

## **Geophysics, satellite imagery, urban survey and archaeological excavations - complementary contributions to reconstruct an ancient urban landscape - the case of Sagalassos (SW-Turkey)**

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**Abstract:** Within the framework of this multidisciplinary project several scientific disciplines, either or not traditionally linked to archaeology, collaborate to reconstruct the development of the site in relation to its natural environment. Apart from a.o. archaeozoology, palynology and geomorphology also archaeoseismology, geochemistry, two-dimensional resistivity imaging for structural geology and high resolution remote sensing complement the multi-method archaeogeophysical prospection, as applied to the town and its hinterland. For the site, where the project's archaeological field work initially mainly focused on the excavation of the town centre, a new integrated research approach was initiated in 1998 to reconstruct the spatial and chronological development of the wider urban area of the town, as part of a PhD by F. Martens. A series of test soundings was excavated throughout the urban area, whereas simultaneously a programme of intensive archaeological survey was carried out between 1999 and 2005, comprising of the systematic collection of all archaeological surface evidence as well as the systematic recording of surface architecture. Important progress was made in the urban research, when from 2002 onwards also geophysical survey was applied at Sagalassos, which was carried out by a team supervised by B. Mušič. The combination of the archaeological research results with the evidence from the geophysical survey and the high resolution remote sensing and geomorphological analyses (V. de Laet), show that an integrated approach combining different research techniques and fields of expertise can lead to a better understanding of ancient urban landscapes and it illustrates how the results of various spatial analyses can be complementary contributions to the reconstruction of past cultural landscape.

**Keywords:** multi-method geophysical exploration, satellite imagery, architectural survey, ancient urban landscape, Sagalassos

## Introduction

The ancient city of Sagalassos in Pisidia is located c.10 km SSW of the modern town of Isparta. Since 1990, a team directed by Marc Waelkens of the Katholieke Universiteit Leuven is conducting interdisciplinary research on the ancient town and its territory. Within the framework of this multidisciplinary project several scientific disciplines collaborate to reconstruct the development of the site in relation to its natural environment (see: WAELEKENS 2004a; 2006; 2008). The abundance of natural and mineral resources present at the site, together with a highly fertile territory (VERMOERE 1999, WAELEKENS et al. 2008), allowed the relatively small Hellenistic site to develop into a centre of regional importance in Roman times (WAELEKENS 2002; 2004a; 2006) (Figs. 1 and 2). Recently, a Classical/Early Hellenistic predecessor of Sagalassos was discovered at Tepe Düzen, ca. 1.8 km southwest of the current site, although the chronology of the occupation at Tepe Düzen and the issue of its possible co-existence for some time with Sagalassos, is still under investigation (but see already VANHAVERBEKE et al. -in press).

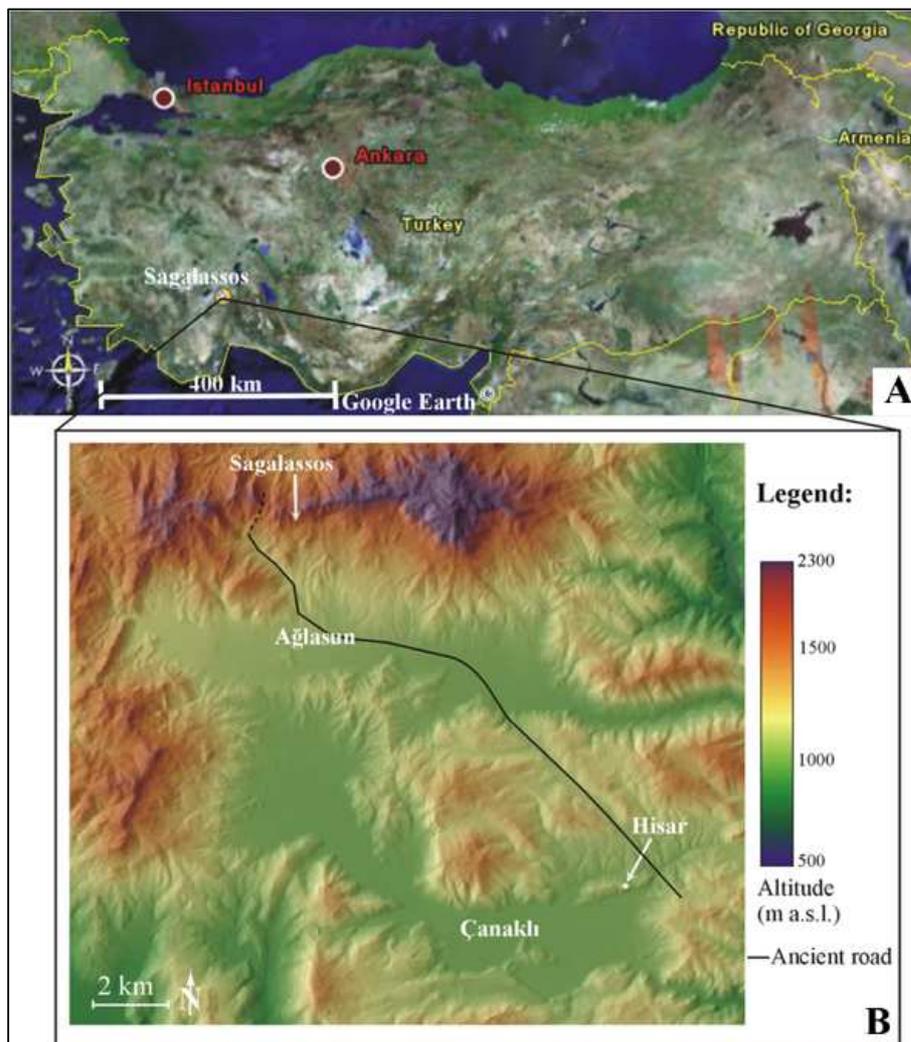


Fig. 1 – Location of the study area in SW Turkey. (A) Situation of the study area in Turkey and (B) physical setting of the archaeological site of Sagalassos (20m resolution DEM derived from 1:25000 topographic map) (after DE LAET et al. 2008).

Archaeological research at Sagalassos has shown that the town was intensively occupied from Hellenistic times into the 7<sup>th</sup> century AD. The site's monumental centre was laid out in several phases between the 1st century BC and the 3rd century AD. The Hellenistic centre mainly concentrated around the Upper Agora, whereby the typical constituents of a Hellenistic town were arranged asymmetrically around this square (MITCHELL 1991; WAEKENS 2004b). The layout of a new more regular town plan was probably already initiated shortly after 100 B.C., contemporary with the layout of a Bouleuterion, and involving the rearrangement of the Upper Town through the construction of a number of buildings and monuments with a common orientation (MARTENS 2007). From early Imperial times onwards, the urban area expanded in eastern direction, where a new residential quarter was arranged and toward the south, where a second urban core was laid out around the Lower Agora in the course of the 1st and 2nd centuries A.D, with a.o. a Temple dedicated to Apollo Klarios, several highly decorative nymphaea and a giant public Bath Building. Also the Upper Town was further furnished with monumental architecture during the 2<sup>nd</sup> century a.o. with another façade nymphaeum and a Macellum (WAEKENS 2002). Excavations evidenced a large-scale building program of urban infrastructure during the later 2nd and 3rd century A.D. In this period an esplanade was arranged between the early 2<sup>nd</sup> century AD Neon Library and the Doric Fountain House, whereas a newly (re)arranged street connected this zone to the Roman Theatre and another (renewed?) west-east axis linked the town's Potters' Quarter, to the Library Esplanade and further to the west to the Upper Town. Despite of a period of internal and external stress in the later 4<sup>th</sup> -early 5<sup>th</sup> centuries AD, when also the Fortification Wall was rebuilt, the town continued to flourish at least until the mid 6th century AD (WAEKENS et al. 2006), as documented at the late antique urban mansion under excavation (UYTTERHOEVEN et al. in press), after which decay gradually set in (VANHAVERBEKE et al. 2004). Recent research has demonstrated that after the devastating earthquake (SIMILOX-TOHON et al. 2004), now dated between 540 and 620 AD (DE CUPERE et al. 2008), the site was not entirely abandoned as previously assumed, by that some parts remained inhabited into the 13<sup>th</sup> century AD (WAEKENS, POBLOME 1993, 1995, 1997; WAEKENS, LOOTS 2000; MARTENS in preparation).

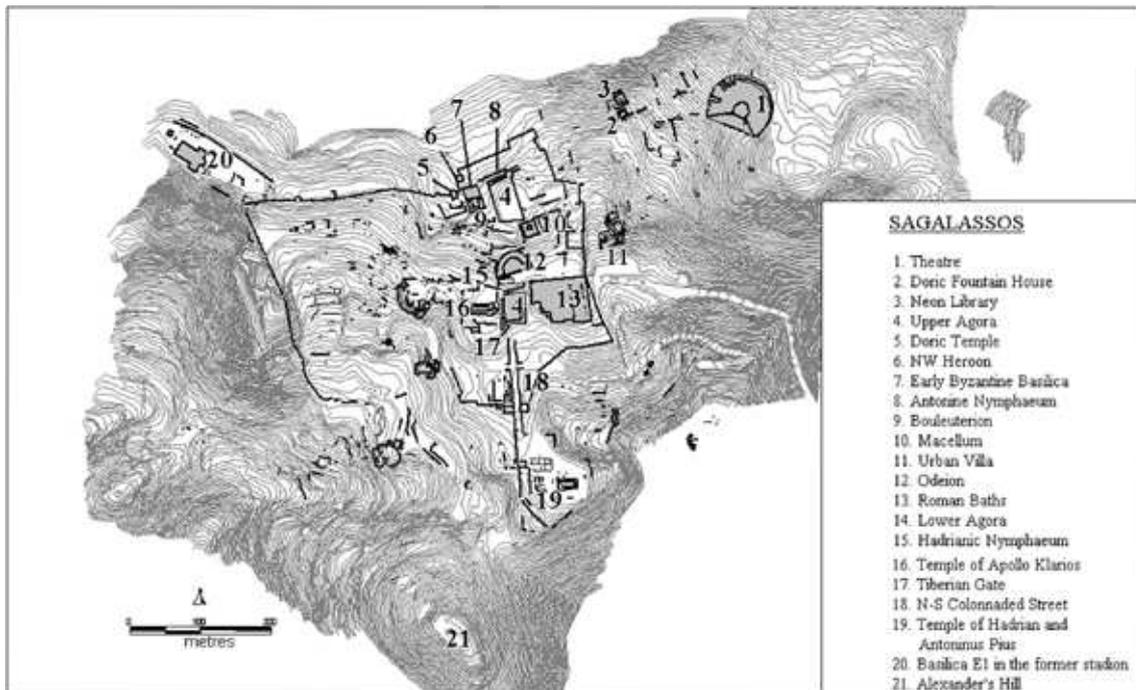


Fig. 2 – Topographic map of Sagalassos (Sagalassos Archaeological Research Project) site with the main known buildings indicated (after MARTENS 2007).

