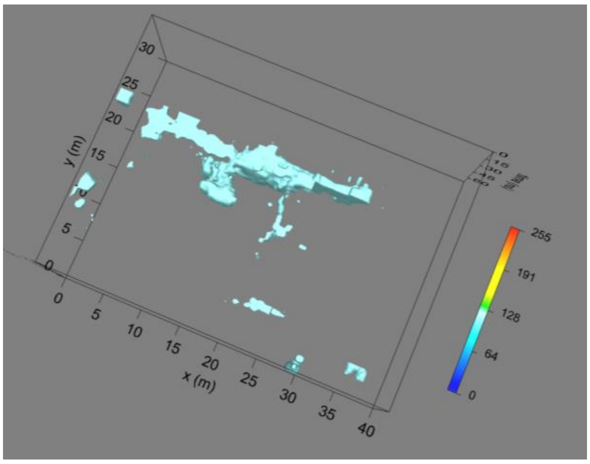

MELITE CIVITAS ROMANA PROJECT: GPR SURVEY IN SOME AREAS NEAR THE DOMUS ROMANA IN RABAT (MALTA)

THE DIRECTOR

DOTT. DANIELE MALFITANA

THE SCIENTIFIC CHIEF

DOTT. GIOVANNI LEUCCI

JUNE 2019

Sede di Catania
c/o Palazzo Ingrassia
via Biblioteca, 4
95124 Catania
Tel. +39 095 311 981
Fax. +39 095 311 981

Sede di Lecce
c/o Campus Universitario
Prov.le Lecce-Monteroni
73100 Lecce
Tel. +39 0832 422 200
Fax. +39 0832 422 225

Sede di Potenza
c/o Area della Ricerca del CNR
c.da S. Lojola
85050 Tito Scalo (PZ)
Tel. +39 0971 427 322
Tel. +39 0971 427 333

Unità di Ricerca Cosenza
c/ o Università della Calabria
Dip. di Biologia, Ecologia e Scienze della Terra
via P. Bucci, 12/B
87036 Arcavacata di Rende (CS)

Unità di Ricerca Palermo
via Litoranea, S.P. 23 Aspra - S. Elia
90017 Santa Flavia (PA)

Partita Iva 02118311006 | www.ibam.cnr.it | E-mail: segreteria@ibam.cnr.it

Abstract

Ground-penetrating radar mapping allows for a three-dimensional analysis of archaeological features within the context of landscape studies. The method's ability to measure the intensity of radar reflections from deep in the ground can produce images and maps of buried features not visible on the surface. A study was conducted in some areas near the Domus Romana in Rabat (Malta) in order to investigate about the buried archaeological structures. The ground-penetrating radar analysis showed them to be anomalies likely associated to archaeological remains.

Introduction

Ground-penetrating radar (GPR) is a near-surface geophysical technique that allows archaeologists to discover and map buried archaeological features for landscape analysis in ways not possible using traditional field methods. The method consists of measuring the elapsed time between when pulses of radar energy are transmitted from a surface antenna, reflected from buried discontinuities, and then received back at the surface. When the distribution and orientation of those subsurface reflections can be related to certain aspects of archaeological sites such as the presence of architecture, use areas or other associated cultural features, high definition three-dimensional maps and images of buried archaeological remains can be produced. Ground-penetrating radar is a geophysical technique that is most effective with buried sites where artifacts and features of interest are located within 2–6 meters of the surface, but has occasionally been used for more deeply buried deposits.

A growing community of archaeologists has been incorporating ground-penetrating radar (GPR) as a routine field procedure for landscape analysis (Conyers 2004a; Conyers and Goodman 1997; Gaffney and Gater 2003; Leucci, 2015; Leucci, 2019). The efficacy and applicability of GPR in the detection of buried structures have demonstrate by several authors (Conyers and Goodman, 1997). Conclusions from these studies indicate that GPR was the most important tool used to delineate structures and to maps and images act as primary data that can be used to guide the placement of excavations.

Ground-penetrating radar data are acquired by reflecting distinct pulses of radar energy from a surface antenna, reflecting them of buried objects, features or bedding contacts in the ground, and

Sede di Catania
c/o Palazzo Ingrassia
via Biblioteca, 4
95124 Catania
Tel. +39 095 311 981
Fax. +39 095 311 981

Sede di Lecce
c/o Campus Universitario
Prov.le Lecce-Monteroni
73100 Lecce
Tel. +39 0832 422 200
Fax. +39 0832 422 225

Sede di Potenza
c/o Area della Ricerca del CNR
c.da S. Lojola
85050 Tito Scalo (PZ)
Tel. +39 0971 427 322
Tel. +39 0971 427 333

Unità di Ricerca Cosenza
c/ o Università della Calabria
Dip. di Biologia, Ecologia e Scienze della Terra
via P. Bucci, 12/B
87036 Arcavacata di Rende (CS)

Unità di Ricerca Palermo
via Litoranea, S.P. 23 Aspra - S. Elia
90017 Santa Flavia (PA)

Partita Iva 02118311006 | www.ibam.cnr.it | E-mail: segreteria@ibam.cnr.it

detected those reflections back at a receiving antenna. As radar pulses are being transmitted through various materials on their way to the buried target feature, their velocity will change, depending on the physical and chemical properties of the material through which they are traveling (Conyers 2004a: 45). Each velocity change generates a reflected wave, which travel back to the surface. The velocity of radar energy in the ground is also important because when the travel times of the energy pulses are measured and their velocity through the ground is known, distance (or depth in the ground) can be accurately measured (Conyers 2004a: 99), producing a three-dimensional data set. Most typically in archaeological GPR radar antennas are moved along the ground in transects and two-dimensional profiles of a large number of reflections at various depths are created, producing profiles of subsurface stratigraphy and buried archaeological features along lines. When data are acquired in a closely-spaced series of transects within a grid, and reflections are

correlated and processed, an accurate three-dimensional picture of buried features and associated stratigraphy can be constructed (Conyers 2004a: 148). This can be done visually by analyzing each profile, or with the aid of computer software that can create maps of many thousands of reflection amplitudes from all profiles in a grid. Ground-penetrating radar surveys allow for a relatively wide aerial coverage in a short period of time, with excellent subsurface resolution of both buried archaeological materials and associated geological stratigraphy. This three-dimensional resolution is what gives GPR an advantage over other near-surface methods with respect to buried archaeological feature resolution.

GPR data acquisition and analysis

A wide range of geophysical methods are applied in archaeology for obtaining high-resolution images of the subsurface. The geophysical method used in this study is based on the detection of variations in the electromagnetic properties of the subsoil and the use of these data to identify artefacts and distinguish between these and natural variations in the soil. The GPR prospecting was carried out with the IDS Hi Mod system with 600 MHz and 200 MHz antennae. Data were acquired in continuous mode along 0.5m spaced survey lines, using 512 samples per trace, 80 ns time range for 600MHz antenna and 160 ns for 200MHz antenna, manual time-varying gain function.

Sede di Catania
c/o Palazzo Ingrassia
via Biblioteca, 4
95124 Catania
Tel. +39 095 311 981
Fax. +39 095 311 981

Sede di Lecce
c/o Campus Universitario
Prov.le Lecce-Monteroni
73100 Lecce
Tel. +39 0832 422 200
Fax. +39 0832 422 225

Sede di Potenza
c/o Area della Ricerca del CNR
c.da S. Lojola
85050 Tito Scalo (PZ)
Tel. +39 0971 427 322
Tel. +39 0971 427 333

Unità di Ricerca Cosenza
c/ o Università della Calabria
Dip. di Biologia, Ecologia e Scienze della Terra
via P. Bucci, 12/B
87036 Arcavacata di Rende (CS)

Unità di Ricerca Palermo
via Litoranea, S.P. 23 Aspra - S. Elia
90017 Santa Flavia (PA)

Partita Iva 02118311006 | www.ibam.cnr.it | E-mail: segreteria@ibam.cnr.it

The investigated areas were three and labelled respectively area A, area B and area E (Fig. 1).

The data were subsequently processed using standard two-dimensional processing techniques by means of the GPR-Slice Version 7.0 software (Goodman, 2013). The processing flow-chart consists of the following steps: (i) header editing for inserting the geometrical information; (ii) frequency filtering; (iii) manual gain, to adjust the acquisition gain function and enhance the visibility of deeper anomalies; (iv) customized background removal to attenuate the horizontal banding in the deeper part of the sections (ringing), performed by subtracting in different time ranges a 'local' average noise trace estimated from suitably selected time–distance windows with low signal content (this local subtraction procedure was necessary to avoid artefacts created by the classic subtraction of a 'global' average trace estimated from the entire section, due to the presence of zones with a very strong signal);

(v) estimation of the average electromagnetic wave velocity by hyperbola fitting; (vi) Kirchhoff migration, using a constant average velocity value of 0.11 m/ns.

The migrated data were subsequently merged together into three-dimensional volumes and visualized in various ways in order to enhance the spatial correlations of anomalies of interest. A way of obtaining visually useful maps for understanding the plan distribution of reflection amplitudes within specific time intervals is the creation of horizontal time slices. These are maps on which the reflection amplitudes have been projected at a specified time (or depth), with a selected time interval (Conyers, 2006). In a graphic method developed by Goodman et al. (2006), termed "overlay analysis", the strongest and weakest reflectors at the depth of each slice are assigned specific colours. This technique allows the linkage of structures buried at different depths. This represents an improvement in imaging because subtle features that are indistinguishable on radargrams can be seen and interpreted in a more easily. In the present work the time-slice technique has been used to display the amplitude variations within consecutive time windows of width Δt=5 ns for 600MHz antenna GPR data and Δt=10 ns for 200MHz antenna GPR data. In order to define the depth of buried structures the electromagnetic (EM) wave velocity, using the characteristic hyperbolic shape of a reflection from a point source (diffraction hyperbola), was used (Conyers and Goodman, 1997).

Sede di Catania
c/o Palazzo Ingrassia
via Biblioteca, 4
95124 Catania
Tel. +39 095 311 981
Fax. +39 095 311 981

Sede di Lecce
c/o Campus Universitario
Prov.le Lecce-Monteroni
73100 Lecce
Tel. +39 0832 422 200
Fax. +39 0832 422 225

Sede di Potenza
c/o Area della Ricerca del CNR
c.da S. Lojola
85050 Tito Scalo (PZ)
Tel. +39 0971 427 322
Tel. +39 0971 427 333

Unità di Ricerca Cosenza
c/ o Università della Calabria
Dip. di Biologia, Ecologia e Scienze della Terra
via P. Bucci, 12/B
87036 Arcavacata di Rende (CS)
Unità di Ricerca Palermo
via Litoranea, S.P. 23 Aspra - S. Elia
90017 Santa Flavia (PA)

Partita Iva 02118311006 | www.ibam.cnr.it | E-mail: segreteria@ibam.cnr.it

One approach for visualising 3D radar data is the 3D contouring by means of iso-amplitude surface (Conyers, 2004; Leucci, 2019). In this case, after an appropriate processing of radar data, a 3D image of the sought diffracting or reflecting object could be easily obtained by i) extraction of a particular complex signal attribute (trace envelope); ii) the grid data are converted to the reflection strength or amplitude envelope by a Hilbert transformation; iii) thresholding; a threshold value must be entered. Hence all amplitudes greater/equal than this value are considered per definition.
The threshold calibration is a very delicate task.

Area A: The 600 MHz antenna processed GPR profiles acquired in the area A (Fig. 2) are shown in Figs 3,…, 9. Several reflection events are visible.
On each GPR processed profile a continuous and slightly undulating reflection event (labelled B and underlined by dashed yellow line) is visible. It is continuous and slightly undulating and irregular, and reaches a maximum depth below the surface ranging from about 0.8m to about 1.7 m. It probably represent the rock boundary.
A hyperbolic shaped reflection events labelled “A” are visible. They size is about 2m and the depth of the top is between 0.8m and 1.4 m (with an average electromagnetic wave velocity of 0.11 m/ns). This reflection event was interpreted as probably due to a buried structures of archaeological interest.
The reflection event labelled “M” is typical of metal object.
In order to identify the depth evolution of buried structures, including their size, shape and location, time slices using the overlay analysis (Goodman et al., 2006; Goodman and Piro, 2013) were built (Fig. 10). The time slices show the normalized amplitude using a range defined by blue as zero and red as 1. In Fig. 11 the depth slices overlapped to the google earth phot of the surveyed area are shows. Several alignments are visible. Relatively high-amplitude anomaly (labelled A) correspond to the anomalies labelled A in the radargram.
In Fig. 12 the data set is displayed with iso-amplitude surfaces using four threshold values 60% of the maximum complex trace amplitude. Obviously, lowering the threshold value, increases the visibility of the main anomaly and smaller objects, but also heterogeneity noise.

Sede di Catania
c/o Palazzo Ingrassia
via Biblioteca, 4
95124 Catania
Tel. +39 095 311 981
Fax. +39 095 311 981

Sede di Lecce
c/o Campus Universitario
Prov.le Lecce-Monteroni
73100 Lecce
Tel. +39 0832 422 200
Fax. +39 0832 422 225

Sede di Potenza
c/o Area della Ricerca del CNR
c.da S. Lojola
85050 Tito Scalo (PZ)
Tel. +39 0971 427 322
Tel. +39 0971 427 333

Unità di Ricerca Cosenza
c/ o Università della Calabria
Dip. di Biologia, Ecologia e Scienze della Terra
via P. Bucci, 12/B
87036 Arcavacata di Rende (CS)
Unità di Ricerca Palermo
via Litoranea, S.P. 23 Aspra - S. Elia
90017 Santa Flavia (PA)

Partita Iva 02118311006 | www.ibam.cnr.it | E-mail: segreteria@ibam.cnr.it

A relatively strong continuous reflections are visible on the threshold volumes between 0.8 and 2.5 m (Fig. 12a). In this case the anomalies labelled A could be interpreted as collapsed structures. The deeper anomalies (Fig. 12b) could be interpreted as walls. This visualization technique help in the interpretation. Clearly the best interpretation must be performed together with the archaeologists.
The analysis of the GPR data acquired with the 200MHz antenna allow to obtain information about the deeper buried structures.
Results evidences some more information than the 600MHz antenna (Figs. 13, 14 and 15). Particularly Fig. 15 in the 3D iso surface evidenced a structure (V) partially void.

Area B: Area B was divided in three zones labelled respectively zone 1, zone 2 and zone 3. In the area B many difficulties were encountered during data acquisition. The presence of obstacles such as trees, stems, weeds has greatly limited the field of action.

Zone 1: For the zone 1 (Fig. 16) the processed radar sections (related to the 600MHz antenna) are shows in Figs. 17,..,19.
Here is possible to see several reflection events (M) related to the presence of metal objects buried in the first 10cm of depth. This type of reflected events have an high amplitude of the electromagnetic wave and mask the reflected events due to structures of archaeological interest. For this reason, the data processing has included the elimination of traces containing this type of reflections. The lower amplitude reflection events (A) are visible.
Also in this case the time slices were built (Fig. 20). The processing that have deleted the metal noise has allow to well evidenced the low amplitude anomalies in the depth slices. Fig. 21 show the depth slices overlapped to the drone photo. The depth slices between 0.6m and 2.5 m in depth are shows. The dashed white lines indicates the presence of some alignment that could be interpreted as walls.
Fig. 22 well evidenced these alignments.
The analysis of the GPR data acquired with the 200MHz antenna allow to obtain information about the deeper buried structures. Fig. 23 shows all depth slices while Fig. 24 show the deeper slices (5.9-6.3m in depth) overlapped to the drone photo. Is possible to see a square structure (F) that could be

related to a foundation. The dimensions are about 5m x 5m. The high amplitude anomalies (V) could be related to the presence of void spaces (channels?). Fig. 25 well evidenced the structures.

Zone 2: For the zone 2 (Fig. 26) the processed radar sections (related to the 600MHz antenna) are shows in Figs. 27 and 28.

Also in this case is possible to see several reflection events (M) related to the presence of metal objects buried in the first 10cm of depth. The lower amplitude reflection events (A) are visible.

Also in this case the time slices were built (Fig. 29). The processing that have deleted the metal noise has allows to well evidenced the low amplitude anomalies in the depth slices. Fig. 30 show the depth slices overlapped to the drone photo. The depth slices between 1.45m and 4.0 m in depth are shows. The dashed white lines indicates the presence of some alignment that could be interpreted as walls.

The analysis of the GPR data acquired with the 200MHz antenna allow to obtain information about the deeper buried structures. Fig. 31 shows all depth slices while Fig. 32 show the deeper slices (5.5-6.0m in depth) overlapped to the drone photo. Is possible to see the high amplitude anomalies (V) could be related to the presence of void spaces (channels?). Fig. 33 well evidenced the structures.

Zone 3: For the zone 3 (Fig. 34) the processed radar sections (related to the 600MHz antenna) are shows in Fig. 35.

Also in this case is possible to see several reflection events (M) related to the presence of metal objects buried in the first 10cm of depth. The lower amplitude reflection events (A) are visible.

Fig. 36 show all the depth slices while Fig. 34 show the depth slices overlapped to the google earth photo. The depth slice between 2.5m and 2.85 m in depth shows the dashed white lines (A) that could be interpreted as walls.

The analysis of the GPR data acquired with the 200MHz antenna allow to obtain information about the deeper buried structures. Fig. 39 shows all depth slices while Fig. 40 show the deeper slices (4.2-4.8m in depth) overlapped to the google earth photo. Is possible to see the high amplitude anomalies (A) could be related to the presence of walls.

Sede di Catania
c/o Palazzo Ingrassia
via Biblioteca, 4
95124 Catania
Tel. +39 095 311 981
Fax. +39 095 311 981

Sede di Lecce
c/o Campus Universitario
Prov.le Lecce-Monteroni
73100 Lecce
Tel. +39 0832 422 200
Fax. +39 0832 422 225

Sede di Potenza
c/o Area della Ricerca del CNR
c.da S. Lojola
85050 Tito Scalo (PZ)
Tel. +39 0971 427 322
Tel. +39 0971 427 333

Unità di Ricerca Cosenza
c/ o Università della Calabria
Dip. di Biologia, Ecologia e Scienze della Terra
via P. Bucci, 12/B
87036 Arcavacata di Rende (CS)

Unità di Ricerca Palermo
via Litoranea, S.P. 23 Aspra - S. Elia
90017 Santa Flavia (PA)

Partita Iva 02118311006 | www.ibam.cnr.it | E-mail: segreteria@ibam.cnr.it

Area E: Area E was divided in two zones labelled respectively zone 1 and zone 2. Area E is strongly urbanized in the first meter of depth.

Zone 1: For the zone 1 (Fig. 40) the processed radar sections (related to the 600MHz antenna) are shows in Figs. 41,..,48.

Here is possible to see in the first meter of depth a man-made area (S) with the presence of underground services (pipes).

Several reflection events (W) for shape and dimensions were interpreted as walls. An interesting reflection events (F) indicated the presence of a structure (6.5m x 5m) partially filled with resulting material (stones, etc.).

Other reflection events labelled A could be related to archaeological structures.

Also in this case the time slices were built (Fig. 49). Fig. 50 show the depth slices overlapped to the google earth photo. The depth slices between 0.5m and 1.3m in depth are shows. The dashed white lines indicates the presence of some alignment that could be interpreted as walls. The filled room was labelled F. Fig. 51 well evidenced these alignments.

The analysis of the GPR data acquired with the 200MHz antenna allow to obtain information about the deeper buried structures. Fig. 52 shows all depth slices while Fig. 53 show the deeper slices (1.8-5.5m in depth) overlapped to the google earth photo. Is possible to see other deeper structures. Fig. 54 well evidenced the structures.

Zone 2: For the zone 2 (Fig. 52) the presence of threes limited the surveyed area. The processed radar sections (related to the 600MHz antenna) are shows in Figs. 56 and 58.

Relatively shallow (from 0.6m to 1.8m in depth) reflection events (T) are visible. These reflection events show a change in the polarity of the electromagnetic wave. This is probably due to the presence of a strong changing in the electromagnetic properties of the subsoil (i.e. voids). The shape and dimensions (about 0.8-1m x 1.8m) of these anomalies suggest the presence of tombs.

Other reflection events labelled A could be related to archaeological structures.

Sede di Catania
c/o Palazzo Ingrassia
via Biblioteca, 4
95124 Catania
Tel. +39 095 311 981
Fax. +39 095 311 981

Sede di Lecce
c/o Campus Universitario
Prov.le Lecce-Monteroni
73100 Lecce
Tel. +39 0832 422 200
Fax. +39 0832 422 225

Sede di Potenza
c/o Area della Ricerca del CNR
c.da S. Lojola
85050 Tito Scalo (PZ)
Tel. +39 0971 427 322
Tel. +39 0971 427 333

Unità di Ricerca Cosenza
c/ o Università della Calabria
Dip. di Biologia, Ecologia e Scienze della Terra
via P. Bucci, 12/B
87036 Arcavacata di Rende (CS)
Unità di Ricerca Palermo
via Litoranea, S.P. 23 Aspra - S. Elia
90017 Santa Flavia (PA)

Partita Iva 02118311006 | www.ibam.cnr.it | E-mail: segreteria@ibam.cnr.it

Fig. 59 show all the depth slices. Fig. 60 shows the depth slices overlapped to the google earth photo. The depth slices between 0.5m and 1.86 m in depth are shows. The dashed white lines indicates the presence of some alignment that could be interpreted as walls. They shows also the position of the tombs (T).

Fig. 61 show the wall structure in 3D.

The analysis of the GPR data acquired with the 200MHz antenna allow to obtain information about the deeper buried structures. Fig. 62 shows all depth slices while Fig. 63 show the deeper slices (4.2-4.7m in depth) overlapped to the google earth photo. Is possible to see the high amplitude anomalies (W) that could be related to the presence of walls. Fig. 64 well evidenced the structures.

