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From Magnetic Prospecting to Virtual Archaeology

Remarkable developments have been made over the last decades in geophysical prospecting for archaeological purposes, beginning in the 1950s with the use of electricity to measure soil resistivity and of magnetics in the form of proton magnetometers (Aitken, 1961, 1974). Until quite recently the use of magnetics in particular had become practically unrivalled through continual improvements involving measuring techniques in the field and procedures for analysis, interpretation and presentation. Milestones included construction of a differential proton magnetometer in the 1960s, automation of digital data collection, electronic processing of the data and finally digital imaging (summarized in Scolar et al. 1990). Building on this work at the Rhenish State Museum in Bonn, at the beginning of the 1980s the author was able to develop caesium magnetometry to the point where it could be used in archaeological prospecting, working first at the Institute for Geophysics at the University of Munich and then at the Bavarian State Conservation Office.

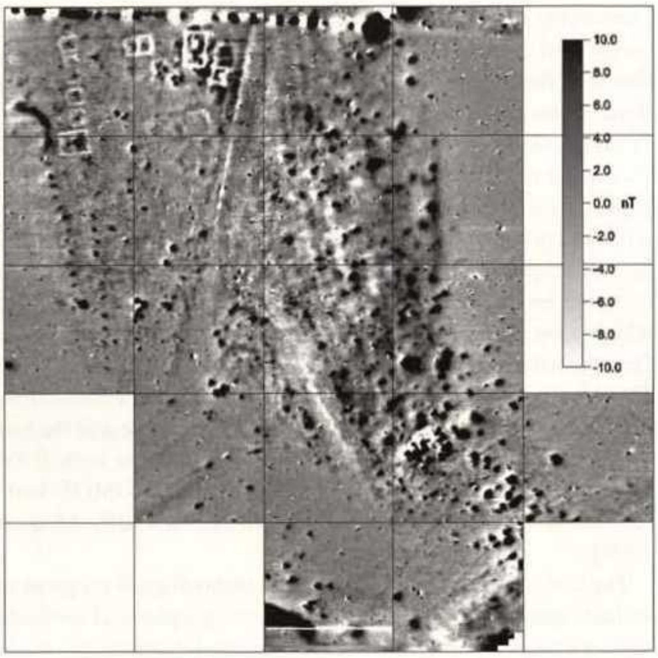

Fig. 1. Roman castellum at Ruffenhofen. Magnetogram of the street of grave monuments. SMARTMAG SM 4G-Special as quadro-sensor. Sensitivity 0.01 nT (10 picotesla), raster 0.1/0.5 m interpolated to 0.25/0.25 m, dynamics –7.0/+7.0 nT in 256 gray scales (black/white) 40 m grid, magnetometer prospecting H. Becker, Mag.Nr. 6928/074-00B.

Fig. 2. Cicah (Siberia). Magnetogram of the measurements from 1999-2000 with the entire Scythian settlement (city) from the 8th-7th centuries BC and the (presumably later) necropolis with four large *kurgans*. SMARTMAG SM4G-Special as duo-sensor. Sensitivity 0.01 nT (10 picotesla), raster 0.1/0.5 m interpolated to 0.25/0.25 m, dynamics –5.0/+5.0 nT in 256 gray scales (black/white), 40 m grid, magnetometer prospecting H. Becker und J. Faßbinder.

Fig. 3. Roman castellum at Ruffenhofen. Defensive walls, towers, gates, trenches, and parts of interior construction in stone shown as vegetation features in the grainfield. Aerial photograph from 5 July 2001, photographer K. Leidorf, archive number 6928/074-3; SW8018-10.

