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Magnetic prospecting in archaeological research: a historical outline[1]

Tomasz Herbich[a]

The article presents an overview of the history of the magnetic method in archaeological research, from its first use in 1958 in England through the 1990s. Brief presentations of the history of research using this method have already appeared in general works dedicated to archaeological geophysics, but merely as introductory chapters, which have focused on initial stages of the application of particular methods (chiefly magnetic and electrical resistivity) and highlighted achievements in the field in Western Europe, primarily the UK. In the present text, the author has also included the history of the use of the magnetic method in other parts of Europe (Central and Eastern Europe) and on other continents. He analyzes technological changes in the instruments used for research, from the proton magnetometer and magnetic balance to the increasingly advanced fluxgate and optically pumped magnetometers. He also examines the changes in measurement technology and data processing that have occurred and the factors shaping the development of the method.

KEY-WORDS: history of archaeological geophysics, magnetic method, magnetic balance, proton magnetometer, fluxgate magnetometer, optically pumped magnetometer

1. INTRODUCTORY REMARKS

Outlining a history of early archaeological geophysics is burdened by a lack of sources, the few existing studies being limited to the applications of the method in Great Britain (e.g. Aitken 1986; Clark 1990: 11-27) and Poland (Misiewicz 2002; Herbich 2011). Short reports have been published on the history of archaeological geophysics in Austria (Doneus *et al.* 2001: 15-17) and the Czech Republic (Hašek 1999: 1-2). Early issues of *Archaeometry* contained brief references to the first applications of the magnetic method to archaeological research in France, Germany and Italy, the United States of America and Poland (e.g. Hesse 1962; Scollar 1961b; Lerici 1961; Johnston 1961; Dąbrowski 1963). Mentions of historical

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[1] The article covers the history of archaeological applications of the magnetic method until the end of the 1990s, because it was prepared in 2011-12 for publication in a volume dedicated to the history of archaeology in the 20th century. The volume has not been published yet, hence the author has chosen to present it in this volume devoted to non-invasive methods of archaeological prospection, without making any significant changes in the text. The author believes this will ensure better circulation of the publication among researchers interested in archaeological geophysics.

[a] Institute of Archaeology and Ethnology, Polish Academy of Sciences, Warsaw, Poland

importance can also be found in general studies, like Tony Clark's "Seeing beneath the Soil", and the collective publication edited by Irwin Scollar (Scollar *et al.* 1990: 513-515) as well as that of Chris Gaffney and John Gater (2003: 13-24), which are concentrated however on activities in Great Britain much less attention paying to research of this kind in other countries.

To give an historical overview of the application of the magnetic method in archaeological research one thus has to peruse the early publications, a task made more arduous by the frequently limited distribution of local publications (and the language barrier in some cases!). The present author has taken up the challenge, knowing full well that he has surely missed a number of publications which would have benefited this presentation by contributing important, but not widely known facts. Recent archival studies by Albert Hesse and Bruce Bevan exemplify this best. Looking through old documents and publications, Hesse found that the first archaeologist to take note of the potential of geophysics in archaeological prospection, the magnetic method included, was the Frenchman Robert du Mesnil du Buisson (Fig. 1). This scholar, famous foremost for his discoveries in Syria, also wrote a textbook on excavation methods (1934), in which he listed, almost prophetically it would seem, the kinds of objects that could be located with the aid of geophysical methods, successively gravimetric, magnetic, electrical and seismic, while making the reservation that


Fig. 1. Robert du Mesnil du Buisson. Courtesy Charles Henri Burgelin

> "it is too early to say how these methods will provide help for archaeology"
> (du Mesnil du Buisson 1934: 105; translation: Hesse 2000: 46).

Hesse believes that du Mesnil du Buisson owed his understanding of geophysics as a supplementary method in geological studies to his close neighbour, Conrad Schlumberger, creator of the geoelectrical method (their family estates in Normandy were only 43 km apart, see Tabbagh 2015: 132-136 and Hulin *et al.* 2015: 141-143), and to articles on geophysical methods which he cited in his textbook. However, since none of these articles or Schlumberger's works ever referred to archaeology, du Mesnil du Buisson must have come up with the idea of applying geophysical prospection methods in archaeology all by himself (Hesse 2000: 46-48).

In turn, Bruce Bevan ascertained that the first practical application of the geophysical method (electrical resistivity) in archaeological research had taken place in the United States in 1938 (Bevan 2000). Prior to Bevan's findings, it was the Englishman Richard Atkinson who was believed to have used the method for the first time in research carried out at Dorchester in 1946 (e.g. Aitken 1961a: 3; Clark 1990: 11-14). The first application of the magnetic method occurred much later, in 1957 or 1958 (depending on the position of the author, see below). The present article focuses on research until the early 1990s. Covering the intense development of geophysics after the beginning of the 1990s would have blown this article way out of size. There is also obvious bias in the presentation as much attention is devoted to the pioneering investigations in Great Britain and to the less well known developments in Poland and Czechoslovakia.

2. THE FIRST APPLICATION OF THE MAGNETIC METHOD: MAGNETIC BALANCE AND PROTON MAGNETOMETER

Archaeologists first took note of the magnetic method as a means of dating a certain category of finds. From the end of the 19th century iron oxides in the clay were known to take on a new permanent orientation as the clay cooled down, the direction corresponding to that of the Earth's magnetic field (Folgheraiter 1896, as quoted by Scollar *et al.* 1990: 513). This phenomenon, called thermoremanent magnetization, proved extremely useful in dating pottery kilns, a common feature at many archaeological sites, but until the late 1950s it was not applied as an archaeological prospection method for the non-invasive registering of archaeological features invisible on the surface.[2]

2.1. Magnetic prospection in Great Britain

The beginnings of the application of the magnetic method as a way of recording features invisible at the ground surface have been noted diligently in the topic literature. Interestingly, there are two versions depending on which project is considered as being first. The more common version is based on Martin Aitken's (Fig. 2) information published in 1958 in a number of places (Aitken 1958a; 1958b; Aitken *et al.* 1958) and repeated by him almost twenty years later (Aitken 1986). This version has been adopted in a number of textbooks on archaeological geophysics (e.g. Clark 1990: 16-17; Gaffney and Gater 2003: 16-17). According to it, on 13 February 1957 the Canadian physicist John Belshé (Fig. 3) gave a lecture at the London Society of Antiquaries about pioneering research carried out in Cambridge on dating with the magnetic method. In the discussion that followed the engineer and archaeologist Graham Webster asked about the potential for a magnetometer to locate features of baked clay, like kilns, for example. Belshé had no reservations about

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[2] Du Mesnil du Buisson had already noted in the late 1940s the disturbing effect of archaeological features made of fired clay while testing his metal detectors in the field (Laming 1952: 72)

Fig. 2. Martin Aitken (left) and Helmut Becker during the “Pioneering Archaeological Prospection” conference organized by the Ludwig Boltzmann Institute for Archaeological Prospection and Virtual Archaeology, Laa an der Thaya (Austria), October 2011. Photo T. Herbich

Fig. 3. Michael Tite, Janine Hesse, Albert Hesse and John Belshé (from left to right) during the “Pioneering Archaeological Prospection” conference organized by the Ludwig Boltzmann Institute for Archaeological Prospection and Virtual Archaeology, Laa an der Thaya (Austria), October 2011. Photo T.Herbich

the efficiency of the method for such applications, especially as he had observed in his own work a meaningful disturbance of the magnetic field caused by features of this kind (Belshé 1956). Webster’s question had a practical dimension: as an archaeologist he was investigating ground under an extension of the A1 trunk road next to the Roman site of Durobrivae at Water Newton near Peterborough in Northamptonshire. Surface finds indicated the presence of furnaces in this region. Webster approached the geology faculty of Birmingham University and Martin Aitken from the freshly established Research Laboratory for Archaeology and the History of Art at Oxford University. Aitken and his lab director Edward Hall jumped at the opportunity for a quick verification of magnetic prospection results (roadworks were set to begin in eight weeks) and began constructing a proton magnetometer, the principles of which had been developed just a few years earlier

(Packard and Varian 1954) and which had just been adapted for fieldwork (Waters and Francis 1958). The first measurements were taken in the field in March 1958. The instrument constructed in Oxford had 1 γ sensitivity and a measurement time of 5 sec. Plans for concurrent measurements with a conventional Askania torsion balance, to be carried out by Tony Rees from Birmingham University, were dropped owing to the time needed for each measurement – about five minutes. Five hectares were surveyed in the course of 10 days, but with little success beyond finding a water-pipe and modern iron objects. Then an anomaly strong enough to correspond to a furnace was discovered in an area adjoining a fragment of a furnace uncovered by the roadbuilders, supporting expectations of more structures of the kind being found in the neighbourhood. In the centre the value of the anomaly reached 100 γ; the area with values exceeding 50 γ was 2.5 m in diameter and disturbances falling in the range 25-50 γ were recorded in a radius of 4 m from the centre of the anomaly. A test pit was excavated immediately, uncovering a section of the top of a furnace at a depth of 1 m (Aitken 1958b: 24-25; 1986; Aitken *et al.* 1958).

Irwin Scollar (Scollar *et al.* 1990: 513-514) was of a different opinion, granting precedence to J. Belshé, whose contact with archaeology occurred not only during the research on dating, but also when observing changes (with a fluxgate magnetometer) of magnetic susceptibility on an experimental forge built in 1957 by chemists and archaeologists from the British Museum. Reporting his interview with Belshé, Scollar wrote:

> "… in September 1957, using a grid of 1.5 m, a series of measurements were made with the Askania instrument in the neighbourhood of Kirkstall Abbey near Leeds and three anomalies were detected which were thought to come from a forge. This can properly be thought of as the first application of magnetic prospecting in archaeology"
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> (Scollar *et al.* 1990: 514).

Scollar's opinion, different from Aitken's, was echoed in the textbook of Aspinall, Gaffney and Schmidt (2008: 46), who presented Belshé's research as the first in the field of magnetic prospection, but considered the contribution of Aitken and his Research Laboratory for Archaeology and History of Art at Oxford University as a turning point.

The survey at Water Newton, besides discovering a furnace, produced results of much further-reaching consequence by demonstrating not only that the baked clay, but also the soil inside pits and ditches could impact on magnetic field intensity changes (Aitken *et al.* 1958; Aitken 1958b). Soil magnetic properties are not as strong as those of baked clay, but with the use of appropriately sensitive instruments it is possible to distinguish archaeological features containing such soils. The increased magnetization of topsoil had been observed already by E. Le Borgne (1955), but it was Aitken's idea to apply this knowledge practically in archaeology. The results of research at Water Newton also constituted persuasive proof of the magnetic method's effectiveness in recording features concealed under the surface. Archaeological structures were not found anywhere in the 20 test pits excavated in different places under the planned road; in one case the anomaly was caused by geological features, in another by a horseshoe. The survey also supplied interesting data on the limitations of the method. Ferrous objects not visible on the surface, in quantities exceeding the researchers' expectations, were found to cause considerable magnetic disturbances (mine detectors were used to eliminate them), as did ferrous elements of fences and the uneven ground surface at the site (Aitken 1958b: 25).