Conclusions

The GPR survey allowed the acquisition of new data about the archaeological buried structures. In the area A several reflection events were underlined. The reflection event labelled A in Fig. 7 show a changing in the polarity of em wave. This important event could be related to a strong changing in the em properties of the subsoil. For example the presence of voids (Leucci, 2019). The 3D iso-surface representation (Fig. 15) highlights the presence of an empty space (partially filled with collapsed material). Other reflection events are probably related to walls and collapsed structures.

Great difficulties have been encountered in the acquisition of data in the area B. Here in fact the presence of trees and stems with weeds has limited the area of intervention. Another negative factor is related to the presence of metal bodies buried a few centimeters from the surface. The events reflected by metal bodies masked the faint reflections of the electromagnetic wave coming from structures of archaeological interest. Here a particular data processing allow to evidence some anomalies relate probably to structures of archaeological interest.

Area B was divided in three zones. Results highlights the presence of walls (probably defensive walls) with a probable tower foundation (Figs. 24 and 25). Other anomalies probably related to a deeper channels are visible in Fig. 24.

In the area E results highlights the presence of: i) tombs (some of them were excavated in the past); walls; ii) an interesting filled room (Figs 50 and 51).

Sede di Catania
c/o Palazzo Ingrassia
via Biblioteca, 4
95124 Catania
Tel. +39 095 311 981
Fax. +39 095 311 981

Sede di Lecce
c/o Campus Universitario
Prov.le Lecce-Monteroni
73100 Lecce
Tel. +39 0832 422 200
Fax. +39 0832 422 225

Sede di Potenza
c/o Area della Ricerca del CNR
c.da S. Lojola
85050 Tito Scalo (PZ)
Tel. +39 0971 427 322
Tel. +39 0971 427 333

Unità di Ricerca Cosenza
c/ o Università della Calabria
Dip. di Biologia, Ecologia e Scienze della Terra
via P. Bucci, 12/B
87036 Arcavacata di Rende (CS)
Unità di Ricerca Palermo
via Litoranea, S.P. 23 Aspra - S. Elia
90017 Santa Flavia (PA)

Partita Iva 02118311006 | www.ibam.cnr.it | E-mail: segreteria@ibam.cnr.it

Is important to underline the opportunity to integrate the GPR data with archaeological data. A joint re-reading (archaeologists and Geophysicists together) of the GPR data is important. This will allow a better interpretation.

GPR THEORY

The success of GPR surveys is to a great extent dependent on soil and sediment mineralogy, clay content, ground moisture, depth of burial, surface topography and vegetation (Conyers 2004a; Leucci, 2007; Leucci, 2015; Leucci, 2019). It is not a geophysical method that can be immediately applied to any geographic or archaeological setting, although with thoughtful modifications in acquisition and data processing methodology, GPR can be adapted to many differing site conditions. In the past it has usually been assumed by most GPR practitioners that the method would only be successful in areas where soils and underlying sediment are dry (Annan and Davis 1992). Although radar wave penetration, and the

ability to reflect energy back to the surface, is often enhanced in a dry environment, recent work has demonstrated that dryness is not necessarily a prerequisite for GPR surveys and even very wet environments are suitable, as long as the medium is not electrically conductive (Conyers 2004b). The GPR method involves the transmission of high frequency electromagnetic radio (radar) pulses into the earth and measuring the time elapsed between transmission, reflection off a buried discontinuity and reception back at a surface radar antenna. A pulse of radar energy is generated on a dipole transmitting antenna that is placed on, or near, the ground surface. The resulting wave of electromagnetic energy propagates downward into the ground where some energy can be reflected back to the surface at discontinuities (Fig. 1).

Sede di Catania
c/o Palazzo Ingrassia
via Biblioteca, 4
95124 Catania
Tel. +39 095 311 981
Fax. +39 095 311 981

Sede di Lecce
c/o Campus Universitario
Prov.le Lecce-Monteroni
73100 Lecce
Tel. +39 0832 422 200
Fax. +39 0832 422 225

Sede di Potenza
c/o Area della Ricerca del CNR
c.da S. Lojola
85050 Tito Scalo (PZ)
Tel. +39 0971 427 322
Tel. +39 0971 427 333

Unità di Ricerca Cosenza
c/ o Università della Calabria
Dip. di Biologia, Ecologia e Scienze della Terra
via P. Bucci, 12/B
87036 Arcavacata di Rende (CS)
Unità di Ricerca Palermo
via Litoranea, S.P. 23 Aspra - S. Elia
90017 Santa Flavia (PA)

Partita Iva 02118311006 | www.ibam.cnr.it | E-mail: segreteria@ibam.cnr.it

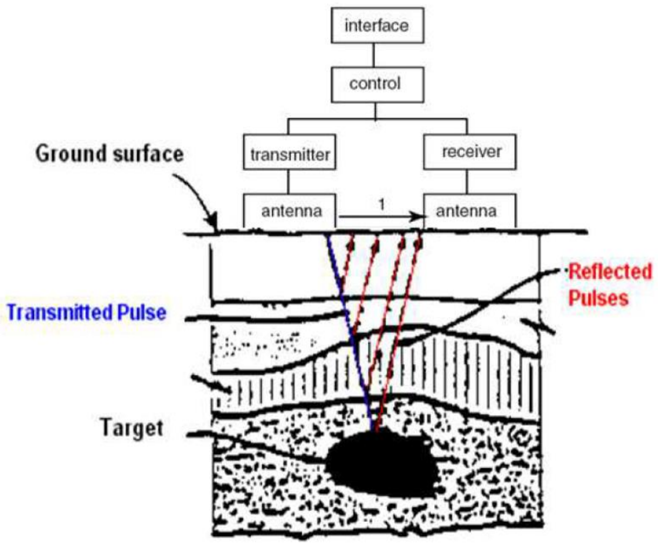

Fig. 1. A block diagram of a GPR system. The interface module enable the user to enter the system parameters, and displays and records the data. The control unit generates the timing signals so that all of the components operate in unison. This unit also does some preliminary data processing. The pulse travel paths in order of arrival are direct air wave, direct ground wave, and reflections.

The discontinuities where reflections occur are usually created by changes in electrical properties of the sediment or soil, lithologic changes, differences in bulk density at stratigraphic interfaces and most important water content variations. Reflection can also occur at interfaces between anomalous archaeological features and the surrounding soil or sediment. Void spaces in the ground, which may be encountered in burials, tombs, or tunnels will also generate significant radar reflections due to a significant change in radar wave velocity. The depth to which radar energy can penetrate and the amount of definition that can be expected in the subsurface is partially controlled by the frequency of the radar energy transmitted. Radar energy frequency controls both the wavelength of the propagating wave and the amount of weakening, or attenuation, of the waves in the ground. Standard GPR antennas used in archaeology propagate radar energy that varies in band width from about 10 megahertz (MHz) to 2500 MHz. Antennas usually come in standard frequencies, with each antenna having one center-frequency, but actually producing radar energy that ranges around that center by about two octaves (one half and two times the center frequency). The most efficient method in subsurface GPR mapping is to establish a grid across a survey area prior to acquiring data. Usually

Sede di Catania
c/o Palazzo Ingrassia
via Biblioteca, 4
95124 Catania
Tel. +39 095 311 981
Fax. +39 095 311 981

Sede di Lecce
c/o Campus Universitario
Prov.le Lecce-Monteroni
73100 Lecce
Tel. +39 0832 422 200
Fax. +39 0832 422 225

Sede di Potenza
c/o Area della Ricerca del CNR
c.da S. Lojola
85050 Tito Scalo (PZ)
Tel. +39 0971 427 322
Tel. +39 0971 427 333

Unità di Ricerca Cosenza
c/ o Università della Calabria
Dip. di Biologia, Ecologia e Scienze della Terra
via P. Bucci, 12/B
87036 Arcavacata di Rende (CS)

Unità di Ricerca Palermo
via Litoranea, S.P. 23 Aspra - S. Elia
90017 Santa Flavia (PA)

Partita Iva 02118311006 | www.ibam.cnr.it | E-mail: segreteria@ibam.cnr.it

rectangular grids are established with a transect spacing of one meter or less. Rectangular grids produce data that are easier to process and interpret. Other shapes of grid acquisition patterns may be necessary because of surface topography or other obstructions. Data from non-rectilinear surveys is just as useful as those acquired in rectangular shaped grids, although more field time may be necessary in surveying, and reflection data must be manipulated differently during computer processing and interpretation for reflection amplitude analysis. The two-way travel time and the amplitude and wavelength of the reflected radar waves derived from the pulses are amplified, processed and recorded for immediate viewing and later post-acquisition processing and display. During field data acquisition the radar transmission process is repeated many times a second as the antennas are pulled along the ground surface in transects. Distance along each line is recorded for accurate placement of all reflections within a surveyed grid. In this fashion two-dimensional profiles, which approximate vertical "slices" through the earth, are created along each grid line.

Radar energy becomes both dispersed and attenuated as it radiates into the ground. When portions of the original transmitted signal are reflected back toward the surface they will suffer additional attenuation by the material through which they pass, before finally being recorded at the surface. Therefore to be detected as reflections, important subsurface interfaces must not only have sufficient electrical contrast at their boundary but also must be located at a shallow enough depth where sufficient radar energy is still available for reflection. As radar energy is propagated to increasing depths, and the signal becomes weaker as it spreads out over more surface area and absorbed by the ground, making less available for reflection. For every site the maximum depth of resolution will vary with the geologic conditions and the equipment being used. Post-acquisition data filtering and other data amplification techniques (termed range-gaining) can sometimes be applied to reflection data after acquisition that will enhance some very low amplitude reflections in order to make them more visible. Many ground-penetrating radar novices envision the propagating radar pattern as a narrow "pencil" shaped beam that is focused directly down from the antenna. In fact, GPR waves radiated from standard commercial antennas radiate energy into the ground in an elliptical cone with the apex

Sede di Catania
c/o Palazzo Ingrassia
via Biblioteca, 4
95124 Catania
Tel. +39 095 311 981
Fax. +39 095 311 981

Sede di Lecce
c/o Campus Universitario
Prov.le Lecce-Monteroni
73100 Lecce
Tel. +39 0832 422 200
Fax. +39 0832 422 225

Sede di Potenza
c/o Area della Ricerca del CNR
c.da S. Lojola
85050 Tito Scalo (PZ)
Tel. +39 0971 427 322
Tel. +39 0971 427 333

Unità di Ricerca Cosenza
c/ o Università della Calabria
Dip. di Biologia, Ecologia e Scienze della Terra
via P. Bucci, 12/B
87036 Arcavacata di Rende (CS)
Unità di Ricerca Palermo
via Litoranea, S.P. 23 Aspra - S. Elia
90017 Santa Flavia (PA)

Partita Iva 02118311006 | www.ibam.cnr.it | E-mail: segreteria@ibam.cnr.it

of the cone at the center of the transmitting antenna (Conyers 2004a; Leucci, 2015). This elliptical cone of transmission occurs because the electrical field produced by the antenna is generated parallel to its long axis and is therefore usually radiating into the ground perpendicular to the direction of antenna movement along the ground surface. The radiation pattern is generated from a horizontal electric dipole antenna to which elements are sometimes added that effectively reduce upward radiation, called shields. Sometimes the only shielding mechanism is a radar absorbing surface placed above the antenna to neutralize upward radiating energy. Because of cost and portability considerations (size and weight), the use of more complex radar antennas that might be able to focus energy more efficiently into the ground in a more narrow beam has to date been limited in archaeology. Some antennas, especially those in the low frequency range from 10 to 100 MHz, are often not shielded and will therefore radiate radar energy in all directions. Using unshielded antennas can generate reflections from a nearby person pulling the radar antenna, or from any other objects nearby such as trees or buildings. Discrimination of individual targets, especially those of interest in the subsurface, can be difficult if these types of antennas are used. However, if the unwanted reflections generated from unshielded antennas can be identified, they can be easily filtered-out later. If reflections are recorded from randomly located trees, surface obstructions, or people moving about randomly near the antenna, they are more difficult to discriminate from important subsurface reflections and interpretation of the data is much more difficult. One of the most important variables in GPR surveys is the selection of antennas with the correct operating frequency for the depth necessary and the resolution of the features of interest (Conyers 2004a). Proper antenna frequency selection can in most cases make the difference between success and failure in a GPR survey and must be planned for in advance. In general the greater the necessary depth of investigation, the lower the antenna frequency should be used (Leucci, 2008). But lower frequency antennas are much larger, heavier and more difficult to transport to and within the field than high frequency antennas. For instance a 100 MHz antenna is about 2 meters long. It is not only difficult to transport to and from the field, but must usually be moved along transect lines using some form of wheeled vehicle or sled. In contrast, antennas greater than 400 MHz are usually 50 centimeters or smaller in maximum dimension, weigh very little, and can easily fit into a suitcase. Low frequency antennas (10–120

Sede di Catania
c/o Palazzo Ingrassia
via Biblioteca, 4
95124 Catania
Tel. +39 095 311 981
Fax. +39 095 311 981

Sede di Lecce
c/o Campus Universitario
Prov.le Lecce-Monteroni
73100 Lecce
Tel. +39 0832 422 200
Fax. +39 0832 422 225

Sede di Potenza
c/o Area della Ricerca del CNR
c.da S. Lojola
85050 Tito Scalo (PZ)
Tel. +39 0971 427 322
Tel. +39 0971 427 333

Unità di Ricerca Cosenza
c/o Università della Calabria
Dip. di Biologia, Ecologia e Scienze della Terra
via P. Bucci, 12/B
87036 Arcavacata di Rende (CS)

Unità di Ricerca Palermo
via Litoranea, S.P. 23 Aspra - S. Elia
90017 Santa Flavia (PA)

Partita Iva 02118311006 | www.ibam.cnr.it | E-mail: segreteria@ibam.cnr.it

MHz) generate long wave-length radar energy that can penetrate up to 50 meters in certain conditions, but are capable of resolving only very large subsurface features. In pure ice, antennas of this frequency have been known to transmit radar energy many kilometers. In contrast the maximum depth of penetration of a 900 MHz antenna is about one meter or less in typical soils, but its generated reflections can resolve features down to a few centimeters in dimension (Conyers 2004a; Leucci, 2008). A trade-off therefore exists between depth of penetration and subsurface resolution. The depth of penetration and the subsurface resolution is actually highly variable, depending on many site-specific factors such as overburden composition, porosity and the amount of retained moisture. If large amounts of electrically-conductive clay, are present, then attenuation of the radar energy with depth will occur very rapidly, irrespective of radar energy frequency. Attenuation can also occur if sediment or soils are saturated with salty water, especially sea water. The ability to resolve buried features is mostly determined by frequency and therefore the wavelengths of the radar energy being transmitted into the ground. The wavelength necessary for resolution varies depending on whether a three-dimensional object or an undulating surface is being investigated. For GPR to resolve three-dimensional objects, reflections from at least two surfaces, usually a top and bottom interface, need to be distinct. Resolution of a single buried planar surface, however, needs only one distinct reflection and therefore wavelength is not as important in its resolution. Radar energy that is reflected off a buried subsurface interface that slopes away from a surface transmitting antenna will be reflected away from the receiving antenna and will be lost. This sloping interface would therefore go unnoticed in reflection profiles. A buried surface with this orientation would only be visible if an additional traverse were located in an orientation where that the same buried interface is sloping toward the surface antennas. This is one reason why it is important to always acquire lines of reflection data within a closely spaced surface grid, and sometimes in transects perpendicular to each other. Some features in the subsurface may be described as “point targets”, while other are more similar to planar surfaces. Planar surfaces can be stratigraphic and soil horizons or large flat archaeological features such as floors. Point targets are features such as walls, tunnels, voids, artifacts or any other non-planar object. Depending on a planar surface’s thickness, reflectivity, orientation and depth of burial it is potentially visible with any frequency data, constrained only by

Sede di Catania
c/o Palazzo Ingrassia
via Biblioteca, 4
95124 Catania
Tel. +39 095 311 981
Fax. +39 095 311 981

Sede di Lecce
c/o Campus Universitario
Prov.le Lecce-Monteroni
73100 Lecce
Tel. +39 0832 422 200
Fax. +39 0832 422 225

Sede di Potenza
c/o Area della Ricerca del CNR
c.da S. Lojola
85050 Tito Scalo (PZ)
Tel. +39 0971 427 322
Tel. +39 0971 427 333

Unità di Ricerca Cosenza
c/ o Università della Calabria
Dip. di Biologia, Ecologia e Scienze della Terra
via P. Bucci, 12/B
87036 Arcavacata di Rende (CS)

Unità di Ricerca Palermo
via Litoranea, S.P. 23 Aspra - S. Elia
90017 Santa Flavia (PA)

Partita Iva 02118311006 | www.ibam.cnr.it | E-mail: segreteria@ibam.cnr.it

the conditions discussed above. Point sources, however, often have little surface area with which to reflect radar energy and therefore are usually difficult to identify and map. They are sometimes indistinguishable from the surrounding material, many times being visible only as small reflection hyperbolas visible on one profile within a grid. In most geological and archaeological settings the materials through which radar waves pass may contain many small discontinuities that reflect energy, which can only be described as clutter (if they are not the target of the survey). Resolution of clutter is totally dependent on the wavelength of the radar energy being propagated. If both the features to be resolved and the discontinuities producing the clutter are on the order of one wavelength in size, then the reflection profiles will appear to contain only clutter and there can be no discrimination between the two. Clutter can also be produced by large discontinuities, such as cobbles and boulders, but only when a lower frequency antenna that produces a long wavelength is used. In all cases the features to be resolved, if not a large planar surface, should be much larger than the clutter, and greater than one wavelength

of the propagating energy in dimension (Conyers 2004a). The raw reflection data collected by GPR is nothing more than a collection of many individual traces along two-dimensional transects within a grid. Each reflection trace contains a series of waves that vary in amplitude depending on the amount and intensity of energy reflection that occurred at buried interfaces. When these traces are plotted sequentially in standard two-dimensional profiles the specific amplitudes within individual traces that contain important reflection information are sometimes difficult to visualize and interpret. Rarely is the standard interpretation of GPR data, which consists of viewing each profile and then mapping important reflections and other anomalies sufficient, especially when the buried features and stratigraphy are complex. In areas where buried materials are difficult to discern, different processing and interpretation methods, one of which is amplitude analysis, must be used. In the past when GPR reflection data were collected that had no discernable reflections or recognizable anomalies of any sort the survey was usually declared a failure and little if any interpretation was conducted. With the advent of more powerful computers and sophisticated software programs that can manipulate large sets of digital data, important subsurface information in the form of amplitude changes within the reflected waves has been extracted from these types of GPR data (Conyers

Sede di Catania
c/o Palazzo Ingrassia
via Biblioteca, 4
95124 Catania
Tel. +39 095 311 981
Fax. +39 095 311 981

Sede di Lecce
c/o Campus Universitario
Prov.le Lecce-Monteroni
73100 Lecce
Tel. +39 0832 422 200
Fax. +39 0832 422 225

Sede di Potenza
c/o Area della Ricerca del CNR
c.da S. Lojola
85050 Tito Scalo (PZ)
Tel. +39 0971 427 322
Tel. +39 0971 427 333

Unità di Ricerca Cosenza
c/o Università della Calabria
Dip. di Biologia, Ecologia e Scienze della Terra
via P. Bucci, 12/B
87036 Arcavacata di Rende (CS)
Unità di Ricerca Palermo
via Litoranea, S.P. 23 Aspra - S. Elia
90017 Santa Flavia (PA)

Partita Iva 02118311006 | www.ibam.cnr.it | E-mail: segreteria@ibam.cnr.it

2004a). An analysis of the spatial distribution of the amplitudes of reflected waves is important because it is an indicator of subsurface changes in lithology and other physical properties. The higher the contrasting velocity at a buried interface, the greater the amplitude of the reflected wave. If amplitude changes can be related to important buried features and stratigraphy, the location of higher or lower amplitudes at specific depths can be used to reconstruct the subsurface in three-dimensions. Areas of low amplitude waves indicate uniform matrix material or soils while those of high amplitude denote areas of high subsurface contrast such as buried archaeological features, voids or important stratigraphic changes. In order to be correctly interpreted, amplitude differences must be analyzed in discrete slices that examine only the strength of reflections within specific depths in the ground. Each slice consists of the spatial distribution of all reflected wave amplitudes at various depths, which are indicative of these changes in sediments, soils and buried materials. Amplitude slices need not be constructed horizontally or even in equal time intervals. They can vary in thickness and orientation, depending on the questions being asked (Conyers and Goodman, 1997). Surface topography and the subsurface orientation of features and stratigraphy of a site may sometimes necessitate the construction of slices that are neither uniform in thickness nor horizontal. To compute horizontal amplitude slices the computer compares amplitude variations within traces that were recorded within a defined time window (that can become depth-windows if velocities are known). When this is done both positive and negative amplitudes of reflections are compared to the norm of all amplitudes within that window. No differentiation is usually made between positive or negative amplitudes in these analyses; only the magnitude of amplitude deviation from the norm. Low amplitude variations within any one slice denote little subsurface reflection and therefore indicate the presence of fairly homogeneous material. High amplitudes indicate significant subsurface discontinuities, in many cases detecting the presence of buried features. An abrupt change between an area of low and high amplitude can be very significant and may indicate the presence of a major buried interface between two media. Degrees of amplitude variation in each time-slice can be assigned arbitrary colors or shades of gray along a nominal scale. Usually there are no specific amplitude units assigned to these color or tonal changes.

Sede di Catania
c/o Palazzo Ingrassia
via Biblioteca, 4
95124 Catania
Tel. +39 095 311 981
Fax. +39 095 311 981

Sede di Lecce
c/o Campus Universitario
Prov.le Lecce-Monteroni
73100 Lecce
Tel. +39 0832 422 200
Fax. +39 0832 422 225

Sede di Potenza
c/o Area della Ricerca del CNR
c.da S. Lojola
85050 Tito Scalo (PZ)
Tel. +39 0971 427 322
Tel. +39 0971 427 333

Unità di Ricerca Cosenza
c/ o Università della Calabria
Dip. di Biologia, Ecologia e Scienze della Terra
via P. Bucci, 12/B
87036 Arcavacata di Rende (CS)

Unità di Ricerca Palermo
via Litoranea, S.P. 23 Aspra - S. Elia
90017 Santa Flavia (PA)

Partita Iva 02118311006 | www.ibam.cnr.it | E-mail: segreteria@ibam.cnr.it

Using three-dimensional GPR reflection data, buried features can be rendered into isosurface images, meaning that the interfaces producing the reflections are placed in a three-dimensional picture and a pattern or color is assigned to specific amplitudes in order for them to be visible (Conyers et al. 2002; Conyers 2004a: 163; Goodman et al. 2004; Leckebusch 2003). In programs that produce these types of images certain amplitudes (usually the highest ones) can be patterned or colored while others are made transparent. Computer-generated light sources, to simulate rays of the sun, can then be used to shade and shadow the rendered features in order to enhance them, and the features can be rotated and shaded until a desired image results.