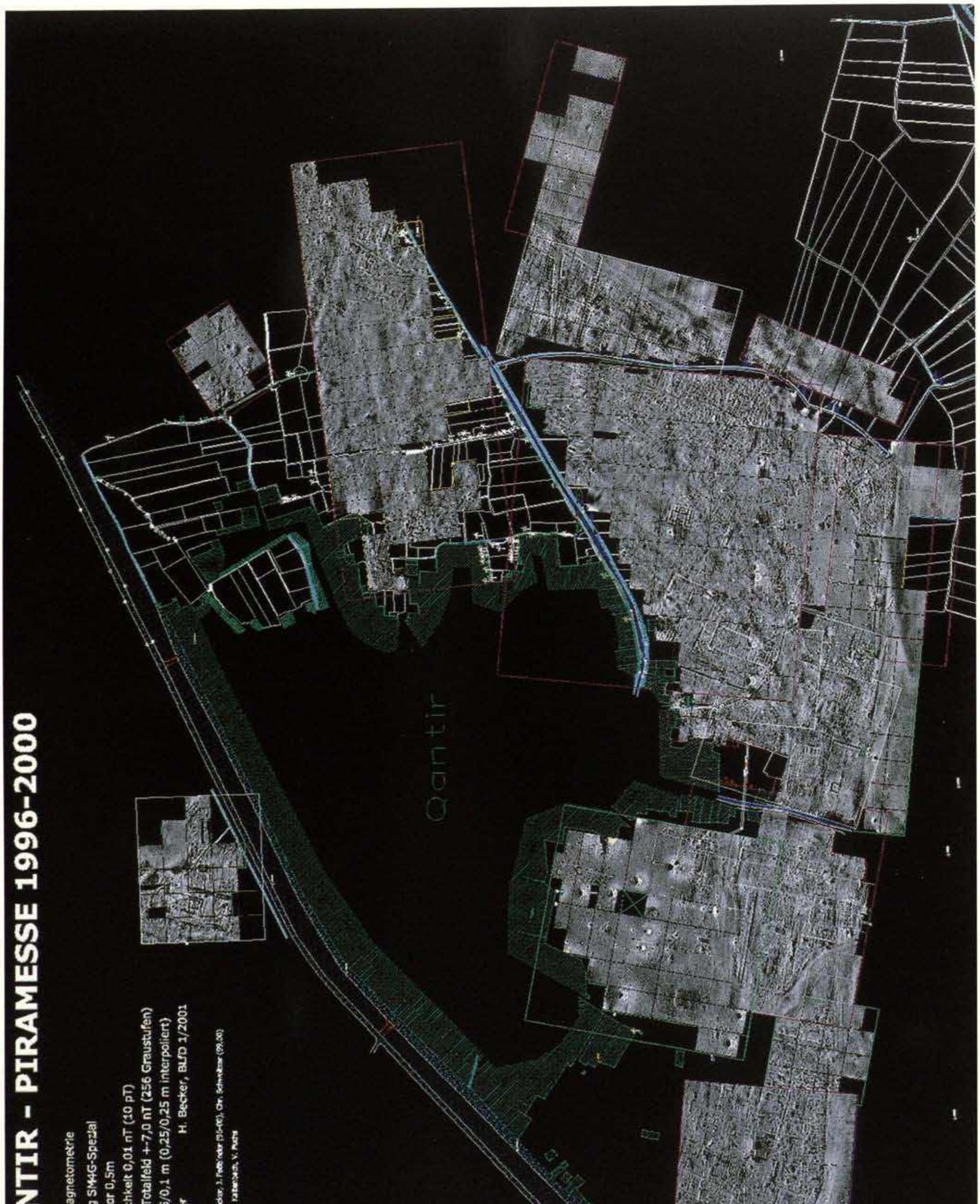

Fig. 4. Qantir-Piramesse. Compilation of the magnetograms from 1996 to 2000 on the topographic map. SMARTMAG SM4G-Special as duo-sensor. Sensitivity 0.01 nT (10 picotesla), raster 0.1/0.5 m interpolated to 0.25/0.25 m, dynamics –7.0/+7.0 nT in 256 gray scales (black/white), mean value between original data and high pass filter, 40 m grid, magnetometer prospecting H. Becker and J. Faßbinder (1996-2000), Chr. Schweitzer (1999, 2000), topography V. Fuchs, D. Kaltenbach.

The development "from nanotesla to picotesla" in the mid-1990s can be characterized as a "quantum leap" in a literal sense: a magnetometer with picotesla sensitivity, heretofore used in aeromagnetics, was put to use on the ground for archaeological prospecting (Becker 1995). Development of the caesium magnetometer, known as CS2/MEP720 (Scintrex/Picodas, Canada), became possible in close collaboration with Robert Pavlik (Picodas) after prospecting of the city fortifications of Homeric Troy in 1992 gained worldwide attention (Becker 1993). Still in use today, it is the most sensitive magnetometer that has ever been employed in archaeological prospecting. In addition to its high sensitivity the essential improvement of the CS2/MEP720 over older caesium magnetometers is a new procedure for time mode sampling of the data. Ten values can be stored per second; at a fast walking tempo this accords with measurement intervals of c. every 10 cm. This time mode sampling of the data first made possible so-called non-compensated (against time variations) measurements (as opposed to time-based variations) through the use of band-pass filters to cancel the high frequency portion of time variations. This simultaneously laid the foundation for use of the gradiometer as a duo-sensor magnetometer.