### The integrated research strategy

To study the urban planning and development of Sagalassos, apart from the large-scale excavations, various non- or minimally invasive research strategies are combined. To obtain insight into the spatial and chronological development of the wider urban area beyond the monumental centre it was decided to initiate a still ongoing programme of test soundings on the network of streets, excavated throughout the urban area from 1998 onwards (MARTENS 2007). Simultaneously also a programme of intensive archaeological survey was started in 1999 (MARTENS 2005), comprising the systematic collection of all archaeological surface evidence as well as the systematic recording of surface architecture. The application from 2002 onwards of a geophysical multi-method approach research design induced an important progress in the urban research. Hereby, the archaeological and architectural survey data and geoarchaeological exploration (see: PAULISSEN et al. 1993, VERSTRAETEN et al. 2000, WAELKENS et al. 2000, SIMILOX-TOHON et al. 2005, DE LAET 2007, MUCHEZ et al. 2008, DEGRYSE et al. 2008) is combined with the evidence from the high resolution multi-method geophysical survey and the very high resolution satellite remote sensing (see. DE LAET 2007, DE LAET et al. 2007, 2008, in press) followed by geomorphological analyses (Fig. 3) (for actual results see: DE LAET 2007). The properties of this methodology as well as its research potential are introduced and exemplified below.

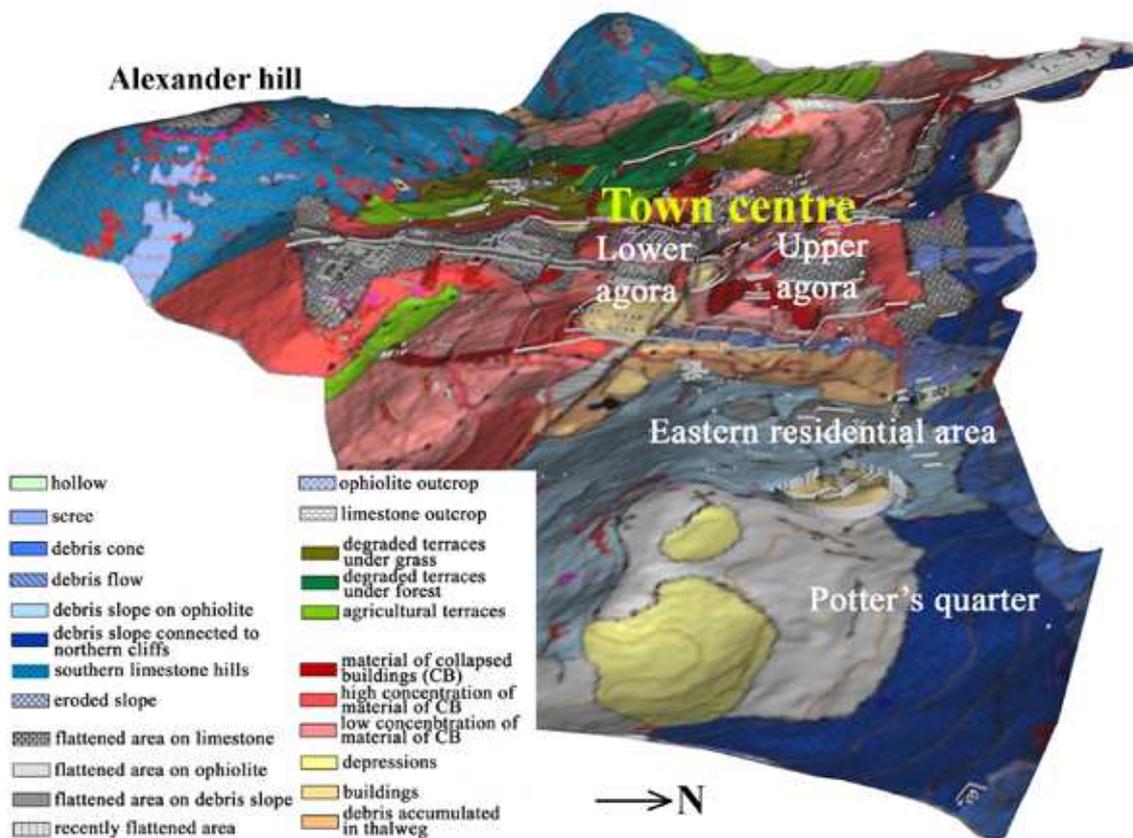


Fig. 3 – Geomorphological map of Sagalassos on digital elevation model (after GOEMANS 1995). For actual results see: DE LAET 2007.

## Methods applied

### Satellite imagery

The methodology applied here is identical to this employed in DE LAET et al. (2007, 2008, in press) - of which some selected parts will be briefly outlined below-, whereby visual as well as automatic methods are applied to analyze very high resolution satellite imagery. Within this study Quickbird-2 imagery of the monumental centre of Sagalassos is examined in order to test its potential for the automatic extraction of archaeological features with different characteristics ranging from excavated monuments to discrete features, by means of GIS, pixel- and object-based methods. Subsequently the obtained results are compared with a visual interpretation and the detailed map of the ancient town. A second objective is to evaluate to what extent Quickbird-2 imagery is able to detect previously unknown features by applying several physically independent and therefore complementary methods (De Laet, V. et al. 2007, 2008, In Press). The site is chosen for its large size and its dense pattern of well visible buildings with regular vertical walls in the monumental quarter as well as large unexcavated areas that are prospected by intensive archaeological and detailed geophysical exploration, applying several physically independent and therefore complementary methods (DE LAET et al. 2008).

### **Archaeological survey and test excavations**

Between 1999 and 2005 over two thirds of the total urban area enclosed within the necropoleis of Sagalassos (31.5ha) was surveyed with an intensive survey strategy which was fine-tuned over three seasons (MARTENS 2005). Hereby c. 11.5 ha in the eastern part of the town was surveyed with a sampling strategy based on a 50m x 50m grid (1999), c. 1 ha was covered with a full coverage strategy within a 10m x 10m grid (2000), whereas another c.10 ha was surveyed with a full coverage technique, based on 20m x 20m squares (2001-2005). This survey involved per square the assessment of the density of surface finds (through counting), the attribution of a visibility rating (using standardized classes), the collection of all surface finds (except for building ceramics) and the mapping of all surface architecture with total station. These data were computerized and analysed in the desktop mapping program Mapinfo (On the results and methodological issues concerning this survey cf. MARTENS 2005; et al. 2008). The results of this field work offered an insight into the chronological development of the urban area and into its functional organization, with a monumental centre surrounded by a western and eastern residential zone bounded by industrial areas and the town's necropoleis.

In addition, between 1998 and 2008 a total of 16 small-scale trenches was excavated under the supervision of F. MARTENS on various main and secondary streets and main channels of the water network throughout the urban area of Sagalassos. Of these trenches 7 were located in the eastern residential quarter, which thus gave a good insight into the chronological development of this particular zone between early Imperial times and into the 6<sup>th</sup> century AD (On the results of these test soundings cf. MARTENS 2007, MARTENS 2008, MARTENS in preparation).

### **Shallow high-resolution geophysics**

The results of the geophysical multi-method survey have proven extremely useful to reconstruct the concept and the spatial organization of the urban plan. In a non-destructive and time-efficient manner a wide view upon the town planning outside the excavated monumental centre is obtained. By using this spatial information, expensive and destructive large-scale excavations can be better planned or can be replaced by small test soundings, carried out at well-selected spots, where particular questions concerning chronology of the layout or the functional use of an area can be answered. (Figs. 2, 3, 4 and 5).