GPR data processing

One of the great advantages of the GPR method is the fact that the raw data is acquired in a manner that allows it to be easily viewed in real time using a computer screen. Often very little processing is required for an initial interpretation of the data, with most of the effort directed towards data visualization. On the other hand, depending on the application and target of interest, it may be necessary to perform sophisticated data processing, and many practitioners find that techniques common to seismic reflection such as migration can be applied. The outcome of processing is a cross-section of the subsurface EM properties, displayed in terms of the two-way travel time, i.e. the time taken for a wave to move from the transmitter to a reflector and return to the receiver. The amount of processing undertaken can range from basic, which allows rapid data output, to the more time consuming application of algorithms designed for use on seismic dataset (Ylmaz, 1987), which produce high quality output (Daniels et al. 1988; Conyers and Goodman, 1997). The processing sequence usually developed for GPR raw data is following done.

zero-time adjust (static shift) – During a GPR survey, the first waveform to arrive at the receiver is the air wave. There is a delay in the time of arrival of the first break of the air wave on the radar section due to the length of the cable connecting the antennae and the control unit. Therefore need to associate zero-time with zero-depth, so any time offset due to instrument recording must be removed before interpretation of the radar image.

Background removal filter (subtract average trace to remove banding) - Background noise is a repetitive signal created by slight ringing in the antennae, which produces a coherent banding effect,

Sede di Catania
c/o Palazzo Ingrassia
via Biblioteca, 4
95124 Catania
Tel. +39 095 311 981
Fax. +39 095 311 981

Sede di Lecce
c/o Campus Universitario
Prov.le Lecce-Monteroni
73100 Lecce
Tel. +39 0832 422 200
Fax. +39 0832 422 225

Sede di Potenza
c/o Area della Ricerca del CNR
c.da S. Lojola
85050 Tito Scalo (PZ)
Tel. +39 0971 427 322
Tel. +39 0971 427 333

Unità di Ricerca Cosenza
c/o Università della Calabria
Dip. di Biologia, Ecologia e Scienze della Terra
via P. Bucci, 12/B
87036 Arcavacata di Rende (CS)
Unità di Ricerca Palermo
via Litoranea, S.P. 23 Aspra - S. Elia
90017 Santa Flavia (PA)

Partita Iva 02118311006 | www.ibam.cnr.it | E-mail: segreteria@ibam.cnr.it

parallel to the surface wave, across the section (Conyers and Goodman,1997). The filter is a simple arithmetic process that sums all the amplitudes of reflections that were recorded at the same time along a profile and divides by the number of traces summed the resulting composite digital wave, which is an average of all background noise, is then subtracted from the data set. Care must be taken in this process not to remove real linear events in the profile. The time window where the filter operates must be specified so that the filter is not applied until after the surface wave.

Horizontal (distance) stretch to get constant trace separation (horizontal normalization) – This correction need to remove the effects of non-constant motion along the profile. Data are collected continuously, and will not be represented correctly in the image if steps are not taken to correct for the variable horizontal data coverage.

Gain – Gain is used to compensate for amplitude variations in the GPR image; early signal arrival times have greater amplitude than later times because these early signals have not traveled as far. The loss of signal amplitude is related to geometric spreading as well as intrinsic attenuation. Various time-variable gain functions may be applied in an effort to equalize amplitudes of the recorded signals. The most commonly applied is an automatic gain control (AGC) that is a time – varying gain that runs a window of chosen length along each trace, point by point, finding the average amplitude over the length of the window about each point. A gain function is then applied such that the average at each point is made constant along the trace.

Topographic corrections – Surveyed elevation data are used to apply topography to the GPR survey profiles. Firstly trace windowing is applied to the data to remove all artefacts in the survey that arrived before the time zero arrivals. The actual elevation recorded along the GPR line are then entered into the data processing package and the time zero arrivals are hung from the topographic profile by applying a time shift to each individual trace.

Frequency filtering - Although GPR data are collected with source and receiver antennae of specified dominant frequency, the recorded signals include a band of frequencies around the dominant frequency component. Frequency filtering is a way of removing unwanted high and/or low frequencies in order to produce a more interpretable GPR image. Highpass filtering maintains the high frequencies in the signal but removes the low frequency components. Low-pass filtering does

Sede di Catania
c/o Palazzo Ingrassia
via Biblioteca, 4
95124 Catania
Tel. +39 095 311 981
Fax. +39 095 311 981

Sede di Lecce
c/o Campus Universitario
Prov.le Lecce-Monteroni
73100 Lecce
Tel. +39 0832 422 200
Fax. +39 0832 422 225

Sede di Potenza
c/o Area della Ricerca del CNR
c.da S. Lojola
85050 Tito Scalo (PZ)
Tel. +39 0971 427 322
Tel. +39 0971 427 333

Unità di Ricerca Cosenza
c/ o Università della Calabria
Dip. di Biologia, Ecologia e Scienze della Terra
via P. Bucci, 12/B
87036 Arcavacata di Rende (CS)
Unità di Ricerca Palermo
via Litoranea, S.P. 23 Aspra - S. Elia
90017 Santa Flavia (PA)

Partita Iva 02118311006 | www.ibam.cnr.it | E-mail: segreteria@ibam.cnr.it

just the opposite, removing high frequencies and retaining the low frequency components. A combination of these two effects can be achieved with a band-pass filter, where the filter retains all frequencies in the pass band, but removes the high and low frequencies outside of the pass band.

Deconvolution - When the time-domain GPR pulse propagates in the subsurface, convolution is the physical process that describes how the propagating wavelet interacts with the earth filter (the reflection and transmission response of the subsurface). Deconvolution is an inverse filtering operation that attempts to remove the effects of the source wavelet in order to better interpret GPR profiles as images of the earth structure. Deconvolution operators can degrade GPR images when the source signature is not known. Deconvolution operators are designed under the assumption that the propagating source wavelet is minimum phase (i.e., most of its energy is associated with early times in the wavelet). This assumption is not necessarily valid for GPR signals. With GPR, the ground becomes part of the antennae, and the source pulse can vary from trace-to-trace and is not necessarily minimum phase. All filtering operations borrowed from seismic data processing must be applied with care as some of the underlying assumptions for elastic waves generated at the surface of the earth are not valid or are different for electromagnetic waves. For more see Ylmaz (1987)

Migration - Migration is a processing technique which attempts to correct for the fact that energy in the GPR profile image is not necessarily correctly associated with depths below the 2-D survey line. As with deconvolution, migration can be seen as an inverse processing step which attempts to correct the geometry of the subsurface in the GPR image with respect to the survey geometry. For example, a subsurface scattering point would show up in a GPR image as a hyperbolic-shaped feature. Migration would associate all the energy in the wavelets making up the hyperbolic feature with the point of diffraction, and imaging of the actual earth structure (the heterogeneity represented by the point diffractor) would be imaged more clearly. Migration operators require a good estimate of subsurface EM wave velocity in order to apply the correct adjustments to the GPR image. For more see Ylmaz (1987).

F-K filter - Fourier transform techniques, or f-k filtering, i.e. by means of filters designed and applied in the frequency-wavenumber (or f-k) domain (Yilmaz, 1987). It is well known that a dipping line in the x-t domain maps to a line passing through the origin and with an orientation

Sede di Catania
c/o Palazzo Ingrassia
via Biblioteca, 4
95124 Catania
Tel. +39 095 311 981
Fax. +39 095 311 981

Sede di Lecce
c/o Campus Universitario
Prov.le Lecce-Monteroni
73100 Lecce
Tel. +39 0832 422 200
Fax. +39 0832 422 225

Sede di Potenza
c/o Area della Ricerca del CNR
c.da S. Lojola
85050 Tito Scalo (PZ)
Tel. +39 0971 427 322
Tel. +39 0971 427 333

Unità di Ricerca Cosenza
c/ o Università della Calabria
Dip. di Biologia, Ecologia e Scienze della Terra
via P. Bucci, 12/B
87036 Arcavacata di Rende (CS)

Unità di Ricerca Palermo
via Litoranea, S.P. 23 Aspra - S. Elia
90017 Santa Flavia (PA)

Partita Iva 02118311006 | www.ibam.cnr.it | E-mail: segreteria@ibam.cnr.it

normal to the original line in the f-k amplitude spectrum. In other words, a line of constant apparent velocity corresponds to a line of constant slope in the f-k domain. In particular, horizontal lines map to the vertical direction, along the f-axis. Dipping events that overlap in the x-t domain can be separated in the f-k domain by their dips. This allows the elimination of certain types of unwanted energy from the data, representing linear coherent noise. Regardless of their location, lines with the same dip (parallel lines), map to the same radial line in the f-k amplitude spectrum, so that f-k filters could be effective for removing at the same time all undesired lines with the same slope, but impractical if one wants to remove only some of them instead of the whole family. Fan filters are generally used for dip filtering. In these cases the amplitude spectrum of the input is multiplied by a suitable function, the amplitude response of the filter consisting of ones in a fan-shaped zone and zeros elsewhere, to obtain the amplitude spectrum of the output, whereas the phase spectrum is left unchanged. Finally, the filtered signal is obtained by a twodimensional inverse Fourier transform.

The Wavelet Transform – It is possible to decompose the radar signal into different scales where signal and certain noises may be effectively separated/isolated (multiresolution analysis) . Subsequent muting of the noise is easily achieved in the Wavelet Transform (WT) domain operating only on the scales where the offending noise appears.

Time-slice analysis – An analysis of the spatial distribution of reflected wave amplitudes is important because it is an indicator of potentially meaningful subsurface changes in lithology or other physical properties of materials in the ground. If amplitude changes can be related to the presence of important buried features, the location of those changes can be used to reconstruct the subsurface in three dimensions. Areas of low-amplitude waves usually indicate uniform matrix material or soils while those of high amplitude denote areas of high subsurface contrast such as buried archaeological features, voids, or important stratigraphic changes. In order to be interpreted, amplitude differences must be analyzed in slices that examine only changes within specified depths in the ground. Each amplitude slice consists of the spatial distribution of all reflected wave amplitudes, which are indicative of these changes in sediments, soils, and buried materials. Amplitude slices need not be constructed horizontally or even in equal depth intervals. They can vary in thickness and orientation, depending on the questions being asked. To produce horizontal

Sede di Catania
c/o Palazzo Ingrassia
via Biblioteca, 4
95124 Catania
Tel. +39 095 311 981
Fax. +39 095 311 981

Sede di Lecce
c/o Campus Universitario
Prov.le Lecce-Monteroni
73100 Lecce
Tel. +39 0832 422 200
Fax. +39 0832 422 225

Sede di Potenza
c/o Area della Ricerca del CNR
c.da S. Lojola
85050 Tito Scalo (PZ)
Tel. +39 0971 427 322
Tel. +39 0971 427 333

Unità di Ricerca Cosenza
c/ o Università della Calabria
Dip. di Biologia, Ecologia e Scienze della Terra
via P. Bucci, 12/B
87036 Arcavacata di Rende (CS)
Unità di Ricerca Palermo
via Litoranea, S.P. 23 Aspra - S. Elia
90017 Santa Flavia (PA)

Partita Iva 02118311006 | www.ibam.cnr.it | E-mail: segreteria@ibam.cnr.it

amplitude slice-maps the computer compares amplitude variations within traces that were recorded within a defined time window. For instance, if data were recorded to a maximum of 30 nanoseconds in the ground, six slices of 5 nanoseconds in thickness would be analyzed and the spatial distribution of amplitudes in each slice would be produced. When this is done both positive and negative amplitudes of reflections are compared to the norm of all amplitudes within that window. No differentiation is usually made between positive or negative amplitudes in these analyses; only the magnitude of amplitude deviation from the norm is expressed. An abrupt change between an area of low and high amplitude can be very significant and may indicate the presence of a major buried interface between two media. Degrees of amplitude variation in each slice can be assigned arbitrary colors or shades of gray along a nominal scale. Usually there are no specific amplitude units assigned to these color or tonal changes. Slices that are produced in thicknesses based on radar travel time can readily be converted to depth slices, if the velocity of energy movement through the material (or its RDP) is calculated. This is the preferred format for most archaeological applications. There are a number of computer programs available that can estimate velocity of radar travel times from individual reflection profiles; alternatively, direct measurements can be made in the field if open excavations are present (Conyers and Lucius 1996). Direct velocity measurements can be obtained by inserting a metal object (a pipe or other object of this sort) horizontally into the face of an excavation and measuring its depth in centimeters. Metal is a perfect radar reflector, and when antennas are pulled over the buried pipe, it will often be visible as distinct reflection hyperbolas. Radar-wave travel times to the object can then be measured and velocity easily calculated. This average velocity can then be used to convert all time measurements to approximate depth in the ground for final data presentation.

Time-depth conversion – The EM-wave velocity can be estimated from GPR data in several ways (Conyers and Goodman 1997; Huisman et al. 2003); the conventional methods involve common depth-point (CDP) and wide-angle reflection and refraction (WARR) data sets. Both methods require two antennae in separate units and relatively long acquisition times. In the first case, both antennae are simultaneously moved apart on either side of the midpoint of the profile. In the second case, the position of one antenna is fixed while the other is moved along the profile direction. The EM-wave

Sede di Catania
c/o Palazzo Ingrassia
via Biblioteca, 4
95124 Catania
Tel. +39 095 311 981
Fax. +39 095 311 981

Sede di Lecce
c/o Campus Universitario
Prov.le Lecce-Monteroni
73100 Lecce
Tel. +39 0832 422 200
Fax. +39 0832 422 225

Sede di Potenza
c/o Area della Ricerca del CNR
c.da S. Lojola
85050 Tito Scalo (PZ)
Tel. +39 0971 427 322
Tel. +39 0971 427 333

Unità di Ricerca Cosenza
c/ o Università della Calabria
Dip. di Biologia, Ecologia e Scienze della Terra
via P. Bucci, 12/B
87036 Arcavacata di Rende (CS)
Unità di Ricerca Palermo
via Litoranea, S.P. 23 Aspra - S. Elia
90017 Santa Flavia (PA)

Partita Iva 02118311006 | www.ibam.cnr.it | E-mail: segreteria@ibam.cnr.it

velocity can be more quickly and easily determined from the reflection profiles acquired in continuous mode, using the characteristic hyperbolic shape of reflection from a point source (Fruhwirth et al. 1996). This is a very common method of velocity estimation and it is based on the phenomenon that a small object reflects EM-waves in almost every direction.

Geophysical measurements

Lara De Giorgi, Ivan Ferrari, Francesco Giuri

Geophysical data Processing

Lara De Giorgi, Giovanni Leucci

Topographical analysis

Ivan Ferrari, Francesco Giuri

References

Annan, A.P. and J.L. Davis, 1992. Design and development of a digital ground penetrating radar system. In J.A. Pilon (editor), Ground penetrating radar. Geological Survey of Canada, Paper 90–4: 49–55.

Conyers, Lawrence B., 2004a, Ground-penetrating Radar for Archaeology. AltaMira Press, Walnut Creek, California. 255

Conyers, Lawrence B., 2004b, Moisture and soil differences as related to the spatial accuracy of amplitude maps at two archaeological test sites. Proceedings of the Tenth International Conference on Ground Penetrating Radar, Delft, The Netherlands, June 21–24, 2004.

Conyers, Lawrence B. and Dean Goodman, 1997, Ground-penetrating Radar: An Introduction for Archaeologists. AltaMira Press, Walnut Creek, California.

Conyers LB. 2006. Innovative ground-penetrating radar methods for archaeological mapping. Archaeological Prospection 13(2): 139–141.

Sede di Catania
c/o Palazzo Ingrassia
via Biblioteca, 4
95124 Catania
Tel. +39 095 311 981
Fax. +39 095 311 981

Sede di Lecce
c/o Campus Universitario
Prov.le Lecce-Monteroni
73100 Lecce
Tel. +39 0832 422 200
Fax. +39 0832 422 225

Sede di Potenza
c/o Area della Ricerca del CNR
c.da S. Lojola
85050 Tito Scalo (PZ)
Tel. +39 0971 427 322
Tel. +39 0971 427 333

Unità di Ricerca Cosenza
c/ o Università della Calabria
Dip. di Biologia, Ecologia e Scienze della Terra
via P. Bucci, 12/B
87036 Arcavacata di Rende (CS)

Unità di Ricerca Palermo
via Litoranea, S.P. 23 Aspra - S. Elia
90017 Santa Flavia (PA)

Partita Iva 02118311006 | www.ibam.cnr.it | E-mail: segreteria@ibam.cnr.it

Davenport, C.G., Lindemann, J.W., Griffin T.J., and Borowski, J.E., 1988. Geotechnical Applications 3: Crime Scene Investigation Techniques, Geophysics: The Leading Edge of Exploration, Vol., 7, No., 8, pp. 64-66.

Davenport, C.G., Griffin, T.J., Lindemann, J.W., and Heimmer, D., 1990. Geoscientists and Law Officers Work Together in Colorado, Geotimes, Vol., 35, No., 7, pp. 13-15.

France D.L., Griffin, T.J., Swanburg, J.G., Llindemann, J.W., Davenport, G.C., Trammell, V., et al., 1992. A Multidisciplinary Approach to the Detection of Clandestine Graves, Journal of Forensic Science, Vol. 37, pp. 1445-1458.

France D.L., Griffin, T.J., Swanburg, J.G., Llindemann, J.W., Davenport, G.C., Trammell, V., et al., 1997. NecroSearch Revisited: Further Multidisciplinary Approaches to the Detection of Clandestine Graves. In: Haglund W.D., Sorg M.H., editors. Forensic Taphonomy: The Postmortem Fate of Human Remains. Boca Raton, Florida: CRC Press, pp. 497-509.

Freeland, R.S., Yoder, R.E., Miller, M.L., and Koppenjan, S.K., 2002. Forensic Application of Sweep-Frequency and Impulse GPR, Ninth International Conference on Ground Penetrating Radar, Santa Barbara, California, USA, April 30-May 2, pp. 533-538.

Fruhwirth R.K., Schmoller R. and Oberaigner E.R. 1996. Some aspects of the estimation of electromagnetic wave velocities. Proceedings of the 6th International Conference on Ground Penetrating Radar, Tohoku University, Sendai, Japan, pp. 135–138.

Gaffney, Chris and John Gater, 2003, Revealing the Buried Past: Geophysics for Archaeologists. Tempus, Stroud, Gloucestershire.

Goodman, Dean and Piro, Salvatore, Nishimura, Yasushi, Patterson, Helen and Vince Gaffney, 2004, Discovery of a 1st century AD Roman amphitheatre and other structures at the Forum Novum by GPR. Journal of Environmental and Engineering Geophysics 9: 35–42.

Goodman D. 2013. GPR Slice Version 7.0 Manual. http://www.gpr-survey.com (accessed June 2013).

Goodman D, Piro S. 2013. GPR Remote Sensing in Archaeology. Geotechnologies and the Environment Series, Vol. 9, Springer-Verlag: Berlin; 233 pp.

Sede di Catania
c/o Palazzo Ingrassia
via Biblioteca, 4
95124 Catania
Tel. +39 095 311 981
Fax. +39 095 311 981

Sede di Lecce
c/o Campus Universitario
Prov.le Lecce-Monteroni
73100 Lecce
Tel. +39 0832 422 200
Fax. +39 0832 422 225

Sede di Potenza
c/o Area della Ricerca del CNR
c.da S. Lojola
85050 Tito Scalo (PZ)
Tel. +39 0971 427 322
Tel. +39 0971 427 333

Unità di Ricerca Cosenza
c/ o Università della Calabria
Dip. di Biologia, Ecologia e Scienze della Terra
via P. Bucci, 12/B
87036 Arcavacata di Rende (CS)
Unità di Ricerca Palermo
via Litoranea, S.P. 23 Aspra - S. Elia
90017 Santa Flavia (PA)

Partita Iva 02118311006 | www.ibam.cnr.it | E-mail: segreteria@ibam.cnr.it

Goodman D, Steinberg J, Damiata B, Nishimure Y, Schneider K, Hiromichi H, Hisashi N. 2006. GPR overlay analysis for archaeological prospection. Proceedings of the 11th International Conference on Ground Penetrating Radar, Columbus, Ohio; CD-rom.

Huisman J.A., Hubbard S.S., Redman J.D. and Annan A.P. 2003. Measuring soil water content with ground penetrating radar: A review. Vadose Zone Journal 2, 476–491.

Leckebusch, J., 2003, Ground-penetrating radar: A modern three-dimensional prospection method. Archaeological Prospection 10: 213–240.

Leucci G., 2008. ground penetrating radar:the electromagnetic signal attenuation and maximum penetration depth, Scholarly Research Exchange: Volume 2008 • Article ID 926091 • doi:10.3814/2008/926091;

Leucci G., 2015, Geofisica Applicata all'Archeologia e ai Beni Monumentali. Dario Flaccovio Editore, Palermo, pp. 368. ISBN: 9788857905068

Leucci G., 2019, Nondestructive Testing for Archaeology and Cultural Heritage A Practical Guide and New Perspectives. Springer ISBN 978-3-030-01899-3;

Miller, M.L., Freeland, R.S., and Koppenjan, S.K., 2002. Searching for Concealed Human Remains using GPR Imaging of Decomposition, Ninth International Conference on Ground Penetrating Radar, Santa Barbara, California, USA, April 30-May 2, pp. 539- 544.