Martin Aitken's work proved to be of prime importance for the application of the magnetic method in archaeological research. In the 12 months following the work at Water Newton, Aitken carried out measurements at 10 sites, six from the Roman Period, two from the Iron Age and one each from the Bronze Age and early Middle Ages (Aitken 1959a). The results demonstrated the range of features detectable with the magnetic method. At an Early Iron Age fortified settlement at Madmarstone (1st century BC - 1st century AD), the smallest of the four mapped pits was 0.7 m in diameter and 0.4 m deep (Aitken 1959a: 32). The larger pits were up to 1.5 m deep. They were filled with potsherds, hut remnants and organic remains (Fowler 1959: 38). At a Roman site at Cox Green a ditch, first noticed in aerial photos, was traced and tested, revealing a width of 2.5 m and a depth of up to 0.7 m; the excavation also showed that the ditch was covered with a 0.25 m thick layer of ploughed soil (Aitken 1959a: 33), which also filled the ditch. The other ditch observed in the aerial photo failed to be mapped by the magnetic method; it turned out that the fill in this case did not differ substantially from the ground in which the ditch had been dug. At Little Houghton, also a Roman site, it was noted that a big contrast between the fill and surrounding matrix permitted even small features, like a ditch 0.45 m wide and 0.35 m deep, to be discerned (Aitken 1959a: 33). The method proved useless at only one site where there was a dense forest and numerous ferrous objects in the ground that were invisible on the surface. Further investigations at Water Newton were carried out on an approximately 3 m grid (the assumption being that no place on the site would be more than 1.5 m away from a measurement point). Six areas of anomalous values, from 6 m to 12 m in diameter, were distinguished in effect. These areas were surveyed in a denser grid in order to determine with precision to 0.6 m the location of maximum values of anomalies and to trace their shape. The last stage in the process of interpretation was to establish the nature of the anomalies and to select spots for testing by archaeological means. All the anomalies reflected archaeological features, but not necessarily of the kind that was expected in each given place. And so anomalies interpreted as furnaces turned out to be pits and what was believed to be a pit tested as part of a ditch. Even so, three furnaces of Roman date were discovered, as well as remains of a forge, a pit filled with slag and the edge of a paved area (Aitken 1959a: 34-35).

Aitken's results to date were published in *Archaeometry*, a periodical of the Research Laboratory for Archaeology and the History of Art in Oxford established in 1958. This had an immediate impact on popularizing the method, as did publication in professional periodicals with a large readership, like *Antiquity* (Aitken 1959b), and popular ones, like the *Illustrated London News* (Aitken 1958a). The latter article reached Poland, giving rise to a description of the magnetic method by Zbigniew Bukowski (1960). Aitken's publication, in 1961, of the general principles of geophysical methods in archaeology, including the magnetic one, summing up the results of the first practical applications of the method in the field, also received a wide response (Aitken 1961a; Polish review: Dąbrowski 1964).

Interest in the magnetic method among archaeologists can be expressed by the number of sites on which measurements were carried out: by 1961 the Research Laboratory had surveyed 50 sites, gathering experience which led to conclusions of a general character regarding the efficiency of the method in investigating particular types of sites in different geological conditions (Aitken 1961b). Considering the time required to take measurements, and the laborious data processing procedures of the time (manual plotting of isolines), Aitken believed the method to be more effective in indicating the general location of specific features than in mapping archaeological sites in detail (Aitken 1961b: 84).

The availability of proton instruments and their low price and simple construction were also conducive to the spread of the method in archaeological applications. Of the two commercial versions of the instrument developed by Littlemore Scientific Engineering Company (in Littlemore near Oxford) in cooperation with the Research Laboratory for Archaeology and the History of Art in Oxford, the one called Maxbleep proved to be more popular; a prototype was ready in 1960 (Aitken 1960). The instrument was furnished with two sensors configured vertically as in a gradiometer, spaced 1 m apart, the lower one running approximately 25 cm above the ground surface. The measurement reading was transmitted as sounds of an appropriate number depending on the extent of the disturbance: twice for anomalies with values of 8 γ and three, four, five and six times respectively for 17, 25, 33 and 42 γ. The cable between the sensors and the electronics of the instrument was sufficiently long to avoid disturbance from the metal parts of the apparatus (Clark 1990: 19). It was also constructed to compensate for the effect of diurnal changes of magnetic field intensity and local disturbances caused, for example, by passing train. The instrument was tested on three sites in Britain: a Roman industrial site at Hartshill and two fortified settlements of the Iron Age at Croft Ambrey and Burrough (Aitken 1960: 40). Hartshill produced 24 anomalies, of which half were tested archaeologically. Nine anomalies turned out to correspond to furnaces. At Burrough anomalies in the range from 20 to 100 γ corresponded to storage pits. In his conclusions based on field experience of the application of the magnetic method on archaeological sites, Aitken spoke out in favor of using the gradiometer for quick mapping of disturbances over large areas, followed by detailed survey with a magnetometer measuring the total value of magnetic field intensity (Aitken 1960: 40).

2.2 MAGNETIC PROSPECTION IN OTHER WESTERN EUROPEAN COUNTRIES: ITALY, GERMANY AND FRANCE

Within a few years of Aitken's first application of the magnetic method it had become a point of interest in centres which had already tested electrical resistivity as a method for prospection. These were the Fondazione Lerici in Milan, Rheinisches Landesmuseum in Bonn and the Centre de Recherches Géophysiques CNRS at Garchy (initially: Centre d'Etudes Géophysiques).

The Foundation, which was established in 1947 by Carlo Maurilio Lerici (Fig. 4) at the Milan University of Technology, set itself the objective of using geophysical methods in search of mineral resources. In 1955 the Foundation ventured into the field of archaeology, gaining international renown thanks to spectacular results on Etrusacn tombs using the electrical resistivity method (Lerici 1958). In 1961 Lerici and a team from the Applied Sciences Centre for Archaeology (MASCA) of the Museum of the University of Pennsylvania conducted a two-month long survey of four sites in Italy: three Etruscan ones (necropolises in Tarquinia and Cerveteri, and a town in Veii) and the Greek colony of Sybaris. The survey aimed at comparing the effectiveness of the electrical resistivity method as used by Italians with the magnetic method which had not been used before in Italy (Lerici 1961; 1962). Measurements were taken with an Elsec proton magnetometer produced by Littlemore Scientific Engineering. Italian researchers were astounded by the effectiveness of the magnetic method: out of 11 anomalies recorded during the prospection in a test area 25 m by 50 m in the cemetery at Tarquinia, only one did not correspond to a rockcut burial chamber; the same area tested by the electrical resistivity method revealed only seven anomalies which could have corresponded to graves (Lerici 1961: 79). The magnetic method also proved useful in locating burial chambers cut in tuff at the necropolis in Cerveteri (Lerici 1961: 80-82). At Sybaris measurements confirmed the existence of a wall several hundred meters long under a layer of alluvium at least 2 m thick, recorded previously by the electrical resistivity method. The blocks of the wall were cut from limestone which in itself has no magnetic properties, but the surrounding accumulations contained soil with a large content of volcanic material of high magnetic suscep-

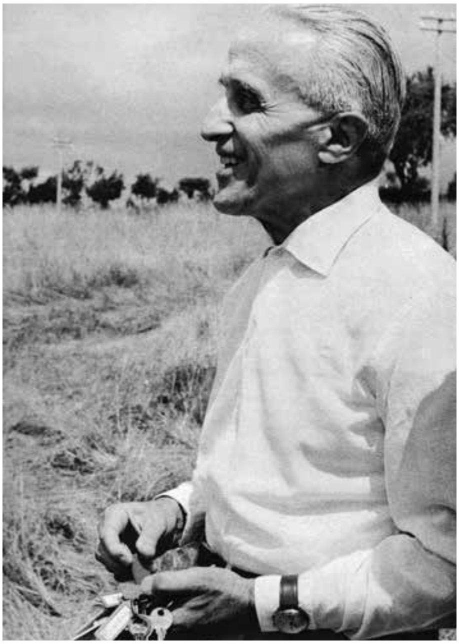
Fig. 4. Carlo Maurilio Lerici. After Lerici (1965)

tibility; consequently, the wall was registered as a reverse anomaly compared to the surroundings (Lerici 1962: 6). The Sezione Prospezioni Archeologiche (archaeological prospecting unit) established by the Foundation in Rome was charged with carrying out research on archaeological sites. In 1961, following joint research with an American team, the unit was furnished with proton magnetometers developed in Oxford. Richard Linington, who came to Italy as a member of the Pennsylvania University team, became a key person at the Foundation, fostering widespread use of the method (Fig. 5). The Foundation not only conducted the field surveys, but also participated actively in popularizing geophysics in this new role. From 1963 it organized annual archaeological prospection methodology courses (including geophysics) and in 1966 it established the journal *Prospezioni Archeologiche*, dedicated in equal measure to presenting fieldwork results and theoretical aspects of research like modeling, data processing and visualization of results. The first volume represented the proceedings of a conference organized by the Foundation in Rome in 1965. Magnetic method-related subjects were taken up by R.E. Linington (1966a), I. Scollar (1966), J. Alldred and M. Aitken (1966a; 1966b), L. Langan (1966). There were three archaeologists among the 14 participants at this conference, most of them natural scientists; one of them was the Polish archaeologist Krzysztof Dąbrowski (more about him in the next section). The missionary character of its programme led the Foundation to conduct geophysical prospection in countries where archaeological interest was strong but the financial support for such methods was not as forthcoming as in Great Britain or Italy. Linington did magnetic research in Poland (Dąbrowski and Linington 1967) and in Czechoslovakia (Linington 1969b), in close cooperation with local archaeologists whose task was to choose as broad a spectrum of sites as possible in order to test the effectiveness of the method on different archaeological features from different periods.

Fig. 5. Richard E. Linington with an Elsec proton magnetometer. After Lerici (1965)

The unit in Bonn, directed by Irwin Scollar, used proton magnetometers of their own design, LMB Mark, featuring a resolution constituting 1/50000 part of magnetic field intensity, which in northern Europe gives a resolution close to 1 γ (Scollar 1961a; 1963) (Fig. 6). Measurements were taken in the differential mode, that is, the

Fig. 6. Irwin Scollar taking test measurements in a park in Bonn with the first ever digital differential proton magnetometer, which he and his technician, Merken, custom-built to his design in the Rheinisches Landesmuseum in Bonn in 1960. Archive of the Ludwig Boltzmann Institute for Archaeological Prospection and Virtual Archaeology

reading being the difference between a sensor moving along measuring lines and a sensor mounted in a fixed position. Scollar worked mainly in the Rhineland where the abundance of sites created an excellent testing ground. The nature and geology of the sites determined the determined the choice of method, conditions being much better for the magnetic method as compared to the electrical resistivity method. Sites located from the air and based on an analysis of aerial photos were selected for further research (Scollar 1961b). First to be surveyed were Roman camps encompassing systems of ditches, fragments of which could be traced on the surface thanks to cropmarks. Since the object of the survey was to follow the earth fill of these ditches, the centre at Bonn focused on the magnetic properties of soils (Scollar 1965: 32-40; 1966: 43-45). I. Scollar worked on improving the instrument, introducing a new model in the mid 1960s (Scollar 1965: 54-89; 1966: 47-50) and another one at the beginning of the 1970s (Scollar and Lander 1972-73). Proton instruments of German make were also tested in Italy, in difficult conditions on sites covered with soils of high magnetic susceptibility. The results were sufficiently good for the instruments to start being used regularly by the Fondazione Lerici team beginning in 1967 (Scollar 1986: 86). I. Scollar also con-

Fig. 7. Albert Hesse taking magnetic measurements in Mirgissa, Nubia. Measurements were taken at each knot on a grid made of string, measuring 10 x 10 m with knots every 1 m. Archive of A. Hesse

tributed significantly to computer data processing procedures and graphic presentation of results, being the first to apply a computer to process measurement data, the first to filter data to make the results more readable, and the first to use dot density maps for presenting the results, where increased numbers of graphic symbols (initially hand-drawn dots) corresponded to increased values on a surface corresponding to one measurement. Further work, already in the 1970s, led to the introduction of the most commonly used greyscale display of magnetometer data (first implemented in his laboratory in 1976; Scollar *et al.* 1986). Scollar also used automatic recording of measurements on paper tape (Scollar 1966: 45-46; Scollar and Krückeberg 1966). He discussed his early experience with the magnetic method and the construction of a proton instrument in a comprehensive publication (Scollar 1965).