Also at this time Jörg Faßbinder completed his dissertation on the magnetic characteristics and genesis of ferrimagnetic minerals in the ground, as related to magnetic prospecting of archaeological monuments (Faßbinder 1994). He had discovered a new biogenic magnetizing process: so-called magnetic bacteria that have built-in magnetite single crystals are involved in the rotting of organic materials and the subsequent formation of soil. When soil formation is complete the bacteria die, leaving the magnetite crystals in the formally organic structure. Traces of a (non-magnetic) wooden post, for example, thus become magnetic and can be identified even from above ground with highly sensitive magnetometers through the anomaly of the geomagnetic field. This makes magnetic prospecting possible for the broad field of wood/earth archaeology at our latitude.

A true triumph in the use of magnetics for archaeological prospecting occurred with introduction of the multi-sensor technique in 1995 (Becker 1999). In the so-called duo-sensor configuration the two sensors of a vertical gradiometer are used horizontally, whereby the total geomagnetic field can be recorded in two tracks. The speed of measurement in the field is thus doubled. The duo-sensor configuration opens up new possibilities for high resolution prospecting, also covering large areas.

A further increase in the speed of measurement using caesium magnetometry was achieved in 1996 with introduction of the specially manufactured SMARTMAG-SM4G caesium magnetometers (Scintrex, Canada): up to four complete magnetometer systems with two gradiometer processors, data storage banks and a power supply can be fitted on a newly constructed cart. The analysis process corresponds to that of a double duo-sensor configuration. Thus the speed of measurements in the field can be increased four-fold. Very strong geomagnetic variations during magnetic storms can be compensated through a fifth magnetometer system as a variometer. In uneven or difficult topography the SMARTMAG-SM4G-Special can also be carried as a duo-sensor. Since a cable between the sensor and the magnetometer processor is not necessary, this arrangement can even be used under extreme conditions by one person. The SMARTMAG-SM4G in the duo-sensor configuration has also proved highly successful for projects in foreign countries, which have been carried out using this apparatus exclusively since 1996. The SMARTMAG duo-sensor configuration can be characterized as the most successful development so far for magnetic prospecting. Measurements made in Bavaria in 2000 were done using the SMARTMAG quadro-sensor if possible. Without this apparatus it would have been quite impossible to measure the huge site at Ruffenhofen with a Roman castellum, *vicus* and street of graves (c. one-half square kilometer) in the brief breaks available between agricultural use. The same is true for the Celtic earthwork enclosure in Weiltingen.

During the prospecting of Piramesse (Becker, Faßbinder), the city of Rameses in the Egyptian delta, an area of more than one square kilometer was covered for the first time (50 million measurements in a raster of 0.1/0.5 m, interpolated to 0.25/0.25 m). With Piramesse estimated to extend c. 30 square kilometers, the area measured so far cannot be considered representative, but nonetheless entire urbanized quarters could already be distinguished, with temples, palaces (probably including one of the main Rameses palaces), villa districts, dense residential areas and a shoreline more than one kilometer in length. Up to four settlement strata are superimposed in some places. The analysis of the measurements from 1996 to 2000 were standardized so that the magnetograms of the prospected areas were presented as the mean of the original data with the high pass filter. The compilation of these mean value magnetograms onto the topographic maps best reflects the "city map" of the Rameses metropolis (fig. 4).

Nearly sensational results were also produced in Cicah (Siberia) where magnetic prospecting was carried further (Becker, Faßbinder). After the major part of a Scythian urban site from the 8^{th}-7^{th} centuries BC could be prospected in just three days in 1999, in 2000 the entire city and its necropolis were to be covered. Because two grave sites had already been surveyed just beyond the outer city gate at the edge of the area measured in 1999, it was anticipated that it would be easy to prospect the necropolis that was presumably directly adjacent. But in fact it was necessary to prospect an area of c. four hectares, without any results, until another grave site was finally found. In order to prospect this (probably more recent) necropolis at a distance of 240 m, an area of more than 26 hectares had to be measured; more than 20 graves, including four large so-called kurgans, were found (fig. 2). The necropolis belonging to the urban site from the 8^{th}-7^{th} centuries is still being sought, although continued prospecting work does not appear very promising without any further points of reference for its approximate location on the expanse of the Siberian steppe.