Ylmaz O., Seismic Data Processing, in: E.B. Neitzel (Ed.), Seismic Data Processing, Society of Exploration Geophysicists, Tulsa USA, 1987.

THE DIRECTOR — **DOTT. DANIELE MALFITANA**

THE SCIENTIFIC CHIEF — **DOTT. GIOVANNI LEUCCI**

Sede di Catania
c/o Palazzo Ingrassia
via Biblioteca, 4
95124 Catania
Tel. +39 095 311 981
Fax. +39 095 311 981

Sede di Lecce
c/o Campus Universitario
Prov.le Lecce-Monteroni
73100 Lecce
Tel. +39 0832 422 200
Fax. +39 0832 422 225

Sede di Potenza
c/o Area della Ricerca del CNR
c.da S. Lojola
85050 Tito Scalo (PZ)
Tel. +39 0971 427 322
Tel. +39 0971 427 333

Unità di Ricerca Cosenza
c/ o Università della Calabria
Dip. di Biologia, Ecologia e Scienze della Terra
via P. Bucci, 12/B
87036 Arcavacata di Rende (CS)

Unità di Ricerca Palermo
via Litoranea, S.P. 23 Aspra - S. Elia
90017 Santa Flavia (PA)

Partita Iva 02118311006 | www.ibam.cnr.it | E-mail: segreteria@ibam.cnr.it

FIGURES

Sede di Catania
c/o Palazzo Ingrassia
via Biblioteca, 4
95124 Catania
Tel. +39 095 311 981
Fax. +39 095 311 981

Sede di Lecce
c/o Campus Universitario
Prov.le Lecce-Monteroni
73100 Lecce
Tel. +39 0832 422 200
Fax. +39 0832 422 225

Sede di Potenza
c/o Area della Ricerca del CNR
c.da S. Lojola
85050 Tito Scalo (PZ)
Tel. +39 0971 427 322
Tel. +39 0971 427 333

Unità di Ricerca Cosenza
c/ o Università della Calabria
Dip. di Biologia, Ecologia e Scienze della Terra
via P. Bucci, 12/B
87036 Arcavacata di Rende (CS)
Unità di Ricerca Palermo
via Litoranea, S.P. 23 Aspra - S. Elia
90017 Santa Flavia (PA)

Partita Iva 02118311006 | www.ibam.cnr.it | E-mail: segreteria@ibam.cnr.it

Sede di Catania
c/o Palazzo Ingrassia
via Biblioteca, 4
95124 Catania
Tel. +39 095 311 981
Fax. +39 095 311 981

Sede di Lecce
c/o Campus Universitario
Prov.le Lecce-Monteroni
73100 Lecce
Tel. +39 0832 422 200
Fax. +39 0832 422 225

Sede di Potenza
c/o Area della Ricerca del CNR
c.da S. Lojola
85050 Tito Scalo (PZ)
Tel. +39 0971 427 322
Tel. +39 0971 427 333

Unità di Ricerca Cosenza
c/ o Università della Calabria
Dip. di Biologia, Ecologia e Scienze della Terra
via P. Bucci, 12/B
87036 Arcavacata di Rende (CS)

Unità di Ricerca Palermo
via Litoranea, S.P. 23 Aspra - S. Elia
90017 Santa Flavia (PA)

Partita Iva 02118311006 | www.ibam.cnr.it | E-mail: segreteria@ibam.cnr.it

Figure 1: the surveyed areas A, B and E

Area A

Figure 2: the surveyed area A

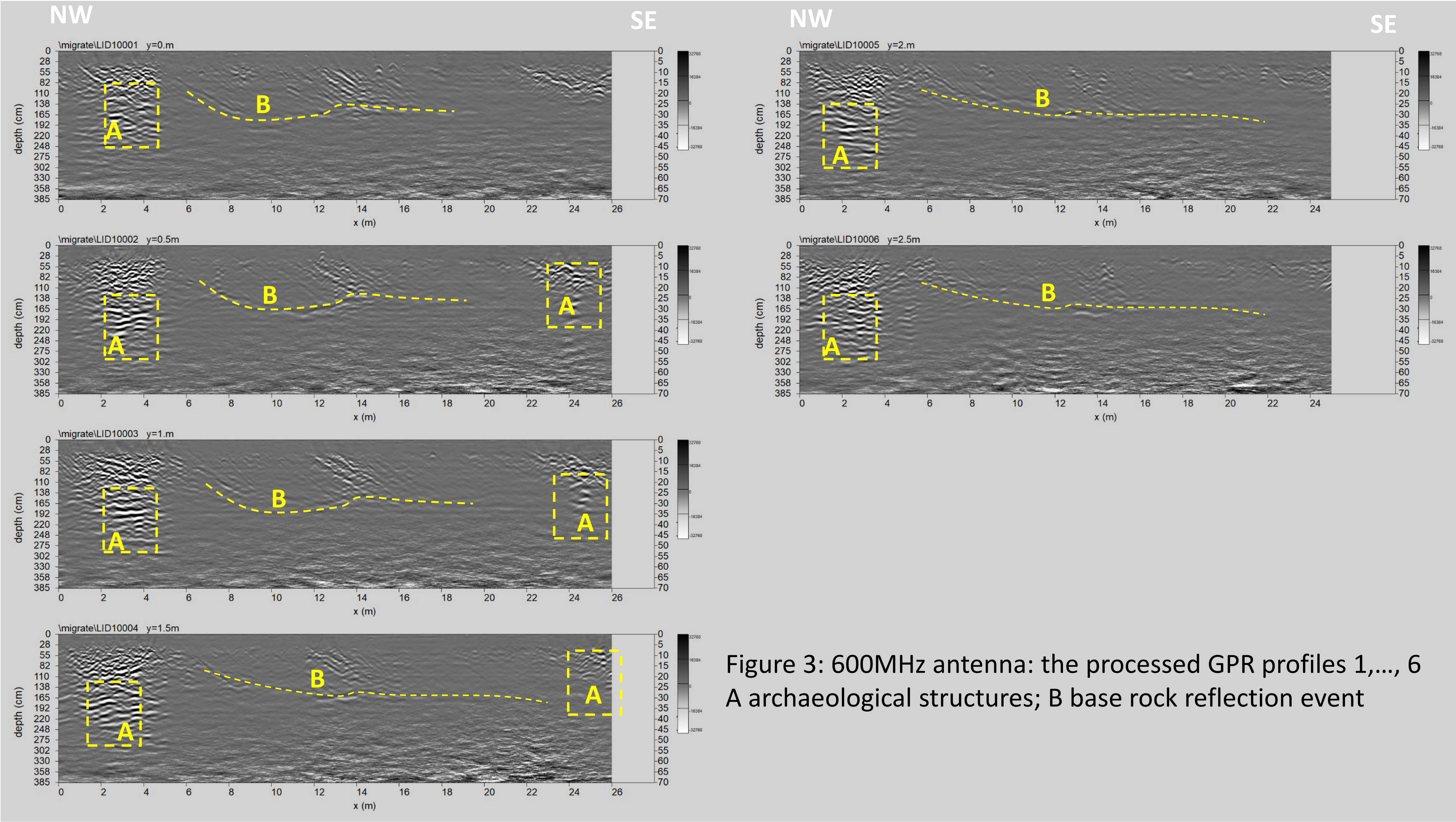

Figure 3: 600MHz antenna: the processed GPR profiles 1,…, 6
A archaeological structures; B base rock reflection event

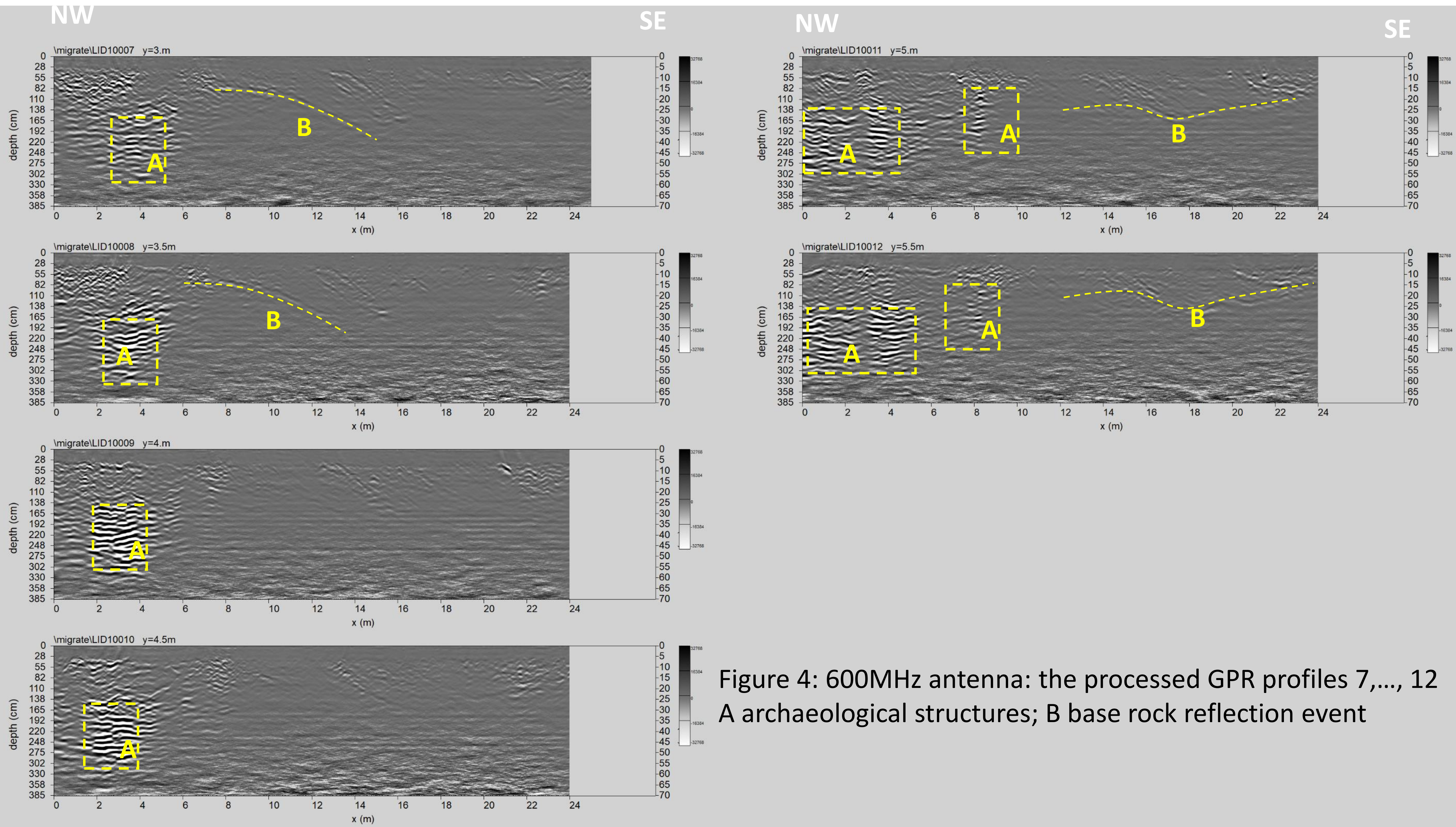

Figure 4: 600MHz antenna: the processed GPR profiles 7,…, 12
A archaeological structures; B base rock reflection event

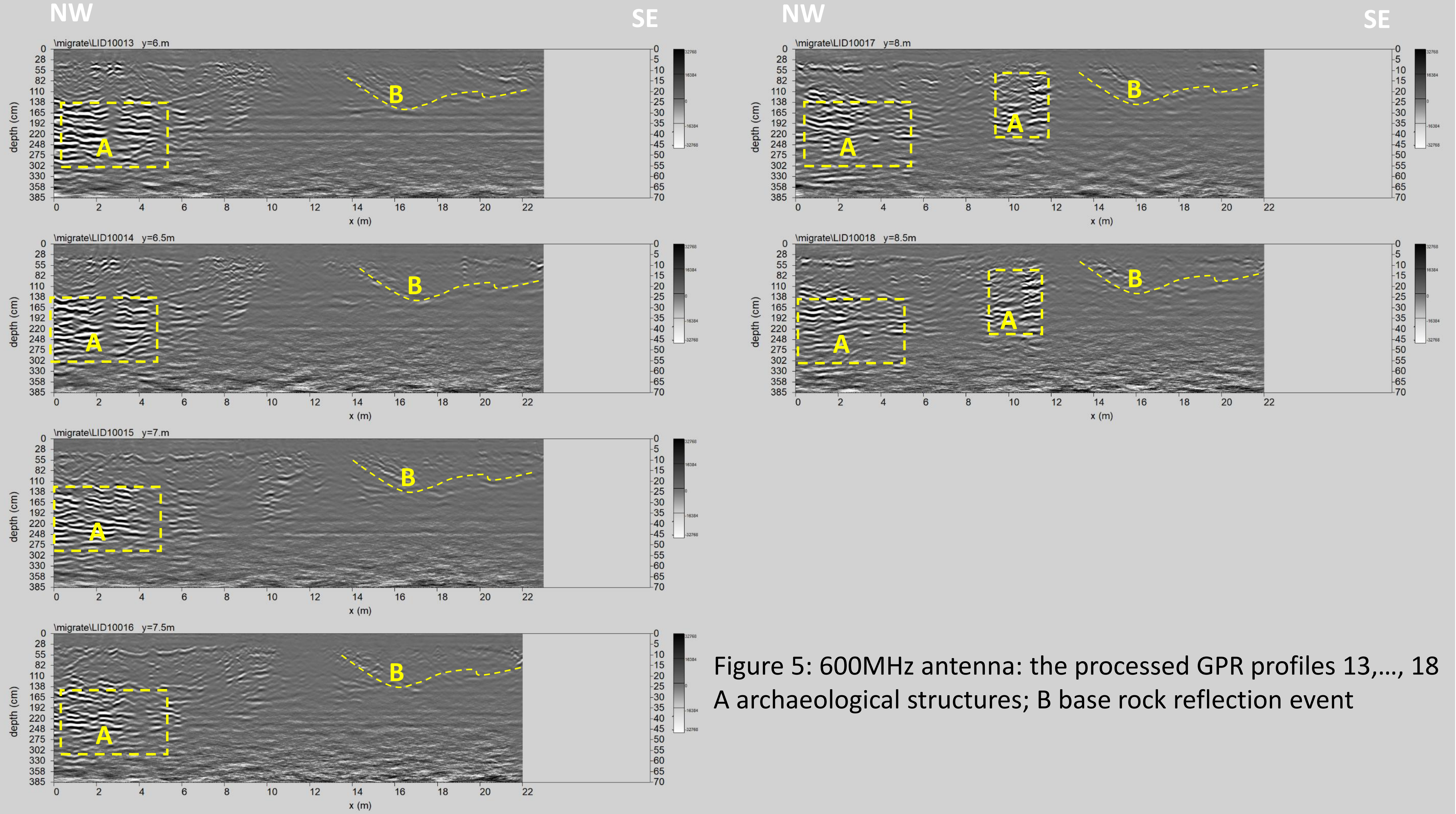

Figure 5: 600MHz antenna: the processed GPR profiles 13,…, 18
A archaeological structures; B base rock reflection event

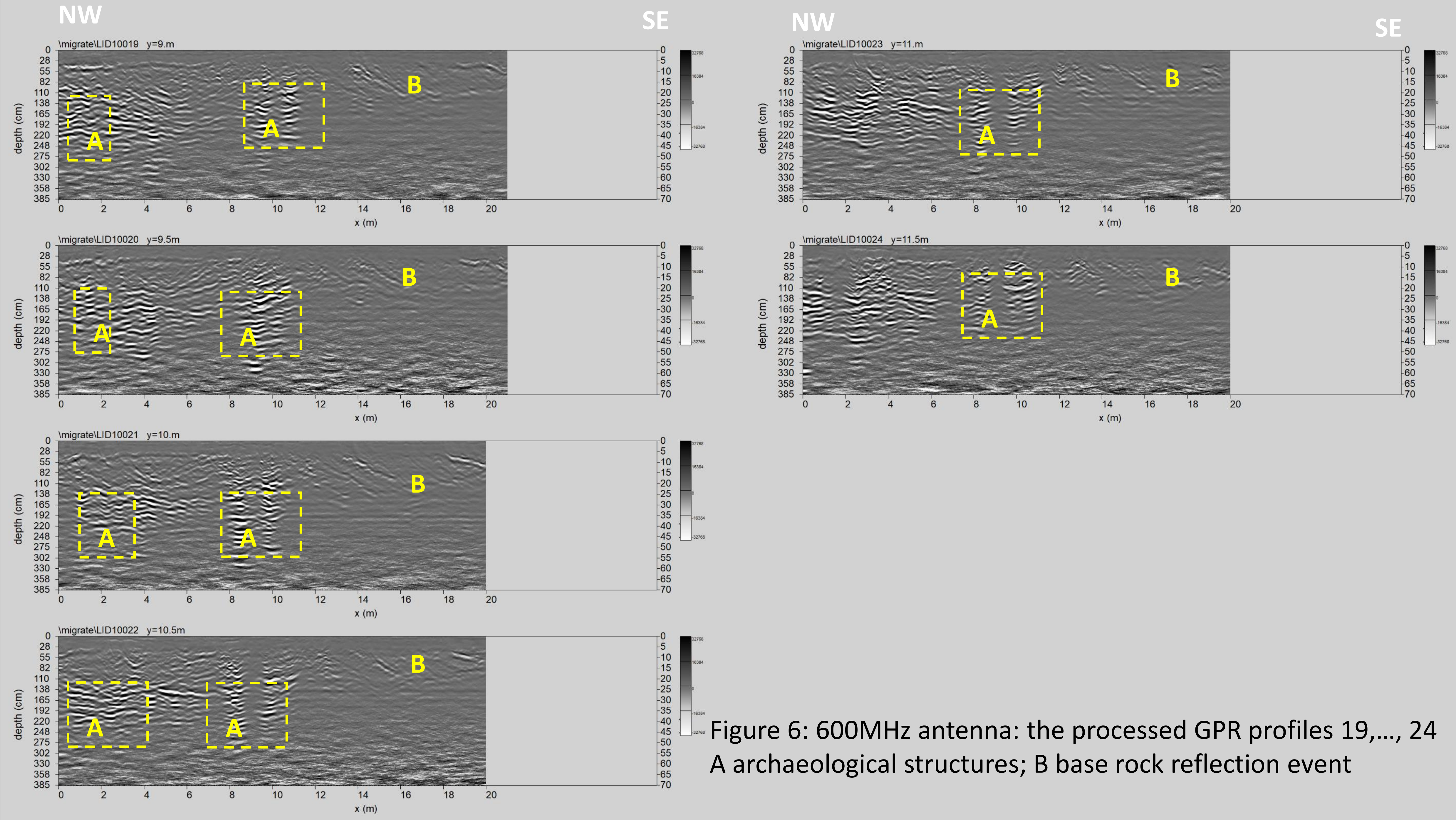

Figure 6: 600MHz antenna: the processed GPR profiles 19,…, 24
A archaeological structures; B base rock reflection event

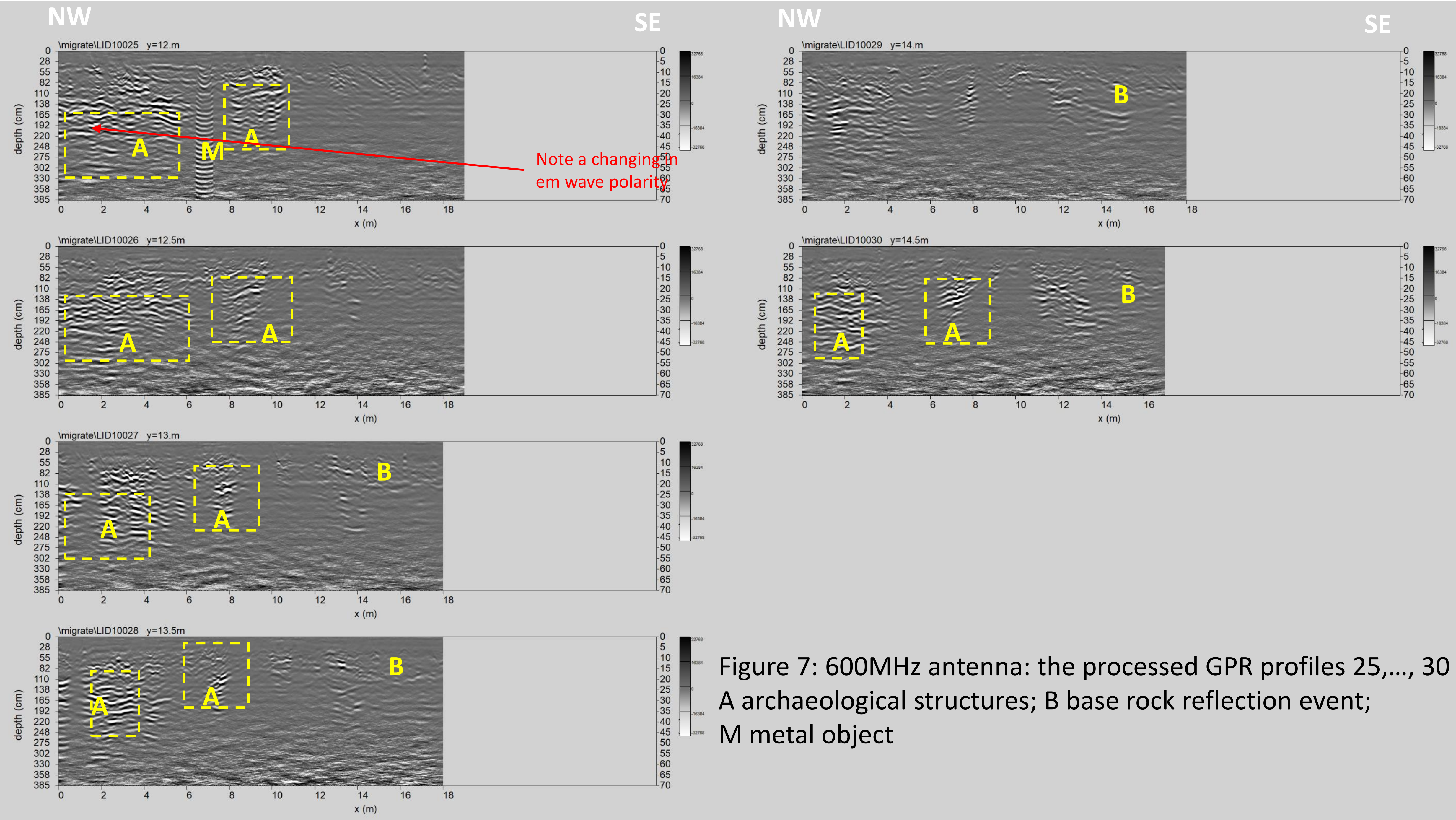

Figure 7: 600MHz antenna: the processed GPR profiles 25,…, 30
A archaeological structures; B base rock reflection event;
M metal object