In France the first documented application of geophysics came in 1960, in the Centre de Recherches Géophysiques at Garchy, a unit formed in 1957 as part of the Centre National de la Recherche Scientifique and initially directed by Louis Cagniard.[3]

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[3] The earliest prospection using the magnetic method in France was carried out by E. Thellier from the Institut de Physique du Globe in Paris. However, the results of measurements (done by R. Scheib from the same institute), which were aimed at registering pottery kilns, were never published (Hesse, personal communication)

The link with archaeologists was provided by contacts with the Centre de Recherches Préhistoriques de la Faculté des Lettres in Paris, directed by André Leroi-Gourhan. Albert Hesse (Fig. 3) was responsible for archaeological prospection at Garchy (he was joined by Allain Tabbagh in 1969); he used the electrical resistivity method from the very beginning and introduced the magnetic method in 1962 after gaining access to a proton magnetometer (Hesse 1962; Hesse, personal communication). In the first of two published instances of measurements with the magnetic method, at the Palaeolithic cave site of Arcy-sur-Cure (Hesse 1966: 98-99), it was unsuccessful, but it did prove useful in locating pits containing coffins at an early medieval cemetery site in Garchy (Hesse 1966: 139-140). A good example of the effectiveness of the method was the tracing of a ditch circle at the Neolithic site of Moneteau (Yonne) (Hesse 1966: 118-123). Outside France, of particular significance was Albert Hesse's survey of a Middle Kingdom fortress located in Mirgissa, Nubia, carried out between 1965 and 1967 in a region to be submerged by the waters of the high dam in Aswan which was then under construction (Hesse 1970) (Fig. 7). During the research, which helped to trace the inner layout of the fortress, the magnetic properties of Nile silt, ancient Egypt's key building material, were observed. Research at Mirgissa constituted the first application of the magnetic method on an archaeological site in the valley of the Nile.[4]

2.3. MAGNETIC PROSPECTION IN POLAND

It took 14 years from Atkinson's electrical resistivity survey in Dorchester for the first application of this method in Poland, which took place at an early medieval stronghold in Kalisz (Dąbrowski and Stopiński 1961), but only three years for the magnetic method counting from Aitken's first measurements. In Poland, the magnetic method was initially limited to using a magnetic balance (Herbich 2011). The magnetic method was applied on an iron-smelting site from the Roman Period (2nd-4th century AD) in the Holy Cross Mountains. The team was an interdisciplinary unit of metallurgists and geophysicists from the Kraków AGH University of Science and Technology: Kazimierz Radwan, Jerzy Kowalczuk (Fig. 8), Tadeusz Stopka, and archaeologist Kazimierz Bielenin from the Archaeological Museum in Kraków (Fig. 9). Having first studied the magnetic susceptibility of slag, the team moved to the site of Nowa Słupia on 19 April 1961 (Fig. 10). The method proved highly effective in locating slag leftovers from iron-smelting furnaces, the results tested immediately in the field by excavations (Kowalczuk and Stopka 1962; Bielenin *et al.* 1963). In the first phase of the research, between 1961 and 1964, 23 sites were surveyed (Bielenin 1992: 46). Geophysical prospection ebbed in intensity in the second half of the 1960s, the last measurements, still using a magnetic balance, being carried out in 1968 (Bielenin 1970). Interestingly, in 1961 the geophysicists from Kraków had no knowledge of any earlier experiments with magnetometry

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[4] For Albert Hesse and his work, see Tabbagh and Herbich 2003.

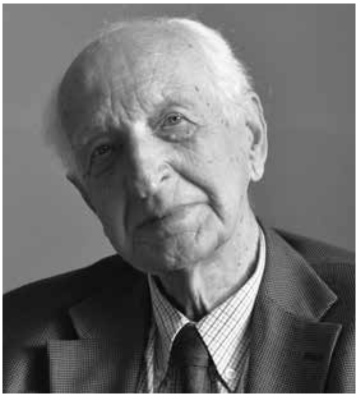

Fig. 8. Jerzy Kowalczuk, October 2011. Photo T. Herbich

Fig. 9. Kazimierz Bielenin in the late 1980s. Archive of the Archaeological Museum in Kraków

Fig. 10. Jerzy Kowalczuk and Tadeusz Stopka preparing to survey with magnetic balances, Nowa Słupia, April 1961. Archive of the Museum of History of the AGH University of Science and Technology in Kraków

Fig. 11. Krzysztof Dąbrowski (in front) during an aerial survey of sites in the region of Kalisz, early 1960s. Archive of T. Baranowski

Fig. 12. Wojciech Stopiński at the 1st National Conference for Archaeological Geophysics in Warsaw, June 9, 2010, giving a lecture to commemorate the 50th anniversary of his geophysical survey of the Zawodzie hillfort in Kalisz, the first Polish archeological-geophysical research. Photo R. Ryndziewicz

in archaeology and were convinced as to the pioneer character of their undertaking in Nowa Słupia (Kowalczuk and Stopka 1961; 1962, Herbich 2011).

Also in 1961 a team put together by Krzysztof Dąbrowski (Fig. 11) from the Institute of the History of Material Culture (now the Institute of Archaeology and Ethnology) of the Polish Academy of Sciences in Warsaw commenced testing the magnetic method in prospection on all kinds of sites from open settlements through fortified strongholds to cemeteries (Dąbrowski 1963). The first measurements were carried out by Wojciech Stopiński (Fig. 12) from the Geophysics Department of the Polish Academy of Sciences in the summer of 1961, using a magnetic balance, at a cremation burial ground from the period of Roman influences in Wesółki (Dąbrowski and Stopiński 1962). Results were verified immediately by excavations and the method proved useful in locating iron grave goods; the metal finds from individual burials weighed between 0.25 kg and 2.05 kg. More importantly, however, the method proved capable of also locating graves with nothing but clay vessels in their furnishing; this was verified once the humus surface layer was stripped in a test trench. That pits containing fill composed of dark soil, stones and fragmented pottery could be mapped suggested that the magnetic method could be applied for surveying open settlements (Dąbrowski and Stopiński 1962: 612-613). Promising results led to the establishment of an interdisciplinary unit for geophysical research including an archaeologist (K. Dąbrowski), a geophysicist (W. Stopiński) and a geologist (E. Stupnicka).

A Polish version of the proton magnetometer was designed in 1965 by Jerzy Jankowski with a team from the Geophysics Department of the Polish Academy of Sciences. The instrument was used for the first time to test iron-smelting sites in Słupia Nowa; tests were continued by J. Jankowski in 1966 at a multi-cultural site in Dębnica in the Wrocław district. The prospection at Nowa Słupia on sites 6 and 7 recorded areas of furnaces (Bielenin 1967; 1992: 46-48). In Dębnica the prospection traced the spatial extent of the settlement and located several concentrations of features: buildings, pottery kilns and metallurgical furnaces (Kaletyn 1968: 283).

In 1965 K. Dąbrowski invited Richard E. Linington to experiment jointly with a proton magnetometer on different kinds of sites typical of Polish territories (Dąbrowski and Linington 1967). K. Dąbrowski had been introduced to the effectiveness of these instruments two years earlier, in 1963, when he participated in the Lerici Foundation's project to investigate a Villanova Culture cemetery in Tarquinia (Linington and Dąbrowski 1964). The method was tested on a number of sites in the Kalisz region: an early medieval stronghold in Jarantów, a cremation burial ground from the late La Téne period in Zagórzyn and an open settlement from the late La Téne and Early Roman Period in Piwonice. Measurements were carried out with an apparatus of the Elsec type and verified archaeologically in 1966 (Dąbrowski and Linington 1967; Linington and Dąbrowski 1968). The results of the survey did not produce a unanimously positive opinion on the method's effectiveness in surveying prehistoric sites in the specific conditions of Poland (Herbich 2011). As said already, the intensity of magnetic prospection ebbed in the later part of the 1960s. Practically, only the geophysicists from Kraków continued to survey iron-smelting sites in the Holy Cross Mountains. Once K. Dąbrowski lost interest in archaeological geophysics, the Warsaw team was dissolved.

2.4. Magnetic prospection in the USA

In the United States magnetic prospection was applied in archaeological research for the first time in 1961. Working for a project directed by Glenn A. Black from the Indiana Historical Society, Richard Johnston from the Angel Mounds Archaeological Research Station used an Elsec instrument to conduct a survey of a native Indian village at Angel Mounds, which represented the Middle Mississippi Culture roughly corresponding to the European Middle Ages (Johnston 1961). The site contained remains of huts and a system of fortifications made up of a wall and palisade, partly observable on the ground. Testing of places where fortifications could be expected produced anomalous values and it proved possible to trace sections of the system where the walls were divided into two parallel structures. Measurements also revealed anomalies corresponding to pits in place of huts (Johnston 1961: 72). The first season of surveying ended with 58,000 measurements being taken on site, tracing some features, like the fortifications, over a distance of approximately 500 m. More measurements were taken in the same year at another native Indian village located at Wetherill Mesa in the Mesa Verde National Park in Colorado. The Angel Mounds success opened the way for the magnetic method to become a regularly used research tool at Indiana University; in 1971 the university established an independent unit, the Glenn A. Black Laboratory for Archaeology, one of the specialties of which is geophysical research.

The Applied Science Centre for Archaeology (MASCA) at the Museum of the University of Pennsylvania contributed significantly to the introduction of the method, although the first and main testing ground, at least in the early phase, was not in America but the Greek colony of Sybaris in southern Italy (Brown 1963). This research, in association with the Lerici Foundation, was mentioned earlier in reference to the Foundation. The Museum conducted intensive archaeological research on a number of continents during the first eight years of its activities; among the 34 magnetic surveys conducted by Elisabeth Ralph's team there were sites in Greece, Italy, Turkey, Ireland and Central America. Only half of the investigated sites were situated in the United States and Canada (Ralph 1969: 15-17).

2.5. MAGNETIC PROSPECTION IN THE USSR

The first trials with magnetic prospection in the Soviet Union were carried out in 1962 by a team from the Laboratory of Technologies Applied to Archaeology, Institute of Archaeology, which was part of the Leningrad branch of the USSR Academy of Sciences (now Saint-Petersburg Institute of the History of Material Culture, Russian Academy of Sciences). The survey covered the Neolithic site of Vyun in the Leningrad region. The proton instruments that were used had a resolution of 10 γ and were applied in differential mode. Measurements were taken along lines 100 m long at intervals of 5 m, reduced to 1.5 m in anomalous spots, tracing the spread of cultural layers in the horizontal plane. This gave an idea of the extent of the site. Explorations demonstrated that anomalous readings corresponded mainly to stones from hearths. It was also noted that rocks outside the cultural layers did not have magnetic properties; an experiment by the laboratory head Sergey Rudenko with heating rocks led to understanding the phenomenon and moreover pointed out the magnetic properties of pottery (Frantov and Pinkevich 1966: 136). In effect S. Rudenko established in the lab a separate unit to deal with applied geophysical methods. In 1963 this unit surveyed the medieval hillfort site near Isyaslav (Khmielnitsk province, Ukraine). The survey used a one-meter grid and revealed mainly iron-smelting sites (Frantov and Pinkevich 1966: 140-141). The Leningrad researchers' field experience and the belief in the usefulness of geophysical methods in archaeological research resulted in a 200-page textbook on archaeological geophysics being published as early as 1966 (Frantov and Pinkevich 1966).