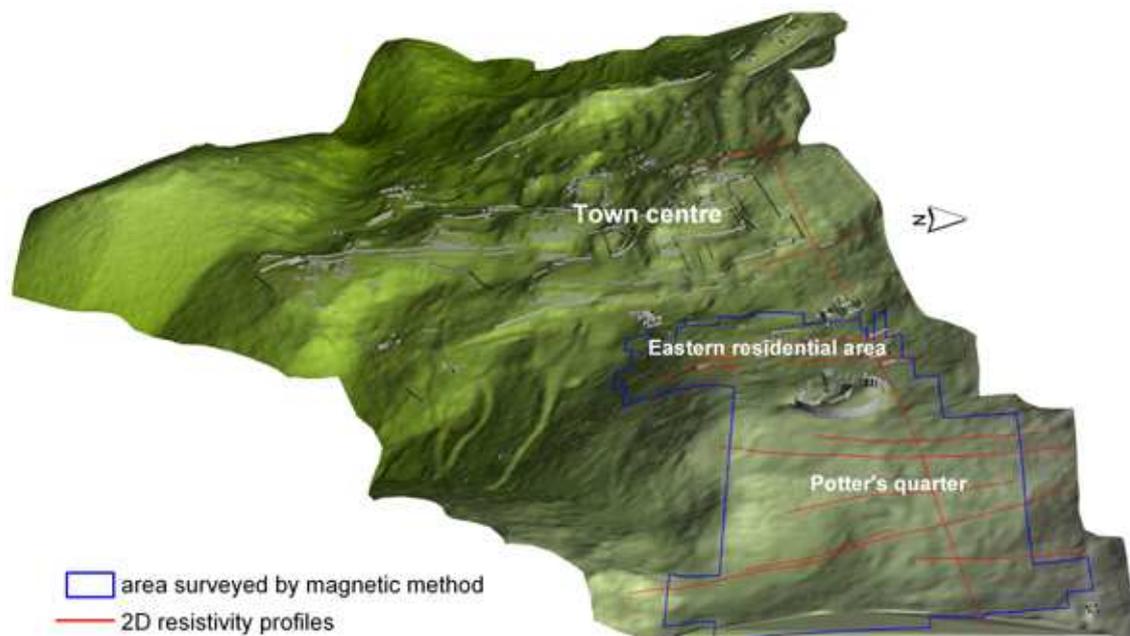


Fig. 4 – Digital elevation model based on the contour lines of the Sagalassos topographical map (Fig. 2).

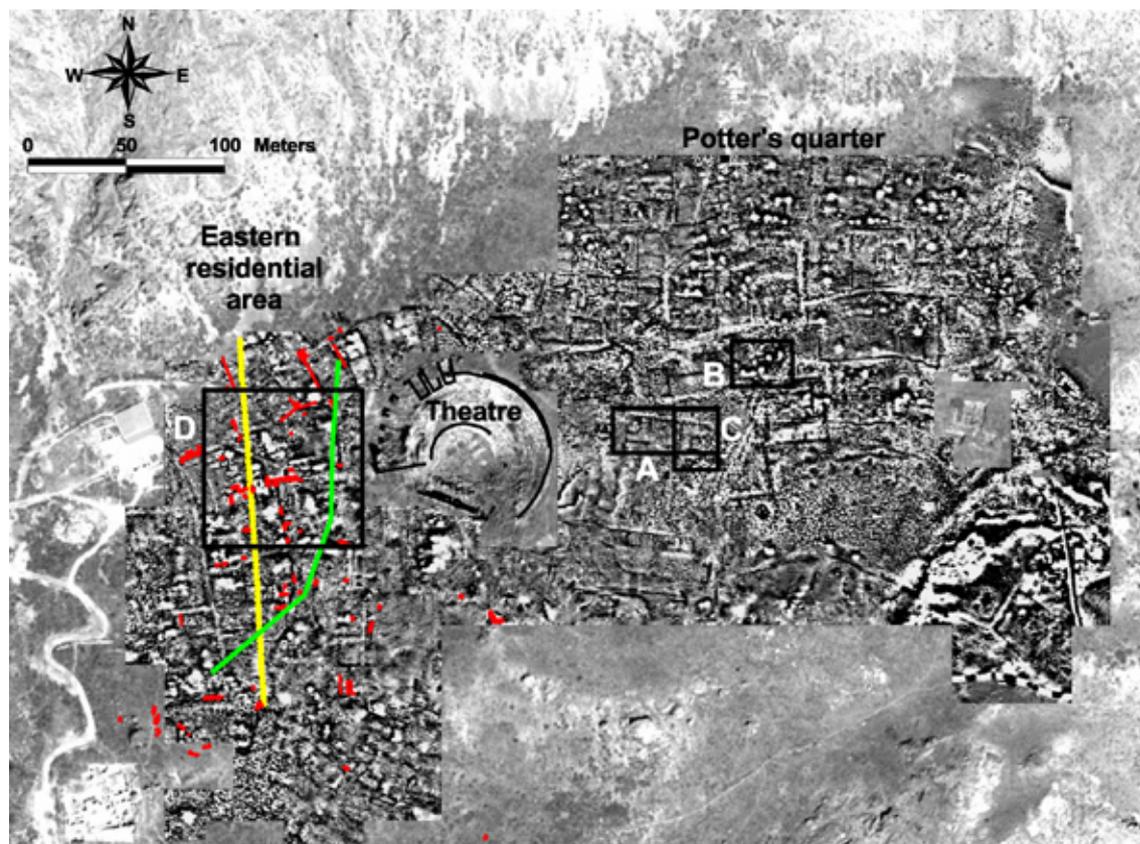


Fig. 5 – Magnetogram showing the total magnetic field gradients (Geometrics G-858) as measured in the Eastern Residential Area and Potters' Quarter positioned on the Quickbird-2 satellite image. Walls and large stone blocks visible at the surface are mapped in red. The position of 2D resistivity pseudosection Sa04p5 (see Fig. 17) and the GPR profile with the 200 MHz antenna are depicted respectively with a yellow and green line (see Fig. 16). The outlined areas (A-D) are briefly discussed in this paper (after MUŠIČ 2008).

The high resolution ultra-shallow geophysical prospecting at Sagalassos incorporates, to different extents, the application of the geoelectric resistivity method (Geoscan RM15), the magnetic method (Fluxgate gradiometer FM36 and Geometrics G-858) supported by measurements of the apparent magnetic susceptibility of samples of soil and stone construction material (Kappameter KT-5), the ground penetrating radar (GPR) method using 200 and 400 MHz antennas (GSSI SIR3000) and measurements of the electric conductivity and magnetic susceptibility by electromagnetic induction (Geonics EM38). Resistivity and conductivity surveys were to a great extent restricted by soil dryness during the summer field campaigns. The most interesting and archaeologically valuable results were obtained mainly through the combination of magnetic and GPR methods.

### **2D resistivity imaging**

Geoelectric resistivity investigations applying two-dimensional imaging at the Potter's quarter and the Eastern residential area were carried out by SIMILOX-TOHON et al. (2004). These were followed by resistivity surveys conducted by Gert VERSTRAETEN (VANFRAECHEM 2007) with Schlumberger-Wenner's electrode layout (WSC) which is moderately sensitive to both horizontal and vertical structures. The WSC layout proved to be the best compromise between the horizontal and vertical resolution.

## **Selected results**

### **Satellite imagery**

A visual interpretation presents excellent results and is therefore recommended before automatic extraction (Fig. 6). It provides information on site location, site extension or site planning. The visual interpretation is used to evaluate the information gathered by different automatic extraction techniques on the same Quickbird-2 imagery. The automatic classification methods applied can recognize archaeological features with a variable success on a Quickbird-2 image. For most landscape elements high-quality results are obtained especially by the object-based classification technique. For excavated structures edge enhancement filtering provides reasonable results, when only a limited perimeter around excavated building remains is taken into account. This technique enables accurately extracting the inner structure of the buildings. In all other cases, filtering does not provide a unique class for ancient features and its overall contribution is not better than any other applied technique. This is due to the complexity of the landscape with many other types of linear features. Floor surfaces and areas paved with limestone slabs are most accurately extracted using an object-based classification technique. Considering the overall classification accuracy, solely object based classification of well-preserved archaeological structures presents valuable results (Fig. 7). For all other archaeological remains, a visual interpretation (Fig. 6) supplemented with a GIS, pixel- and/or object-based classification is obligatory to accurately extract excavated features. The unsatisfactory overall classification results of the pixel-based technique are primarily due to the spectral similarity between archaeological remains and the surrounding limestone substrate, a coincidence that is seldom an issue for other landscape elements.