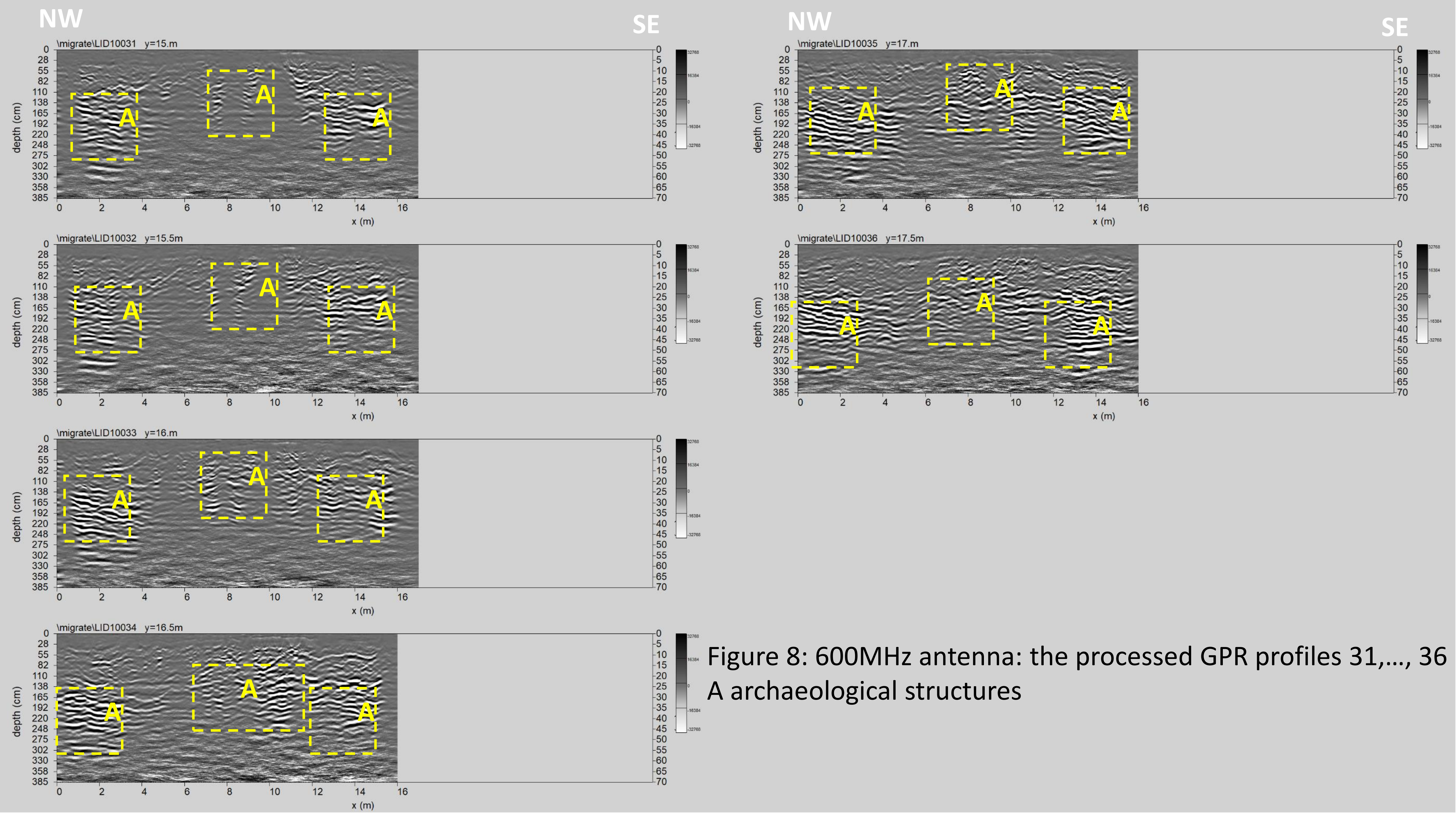

Figure 8: 600MHz antenna: the processed GPR profiles 31,…, 36
A archaeological structures

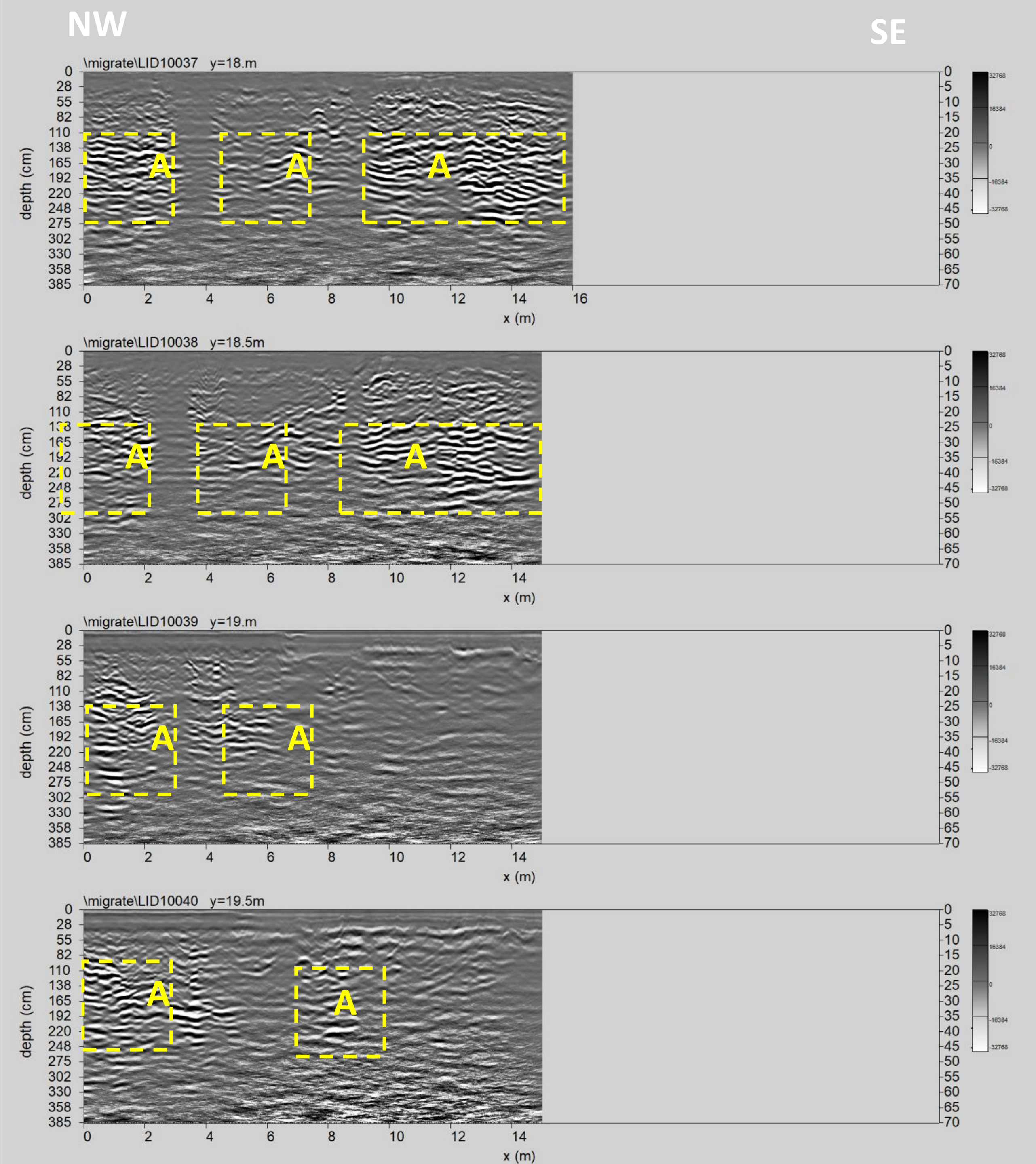

Figure 9: 600MHz antenna: the processed GPR profiles 37,…, 40
A archaeological structures