3. INTRODUCING OTHER TYPES OF MAGNETOMETERS: FLUXGATE AND OPTICALLY PUMPED

Like the proton magnetometer, the fluxgate magnetometer was introduced by the Research Laboratory for Archaeology and History of Art in Oxford. It was tested together with other types of magnetometers by Michael Tite (Fig. 3) on an Iron Age hillfort at Rainsborough Camp near Oxford, in June 1961. First, the inside of the hillfort, close to 3 ha in area, was surveyed with a proton magnetometer, recording about 90 anomalies of an amplitude from 25 to 50 γ and diameter from 1.25 to 2.50 m. Excavations verified that the anomalies corresponded to features like pits, gullies and hearths. Further the testing was carried out in two small areas, 15 m by 15 m and 7.5 m by 7.5 m, where number of anomalies registered was than in other parts of the site; the objective was to compare the effectiveness of a proton magnetometer measuring the total value of field intensity, a proton gradiometer measuring the vertical gradient (resolution approx. 2 γ) and a fluxgate magnetometer (resolution 1 γ), also in gradiometer mode measuring the vertical gradient (Tite 1961). The magnetic images produced by each of the instruments were similar, but the intensity of the anomalies varied: three out of five structures measured with the proton magnetometer demonstrated values twice as high as those produced by a fluxgate magnetometer. However, the tests left no doubt as to the superiority of the latter instrument compared to other devices as far as measuring time was concerned: it was short enough to make it unnecessary to stop at each measurement point. Gradiometers were also shown to be less influenced by external disturbance. Taking into account the lower resolution of the proton gradiometer, the tests demonstrated the usefulness of the fluxgate instrument.

Fig. 13. Tony Clark with a Plessey fluxgate gradiometer, 1970s. Archive of The English Heritage

These strengths led the Research Laboratory in Oxford to develop a fluxgate instrument for wider application in archaeological research. This task was accomplished by John Alldred (1964). Proper operation of the instrument demanded, among other things, that the tube with the sensors be carried vertically during measurements. The sensors in J. Alldred's instrument were 1.20 m apart and the combined length of the tube was 2 m. Moving the instrument up and down the measuring line required two people. The cable connecting the magnetometer to the electronics was 70 m long. Resolution of the instrument when inactive was 1 γ, whilst tilting from the vertical during movement, if the tilt did not exceed 15 degrees, caused a drop in sensitivity to 3 γ. The fluxgates had to be parallel to one another to within 0.003 degrees, which necessitated manual regulation. Three large survey projects (a combined area of 10 ha) carried out with the fluxgate gradiometer over two seasons indicated that work was two to three times quicker than with the proton magnetometer. Assuming a distance of 1.50 m between measurement lines, a team of four (two carrying the magnetometer, one at the measuring device and the fourth laying out the lines) could survey 1 ha in three hours (Alldred and Aitken 1966a: 53-54).

Fig. 14. Elizabeth Ralph, leading researcher at MASCA. Archive of the University of Pennsylvania Museum of Archaeology and Anthropology

An improved version of the fluxgate gradiometer was developed by the Plessey Company in 1968. Now the instrument could be carried by one person (Philpot 1972-73) (Fig. 13). The instrument was ideally suited to the needs of the unit doing most of the geophysical surveying in Great Britain at the time, the Ancient Monuments Laboratory established in 1967 by the Ministry of Public Buldings & Works. The unit at first employed only one person, Tony Clark (Clark 1975: 297; 1990: 20, 23-24). The instrument signal and its physical position on the survey grid were plotted as stepped graphical traces on paper by a chart recorder, allowing the immediate analysis of the results, presented as multiple trace plots; then the values read from the curves were used to draw maps of isolines (Clark and Haddon-Reece 1972-1973). The system was in use for 15 years until it was replaced by digital recording on a portable microcomputer. Trace plots were still used to read results in the field, but the computer stored the data on tape for subsequent processing (Clark 1986: 1405-1412). All structures of elongated shape such as ditches and walls (as long as these were not parallel to the measurement line) were visualized particularly well on trace plots. Data processing could eliminate anomalies of high amplitude generated by modern ferrous metal objects on or near the surface. The first application of the new version of the instrument in archaeological prospection took place on a site with two Romano-British pottery kilns in Lingwood (Philpot 1972-1973: 104, Clark and Haddon-Reece 1972-1973: 107). Large areas could be surveyed in a short period of time with this apparatus. For example, the survey of a Roman villa complex at Wharram le Street, Humberside, over an area of 5.5 ha and with 1-m spacing between measurement lines took only four days. The largest survey covered 18 ha. Operating on areas of such size allowed the mapping of many sites of considerable size, such as the above mentioned Roman villa at Wharram le Street and the complex of circular ditches of Bronze Age barrows at Radley in Oxfordshire (Clark 1986: 1407, 1409-1410).

The optically pumped instrument was introduced into archaeological prospection by researchers from MASCA (Fig. 14). Conditions which they encountered in Sybaris demanded a much more sensitive instrument than the proton magnetometer used in 1961 and 1962. Excavations had demonstrated that the ruins of the 6th century BC Greek town were located at a depth of from 4 m to 6 m, covered with layers of alluvial clay. The proton magnetometer had been proven to be effective in searching for archaeological structures down to a depth of 3 m, which in this particular case recorded only the Roman-age remains. An American company, Varian Associates, came through with a proposal for an optically pumped magnetometer with sensitivity a hundred times greater than that of a proton magnetometer (0.01 γ). The instrument that was used had rubidium sensors (Ralph 1964; Breiner 1965). Following tests carried out in May 1964 at Fort Lennox in Canada, the instrument was used in Sybaris in October of the same year. A differential configuration with one fixed sensor and one being moved along measuring lines proved to be the most effective. Readings were plotted as curves and anomalous values were also indicated by an emitted sound signal. Measurements were four times faster than with the proton magnetometer (Ralph 1964: 23-25). The manufacturer sent representatives to supervise the fieldwork and in effect undertook to construct an instrument that would take into account the special requirements of archaeological surveying. The readout provided values with a resolution of only 0.1 γ, but the instrument in differential configuration was not too heavy for one person to manage (Langan 1966: 64-65). Almost ten years of magnetic prospection at Sybaris failed to produce a town plan; however, it did approximately identify the areas of occupation in antiquity – which in the case of ruins scattered over 100 km^2 is no mean feat. This research was important in that it created an excellent testing ground for new types of magnetic instruments (Ralph 1969). The effectiveness of the optically pumped instruments was demonstrated persuasively for archaeologists by the Sybaris team's research on another site, the ancient town of Elis on the Peloponnesus, founded in the 5th century BC. A survey carried out in 1967 with a caesium magnetometer recorded rows of houses and walls. The conditions were exceptionally suitable: ruins could be found within a metre of the ground surface and reused terracotta rooftiles (material of a high magnetic susceptibility) were commonly used as building material in the walls. For the first time it became possible to map an entire ancient Greek town based on the magnetic measurements (Ralph 1969: 21).

4. APPLICATIONS OF THE MAGNETIC METHOD FROM THE END OF THE 1960s THROUGH THE 1980s: GRADUAL DEVELOPMENT

Reviewing publications on the applications of geophysics in archaeology one has the impression of a certain stagnation in the 1970s, which followed in the wake of the exciting pioneering days when instruments were being tested and the effectiveness of geophysical methods, including the magnetic one, established. This impression is due to a number of factors, not the least being the absence of a periodical devoted to the issues of archeological geophysics. The number of publications concerning geophysics published in *Archaeometry* clearly dropped over the years: in the first seven volumes (1958-1964) archaeological geophysics were the subject of 28% publications, 90% of which concerned the magnetic method. In issues 8, 10 and 11 there was only one article on geophysics (devoted to the magnetic method). Volume 9 was an exception from this clear trend as 33% of the issue was devoted to geophysics, but only one of the seven articles dealt with the magnetic method. The shift in interests observed in the periodical reflected the changing interests of the team of the Research Laboratory in Oxford, which began to concentrate on dating methods and physico-chemical analyses of finds, searching for innovative solutions in these fields.

The main forum for publishing archaeological geophysics was at this time the annual journal *Prospezioni Archeologiche*, which appeared for nine successive years in 1966-1974. The next and last, tenth volume was published twelve years later, in 1986, dedicated to the memory of the journal's founder, C.M. Lerici, who died in 1981, and his co-editor, R.E. Linington, who died in 1984. It should be noted that in that early period *Archaeometry* was focused specifically on publications concerning the magnetic method, while *Prospezioni Archeologiche* was open from the beginning to all kinds of geophysical methods.

The contents of these two periodicals identifies centres of research and development of the magnetic method: work on the proton and fluxgate magnetometers was carried out foremost in Great Britain (Aitken 1959c; 1960; Tite 1961; Mudie 1962; Hall 1962; Alldred 1964; Alldred and Aitken 1966a; Harknett 1969) and in Germany (Scollar 1961b; 1970a; 1986), while the optically pumped instrument was developed in the United States (Ralph 1964; Langan 1966); studies in Germany focused on applying computers to processing the measurement data and presenting the results (Scollar and Krückeberg 1966; Scollar 1968; 1969; 1970b), while in Italy the principal objective was data modeling and processing (Linington 1964; 1966b; 1968; 1969a; 1970).

The contents of the periodicals also demonstrates where, besides Great Britain, Italy, Germany and the United States, local research centers invested in the magnetic method. One should mention here France (Hesse 1962; 1967), Poland (Dąbrowski 1963; Dąbrowski and Linington 1967; Iciek *et al.* 1974a) and Czechoslovakia (Linington 1969b).

Changes in the organization and financing of science impacted the development of the magnetic method, as also did new legislation on protection of the archaeological heritage. Great Britain was again a leader, the processes observed there being copied to a greater or lesser degree in other countries in the coming decades. The Ancient Monuments Laboratory based in London, was focused primarily on practical applications of the method and improvements to instruments in use. An increasing emphasis on 'rescue archaeology', on a larger scale than before, is exemplified by the gas industry's infrastructure programme of pipeline develoment. British Gas, which spearheaded this effort, hired an archaeologist and a geophysicist to conduct extensive ground surveying, mainly using the magnetic method (Gaffney and Gater 2003: 20). In 1971, a unit charged with training in prospection methods was established at the University of Bradford. This unit, directed by Arnold Aspinall (Fig. 15) and focused mainly on supplementary training for archaeologists, taught the practical side of the application of the magnetic and electrical resistivity methods, as part of graduate and postgraduate courses in scientific methods in archaeology. Archaeological geophysics also became part of the curriculum at some universities with archaeology departments, for example Richard Atkinson (Fig. 16) lectured on the subject at the University of Cardiff in the early 1970s. A new updated textbook by M.J. Aitken (1974) also served the purposes of education, as did his contribution to a collective work on science in archaeology with chapters on archaeological geophysics including the magnetic method (Aitken 1975). In 1984 Bradford Roger Walker founded Geoscan Research, a company specializing in the production of instruments for geophysical surveying, fluxgate gradiometers in particular, as well as instruments for electrical resistivity research (Gaffney and Gater 2003: 56-60, 62-64).