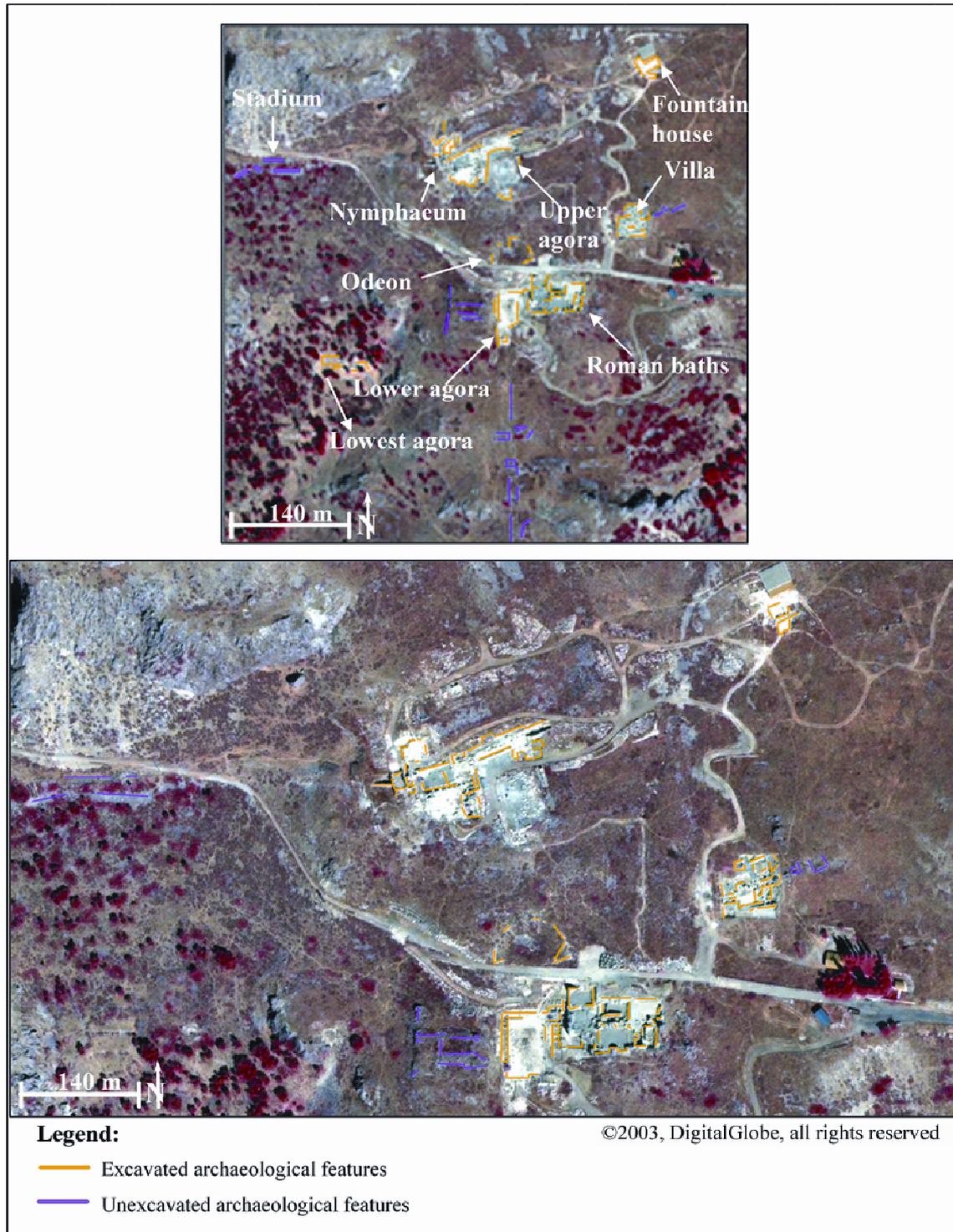


Fig. 6 – Visual interpretation of the archaeological features on Quickbird-2 imagery (after DE LAET et al. 2008).

With building materials different from the limestone substrate in the immediate vicinity, it is expected that their automatic extraction would be more successful. Since herding flocks is prohibited at the protected site of Sagalassos shrubs and trees are expanding due to the absence of grazing. Without shrubs and trees, much of the areas actually under shadow would disappear and the classification of archaeological structures would be more straightforward. A visual interpretation presents excellent

results and is therefore to be preferred over automatic extraction (Fig. 6). It provides information on site location, site extension or site planning. The visual interpretation is used to evaluate the information gathered by different automatic extraction techniques on the same Quickbird-2 imagery. Automatic extraction techniques should nevertheless be further refined because they are less subjective than visual interpretation and less time consuming when applied on large areas and on sites with well visible structures. The interpretation of surface marks is, however, very much dependent on the time of acquisition and the type of imagery applied. Satellite remote sensing, geophysical prospecting and field walking are therefore complementary techniques (see Fig. 8) (DE LAET et al. 2008).

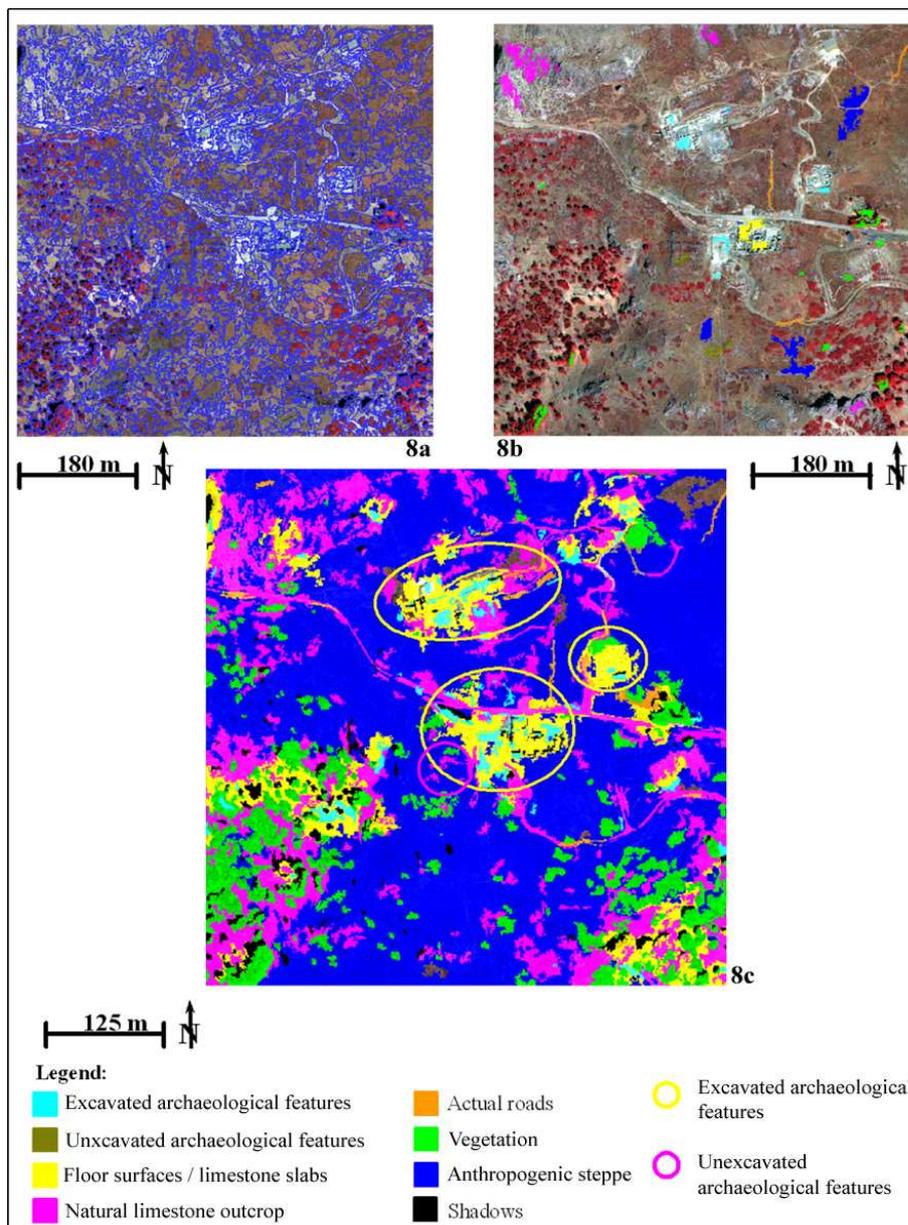


Fig. 7 – Object-based segmentation and image classification results (A) segmentation level 1: archaeological remnants (B) classification signatures for the various landscape categories (C) classification results (after DE LAET et al. 2008).

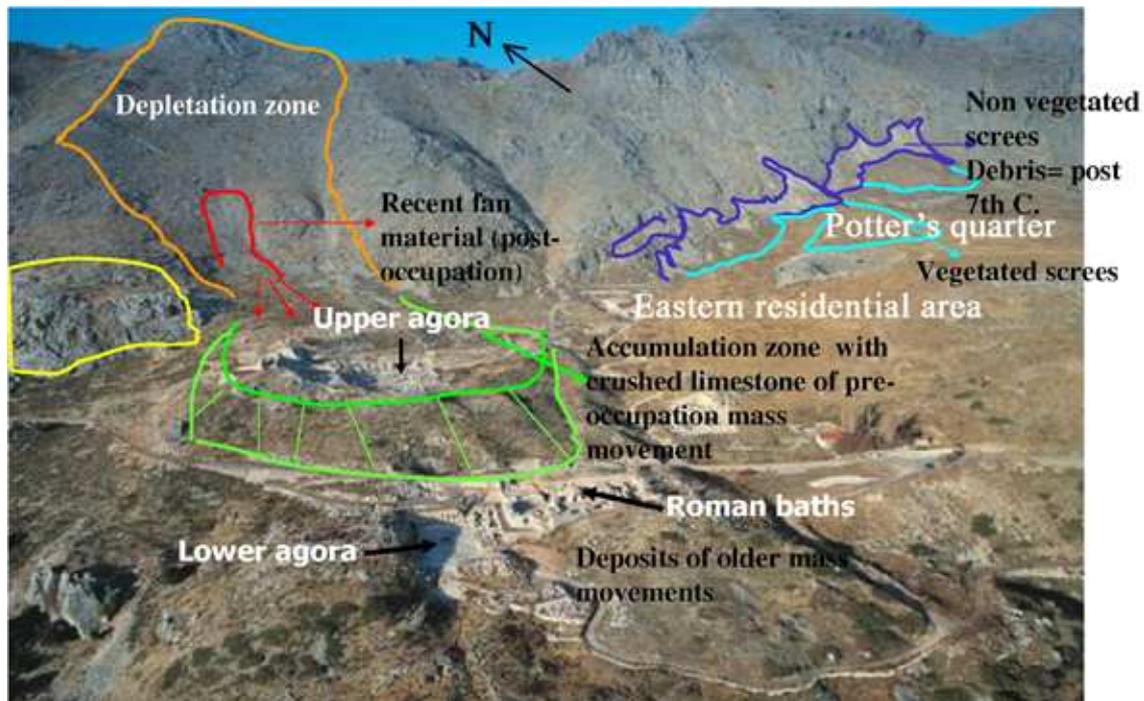


Fig. 8 – The dynamics and extension of mass movements at Sagalassos for instance were defined on the basis of field observation and satellite imagery (after DE LAET 2007).