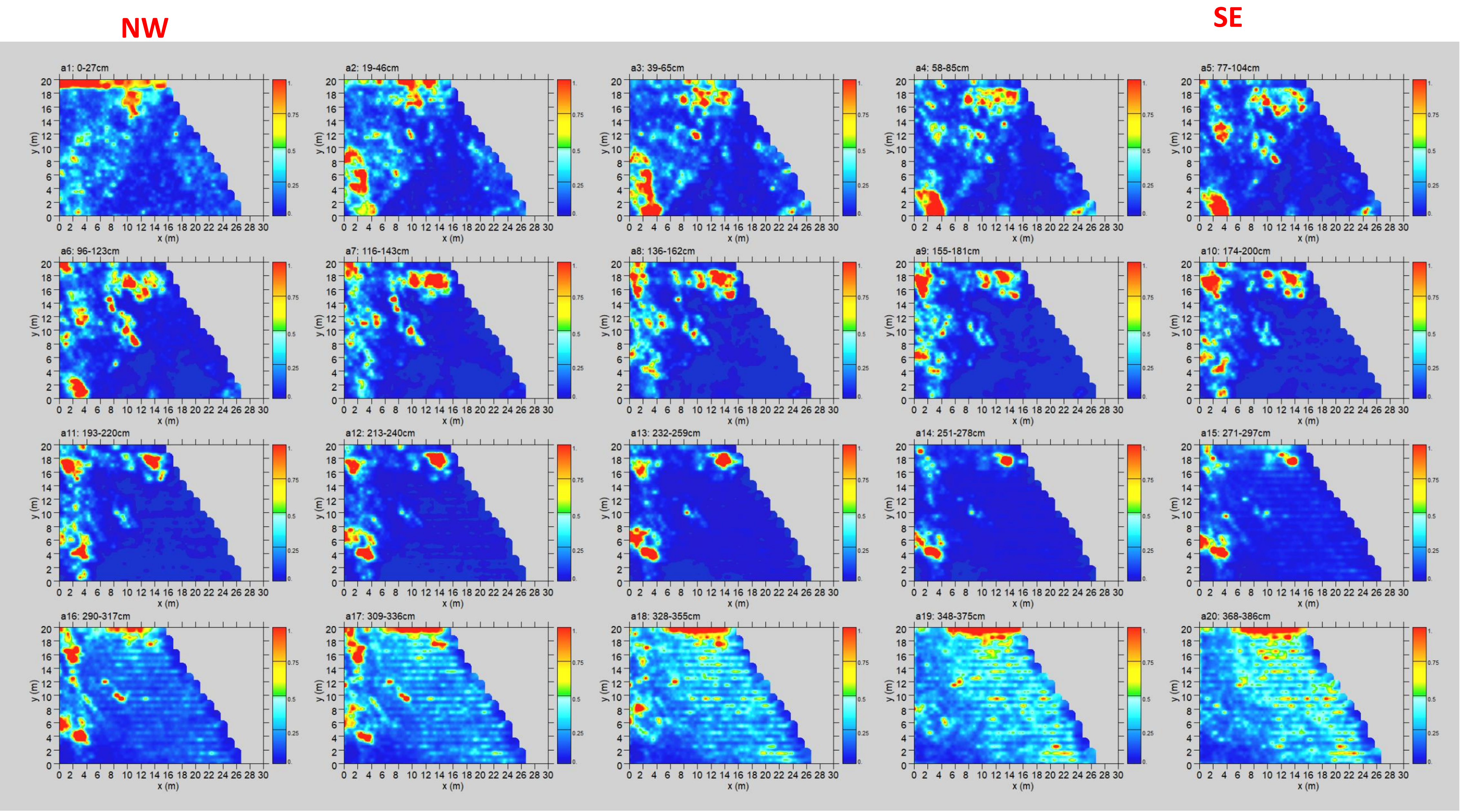

Figure 10: the GPR depth slices related to the 600MHz antenna profiles

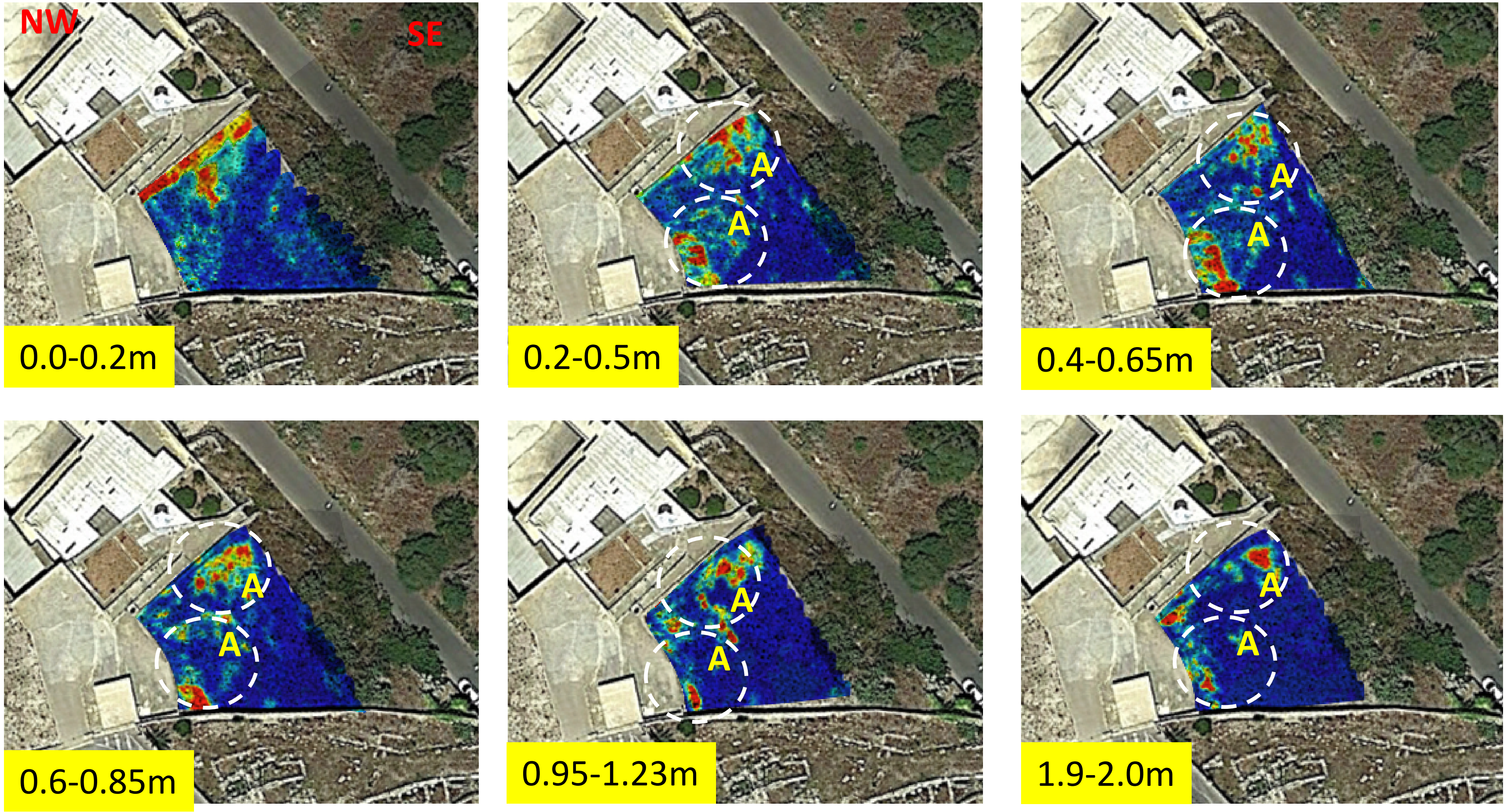

Figure 11: 600MHz antenna: the GPR depth slices overlapped to google earth photo

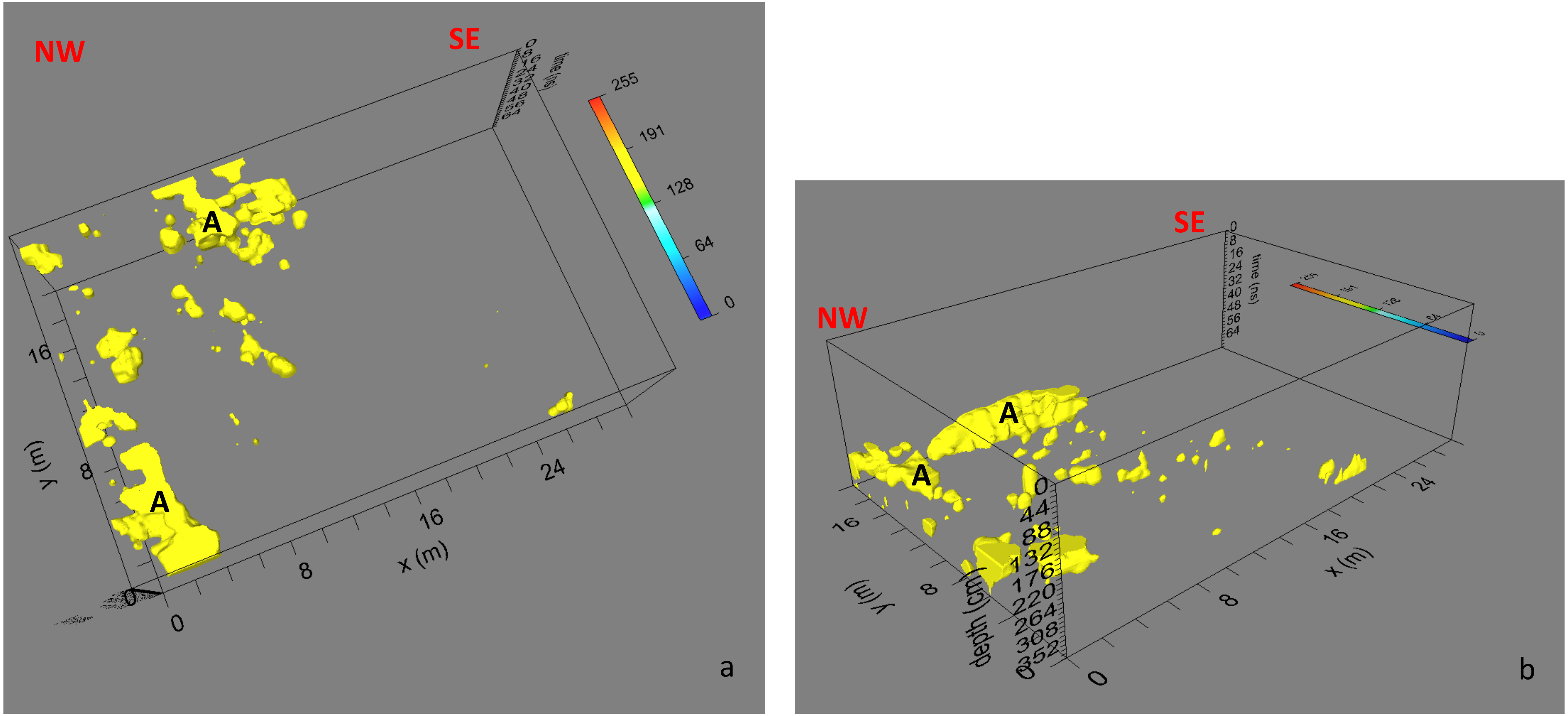

Figure 12: 600MHz antenna: the GPR iso – surfaces

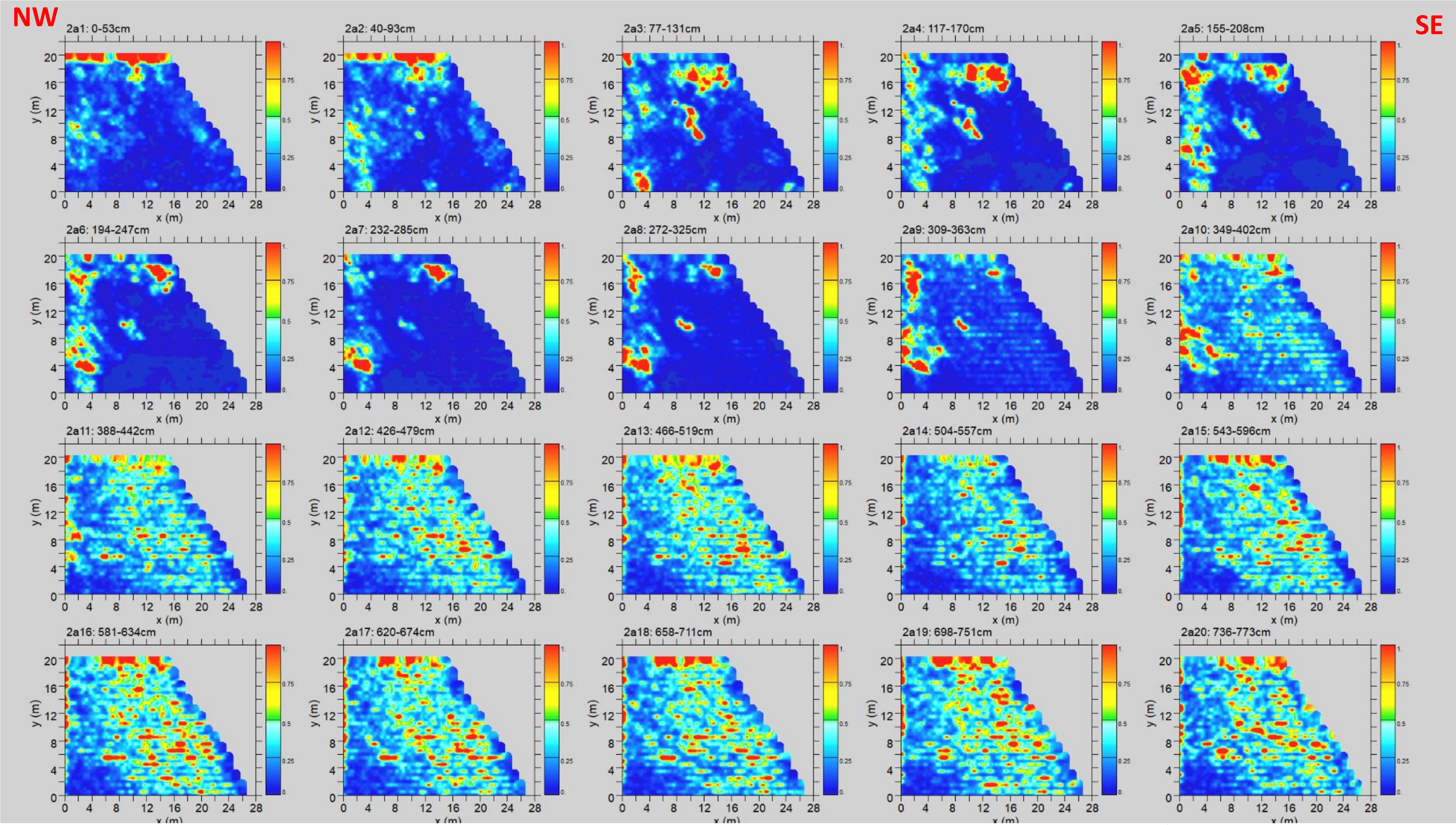

Figure 13: the GPR depth slices related to the 200MHz antenna profiles

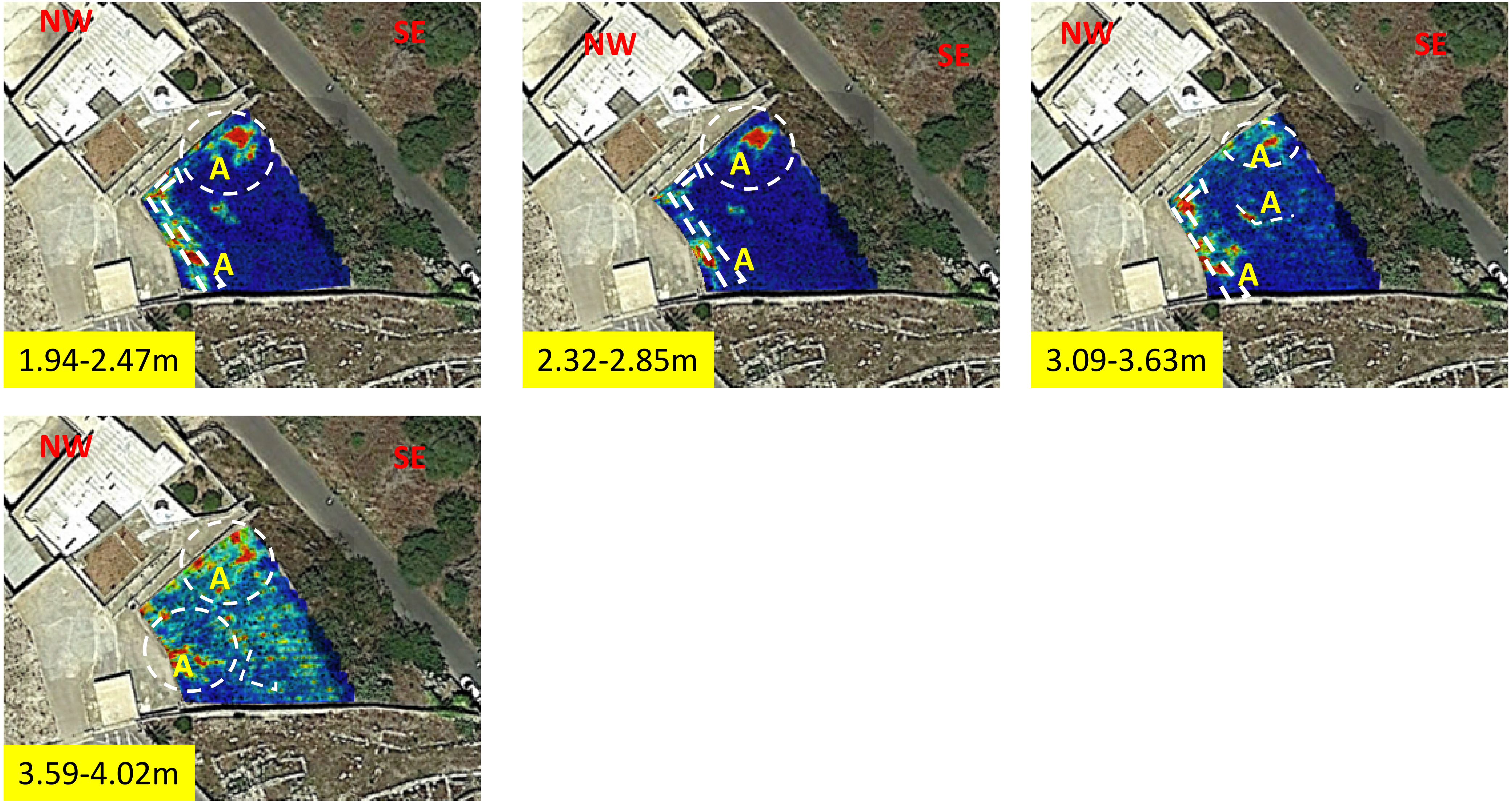

Figure 14: 200MHz antenna: the GPR depth slices overlapped to google earth photo

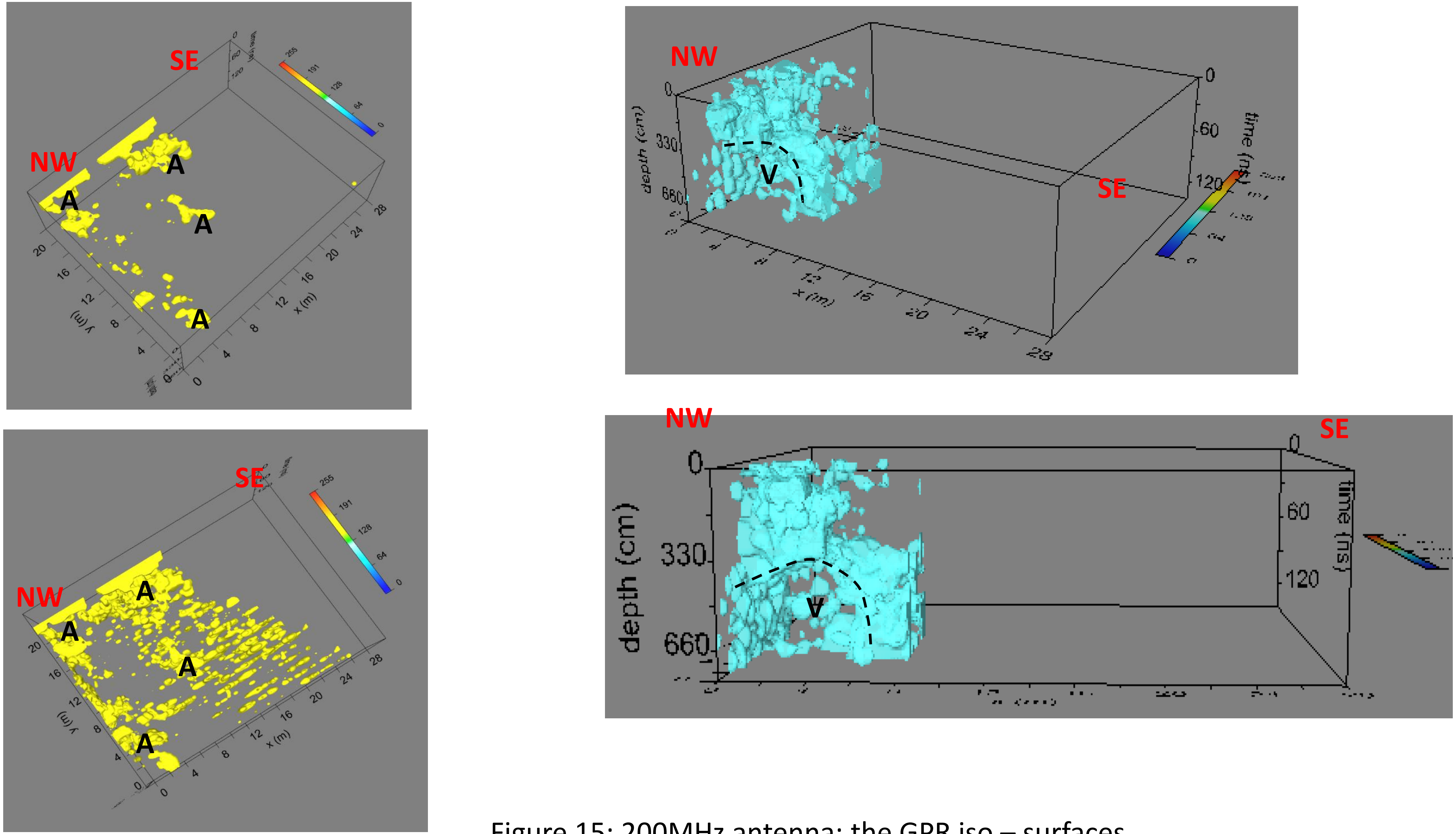

Figure 15: 200MHz antenna: the GPR iso – surfaces

Area B-zone 1

Figure 16: the surveyed area B: zone 1

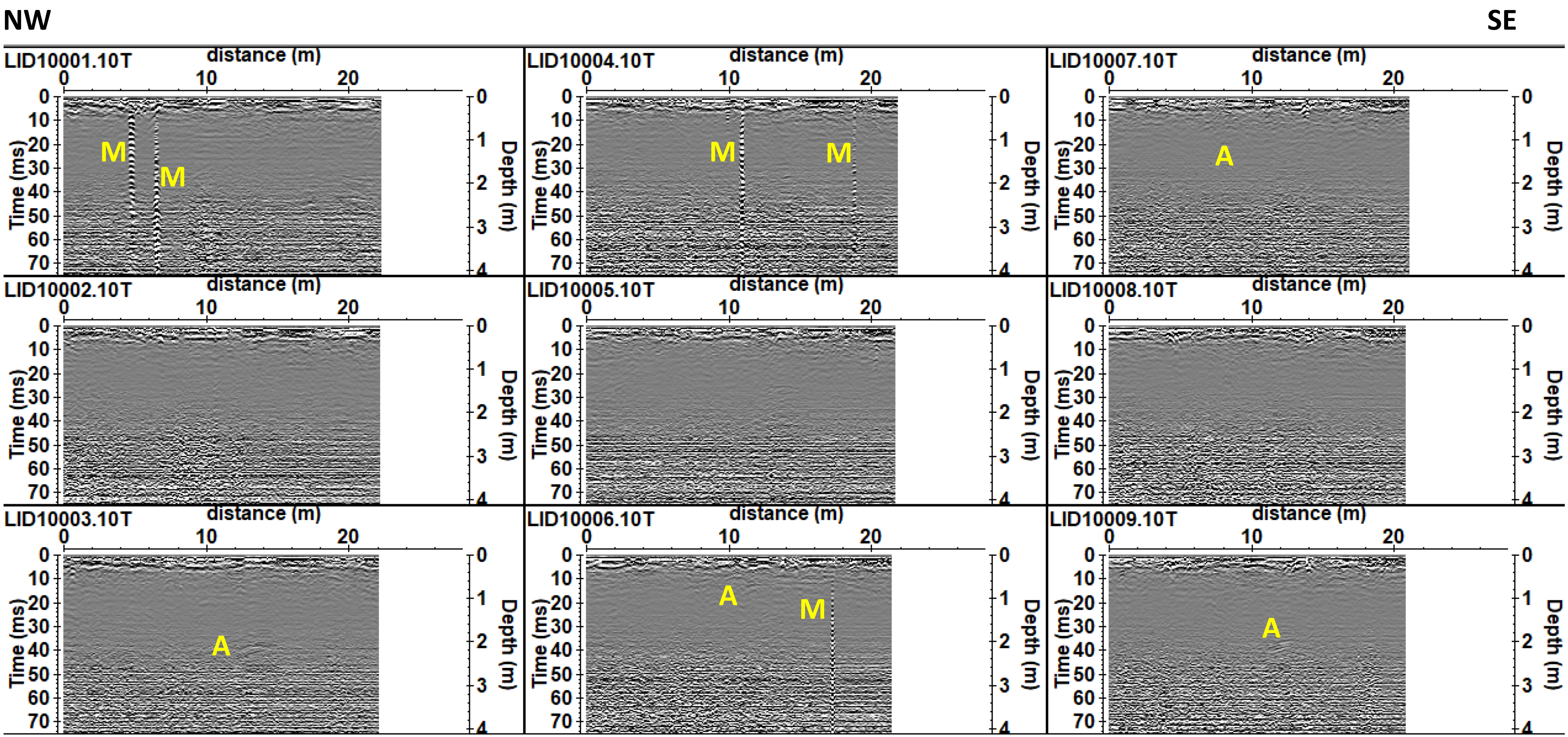

Figure 17: 600MHz antenna: the processed GPR profiles 1,…, 9.
Due to the morphological condiction the A archaeological structures reflection events were very low; M metal object

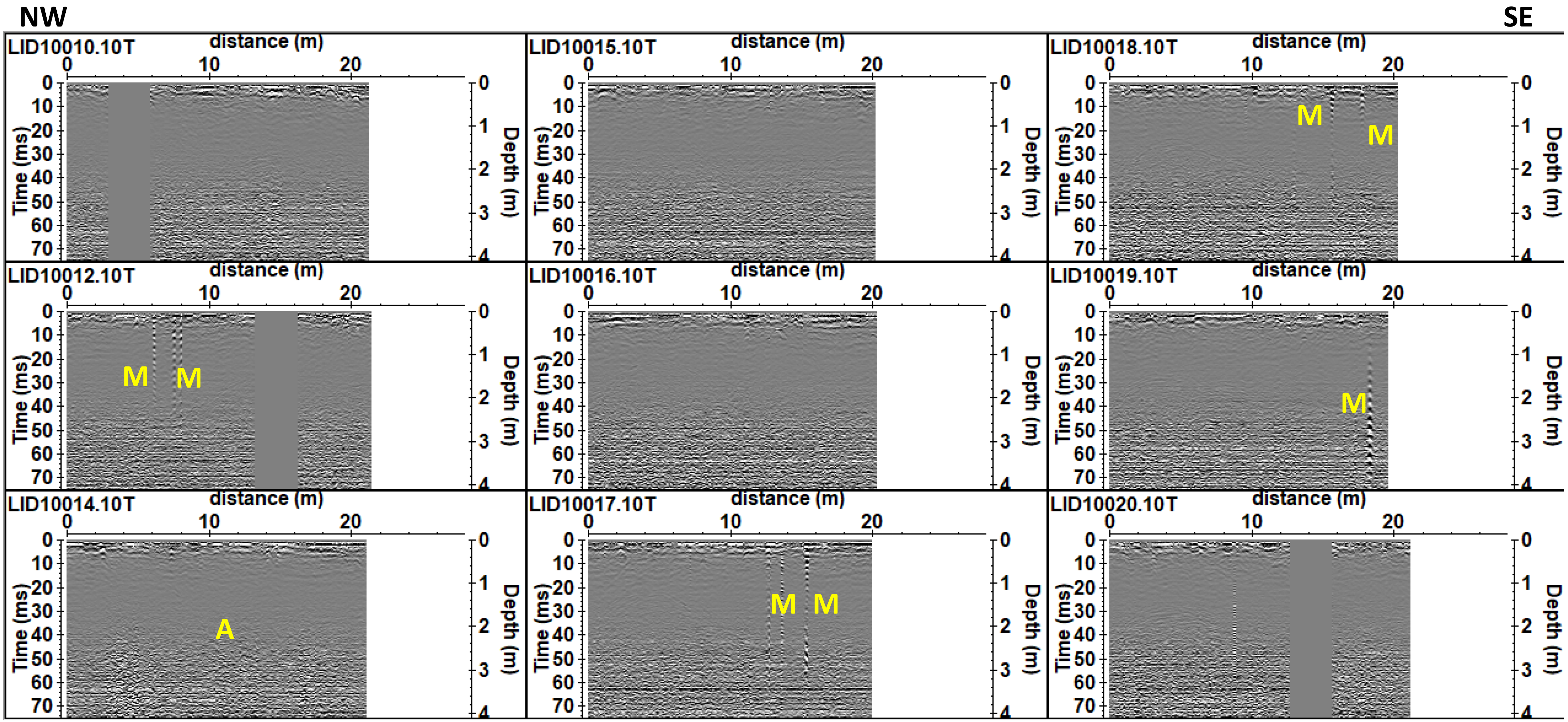

Figure 18: 600MHz antenna: the processed GPR profiles 10,…, 20.
A archaeological structures; M metal object

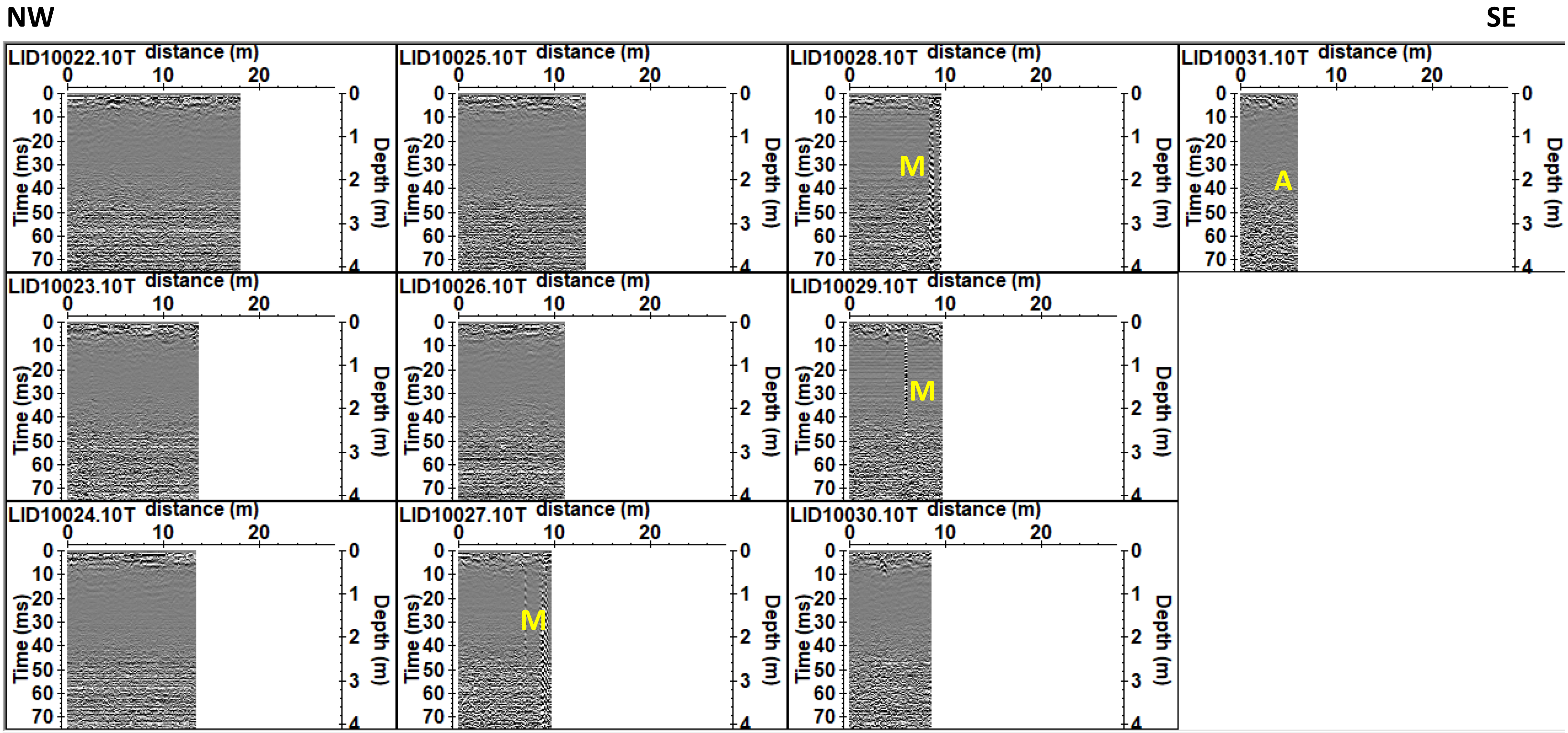

Figure 19: 600MHz antenna: the processed GPR profiles 22,…, 30.
A archaeological structures; M metal object