Continued collaboration with the archaeologists and engineers of the Technical Center for Protection of Cultural Properties in Shaanxi Province (China) is described by Jörg Faßbinder in his progress report. Since it was again not possible to work in the mausoleum of the First Chinese Emperor Qin Shihuang, we concentrated on one of his residences near the village of Wah ze Gang. The caesium magnetometer SMARTMAG SM4G-Special was used here as a duo-sensor.

Although the discussion so far has focused primarily on the development of measuring techniques using caesium magnetometry and on the presentation of magnetograms, it must also be emphasized that, with as much as a ten-fold increase in the speed of measurement, the problems of magnetic prospecting are now to be found on a totally different plane. The areas prospected with the multi-sensor technique have sometimes covered more than 200 hectares per year, which puts the processes of visualization, analysis and interpretation to a new test. This

Fig. 5. Roman castellum at Ruffenhofen. Magnetogram of the castellum from a bird's eye view as the basis for reconstruction and computer animation.

amount of data cannot be tackled with traditional (manual) methods of analysis. Some aspects of measuring technology have also changed on an international level: there is now a demand for a combination of techniques in geophysical prospecting, in particular high resolution magnetics, electricity and ground-penetrating radar. In the Bavarian State Conservation Office we unfortunately have not been able to contribute to the use of ground radar, which is so far the only method for three-dimensional representation of underground archaeological structures, because we still do not have the essential apparatus. The situation is even worse regarding visualization, analysis and interpretation of data: long overdue developments in the presentation and interpretation of the magnetograms cannot be completed because we do not have the modern computers and analysis programs. Current developments are focusing on automatic production of plans through pattern recognition, 3-D visualization of the magnetograms on the digital field model, interpretation based on geographic information systems (ArcViewGIS) and computer animation and simulation. Archaeological prospecting could achieve a new dimension with this step toward virtual archaeology. The first test run using 3-D visualization and computer animation helps to illustrate how urgently we need to introduce these methods into the routine work of archaeological prospection:

The Roman castellum at Ruffenhofen in Middle Franconia at the foot of the Hesselberg is one of the fortresses along the limes. The location of the castellum has long been known; already in 1892 it was investigated in excavations by the Imperial Limes Commission. In 1981 a series of aerial photographs by O. Braasch threw new light on a site that had been neglected by researchers. The photos rather clearly show a previously identified storehouse, part of the defensive wall, the plan of the *principia*, and four (!) trenches.

Ruffenhofen subsequently became an El Dorado for aerial archaeology. In addition to O. Braasch, the images by H. D. Deinhard, K. Leidorf, J. Mang and H. Thoma helped to greatly further knowledge of the area of the castellum and *vicus,* making it possible to produce sketches. Up till now the absence of exact