### Shallow high-resolution geophysics

#### Magnetic method

Geophysical prospection results are represented briefly here with an emphasis on the methodological approach and the application of some specific and non-conventional procedure steps, whereas another paper shall elaborate further on the contribution for the archaeological research on the town planning and urban development of Sagalassos (MUŠIČ et al. in preparation). Due to the long period of occupation including several construction and destruction events, the building history of the urban architecture is often extremely complex. Besides surface obstacles (stone blocks and vegetation), variable surface morphology and geomorphological and geological compositions can add additional sources of noise to an archaeologically already complex situation. This strong noise of different origin should be eliminated or at least significantly reduced to achieve an acceptable signal to noise ratio. Due to the bipolar nature of the geomagnetic field, magnetic anomalies located anywhere other than at the magnetic poles are more or less asymmetric. Bipolarity may complicate interpretations in the sense that it makes reliable recognition, separation and interpretation of closely spaced magnetic anomalies generated, for instance, by internal room subdivision/ruination material/different building phases etc., extremely difficult and sometimes entirely impossible. Reduction-to-pole (RTP) takes the anomaly, as measured at any latitude, and transforms it into settings on magnetic pole, where the field inclination is vertical and the anomalies from symmetrical bodies are symmetrical. In practice it corrects for the offset between the locations of anomalies (closed highs or lows on a contour map) and their sources which is a consequence of the vector nature of the Earth's magnetic field. RTP simplifies anomalies, and centers the 'highs' over the causative magnetic bodies and diffuses the attendant

'lows'. The effect of RTP transformation is portrayed on two magnetically different situations that are characteristic for the magnetic response of the most frequent sources of magnetic anomalies at Sagalassos: small traditional brick-built kilns (thermoremanent magnetization) (Figs. 9 and 10) and walls composed of limestone blocks (induced type of magnetization) (Fig. 11).

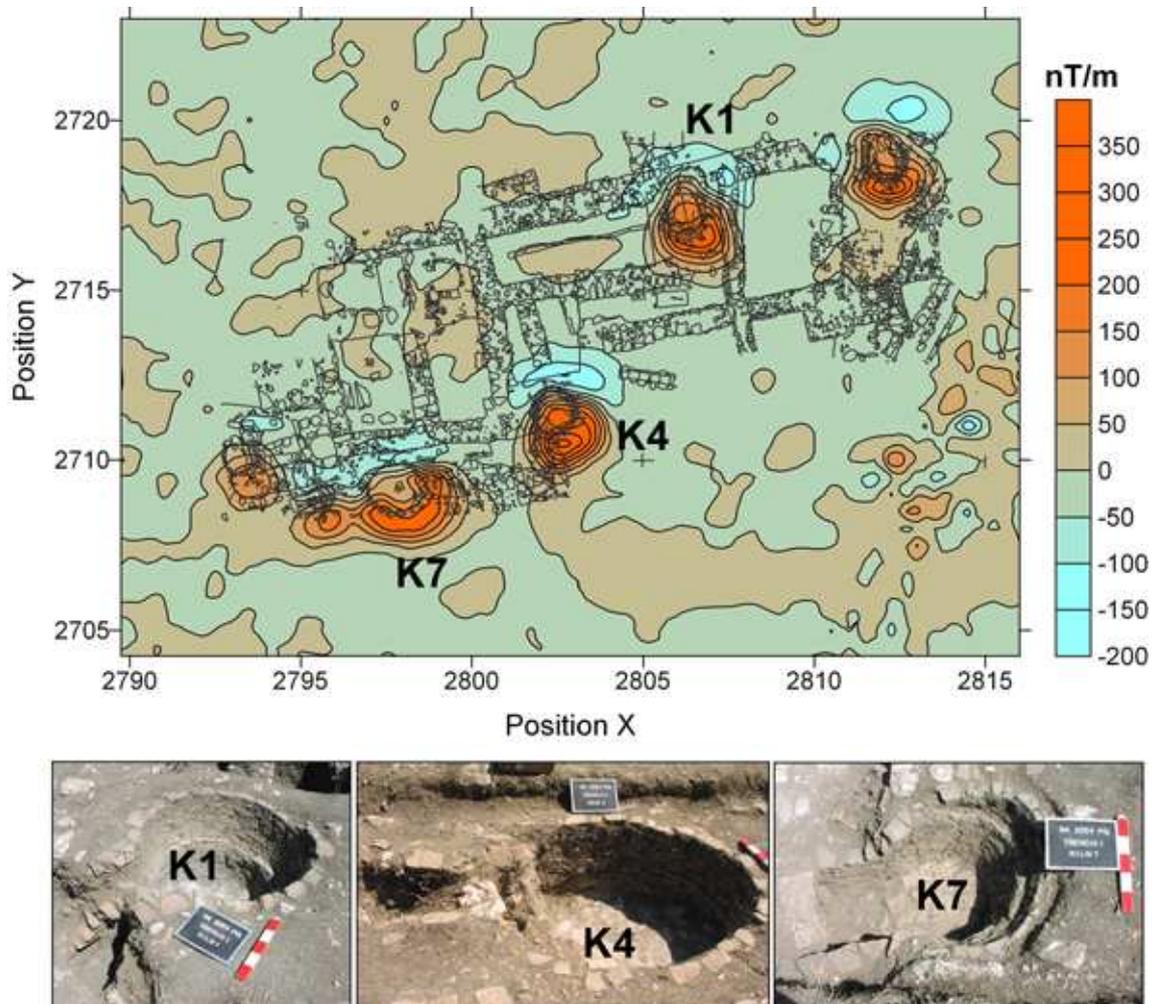


Fig. 9 – The so-called “Coroplast workshop” in the Potters’ Quarter. Portrayal of RTP transformation on a specific case of archaeological remains with thermoremanent magnetization. The comparison of the magnetograms with the magnetized bodies (kilns) shows significant space dislocations of »raw« bipolar magnetic anomalies. A comparison is made of the magnetic anomalies with the kilns excavated under supervision of J. Poblome in 2004 (see also Fig. 10). The investigated area is indicated on Fig. 5: B (after MUŠIČ 2008).

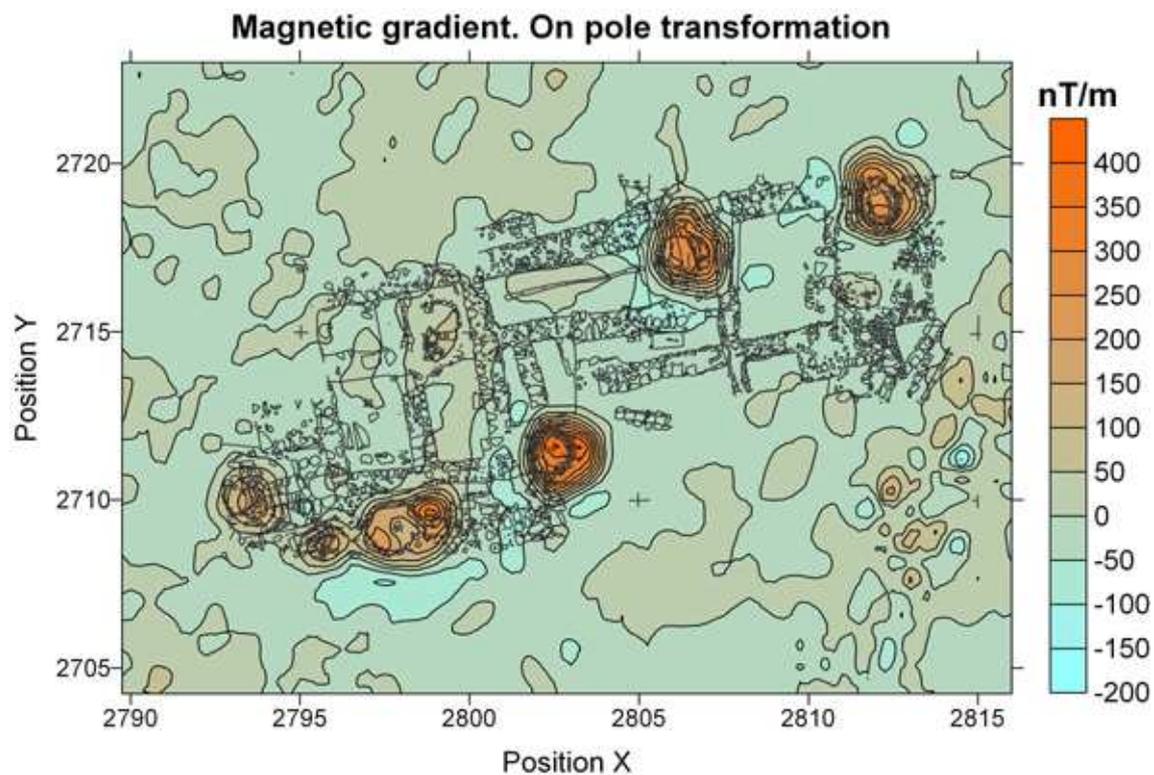


Fig. 10 – After RTP transformation, magnetic anomalies are placed exactly above the kilns (see Fig. 9). A comparison is made of magnetic anomalies with the walls excavated under supervision of J. Poblome in the same potters' workshop in 2004. The area used for RTP transformation is depicted on Fig. 8: B (after MUŠČ 2008).