NW

SE

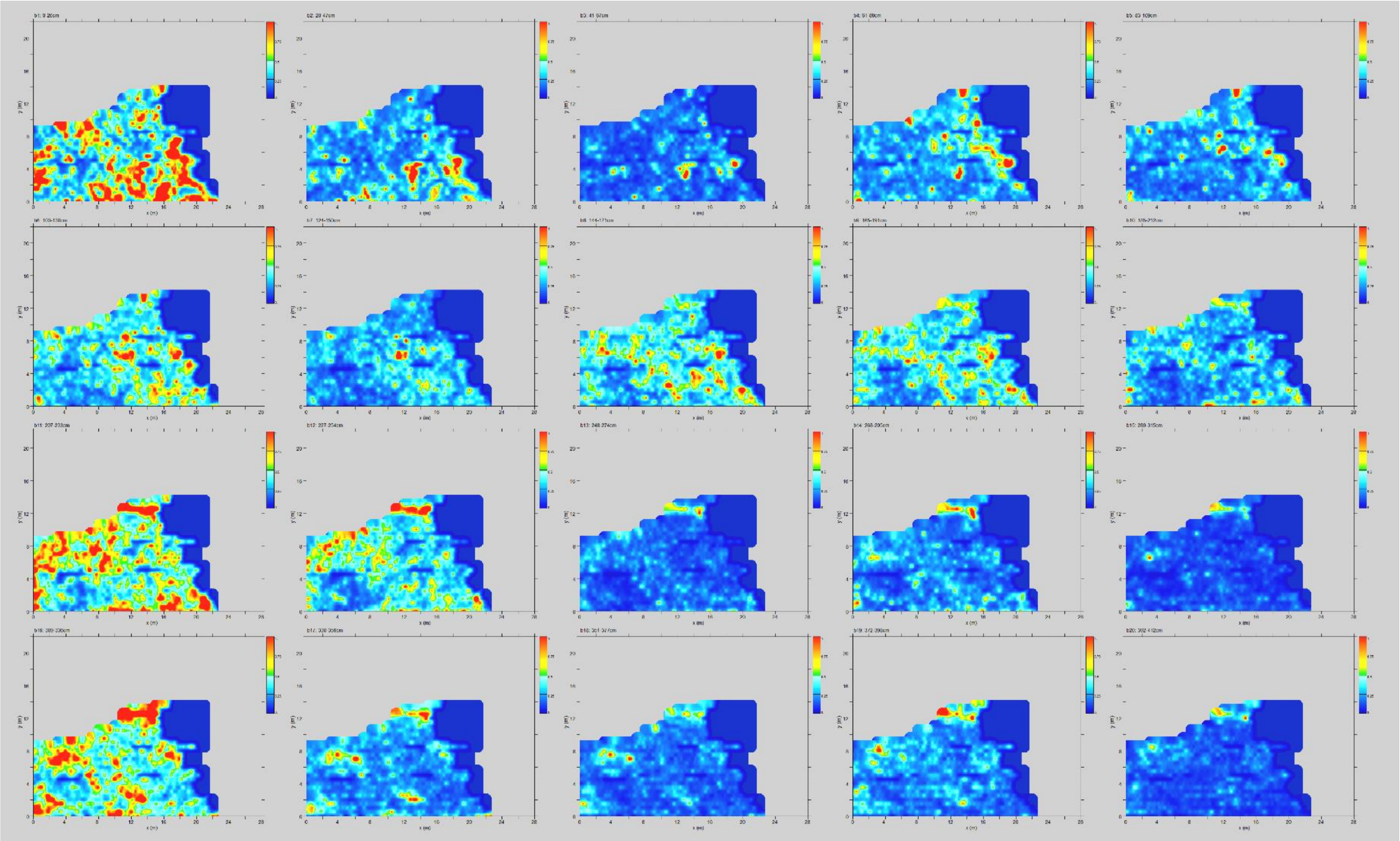

Figure 20: 600MHz antenna: the GPR depth slices. A processing that considered the overlapped slices was applied in order to evidenced the lower amplitudes anomalies related to the archaeological structures

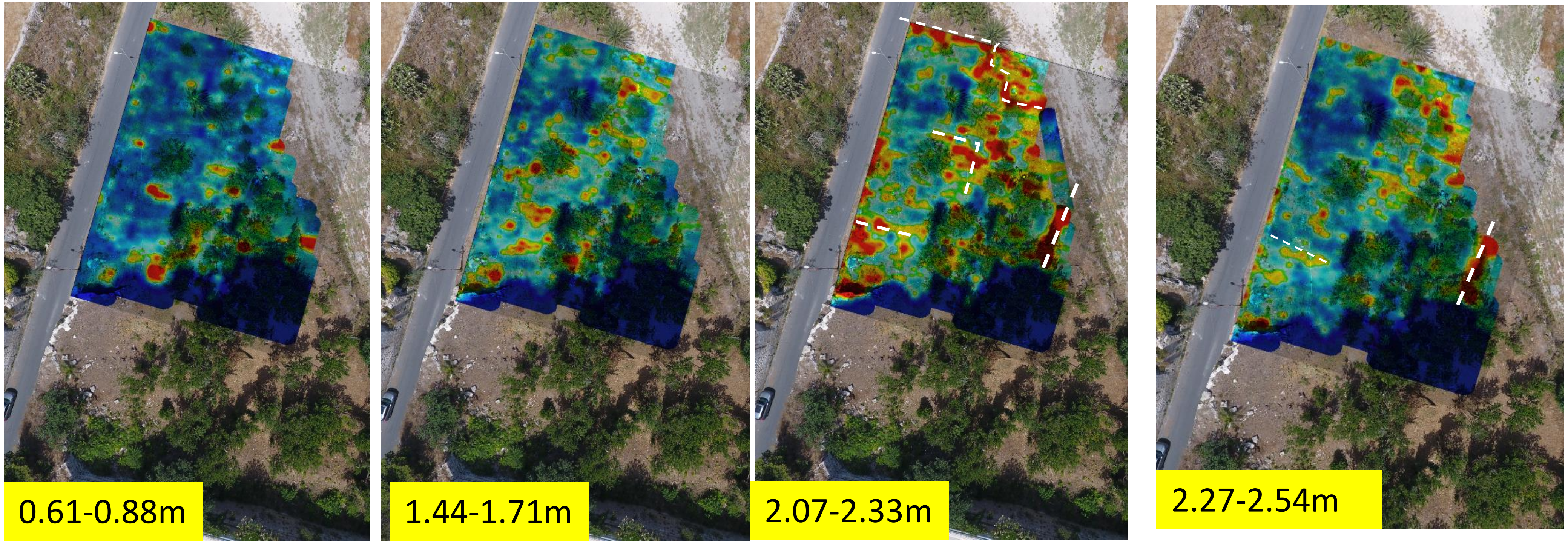

Figure 21: 600MHz antenna: the GPR depth slices overlapped to drone photos.

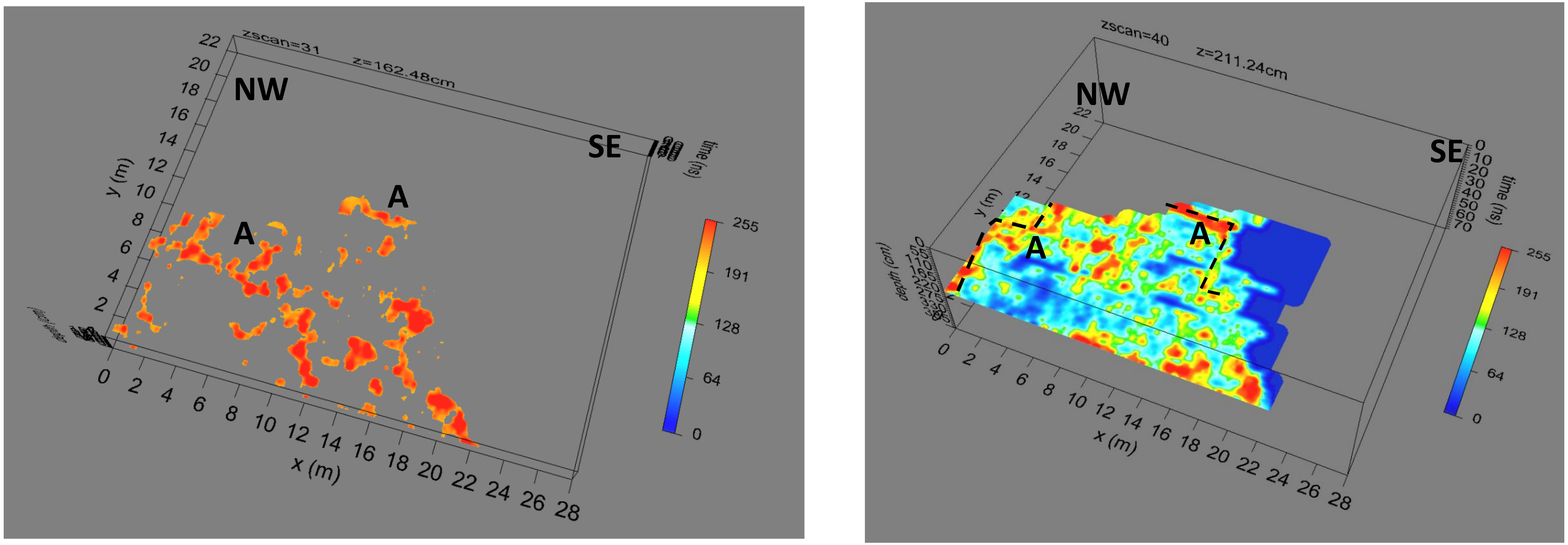

Figure 22: 600MHz antenna: the GPR iso – surfaces

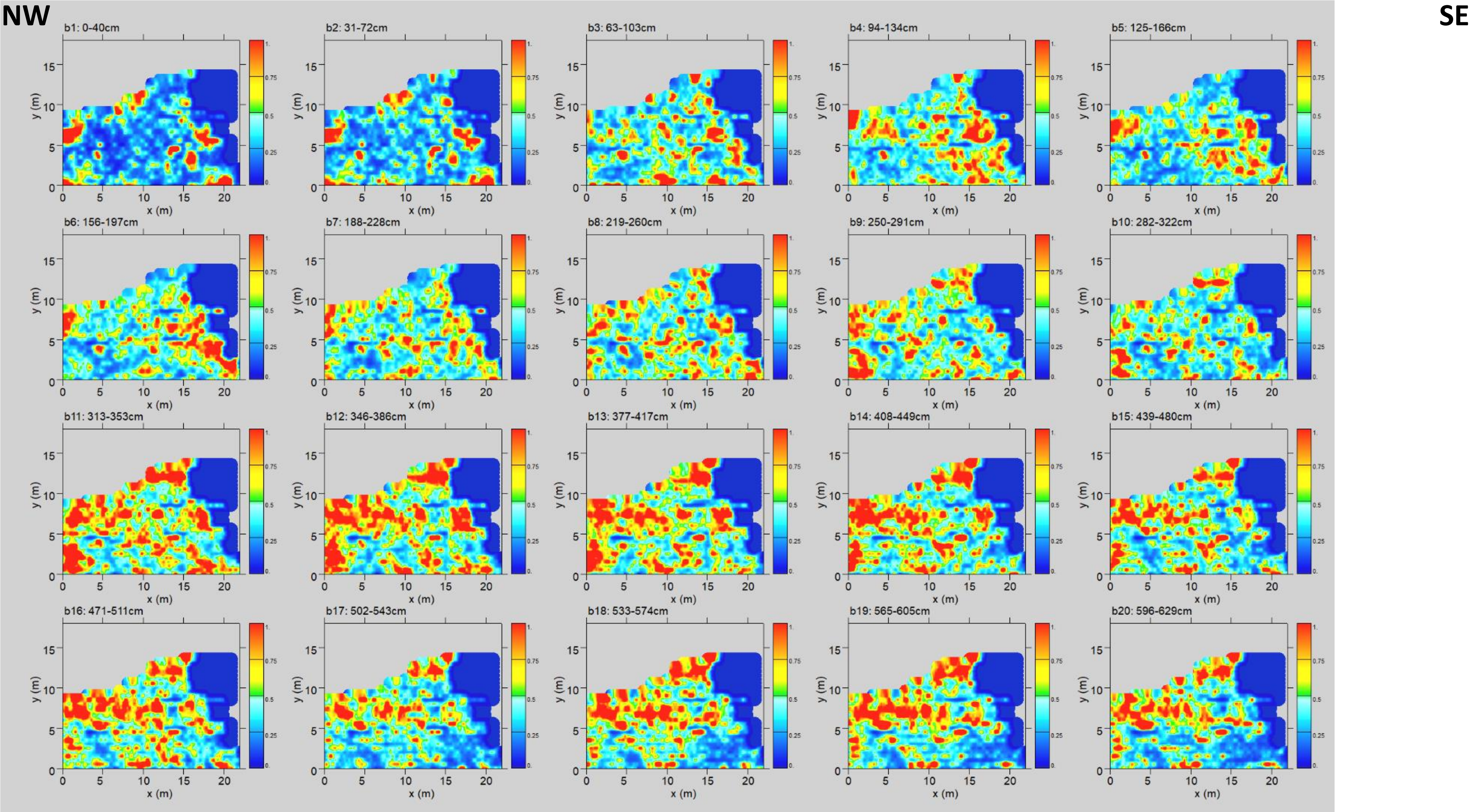

Figure 23: 200MHz antenna: the GPR depth slices.

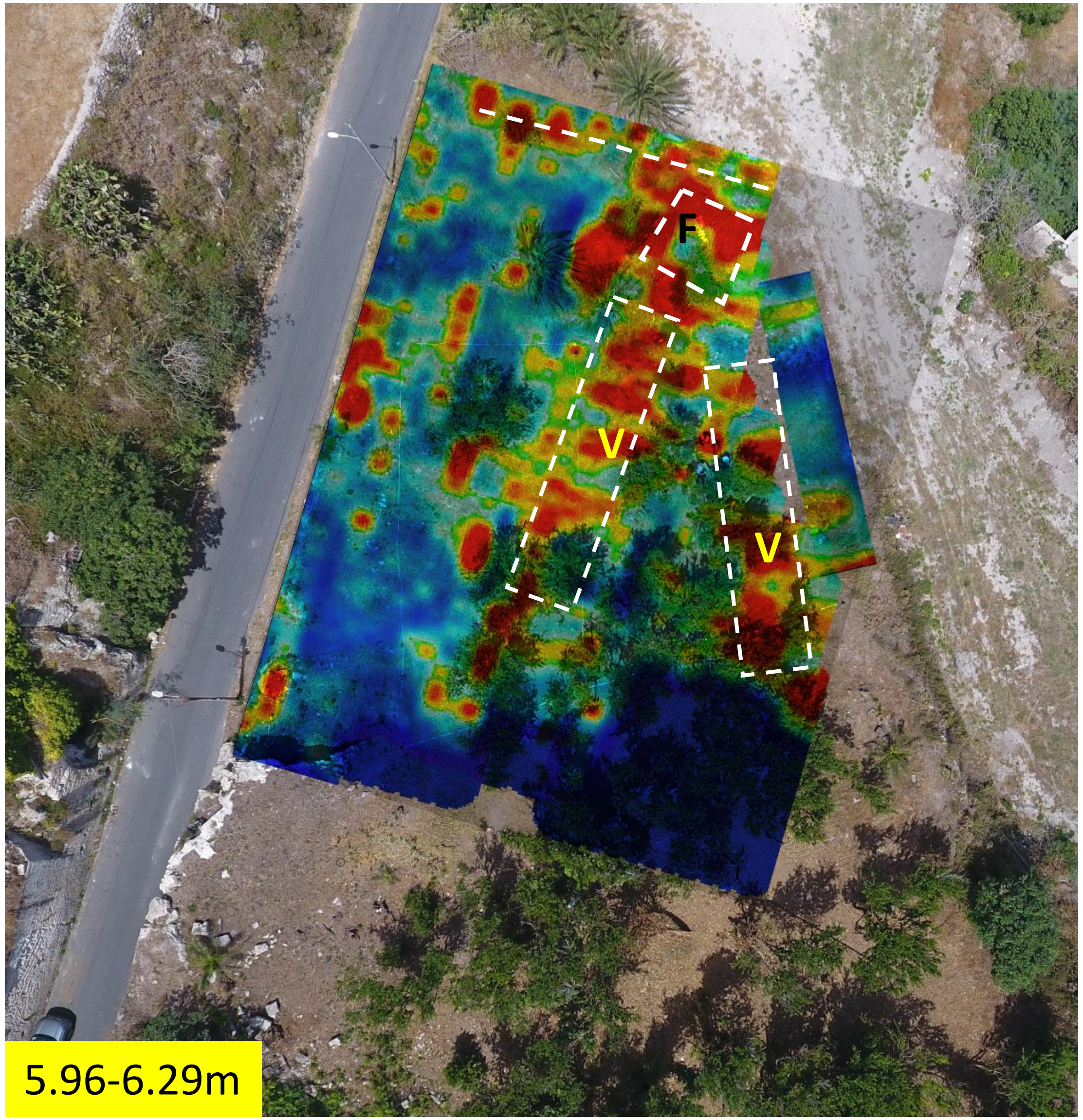

Figure 24: 200MHz antenna: the GPR depth slices overlapped to drone photo.
F: probable foundations (tower?); V: spaces voids (channels?)

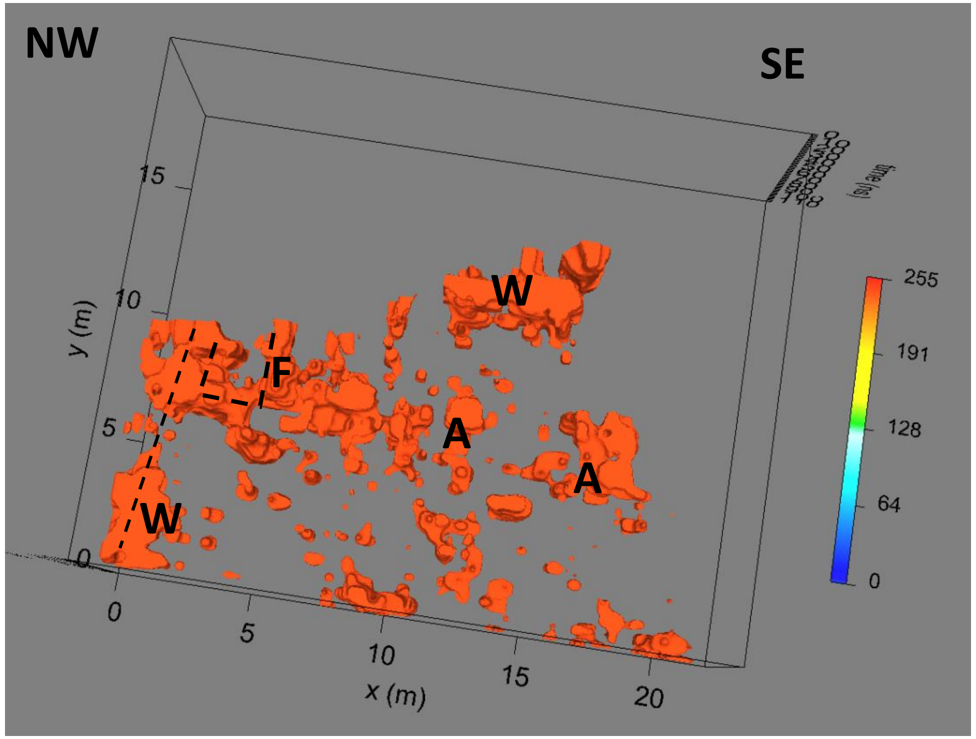

Figure 25: 200MHz antenna: the GPR iso – surfaces: W: walls; F: foundations; A: archaeological structures