Fig. 15. Arnold Aspinall, creator of the Bradford school of Archaeological Sciences and co-editor of *Archaeological Prospection* journal, 1990s. Archive of Armin Schmidt

Fig. 16. Richard Atkinson. Archive of Irvin Scollar

Fig. 17. Kath Walker of Geoscan Research with a prototype of a FM36 fluxgate gradiometer, 1986. Archive of Geoscan Research

Instruments made by this company monopolized the British market, being used by research institutions as much as by commercial companies (Fig. 17).

It was these four elements that established the magnetic method as an important research tool: firstly, routine and experimental prospection (especially by the Ancient Monuments Laboratory); secondly, the need to survey in advance of development (for example by British Gas); thirdly, training specialists; and fourthly, production of specialized instruments. Added to this was a new trend in archaeology: concentrating on reconstruction of the landscape and environment, covering cultural and geographical regions rather than individual sites (Gaffney and Gater 2003: 20-21). This kind of research encouraged the application of tools, such as the magnetic method, that could map archaeological features over large areas.

In the two decades between the end of the 1960s and the 1980s, changes also occurred as far as the leading centres of archaeological geophysics were concerned. In Italy, after the death of its founder the Lerici Foundation limited its participation in archaeological research. The Istituto delle Technologie Applicate ai Beni Culturali in Monetlibretti near Rome with a geophysics section was created within the framework of the state Consiglio Nazionale delle Ricerche. Unlike the Lerici Foundation, this section was interested chiefly in testing and implementing new measurement techniques and instruments with less emphasis on broad-scale practical application of new methods. The results of research on a settlement and cemetery from the 8th century BC at Acqua Acetosa on the Via Laurentina near Rome provides a good example of this approach (Brizzolari *et al.* 1991). Another example is Suasa, an important Roman-age site (Bruzzi *et al.* 1991). The magnetic method was one of at least three geophysical methods applied in this research. Proton magnetometers were used at Acqua Acetosa and fluxgate instruments at Suasa. At Acqua Acetosa all applied methods (electrical resistivity and seismic as well as magnetic) recorded the same features, but traced their extent differently (Brizzolari *et al.* 1991: 144-145); in the case of the prospection at Suasa, building remains were best imaged on the electrical resistivity map, but the magnetic method

Fig. 18. Helmut Becker using a Varian V101 caesium magnetometer in gradiometer mode. Survey in Aiterhofen, Lower Bavaria, in 1979. Archive of Jörg Fassbinder

did reflect the extent of the occupied area; the least distinct results were produced by the electromagnetic method (Bruzzi, dall'Aglio and de Maria 1991: 170-174).

In Germany, Irwin Scollar of the laboratory at the Rheinisches Landesmuseum reduced his participation in fieldwork in favour of work on processing data as digital images (Scollar *et al.* 1986; 1990), whereas the Bavarian State Department of Monuments and Sites in Munich gained prominence with the establishment in 1982 of a unit directed by Helmut Becker (Figs 2 and 18) (Becker 2015: 119-123; Jörg W.E. Fassbinder joined the unit in 1986). In Germany, this unit, which chiefly used magnetic prospection, operated not only in Bavaria, but was also very active in Turkey, southern Europe and the Near East. It specialized in combining magnetic prospection with aerial photography, taking advantage of I. Scollar's experimental work with data processing (Becker 1984; 1985; 1990a). The unit quickly abandoned proton magnetometers in favour of caesium instruments with 0.1 nT resolution[5], either as gradiometers (for areas with high magnetic disturbance near power lines, electrical trains etc.) or differential measurements (in areas without disturbances). The salvage character of the work and need for site protection in the face of threats from development and erosional processes, induced the Munich unit to place sensitivity and speed at the top of its list of priorities, meaning covering large areas in the shortest possible time with high measurement density. One way to achieve this goal was to automate the measurement recording. H. Becker first tested recording measurements on tape using proton magnetometers (Becker 1979) and the first data logger (registering data from a caesium magnetometer) connected to a portable computer Epson HX20 was in 1984 (Becker 1985), improved by J.W.E. Fassbinder in 1985-1986. This was also an important step towards the so-called "time mode sampling" which gave much higher resolution (with 10 samples per second meaning about 12 cm at normal walking speed). Another way of

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[5] 1 nT (equal to 1 γ) as a unit of intensity of the Earth's magnetic field had been introduced in the 1960s, but was not commonly used in archaeological publications before the late 1980s.

achieving the goal was to expedite the moving of the instruments by mounting them on specially constructed carts. This system allowed for coverage of an area of 1-1.5 ha, with a sampling grid of 0.5 m (that is, recording 40,000 to 60,000 measurements) in two days by just two people: one person moving the mounted sensors and the other controlling the magnetometer readout and the data log. Portable computers facilitated data processing in the field (Becker 1990a: 30-32).

Inspired by the results produced by the highly sensitive caesium instrument, allowing detection of single postholes, the Bavarian team focused on researching the magnetic properties of soils. This led to the discovery of the presence of magnetic bacteria in the topsoil (Fassbinder *et al.* 1990; Fassbinder and Stanjek 1993; Fassbinder 1994; Stanjek *et al.* 1994) providing a giant step toward more informed interpretation of magnetic results, explaining for the first time anomalies produced by features of organic origin, not transformed by high temperatures caused by fire, as observed previously by E. Le Borgne (1960).

H. Becker's team's most interesting results included mapping of different kinds of sites from the Neolithic, like ditch circles (for example, at Schmiedorf and Kothingeichendorf, Becker 1987a and 1988), enclosures (Becker 1990b) and remains of long houses (at Baldingen, Becker 1987b), and in the Roman Period reconstructing the layout of the camp at Markbreit (research in 1986-1991 covered close to 25 ha of the site, Becker *et al.* 1992). Belief in the usefulness of magnetic results was enhanced by the manner of presentation introduced by the Munich group, showing the results as monochrome maps with 256 levels of greytone, giving an extremely readable presentation of the results and easy identification of anomalies – much better than the dot-density maps and contour line maps. The software used by the unit was geared to a graphic identification of archaeological features (ordinarily the effect of combined analyses of magnetic maps and aerial images produced by associate Otto Brasch), giving in effect a site map that archaeologists could read.

Fig. 19. Wolfgang Neubauer surveying a Germanic settlement in Drösing (Lower Austria) using a Geonics proton magnetometer, summer 1985. Archive of the Vienna Institute for Archaeological Science,University of Vienna, Photo A. Stuppner

A geographic information system (ARGIS) using digital cartography and with links to aerial archaeological databases and an inventory of all known archaeological sites in Bavaria was developed in Munich in 1991. Site plans kept in the ARGIS system were derived from rectified and collated aerial photos combined with geophysical survey maps. This served the purposes of archaeological monument protection services perfectly (Becker 1992).

In Austria, development of magnetic method applications in archaeology took a similar course as in Germany. Proton magnetometers were quickly rejected in favour of optically pumped instruments. Surveying with proton magnetometers was conducted in the 1970s and 1980s by the Institute for Geophysics of the Montanistic University of Leoben (Walach 1993). From 1985 Wolfgang Neubauer and Georg Walach worked on sites in Lower Austria. In spite of low resolution (1 nT), long measurement time (5 seconds) and a relatively coarse sampling interval (1 m), their results were promising for Neolithic ditch circles at Kammeg and Rosenburg, and at the Germanic settlement in Drösing (Neubauer 1990) (Fig. 19). In the late 1970s, Peter Melichar of the Department of Geophysics, Central Institute for Meteorology and Geodynamics in Vienna, adapted surveying with caesium magnetometers specifically to archaeological research within the framework of the "Neue Wege der Ur- and Frühgesichtsforschung" programme directed by the prehistorian Herwig Friesinger. A gradiometer version of the instrument was used and measurements were recorded automatically; a built-in printer permitted the raw data to be visualized right after the measurement. Cooperation between P. Melichar and W. Neubauer at the initiative of the latter gave a new stimulus in the late 1980s. Among successful surveys one should mention research on the Neolithic ditch circles at Strögen (Neubauer *et al.* 1995) and at Hornsburg (Melichar and Neubauer 1993).

In France the Centre des Recherches Géophysiques (part of the Centre National de la Recherche Scientifique) at Garchy did not lose its leading role, but concentrated on developing the electromagnetic method (Tabbagh 1986) and on quick electrical resistivity surveys (Dabas *et al.* 1990), whilst applying the magnetic method only sporadically in supplementary mode. Intensive work was also carried out on creating software for presenting results in the form of digital imagery. The first version of such software, prepared by Jeanne Tabbagh, was implemented in the early 1980s.

Polish researchers returned to magnetic prospection in the early 1970s when a team of geophysicists, archaeologists and historians headed by archaeologist Jacek Przeniosło (Fig. 20) operated in the area of Carthage in Tunisia (Iciek *et al.* 1974a). The team also used the electrical resistivity and gravimetric methods. The volume published on this research (Iciek *et al.* 1974b) was the first comprehensive presentation in book form of a site investigation that began with a geophysical survey (itself preceded by a careful review of historical and archaeological sources) and then followed up with excavation to verify and supplement the geophysical results. The analysis focused on reconstructing the topography of the town and contributing new information on its known history. The success of this research prompted the Institute of Archaeology and Ethnology of the Polish Academy of Sciences to establish a unit charged specifically with geophysical research; until 1990 it was headed by archaeologist J. Przeniosło. Proton magnetometers of Polish make were in use by the unit (successive models PMP4, PMP5), but the magnetic method was used rather sporadically, mainly due to the different specializations of the associated consultants from the State Enterprise for Geophysical Investigations in Warsaw: the geophysicist Aleksander Jagodziński, who specialized in the electrical resistivity method and the electronics engineers Janusz Konopacki (Fig. 20) and Leon Mucha, specialists in constructing electrical resistivity measuring devices (Misiewicz 2002: 113-114).

The most important magnetic research of the 1970s in Poland was conducted by geophysicists from the Kraków AGH University of Science and Technology who worked on a number of sites within a newly discovered ancient iron-smelting complex in the Masovia region. Surveying identified the extent of the areas where slag was present (Jarzyna *et al.* 1975, Woyda 1977). In 1981-82 the author surveyed a Palaeolithic haematite mine in Rydno (Holy Cross Mountains region), tracing the distribution of outcrops of the haematite-producing layer corresponding to the potential extent of extraction activities (Herbich 1984). In the middle of the 1980s the author started to work in Egypt; the magnetic method was applied without much success in a survey of the Coptic monastery at Naqlun (Godlewski *et al.* 1990), but it led to the discovery of the funerary chapel of an unknown vizier of the 6th Dynasty from the Old Kingdom in Saqqara (Myśliwiec and Herbich 1995; Herbich 2003: 16-18).