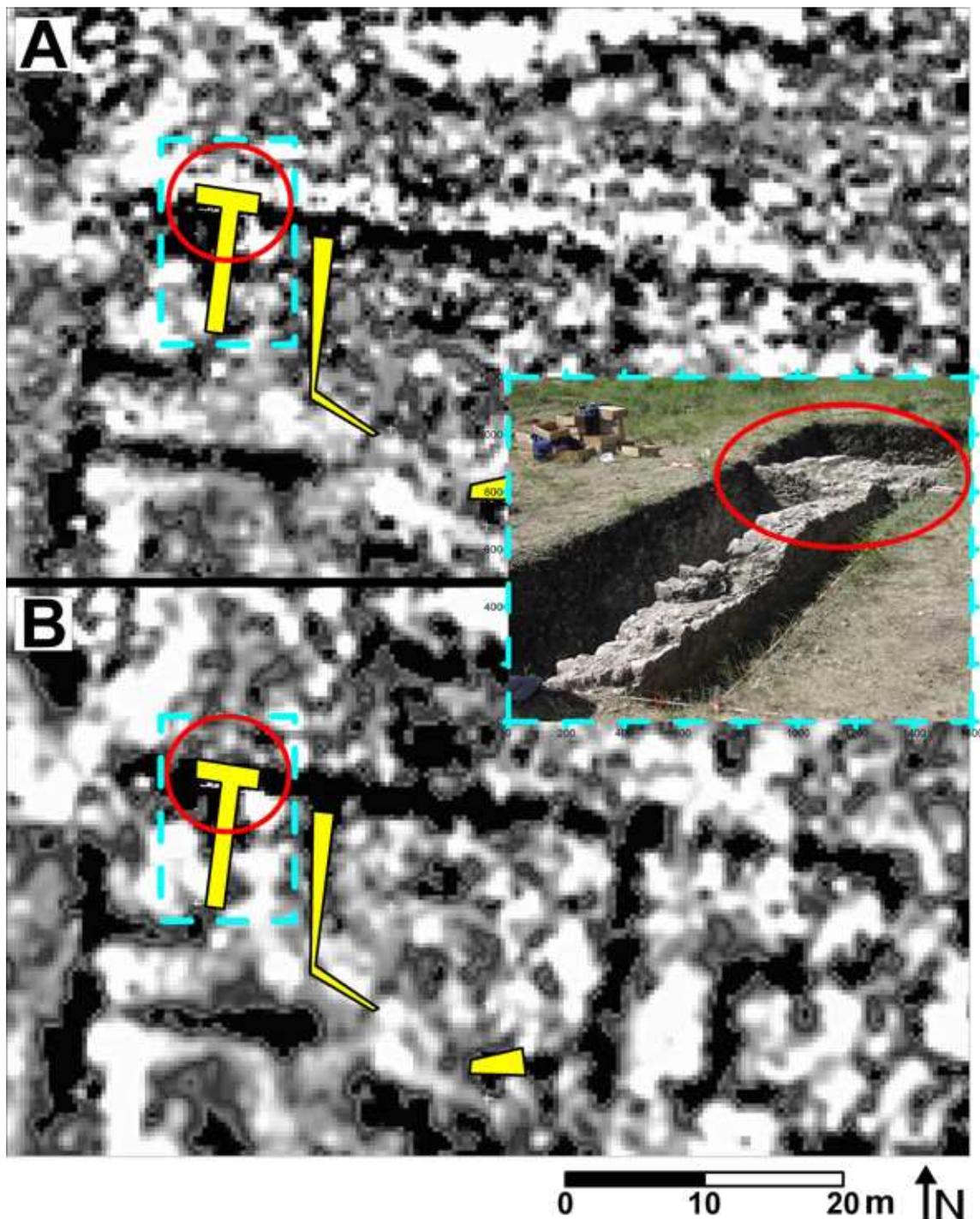


Fig. 11 – A: »Raw« data with distinct bipolarity of the magnetic anomalies. B: after RTP transformation. A comparison of magnetic anomalies with the walls of the “Gymnasium” excavated under supervision of P. Talloen in 2004 portrays the efficiency of RTP transformation in eliminating magnetic bipolarity above the walls (see detail inside of circle). The area used for RTP transformation is depicted on Fig. 5: A (after MUŠIČ 2008).

The upward continuation is the use of measurements of a magnetic field at one elevation, level or surface to determine the values of the field at a higher level. The technique is most often used to reduce scattered measurements to a common level in order to simplify the interpretation. It significantly reduces background noise of small magnetic sources close to the surface and therefore enhances magnetic anomalies originating at greater depths (Fig. 12).

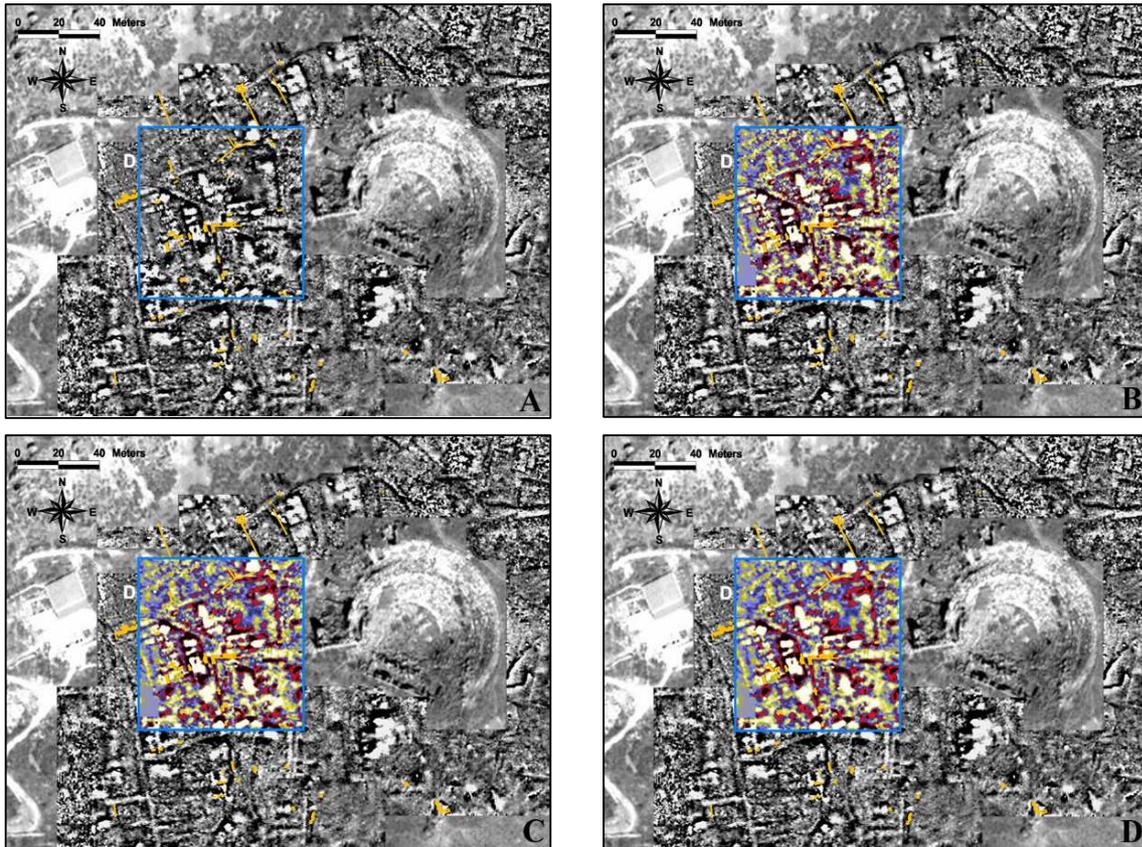


Fig. 12 – The application of the upward continuation algorithm to area D. “Raw data” of total magnetic field gradients (A). The upward continuation 0.1 m above the actual level of the magnetic profile (B), 0.2 m above the actual level (C) and 0.3 above the actual level (D).

For a more reliable interpretation, theoretical 2D and 3D archaeo-physical models were applied (e.g.: EPPELBAUM et al. 2001). These are generated from the interpretations based on measured values of the magnetic field and comparisons with the calculated magnetic anomalies for the presumed archaeo-physical models (Fig. 13). The variables which are taken into account are the supposed form of the structures, their estimated size as well as their depth and the magnetic susceptibility values. The latter is obtained through susceptibility measurements on adequate surface material. The most suitable archaeo-physical model is the one with the smallest difference between the measured and theoretical or calculated values. Additionally, data regarding the inclination (I), declination (D) and intensity of the Earth’s magnetic field (F) in the investigated area are also required.

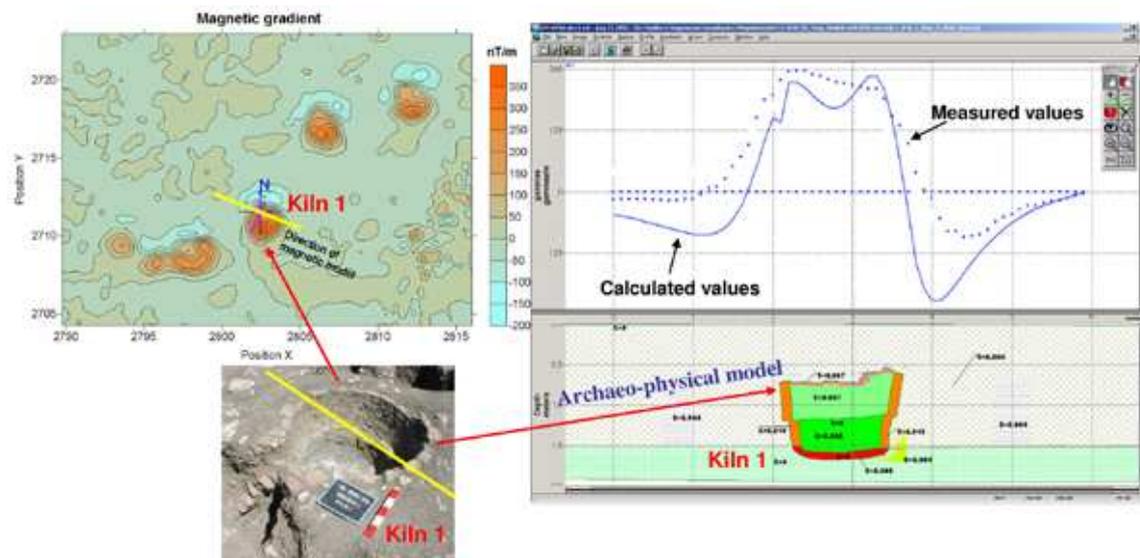


Fig. 13 – The calculation of magnetic anomalies for 2D archaeo-physical model based on the properties of a potters' kiln excavated under the supervision of J. Poblome in 2004.

