satisfaction one can sometimes found in publications:

> The survey of the Serapeum Way proved to be one of those wonderful moments in subsurface exploration where a long lost description of an archaeological feature suddenly comes to light in glorious detail on the computer screen.[64]

The author only hopes that the satisfaction felt by geophysicists working in archaeological teams is shared by the heads of those teams, and above all – by Professor Seidlmayer.

Acknowledgements

In order to write an article that requires extensive library search, while libraries are closed due to the pandemic, the author had to obtain various information directly from people involved in the research described in this paper. I would like to sincerely thank Ladislav Bareš, Zoltan Horvath, Nozomu Kawai, Campbell Price, Colin Reader, Daniela Rosenow and Ana Tavares for their help. To obtain the necessary literature, I was helped by Bruce Bevan and Kamil

62 Pusch/Becker 2017; Forstner-Müller et al. 2011.

63 Herbich/Ryndziewicz 2019; Obłuski et al. 2021.

64 Mathieson/Dittmer 2007, 243.

Kuraszkiewicz. Roman Krivanek and Jon Dittmer gave consent to use graphic results of their research. Vladimir Hasek's photo was made available by the Institute of Egyptology, Charles University in Prague. I am also very grateful to Alessandro Pezzati and Evan Peugh from the Penn Museum Archives, University of Pennsylvania, for the opportunity to become acquainted with documents from the archives of Elizabeth Ralph.

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Figure 12: Dahshur. Magnetic map of the the 4th Dynasty settlement and the harbor area. FM; dynamics –8/+8 nT. White line marks the location of the area surveyed with CM (map created by data from CM shown as box A). B – magnetic map (CM) of lower causeway and harbor area. White arrows marking north and south walls of the harbor basin.
CM maps courtesy of DAI. Map: Tomasz Herbich. Satellite image by Google Earth.

Figure 13: Dahshur. Eastern complex of the 4th Dynasty workers' barracks located south of the Red Pyramid. Above: magnetic map (FM), dynamics –2/+2 nT. Below – reconstruction of the barracks based on the magnetic map.
Map and drawing: Tomasz Herbich.

Figure 14: El-Lahun. Magnetic map (FM) on Google Earth image. Dynamic –6/+6 nT.
Map: Tomasz Herbich. Satellite image by Google Earth.