Research using the magnetic method in Czechoslovakia was initiated by Richard Linington from the Lerici Foundation in 1967. Together with researchers from the Archaeological Institute of the Czechoslovakian Academy of Sciences in Prague, he made a reconnaissance and selected a number of sites for magnetic surveying, the criteria being to cover as wide a chronological and typological range as possible. Surveying was undertaken in 1968 at four sites: a Funnel Beaker Culture settlement at Makotřasy, a large Celtic *oppidum* at Závist, a deserted medieval village at Svídná and a 5th-7th century AD settlement at Březno (Linington 1969b). Measurements were taken with a differential proton magnetometer developed in Bonn (Scollar 1965; 1986) and covered a combined area of 8 ha. On the first two of these sites, the survey proved to be of great value in that it solved important archaeological problems without the need for excavation. In Makotřasy, a ditch was traced around the site for a combined distance of about 500 m, allowing the squared shape of the settlement to be reconstructed (300 m to

Fig. 20. Jacek Przeniosło (right), head of the geophysical laboratory of the Institute of Archaeology and Ethnology, Polish Academy of Sciences, between 1972 and 1990 and Janusz Konopacki, head of a unit producing geophysical instruments at the State Geophysical Research Enterprise between 1980 and 1990. In 2011. Photo T. Herbich

the side); and at Závist a defensive ditch with an entrance was located (Linington 1969b: 133; 137). The invasion of Czechoslovakia in 1968 by troops from the Warsaw Pact interfered with further prospecting by Linington. His survey initiated extensive application of the method throughout Czechoslovakia in the next two decades, but the results did not filter into Western literature in any way. The Czech element of the work was carried out within the framework of cooperation between the Archaeological Institute of Czechoslovak Academy of Sciences, Prague, the Department of Applied Geophysics at the Faculty of Natural Sciences, Charles University and the state enterprise Geofyzika, Brno and Prague. In Moravia and Slovakia the units responsible were the Archaeological Institute of the Czechoslovak Academy of Sciences in Brno, the Geofyzika Brno enterprise, the High School of Mining in Ostrava, the Archaeological Institute of the Slovak Academy of Sciences in Nitra and the Department of Applied Geophysics at the Faculty of Natural Sciences, Komenský University in Bratislava. Four nationwide conferences on *Geophysics and archaeology* were organized between 1973 and 1982, all crowned by published proceedings (for references, see Pleslová-Štiková 1983: 14). The first independent attempts were made using a magnetic balance during tests carried out by Vilém Bárta at Makotřasy in 1968 and at Sázava-Černé Budy in 1969 (Bárta 1973). Proton magnetometers were used for magnetic prospection from the beginning of the 1970s, taking extensive measurements at the Great Moravian site Sady and starting a programme of regular investigations of metallurgical sites in the Boskovice area (Hašek 1999: 3). In 1976, an Interdisciplinary Improvement Team was established to prepare a comprehensive programme of research in Bohemia and Moravia. František Marek from the Department of Applied Geophysics at the Faculty of Natural Sciences of Charles University in Prague turned out to be a key figure in archaeological geophysics; important research was carried out by, among others, Jan Tirpák from the Archaeological Institute of the Slovak Academy of Sciences in Nitra and Vojtěch Gajdoš from the Department of Applied Geophysics in Bratislava, representing institutions with a base in Slovakia. The main task was to study all opportunities for the application of geophysical methods in archaeology and their practical use in field prospection. The number of surveys carried out by the year 1995 is the best proof of the team's activity: in Moravia alone 161 sites were investigated, the combined area being of 250 ha, mainly with the magnetic method (Hašek 1999: 4). Among the most important projects, all combined with archaeological verification, was the complete tracing a ditch encircling the settlement at Makotřasy (Pleslová-Štiková *et al.* 1980; Marek 1983: 64-68) and the location of Neolithic circular enclosures, for example, at Bylany (Marek 1983: 61-62; Pavlů and Zapotocká 1983) and Lochenice (Marek 1983: 58-50; Buchvaldek and Zeman 1983).

The chief reason why the activity of geophysicists in Czechoslovakia was not reflected in Western archaeological-geophysical literature appears to have been political: science was closely controlled by the communist regime (much more strictly than in Poland, for

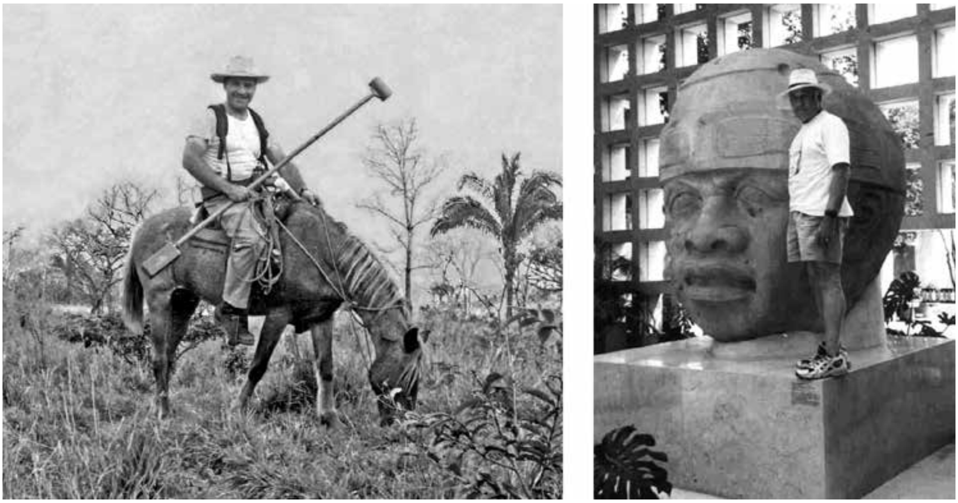

Fig. 21. Sheldon Breiner identifying areas of anomalous magnetic values at the Olmec Site of San Lorenzo, Veracruz, Mexico, with the use of a caesium magnetometer in an initial ("search" mode) phase of the magnetic survey, March 1968 (left) and standing in the Anthropology Museum in Xalapa, Veracruz state, by one of the Olmec heads found as a result of the survey (right). Archive of Sheldon Breiner

instance), results of research could be popularized outside the country only by scientists with political attitudes accepted by the regime. Geophysicists were in the minority in this case, hence the results were propagated mainly in archaeological circles, with little opportunity for wider presentation among archaeological geophysicists.

In the United States, the number of centres applying the magnetic method grew in the late 1960s and early 1970s. Sheldon Breiner, a geophysicist involved with developing applications of the then-new optically pumped instruments at Varian Associates (on whose behalf he participated in the research of the MASCA team in Sybaris, see above) created his own company Geometrics, and with a caesium magnetometer joined a research project at an important Olmec Site in San Lorenzo in southern Veracruz, Mexico. The project aim was to search for basalt carvings (with a minimum size of one cubic meter) that were presumed to be buried in the soil plateau. Laboratory research showed that the basalt blocks were characterized by a high induced and remanent magnetization, strongly in contrast with the total magnetization of the surrounding fill. In the first phase of the research, in 1968, the aim of the survey was to identify anomalies in the area (Fig. 21, left), excavate to confirm and divide the entire area into mappable grids. Measurements were carried out over a 2m grid , adjusted to the size of the sought-after basalt objects and to the range of anomalies created by them. A total of 80,000 measurements were taken; the survey located 17 objects of this kind in the area (including two colossal heads, Fig. 21, right), practically impossible to discover with traditional excavation methods: one of the heads was located at a depth of 5 m in the ground (Breiner and Coe

Fig. 22. John Weymouth (left) overseeing the magnetic survey at the Hopeton Site in the Hopewell Cultural National Historical Park, Ohio, in 2001. Archive of the National Park Service

1972). Breiner summarized his experience of working with portable magnetometers in a 58-page brochure, of which a million copies were printed (not counting copies translated into different languages e.g. Chinese and Russian) (Breiner 1973). The brochure was directed mainly at researchers working in geological exploration (using proton magnetometers), but also contained a chapter on archaeology (Breiner 1973: 45-48).

In the mid-1970s John Weymouth (Fig. 22) from the University of Nebraska began research on aboriginal occupation sites in the Great Plains of North America, using proton magnetometers to survey large areas. The most spectacular results came from a survey of the Sakakawea Village at the Knife River Indian Villages National Historic Site. Measurements covered 15 ha over a one-metre grid. A number of houses were observed in the magnetic record, each with a central anomaly. Areas between the houses with strong magnetic readings were middens, the house floors being less magnetic. The central anomalies in the houses corresponded to hearths (Weymouth 1986a: 353-356). Between 1978 and 1982 J. Weymouth's group investigated about 100 sites in the Dolores Archaeological Program alone (Weymouth 1986a: 362). J. Weymouth's work turned the University of Nebraska into an important centre for training in the field of archaeological geophysics (Weymouth 1986b). Large areas were also surveyed by teams from the University of Pennsylvania Museum (MASCA). By 1976 the number of sites surveyed by Elizabeth Ralph reached 49 in 13 countries. During this research 750,000 magnetic measurements were plotted and contoured by hand, an output which, according to Bruce Bevan (1995: 89), has never been equalled. Large-scale projects were continued: an interdisciplinary survey at the Valley Forge National Historic Park covered 20 ha with a caesium magnetometer over a grid from 2 to 0.5 m (Parrington 1979). In the Tombigee Historic Townsites Project in Mississippi approximately 44 ha were investigated in the course of three months; archaeological verification demonstrated that earth features were detectable only if the fill included ferrous fragments. Brick features (kilns, hearths and chimney walls) were also discovered as long as they occurred in concentrations (Weymouth 1986a: 367-368).

Sheldon Breiner's pioneering work in Mexico was followed by a survey carried out by other North American researchers. A team headed by geophysicist H.F. Frank Morrison form the University of Berkeley surveyed La Venta Pyramid. According to Luis Barba (personal communication) this is the earliest published research concerning the application of magnetometry in Mexican archaeology (Morrison *et al.* 1970). The magnetic method was also used by Mexican researchers: firstly in 1969 in the main plaza of Mexico City, near the cathedral, to search for large stone sculptures from the pre-Spanish era. Gravimetric and seismic methods were also applied. Sculptures were not found, but this was the first attempt to use geophysics with an archaeological objective in an urban environment in Mexico (Castillo-García and Urrutia-Fucugauchi 1974). Luis Barba then became a leading person in Mexican archaeological geophysics; his first use of the magnetic method took place in 1980 when he investigated the site of San Jose Ixtapa with a Varian caesium magnetometer. The anomalies detected (over a 5 m grid) suggested the presence of industrial remains, with excavation revealing a mercury production site dated to a pre-Spanish period (Limón and Barba 1981).

In the Soviet Union, the magnetic method was applied mainly to investigate industrial sites containing iron-smelting furnaces and pottery kilns, that is, features that were easily traced owing to the high amplitudes of anomalies observed in the Earth's magnetic field. The trend was set by a survey carried out in 1978 in Chernaya Gora in the Sebezh region, as a result of which the settlement site was reclassified as definitely an industrial site (Miklayev *et al.* 1986). Industrial site prospection became Tatyana

Fig. 23. From left to right: Tatyana Smekalova with an Overhauser magnetometer GSM-19WG by GEM Systems (Canada) and cesium magnetometer M-33 by Geologorazvedka (Russia), Olfert Voss and Bruce W. Bevan with MMP-60 proton magnetometer by Geologorozvedka on the iron smelting site of Snorup in Jutland, Denmark, in 1996. After Smekalova *et al.* 2005: 16

Smekalova's specialty in the USSR (later Russia and Ukraine). She was also invited to carry out magnetic surveys of iron-smelting sites in Denmark (e.g. Smekalova, Voss and Abrahamsen 1993) (Fig. 23).