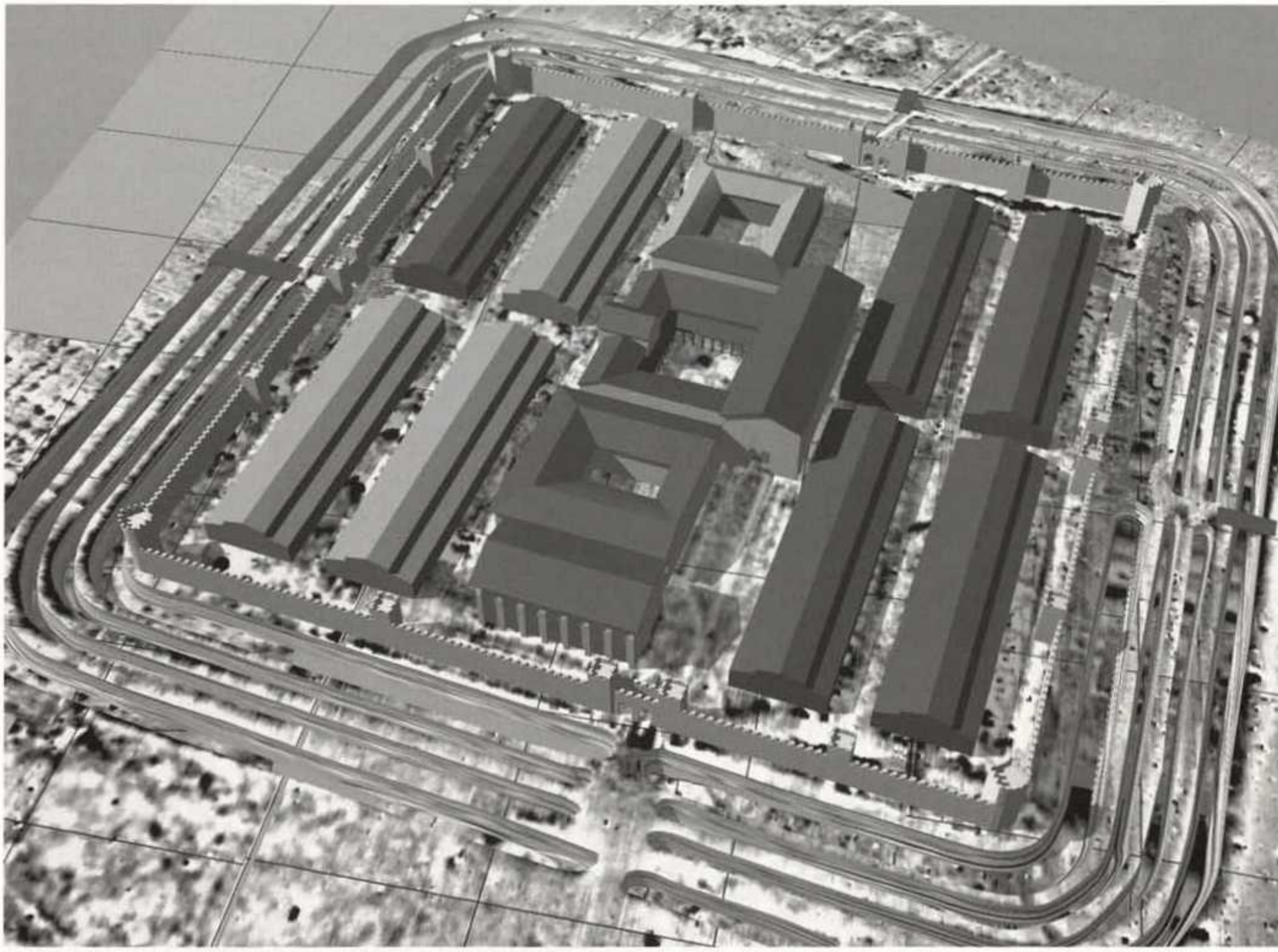

Fig. 6. Roman castellum at Ruffenhofen. Still image from the computer animation with the inner structures of the castellum, computer animation H. Becker, A. Pohl 2000

control points for distortion correction of the oblique photos has made it difficult to unify them for a ground plan that covers the entire area. A new aerial photo by K. Leidorf from July 2001 shows practically the entire castellum and the baths so that a majority of the previous images from the last twenty years can be considered outdated – further proof of the importance of continuity in aerial archaeology (fig. 3).

The castellum is in a desolate condition today. Plowing has already brought the lower layers of the foundation walls to the surface and large numbers of important metal artifacts have been stolen.

From 1998 to 2000 the castellum and large sections of the *vicus* were magnetically prospected for the first time (Becker et al. 2000). A newly developed equipment cart with a quadro-sensor arrangement for the caesium magnetometer Scintrex SMARTMAG SM4G demonstrated its successful use in the field here. The advancements made in measuring using this new technique are such that now large archaeologically relevant landscapes can be surveyed in a relatively short time. The magnetograms show astonishingly clearly the entire castellum, the large baths, and almost the entire camp which stretches 700 m to the south (see the detail in fig. 5). A large fire in the entire castellum caused such a strong contrast in the magnetization that it is possible to distinguish between stone and wooden buildings. In the strongly magnetized fire debris, the almost non-magnetic walls of sandstone produce a negative anomaly (light in the magnetogram), whereas wooden foundations are characterized as a positive magnetic anomaly (black).