2D magnetic modelling based on the Earth's magnetic field model (IGRF, <http://www.ngdc.noaa.gov/AGA/vmod/igrf.html>), allowed us to calculate aspects such as the depth of the anomaly and its geometrical properties, whereas in the case of architectural elements even the type of building material could be determined. By comparing the measured magnetic anomalies and their sources with the excavated archaeological remains, step by step reliable magnetic models were developed and archaeo-physical magnetic models of the archaeological structures were created (e.g.: MUŠIČ et al. 1998; DESVIGNES et al. 1999, 85–105; HAŠEK 1999, 25–42; COSKUN et al. 2000, 179–186; TSOKAS et al. 2000, 17–30; EPPELBAUM et al. 2001, 163–185; KOCHNEV et al. 2004, 64–68; DIAMANTI et al. 2005, 79–91).

#### Ground penetrating radar method

The GPR method is the only technique among the geophysical methods applied within the Sagalassos geophysical survey project that is used for geophysical sounding. It enables a precise 3D visualization as well as analyses of the measurement's results in a 3D environment (Figs. 14 and 15). Apart from the reconstruction of the complex building history of individual structures, this method, for instance, also has a great potential for tracing well preserved built channels of the town's ancient water network, an approach which is currently being tested. On the basis of expected maximum depth of a wall foundations extracted from two-dimensional resistivity imaging (see: SIMILOX-TOHON 2005, VANFRAECHEM 2007), the 200 MHz antenna was selected as a compromise between penetration depth and horizontal and vertical resolution of the GPR results (see figs. 16 and 17). GPR sounding was used to determine the depth and height of preservation and the mutual spatial relationship of architectural elements in areas where results from the magnetic prospection were deemed it advantageous to check for reliable 3D visualization of architectural remain (see figs. 18 and 19).

The GPR method measures the time between transmitting and receiving the backscatter from the underground reflector expressed in nanoseconds ( $10^{-9}$ s). By knowing the dielectric permittivity, and thus also the propagation velocity of the EM waves in the investigated media, reflection time can be calculated in terms of units of length, or rather depth sections. The portion of the electromagnetic energy reflected at a certain limit between two diverse materials (e.g. wall/ground-surrounding medium, etc.) depends upon the contrast in the dielectric permittivity (and to a lesser degree on the electrical conductivity and the magnetic permeability) and the ratio between the wavelength of the EM waves (determined by the frequency of the transmitter) and the width of the archaeological structure (JOL 1995) (see figs 14 and 15).

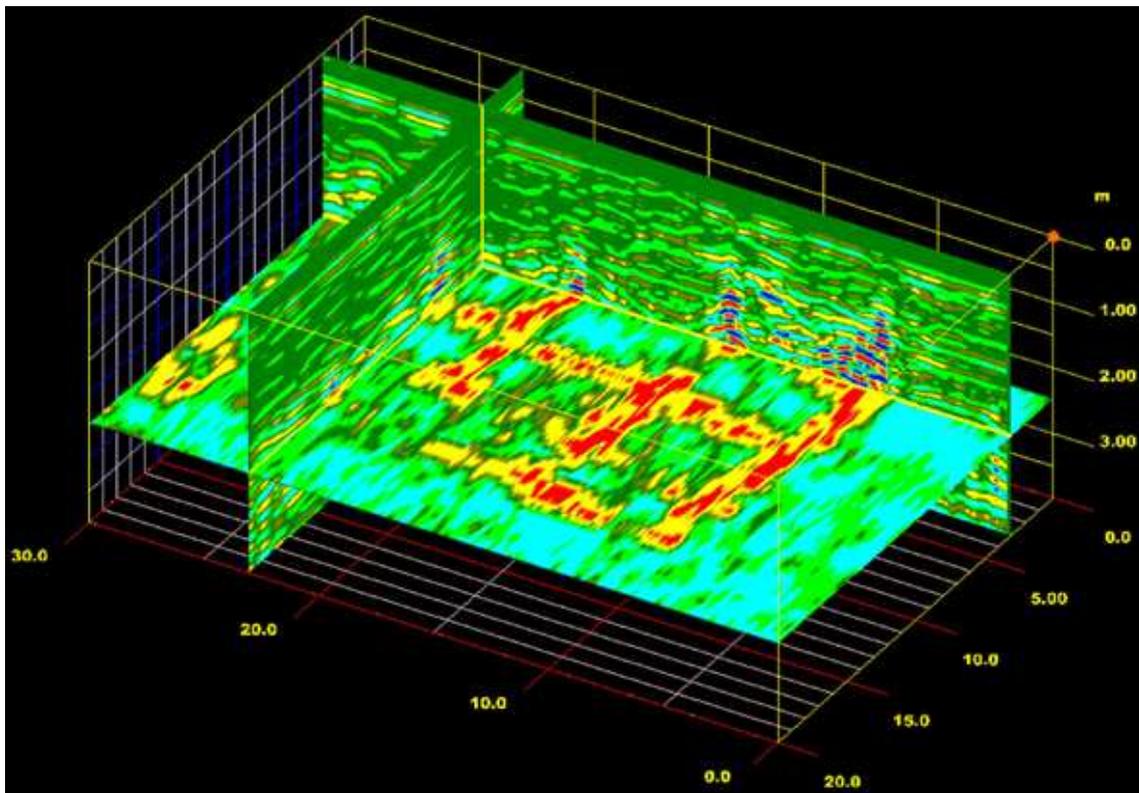


Fig. 14 – 3D representation of GPR echoes from area C (see Fig. 5).

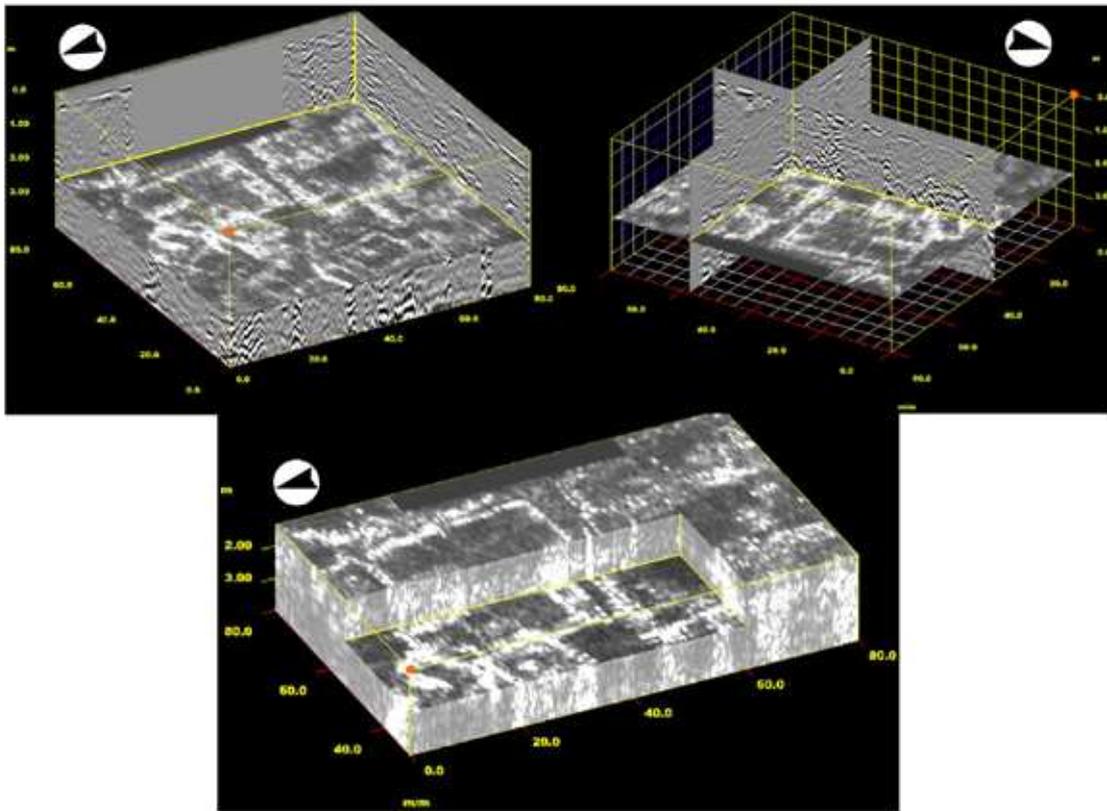


Fig. 15 – 3D representation of GPR echoes from area D (see Fig.5).

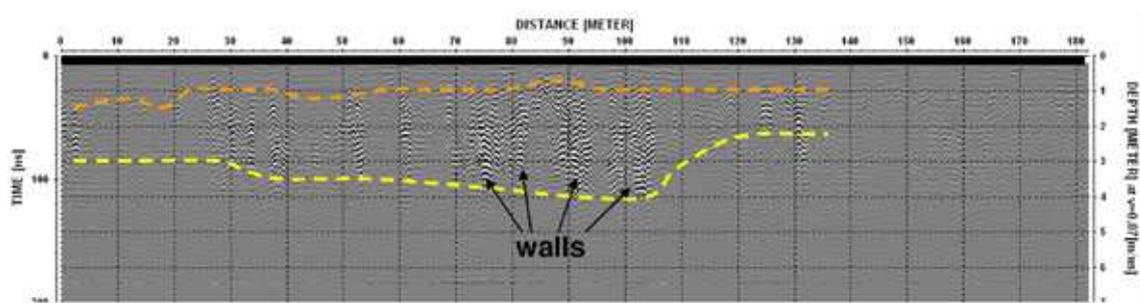


Fig. 16 – The GPR profile measured with a 200 MHz antenna across the Eastern Residential Area clearly shows differences in depth, thickness and preservation level of the architectural remains laid out on this south facing slope.