In Japan, the magnetic method was introduced to archaeological prospecting in 1967. The first attempt – aimed at tracing burials and settlement remains – gave no result due to "inappropriate target selection and improper understanding of magnetic field nature" (Nishimura, personal communication). Soon after this failed attempt, the method was applied to investigate kiln sites by researchers form the National Research Institute for Cultural Properties, Nara (NRICP) (Iwamoto 1974; Nakamura 1974). Proton magnetometers, a Japanese-made instrument and a Geometrics G-816 were used, initially in a single mode, than in differential mode together with a more advanced instrument Geometrics G-826. The proton magnetometers, together with a fluxgate gradiometer by Plessey, were then widely used by Yasushi Nishimura (of NRICP) to investigate sites of industrial character. Proton instruments were used to locate features in deeper layers; fluxgate machines (from the mid-1980s, the FM18 by Geoscan Research) were used to obtain a more detailed image of structures (Nishimura, personal communication).

5. 1980S AND 1990S: RAPID DEVELOPMENT OF APPLICATIONS OF THE METHOD

5.1. FACTORS SHAPING THE DEVELOPMENT OF ARCHAEOLOGICAL GEOPHYSICS, INCLUDING THE MAGNETIC METHOD

The rapid increase in the number of projects applying the method in the 1980s and 1990s was due to a number of factors: technological development, changes in archaeological priorities and in conservation law, and finally changes in archaeology education programmes. The influence of these factors varied from country to country, affecting each differently. But the process itself was the same for all of the chief methods of archaeological geophysics used commonly in archaeological research, including the magnetic method.

Technological changes already taking place in the leading countries in the 1980s, undoubtedly spearheaded a qualitative advance: slow proton magnetometers were almost entirely replaced by instruments with shorter measuring times (of the order of 0.1 sec.) and accuracy in the range of 0.1 (fluxgate) – 0.01 to 0.001 nT (caesium), recording the readings in the instrument's memory. Automation resulted in accelerated rates of ground coverage, whilst higher resolutions resulting from more accurate measurements and increased sampling density led to a much higher level of feature identification than had previously been achieved. Better quality instruments and their ever-growing internal logging capacity (allowing longer periods of fieldwork between successive data downloads) were enhanced by progress in the computing power of a popular newcomer, the personal computer, which allowed for different ways of digital processing of data to assist with the reading of the geophysical image. Improved PCs supported new software for visualizing geophysical results, rendering on a map features that had not been visible in previous graphic presentations: in magnetometry, greytone maps gradually superseded dot density and contour images to become the standard form of presentation.

The process of change is best described in the case of Great Britain, ever a leader as far as application of geophysical methods is concerned. Here, the main driver of change from the early 1990s was the need to provide economic, rapid and large-scale non-destructive archaeological evaluation as a requirement in advance of land development. This coincided with an increasing appreciation of the value of prospecting methodologies for the broader investigation of landscape and context, rather than simply on sites in isolation (Heron and Gaffney 1987: 78). According to C. Gaffney and John Gater (2003: 20-22), the growing importance of landscape issues encouraged these changes but it was a different process that acted as a catalyst. Chris Gaffney and J. Gater wrote:

> "While the inevitable trickle down of technology into the discipline (…) created a platform on which to work, this in itself cannot be regarded as the reason for the subsequent explosion in activity. (…) the information required by archaeologists changed during this period – the rapid evaluation of large tracks of land became the norm, and where traditional avenues of investigation were weak, geophysical techniques were strong. In particular the development boom of the late 1980s/90s and the general absorption of archaeology into the environmental assessment of large-scale developments, provided great incentive for those attempting to establish geophysical techniques within the archaeological methodologies."
>
> (Gaffney and Gater 2003: 21)

Numbers best illustrate the changes of approach to archaeological geophysics: about 60 surveys were carried out in Great Britain in 1980, but ten years later this number had grown to about 250 per year. The reason for this was the recognition by developers, working to new Planning Policy Guidelines, that geophysical survey could identify areas of archaeological importance at less expense than large-scale evaluation by excavation (Gaffney and Gater 2003: 22). The methodology could be used to evaluate large areas and then to target sites for more detailed excavation.

The increasing influence of this commercial practice in Great Britain was also symptomatic of changes taking place in other countries. In 1980, about half of the geophysical surveys in England were carried out by the Ancient Monuments Laboratory (AML), the other half being conducted by others, including British Gas. In 1979 , British Gas employed a geophysicist on the routes of planned gas pipelines. By 1990 AML was estimated to have undertaken only about 10% of geophysical surveys in England, the rest being carried out by commercial groups (Gaffney and Gater 2003: 20, 23; Gaffney 2008: 315). J. Gater's and C. Gaffney's GSB Prospection was the largest of these groups; from its establishment in 1986 to 2000 the group conducted over 1500 surveys, about 80% of which used the magnetic method (Gater, personal communication) (Fig. 24).

Fig. 24. Chris Gaffney (left) and John Gater after receiving a honorary degree from the University of Bradford, July 2006. Archive of Chris Gaffney

There is no doubt that the situation of archaeological geophysics was affected by developments in education and training. Prior to the wider dissemination of training in archaeological geophysics to archaeologists, researchers in archaeological geophysics were commonly geophysicists and physicists few of whom were actually employed full time in archaeology. Most of them were anchored in other fields, working in archaeology sporadically at best. Besides Bradford University, archaeological geophysics as part of the regular study *curriculum* was made available at Glasgow and Durnham Universities. An undergraduate degree in archaeological sciences became obtainable from Bradford in 1975, turning the university into a leading centre for British archaeological geophysics (Gaffney and Gater 2003: 19). A postgraduate masters course devoted to archaeological prospection alone was initiated at Bradford in 1995.

British experience demonstrated the effectiveness of using surveyors with archaeological background and basic expertise in geophysics. This created a new and economically advantageous situation: an archaeological graduate, trained to use geophysical methods, has lower financial expectations than a geophysicist who could be working for a geological company with a budget unimaginable in archaeology. A growing body of specialists capable of carrying out measurements and interpreting them properly lowered the costs of survey, thus making it more easily accessible.

The other factor contributing to progress in applying geophysical methods in archaeological research was from the sphere of what could be called "scientific communication". Archaeological geophysicists carry out surveys as part of the entire research process, including the analytical stage as well as synthesis and formulating conclusions. They can therefore adapt and change the research methodology to achieve greater effectiveness in given conditions. Practice has demonstrated repeatedly that results offered by researchers with just a geophysical background, uninformed by archaeological context, often proved unintelligible or of limited value to those who commissioned the survey. This made some archaeologists wary of geophysical methods in archaeology: disappointed once, they were not inclined to continue research with the use of such methods.

Changes in other countries applying geophysics to archaeology followed a similar scenario, although the impact of the two factors mentioned above: economic and "scientific communication", was different and occurred at different times. Commercial groups appeared in Germany and France two decades later than in Great Britain. In Poland the process was another decade late and kick-started only in the beginning of the 21st century. In Great Britain the developed structure of archaeological geophysics helped to avoid the painful misunderstandings that occurred, for example, in Germany, France and Poland, between geophysicists anchored in geology and archaeologists commissioning archaeological surveying.

It has already been observed that landscape research was an important beneficiary of the more extensive surveys in Great Britain. In other countries, large-area surveying did not arise from methodological debate but from conservation law: for example, the geophysical laboratory of the Bavarian State Department of Monuments and Sites in Munich used magnetometry to determine site extent for preservation purposes, that is, to establish areas under absolute protection.

The methods were also popularized thanks to the effective exchange of knowhow. The first such forum to be established was the *Archaeological Prospection* conference, organized biannually from 1995 and specifically dedicated to archaeological geophysics. Previous to that the subject had been presented at *Archaeometry* conferences, which were also biannual, but which were focused on material analysis and dating methods, leaving geophysics on the fringes. In the early 1990s, annual assemblies of the European Geophysical Society became an important forum, but archaeological geophysics remained marginal with regard to the mainstream, as at the *Archaeometry* conferences. The 1999 *Archaeological Prospection* conference in Munich set a standard for publishing abstracts of papers or extended versions in the form of short articles with references and illustrations (Fassbinder and Irlinger 1999). This has turned out to be an excellent review of the current situation in archaeological geophysics, giving insight into the work not only of big research centres but also commercial groups which, unlike the latter, are not obliged to publish their results.

The second forum of information exchange was provided by the journal *Archaeological Prospection*, which is dedicated to archaeological geophysics (with only minimal input from other prospection methods). It was the first periodical after *Prospezioni Archeologiche* to deal with the discipline exclusively. Groups of researchers associated with Bradford University called for the establishment of a periodical of this kind at the *Archaeometry* conference in Ankara in 1994. The first issues, edited by M. Pollard and A. Aspinall, was published with the date of November 1994.

Important monographs were published at the turn of the 1980s and 1990s: Tony Clark's (1990; revised edition 1996) introduction to the theory, history and practice of geophysical methods for archaeologists, illustrated with cases of practical application of the methods; and a study by I. Scollar, A. Tabbagh, A. Hesse and I. Herzog (Scollar *et al.* 1990) laying emphasis foremost on the theoretical principles of methods used. In 1995, the Ancient Monuments Laboratory (now part of the English Heritage) drew up and published guidelines on geophysical survey in archaeological evaluation (English Heritage 1995), intended to help achieve standardization of applied geophysical methods in archaeology.

5.2. Changes in magnetic method measurement methodology

The principal change in magnetic method measurement methodology which occurred in the 1990s was the development of multi-sensor mobile systems, moved either on carts or carried by the operator. The multi-sensor idea was generated in order to accelerate working speed; it permitted changes of magnetic field intensity to be recorded simultaneously along a number of measuring lines. The leading centres were based in Munich (Helmut Becker's lab), in Vienna (group drawing on the experience of Peter Melichar, directed by Wolfgang Neubauer) and in Kiel (Harald Stümpel and his team in the Institute of Geosciences/Geophysics, University of Kiel). H. Becker's definition of the "3 s rule": sensitivity, speed and spatial resolution (Becker 1999a: 100) triggered the work on multi-sensor designs. Systems based on caesium magnetometers and fluxgate gradiometers were selected for development in order to achieve the most precise images.

The Munich group's testing ground for developing caesium magnetometer prospection was ancient Troy. Here, measurements with a fluxgate gradiometer (Jansen 1992) demonstrated the effectiveness of the magnetic method for identifying the Roman city (Troy X) but could not trace features belonging to earlier phases in the existence of the town. Measurements with a caesium magnetometer, began by H. Becker and J.W.E. Fassbinder, recording the total field values with a resolution of 0.1 nT were designed to reach the deeper-lying layers. They did in fact trace architecture from Late Bronze Age Troy VI, providing in effect a map of the town from that age, extending over an area of at least 18 ha with an estimated population of 6000 inhabitants (Becker 1999c). Information about this mapping of Homeric Troy made the news, catching the attention of Robert Pavlik, constructor for the Picodas company, who offered to build an instrument with picotesla sensitivity, creating in effect the most sensitive system yet used in archaeology: CS2/MEP720 (Scintrex/Picodas). It enabled measuring with an accuracy of up to 1 picotesla (0.001 nT) (Becker 1995). Initially, the system operated as a one track gradiometer or variometer configuration of sensors. It was tested in 1994 at the site of Monte da Ponte in Portugal and in the same year again in Troy. H. Becker wrote:

> "It took the author almost two years [before] realizing that the two sensors of gradiometer CS2/MEP720 could also be moved parallel in fieldwork covering two tracks for total field measurement at same height above the ground. This simple "trick" doubles the sampling-

speed. Every sensor added to the system multiplies the survey speed and opens a wide range for magnetic prospecting over large areas with limited time."