Prospecting of the *vicus* was largely completed in 2000. The great success of the millenium year was the prospecting of a necropolis belonging to the castellum (fig. 1). A double row of fire burials and numerous stone grave monuments are lined up so that they appear to be arranged in their own street of graves. This almost recalls, on a smaller scale, the street of graves in Palmyra in Syria. As in Palmyra, the large grave monuments in Ruffenhofen must also have had inscriptions, from which it will finally be possible to read the name of the castellum and its division. Continued prospecting will show if this is the only

Fig. 7. Roman castellum at Ruffenhofen. Magnetogram of the castellum with the *vicus* and the baths. SMARTMAG SM4G-Special as quadro-sensor. Sensitivity 0.01 nT (10 picotesla), raster 0.1/0.5 m interpolated to 0.25/0.25 m, dynamics –7.0/+7.0 nT in 256 gray scales (black/white), 40 m grid, magnetometer prospecting H. Becker, Mag.Nr. 6928/074-00A.

necropolis or if others might be located at a greater distance on the streets leading out of the castellum. With production of the magnetograms it immediately became clear to the experts that this is an archaeological monument of great significance. Where else is a Roman castellum, the entire *vicus* and a street of graves located in the open landscape? The problems facing preservationists for the protection of this unique archaeological ensemble were deemed enormous, even hopeless: an area of one-half square kilometers (50 hectares) would have to be removed from intensive agricultural use and given special protection.

On the basis of the magnetograms and known reconstructions of Roman buildings and other castella, an initial computer animation was developed by Alexander Pohl for the castellum with its interior structures. After a very exact and detailed reconstruction with a walk-through animation of individual buildings (barracks, warehouse, gate, *principia* with vestibule), faithful down to the smallest architectural feature, it became obvious that the computer available to us was not sufficient for a complete animation of the entire castellum. Therefore a simpler model – described as a "shoe box model" – was designed. A still image from the computer animation of the castellum, which can be walked-through from different perspectives, can be seen in fig. 6 (Becker, Pohl). A project that at first seemed like child's play instead turned out to be the very best medium for conveying the importance of this archaeological monument to the public. While the experts were still discussing among themselves whether the proposed reconstruction of the defensive walls and the battlemented towers would be possible, working groups had long gone into action in the Hesselberg district and plans had been developed for how the castellum could be protected, researched further, and made accessible to the public. By July 2001 the community-led negotiations with the farmers had proceeded so far that the entire castellum could be removed from intensive agricultural use – probably the most important prerequisite for lasting protection. Erection of an information booth on the castellum in the small museum of Weiltingen is also planned. Defensive walls, towers and fortification ditches of the castellum are to be marked in the landscape using special plantings.

The expectations concerning conveyance of the importance of an archaeological monument which is rather problematic from a preservation perspective to the public seem to be fulfilled. Inscription of the limes on the World Heritage List presumably could also raise the castellum in Ruffenhofen to this level. There remains an urgent need to continue to expand this very successful start in virtual archaeology.

References

Aitken, M. J., *Physics and Archaeology*, London 1961 and Oxford 1974.

Becker, H., 1993, "Die Suche nach der Stadtmauer des homerischen Troia", in: *Denkmalpflege Informationen*, hrsg. v. Bayer. Landesamt für Denkmalpflege, Ausg. D Nr. 18 / 22. März 1993, 1-12.

Becker, H., 1995, "From Nanotesla to Picotesla – a new window for magnetic prospecting in archaeology", in: *Archaeological Prospection*, 2, 217-228.

Becker, H., 1999, "Duo- and Quadro-Sensor Configuration for High-Speed/High-Resolution Magnetic Prospecting with Caesium Magnetometer", in: *Archaeological Prospection*, Arbeitshefte des Bayerischen Landesamtes für Denkmalpflege, vol. 108, 100-105.

Becker, H., Deinhardt, H.-D., Thoma, H., 2000, "Prospektion des Kastells Ruffenhofen mit Luftbild und Geophysik, Gemeinde Wittelshofen, Landkreis Ansbach, Mittelfranken", in: *Das archäologische Jahr in Bayern 1999*, Stuttgart 2000, 56-59.

Becker, H., 2001, "Prospektion und Visualisierung der spätkeltischen Viereckschanze von Weiltingen, Markt Weiltingen, Landkreis Ansbach, Mittelfranken", in: *Das archäologische Jahr in Bayern 2000*, in press.

Faßbinder, J. W. E., 1994, *Die magnetischen Eigenschaften und die Genese ferromagnetischer Minerale in Böden im Hinblick auf die magnetische Prospektion archäologischer Bodendenkmäler*, Buch am Erlbach 1994.

Faßbinder, J. W. E., Stanjek, H., Vali, H., 1990, "Occurrence of magnetic bacteria in soil", in: *Nature*, 343, 161-163.

Scolar, I., Tabbagh, A., Hesse, A., Herzog, I., 1990, *Archaeological prospecting and remote sensing*, Cambridge University Press 1990.