## 2D resistivity imaging

Several 2D resistivity profiles across the Potters' quarter and the Eastern Residential Area revealed the presence of five general stratigraphic layers, i.e. from bottom to top: the bedrock composed either of limestone or ophiolitic melange, the weathered top of this bedrock, old colluvial material, recent colluvial material that covers archaeological structures and recent scree deposits (SIMILOX-TOHON et al. 2004).

The used probe array ensures a better resolution in vertical than in horizontal direction and therefore provides a more general impression about the lateral resistivity distribution. Comparison between two-dimensional resistivity imaging, magnetic and GPR method shows that “small, high resistivity

embedded bodies” (SIMILOX-TOHON et al. 2004) can be interpreted as extremely high resistivity areas inside residential complexes composed of well preserved walls associated with ruination material and/or preserved floors made of stone slabs (Fig. 17).

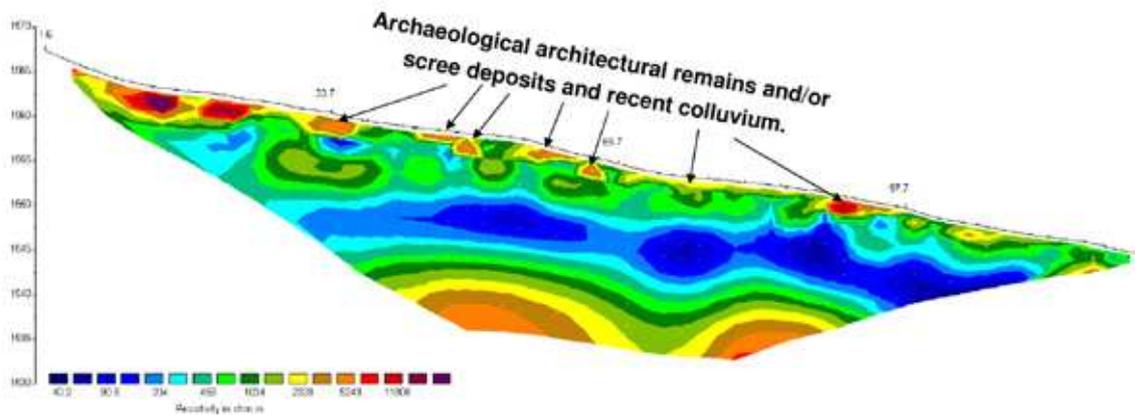


Fig. 17 – The conventional inversion result of the measured apparent resistivity pseudosection in profile Sa04p5. For the position of the profile see Figs. 4 and 5 (after SIMILOX-TOHON 2004).

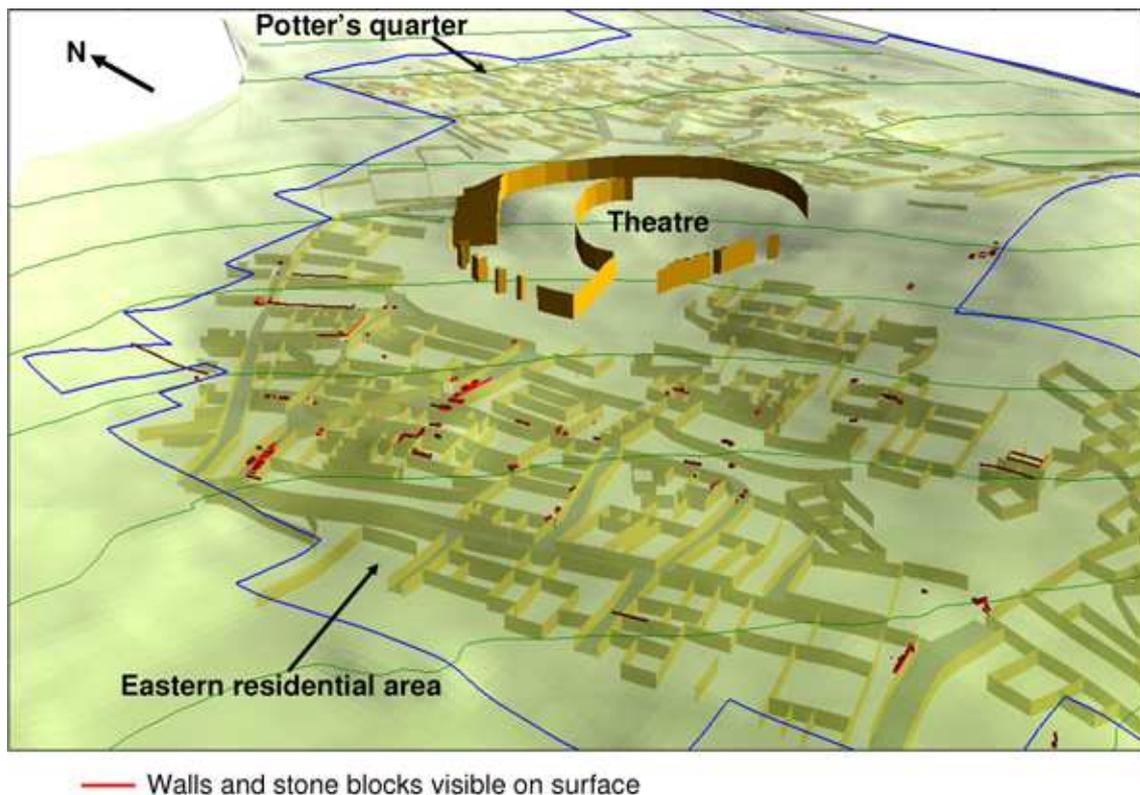


Fig. 18 – The Eastern Residential Area: A 3D portrayal of the architectural remains interpreted on the basis of multi-method geophysical survey and surface walls mapped by architectural survey (see: MARTENS 2005).

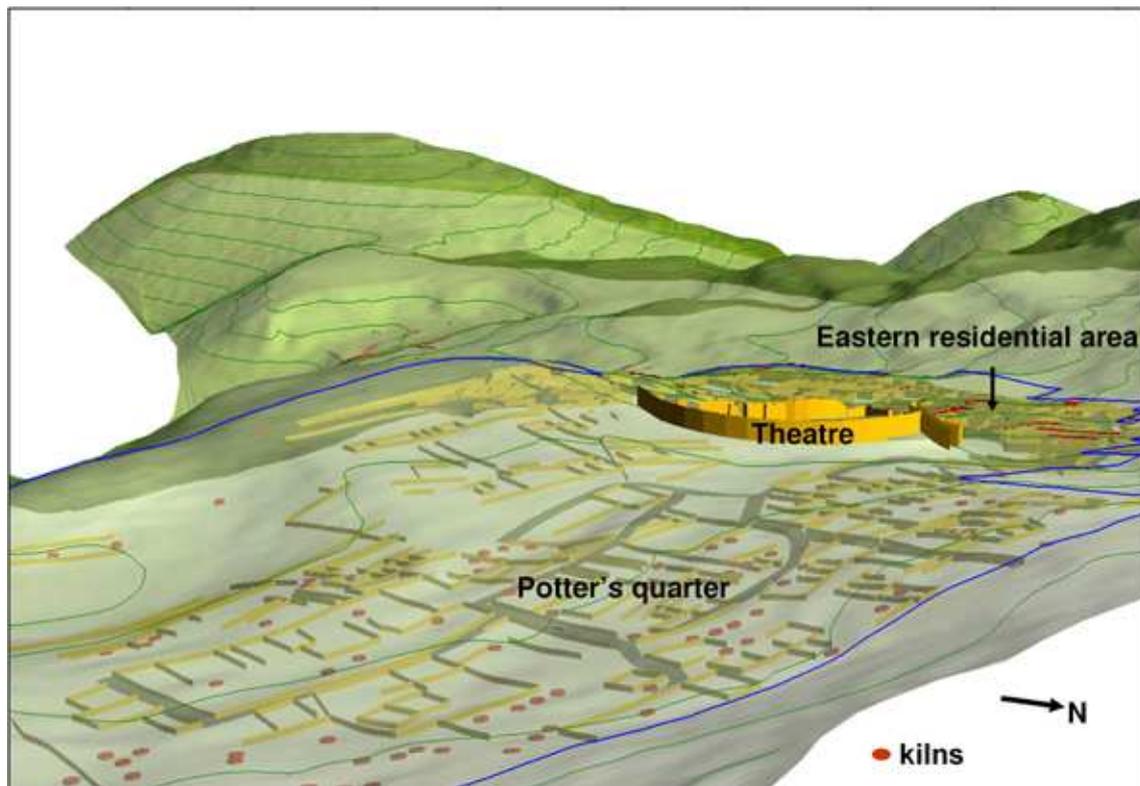


Fig. 19 – The Potters' Quarter. A 3D portrayal of the architectural remains interpreted on the basis of multi-method geophysical survey.

## Conclusions

The current paper has outlined the properties of the multi-method approach applied at the ancient site of Sagalassos (Turkey) to investigate various aspects of its urban development. Although the contribution of this strategy to the unraveling of specific archaeological research questions will be treated more in depth in another paper (MUŠIČ et al. in preparation), it is apparent that such an integrated approach combining different research techniques and fields of expertise leads to a thorough understanding of an ancient urban landscape. As each site poses unique conditions, obviously, every research technique also poses particular site-related issues which have to be remedied to obtain the desired degree of reliability of the research results. The current paper illustrates how the results of the various spatial analyses can perfectly be joined as complementary contributions to the reconstruction of past urban landscape.

## Acknowledgement

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