(Becker 1999a: 100)

Fig. 25. Jörg Fassbinder taking measurements on Easter Island, using Smartmag SM4G caesium magnetometers by Scintrex, Canada. Archive of J. Fassbinder

Thus, by 1995, the system had fulfilled both the speed and sensitivity conditions. The key to this new measurement technique was the MEP720 processor with electronic bandpass filters of different frequency, adapted to cancel high frequency magnetic disturbances. A system of filters enabled a credible identification of manmade anomalies; the only anomalies which could not be removed were temporal variations with a wavelength compatible to the measuring time for surveying a 20 m line (measurements taken over a 20 m grid) (Becker 1999a: 102). The system was moved on a cart, limiting its usefulness only to sites where it could be wheeled. The next system to be constructed, Smartmag SM4G gradiometer by Scintrex, solved the issue of covering difficult ground. The system was mounted on a wooden frame carried by the operator and the probes were set 0.5 m apart. (Fig. 25) With a resolution 0.01 nT the sensors were less sensitive than in the CS2/MEP720 system, but still ten times more sensitive than the fluxgate instruments which dominated the market. This system also measured total magnetic field intensity. It was tested in 1996 at Monte da Ponte in Portugal (Becker 1999d). H. Becker and J.W.E. Fassbinder conducted dozens of surveys with the system outside the borders of Germany, within the framework of cooperative programmes with various archaeological institutes. Amogst the most spectacular mapping projects to be mentioned were the Ramesside capital of Egypt in the New Kingdom, Qantir in the Eastern Nile Delta, initiated in 1996 (Pusch *et al.* 1999; Becker and Fassbinder 1999a), the unknown architecture of the Hellenistic district in Palmyra in Syria (Becker and Fassbinder 1999b) and the Scythian settlement and mound burials (with complete grave furnishings) in Siberia (Becker and Fassbinder 1999c). The higher sensitivity system on a cart continued in use, mainly on sites in Germany or in the immediate vicinity of its borders (e.g. in Słonowice, Herbich and Tunia 2009). To

Fig. 26. Peter Melichar surveying a Roman villa in Zillingtal (Burgenland, Austria) using a Varian cesium gradiometer, autumn 1992. The cart with a mechanical distance measurement unit with 1 cm accuracy was developed by Friedrich Parisch. Data were stored on a logger developed by P. Melichar in 1986. Archive of the Vienna Institute for Archaeological Science, University of Vienna. Photo F. Parisch

increase the speed of fieldwork, Becker developed Smartmag's two-sensor system into a four-sensor one mounted on a cart, which he called a "magnetoscanner". With this instrument he completed several large-area projects, in Italy, e.g. Ostia (discovering among others an Early Christian basilica, Becker 1999b) and in Bavaria, e.g. Ruffenhofen (reconstruction of a complete plan of the Roman *castellum* with *vicus*, bath and cemeteries, Becker 2001: 10-12). In this last case, the measurement speed was of key significance in view of the fact that the site had to be covered within short periods between agricultural activities. The four-sensor system, however, did not earn the same regard as the manually carried two-sensor one which is still in use.

H. Becker and J.W.E. Fassbinder's work on important sites, covering large areas, brought spectacular information on these sites. There can be no doubt that the results, well published with excellent graphic presentation, helped to popularize the magnetic method, especially as they were also shown in media of broader scope (such as the film about Qantir for Discovery Channel).

The Vienna group also concentrated on developing caesium magnetometry, initially based on Becker's work. The group was interested in working with high resolution sensors in different configurations, mounted on carts by the operator (Doneus *et al.* 2001: 21-23) (Fig. 26). The combined efforts of researchers anchored in academic centres and in a private company (Archeo Prospections) created a group active in field prospection, at the same time perfecting ways of visualizing results and their archaeological interpretation (Neubauer *et al.* 1996; Doneus *et al.* 2001: 24). Their testing ground was Carnuntum, the Roman town near Vienna (Neubauer and Eder-Hinterleitner 1997). Surveying in

Fig. 27. Harald Stümpel (right) and Ercan Ercul of the Univeristy of Kiel surveying the Hittite site of Sarissa in Anatolia, Turkey, with a system of five fluxgate sensors mounted on a portable rack. Archive of H. Stümpel

different regions of Austria resulted in the discovery and mapping of dozens of Neolithic sites with characteristic ditched circular features (Neubauer and Melichar 2010).

The effectiveness of caesium magnetometers did not weaken the popularity of fluxgate gradiometer applications, chiefly because of the relative cheapness of these instruments and their easy use in the variant developed by Roger Walker, furnished with easy-to-use Geoplot software also sold by Geoscan Research. Until the introduction of the instrument constructed by Bartington (Bartington and Chapman 2004), the Geoscan fluxgate instruments dominated the British market and were also used in other countries. Despite being slower to use in the field compared to the multi-probe systems, these instruments were used on a large number of large sites such as at the Roman city of Wroxeter (using Geoscan magnetometers: Gaffney *et al.* 2000).

In the 1990s, a multi-probe system produced by Förster, a German company producing fluxgate gradiometers, was introduced in archaeology. The system did not grow from archaeological experience (as was the case of the caesium systems), but was developed for military needs, that is, primarily to locate unexploded ordnance. The instrument was adapted for archaeological purposes by a team from the Institute of Geosciences/Geophysics, University of Kiel in 1992-94 (Stümpel 1995; Jöns 1999). A system with five probes mounted on a portable rack carried by two people was employed to map the Hittite town of Sarissa in Turkey (Trinks *et al.* 1999) (Fig. 27). The system was improved over a number of years, with the sensors being mounted on a cart pulled by a small tractor, leading to a spectacular mapping of the entire site (65 ha) of the Greek colony of Selinus (Selinunte) in eastern Sicily (Erkul *et al.* 2003a; 2003b).

6. CONCLUDING REMARKS

The popularization of the magnetic method at the end of the 20th century and its application as a standard in surveying extensive areas led to considerable changes in the nature of archaeological projects. This process is illustrated very well by the changes which have taken place in Egypt, a country where archaeology is well advanced, but where the geophysical tradition was not so well grounded previously. The introduction of magnetic prospection laid the ground for a new field of studies, that is, ancient Egyptian urban planning. In the 1960s there were still researchers persuaded that, unlike Mesopotamian civilization, Egyptian civilization had no established towns (Wilson 1960: 126-127). Extensive excavation in the second half of the 20th century, especially in the Delta, demonstrated the falseness of this assumption. But it was the magnetic method which proved to be the ultimate tool in successfully tracing urban development processes and changes in urban planning over large areas. The best illustration of this situation has been provided by research in the complex of capitals of Egypt from different periods, located at Tell el-Dab^{c}a/Qantir in the Eastern Delta of the Nile, where measurements have covered more than 2 km^2 in Qantir (Becker and Fassbinder 1999a; Becker 2001: 8) and 1.5 km^2 in Tell Dab^{c}a (Forstner-Müller *et al.* 2007; Forstner-Müller *et al.* 2015: 157-161). Combined with knowledge drawn from excavations and source studies, the survey has permitted urban analyses of various parts of this area at different time periods (Pusch *et al.* 1999; Forstner-Müller 2010; Bietak and Forstner-Müller 2011).

Fig. 28. Manfred Bietak explaining the topography of the New Kingdom palatial complex at Tell el-Dab^{c}a in the Nile Delta, Egypt, October 2004 (magnetic map by Tomasz Herbich and Christian Schweitzer, survey 1999-2001). Author's archive

Common use of the magnetic method for surveying large-area sites where there was virtually no surface expression of buildings (especially in areas of agricultural cultivation), had one other practical aspect. Archaeologists were now able to understand sites in their broader context, within a landscape setting, and were no longer dependent on the restricted key-hole view provided by excavation of just 1-10% of a site. Magnetic maps are perfectly suited to presentations of site topography within the original landscape (Fig. 28).

The section titles of this article render the nature of developments in the application of the magnetic method over forty years from proton magnetometers and magnetic balances to fluxgate magnetometers, from slow development in the 1960s and 1970s to the boom of the 1980s and 1990s. Apart from describing more or less known applications of the method, the author has made an effort to highlight research which has so far not made the history books or has been mistakenly appraised due to the complete lack of, or restricted contact between scholars on either side of the Iron Curtain (depending on country and historical circumstances). So deeply grounded were such opinions that Helmut Becker's expressed conviction (2009: 131) was that that archaeological geophysics in the Czech Republic and in Slovakia had not started before 1990, while the truth of the matter was that not only were geophysical methods being applied to research on local sites in the 1960s (see above), but they were also used in Czechoslovakian research on sites abroad, as for example in the important work carried out with the magnetic method in the complex of pyramids from the Old Kingdom at Abusir in Egypt (Verner and Hašek 1981). There is still a need for summary evaluation of applications of the magnetic method in countries where it was definitely being used by local researchers; however, access to these source materials is restricted, not the least because of language issues. Our knowledge in this respect has been augmented by two papers of a historical nature published in 2011. One of these presented an account of the earliest surveying with the magnetic method in Poland (Herbich 2011), the other focused on the history of archaeological geophysics in Sweden (Viberg *et al.* 2011). One can only hope that researchers in other countries will take up historical studies of this kind as soon as possible, while the pioneers and their immediate successors can still have a part in their preparation.[6]

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This article has been inspired by Prof. Jerzy Jankowski who encouraged me to write on the magnetic method in archaeology. The study in the form anticipated

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[6] The conference "Pioneering Archaeological Prospection" organized at Laa an der Thaya (Austria) in October 2011 by the Ludwig Boltzmann Institute for Archaeological Prospection and Virtual Archaeology in Vienna was an excellent initiative addressing the idea of recording the beginnings of archaeological geophysics.

by Prof. J. Jankowski never appeared, however this present paper is based largely on the first chapter of the study, outlining the history of the method's application in archaeological research. The other person who has played an inspirational role is Dr. Zofia Stoss-Gale, who informed me years ago that a dozen or so early volumes of *Archaeometry* were available free from the Research Laboratory for Archaeology and History of Art in Oxford. Thanks to her the volumes, which are not held by any library in Poland, came to be in my possession and have given me insight into early applications of the method. The author gratefully acknowledges remarks made by colleagues who have read earlier drafts of the article and shared their comments: Helmut Becker, Jörg W.E. Fassbinder, Chris Gaffney, Albert Hesse, Christian Schweitzer and Irwin Scollar. The following found time to answer my questions, written and oral: Luis Barba, Bruce Bevan, John Gater, Daria Hookk, Roman Křivánek, Yasushi Nishimura, Harald Stümpel, Alain Tabbagh and Sheldon Breiner. The author is also very grateful for helpful remarks (and linguistic correction) to Andrew David who, as well as Armin Schmidt, read the article at the editors' request. Separate thanks are due individuals and institutions providing images: Archaeological Museum in Kraków, Tadeusz Baranowski, Christophe Benech, Charles Henri Burglin, Sheldon Breiner, Steve De Vore, English Heritage, Jörg W.E. Fassbinder, Chris Gaffney, Geoscan Research, Albert Hesse, Ludwig Boltzmann Institute for Archaeological Prospection and Virtual Archaeology in Vienna, the Museum of History of AGH University of Science and Technology in Kraków, Armin Schmidt, Tatyana Smekalova, Harald Stümpel, University of Pennsylvania Museum in Philadelphia.

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