Area B-zone 2

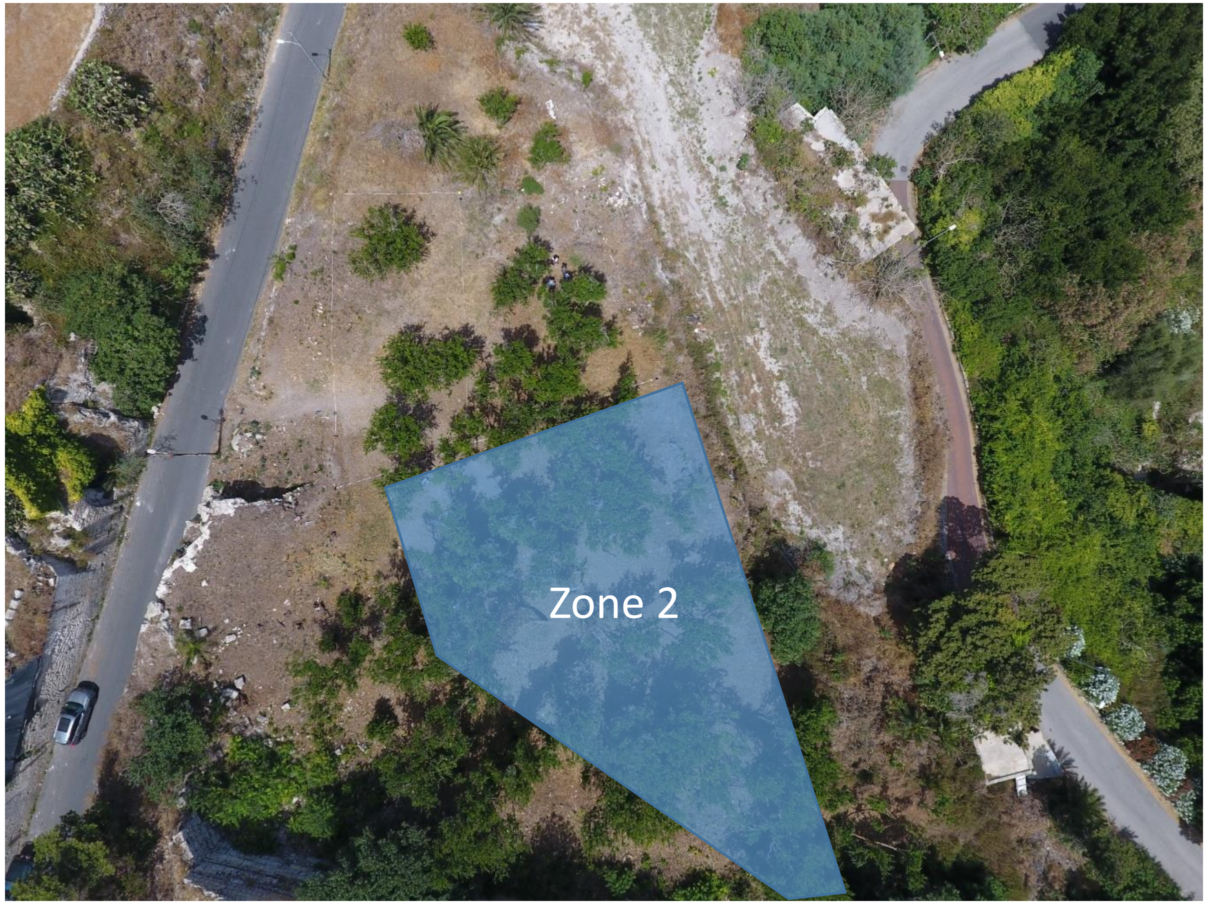

Figure 26: the surveyed area B: zone 2

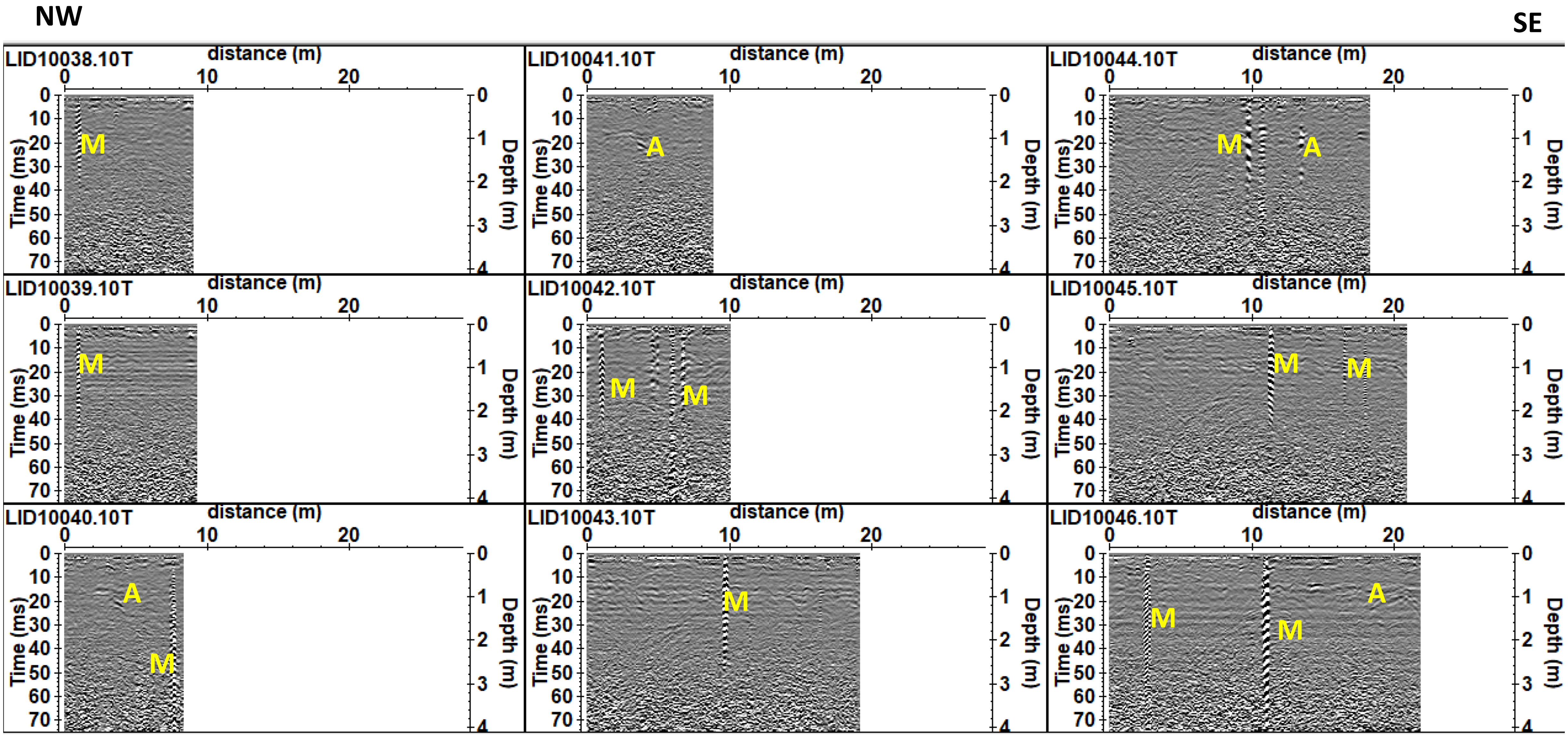

Figure 27: 600MHz antenna: the processed GPR profiles 38,…, 46.
A archaeological structures; M metal object

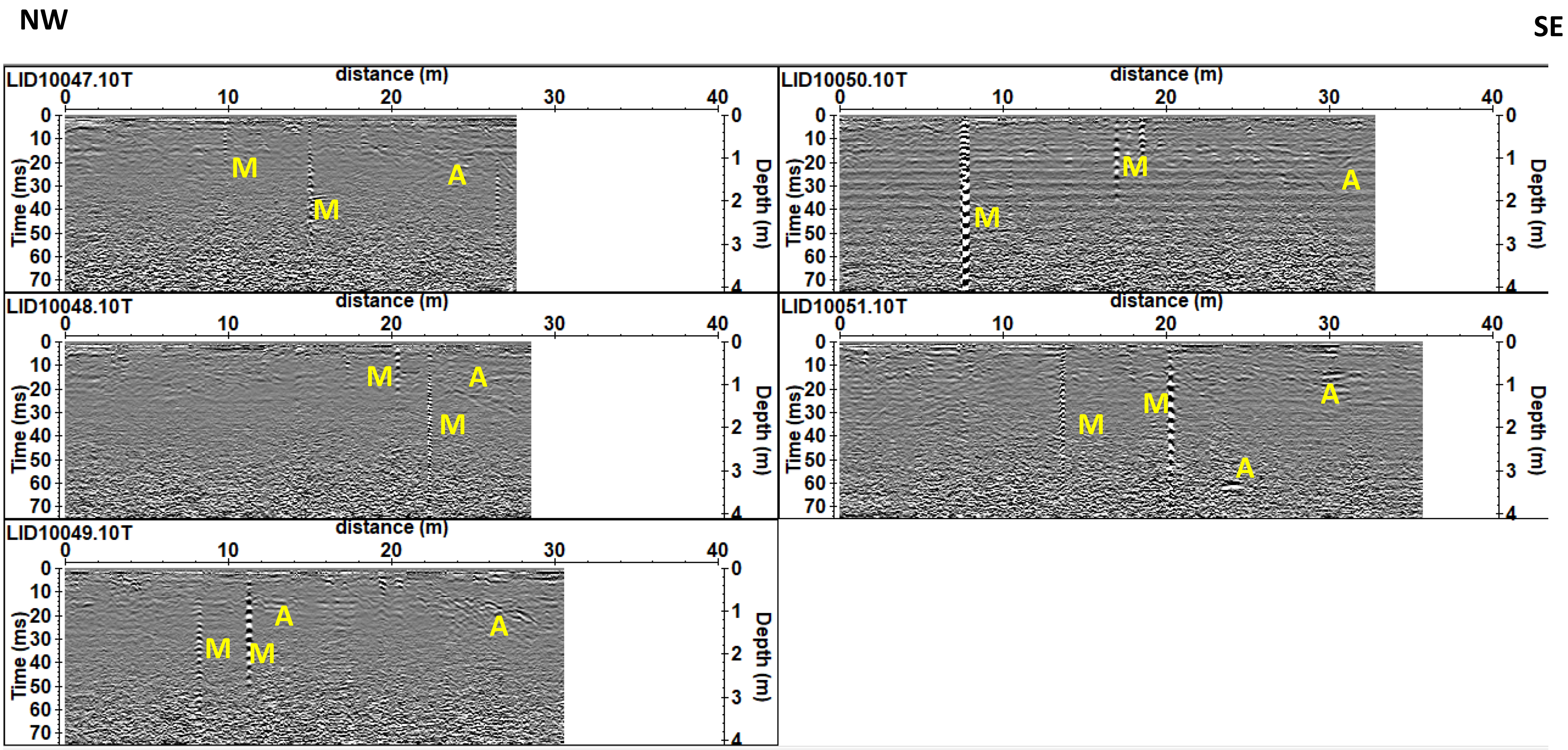

Figure 28: 600MHz antenna: the processed GPR profiles 47,..., 51.
A archaeological structures; M metal object

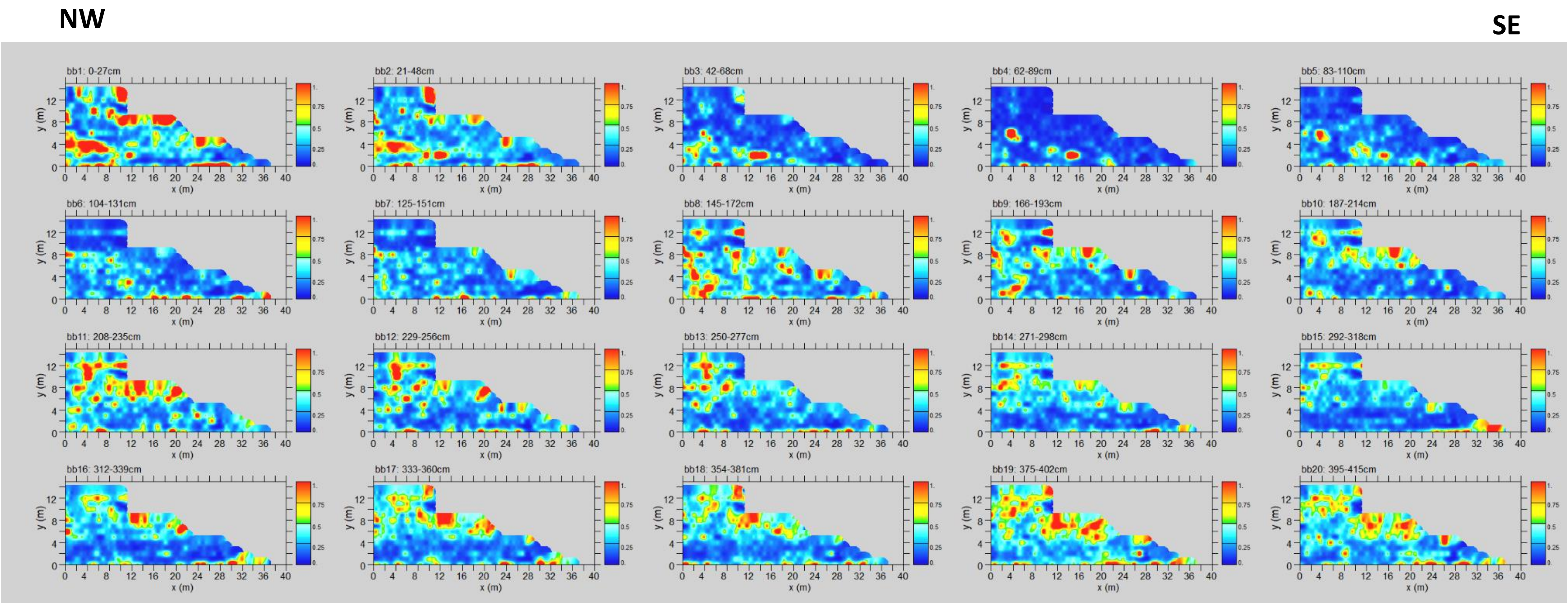

Figure 29: 600MHz antenna: the GPR depth slices. A processing that considered the overlapped slices was applied in order to evidenced the lower amplitudes anomalies related to the archaeological structures

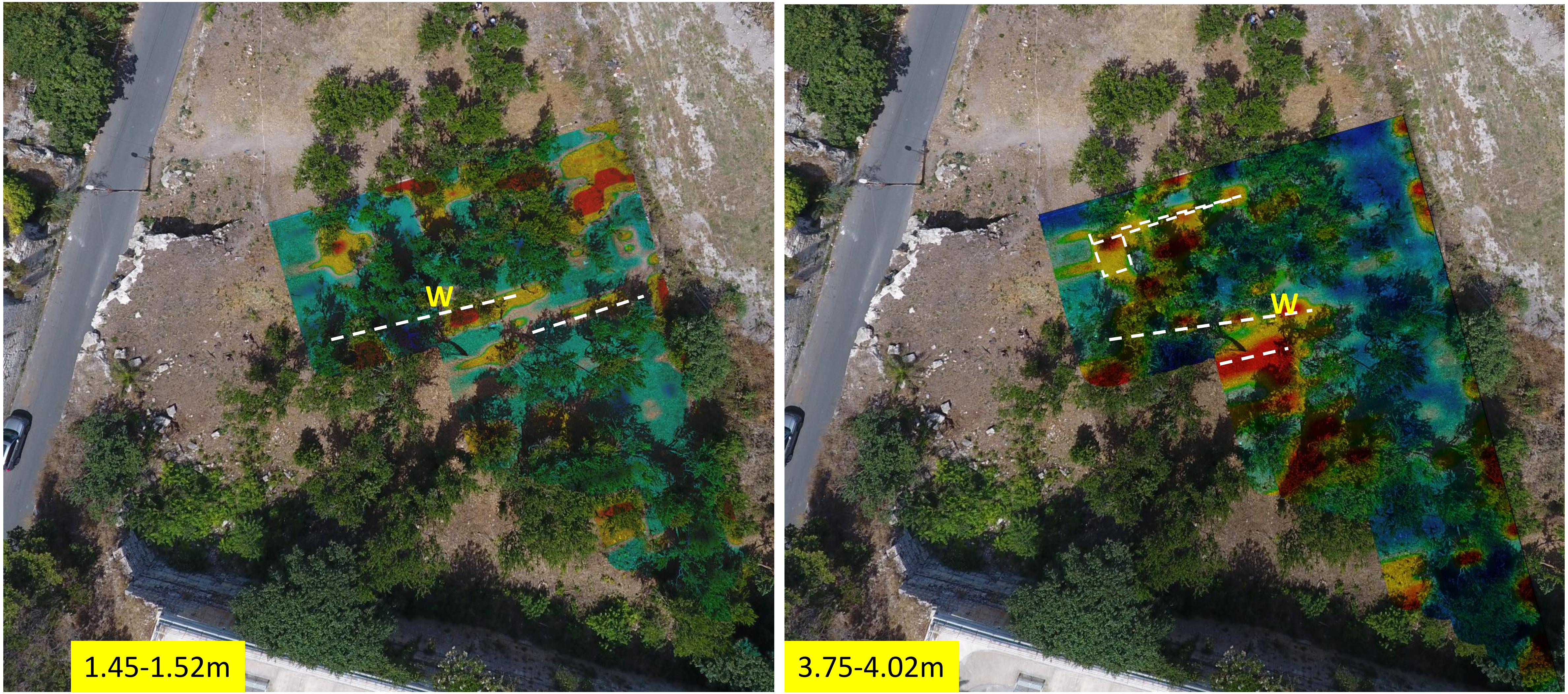

Figure 30: 600MHz antenna: the GPR depth slices overlapped to drone photo.
W: probable wall

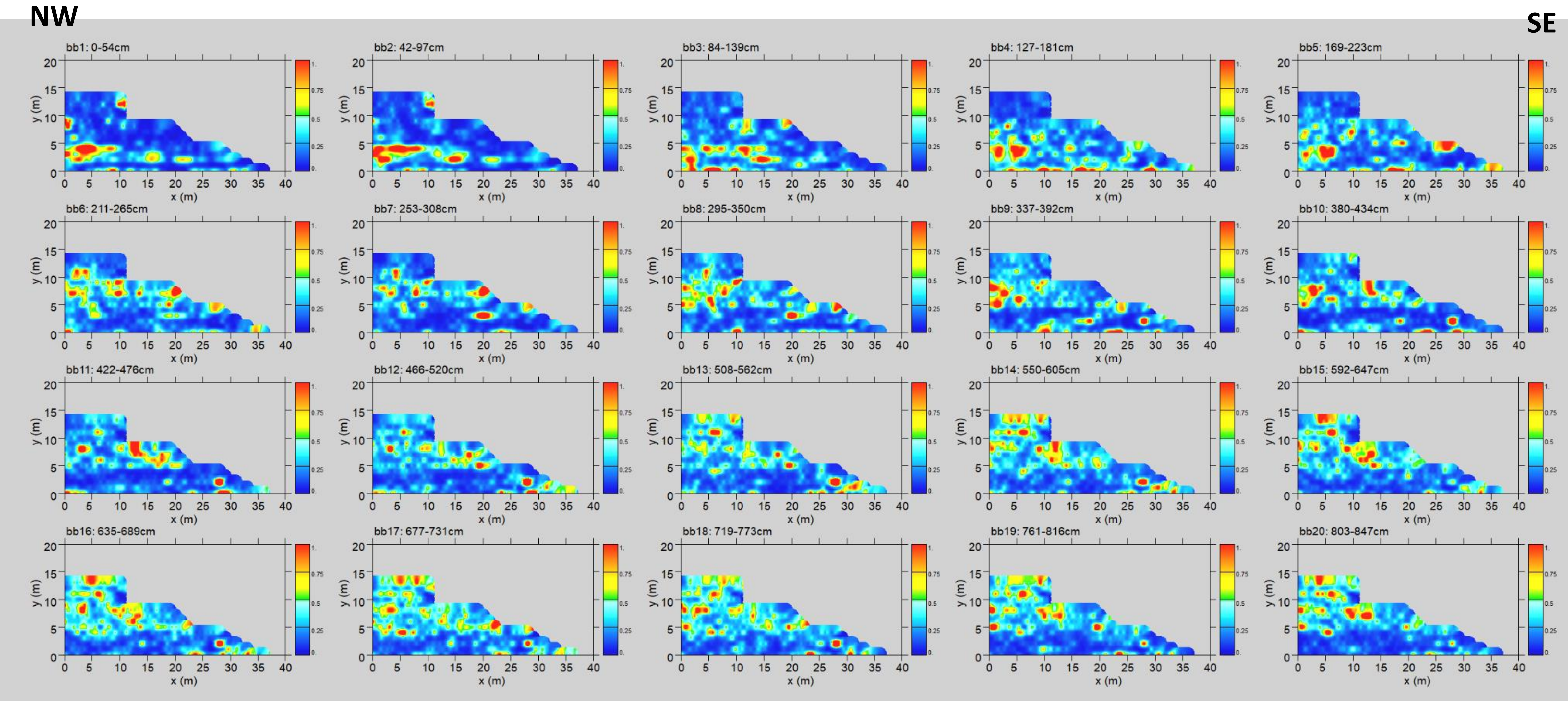

Figure 31: 200MHz antenna: the GPR depth slices

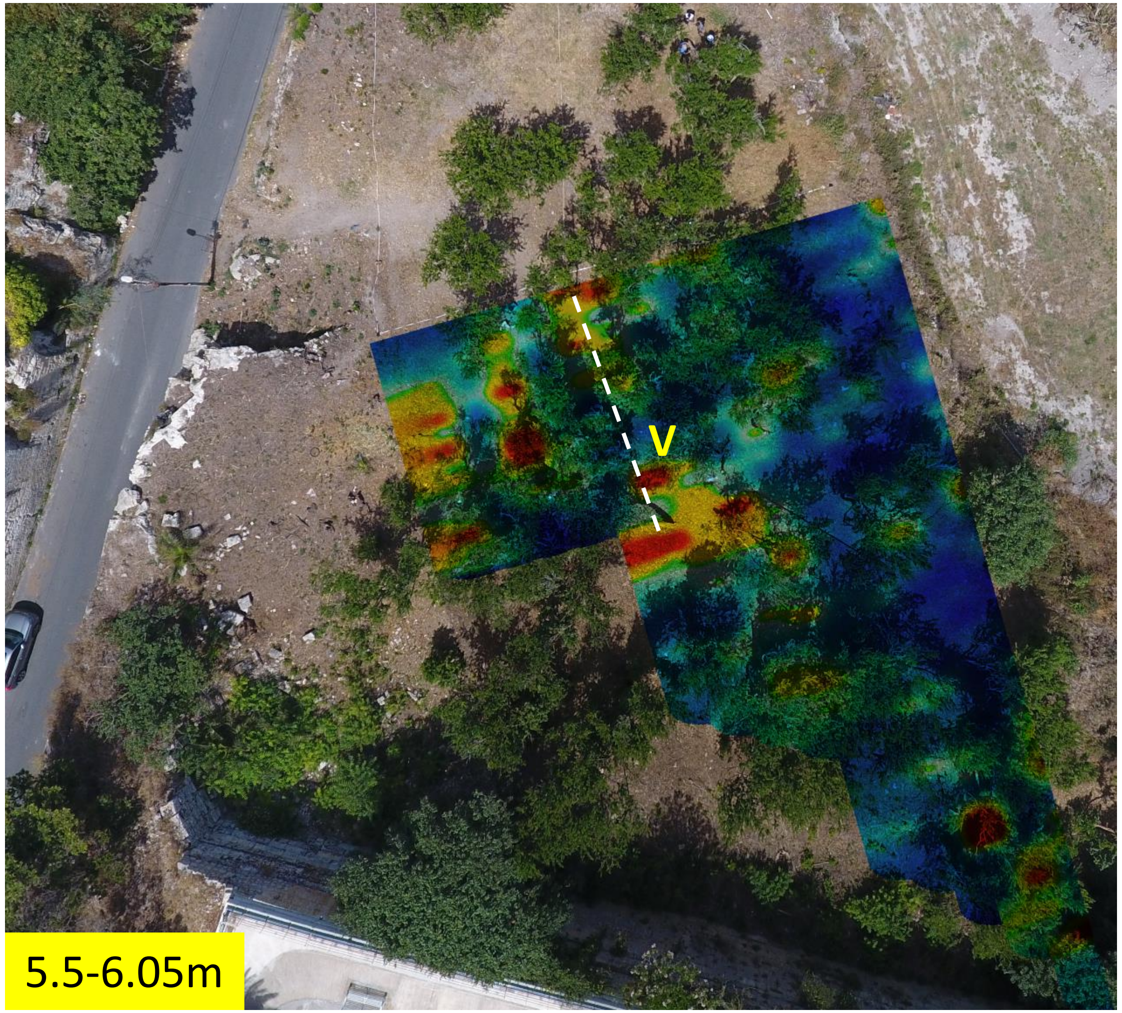

Figure 32: 200MHz antenna: the GPR depth slices overlapped to drone photo.
V: probable void spaces

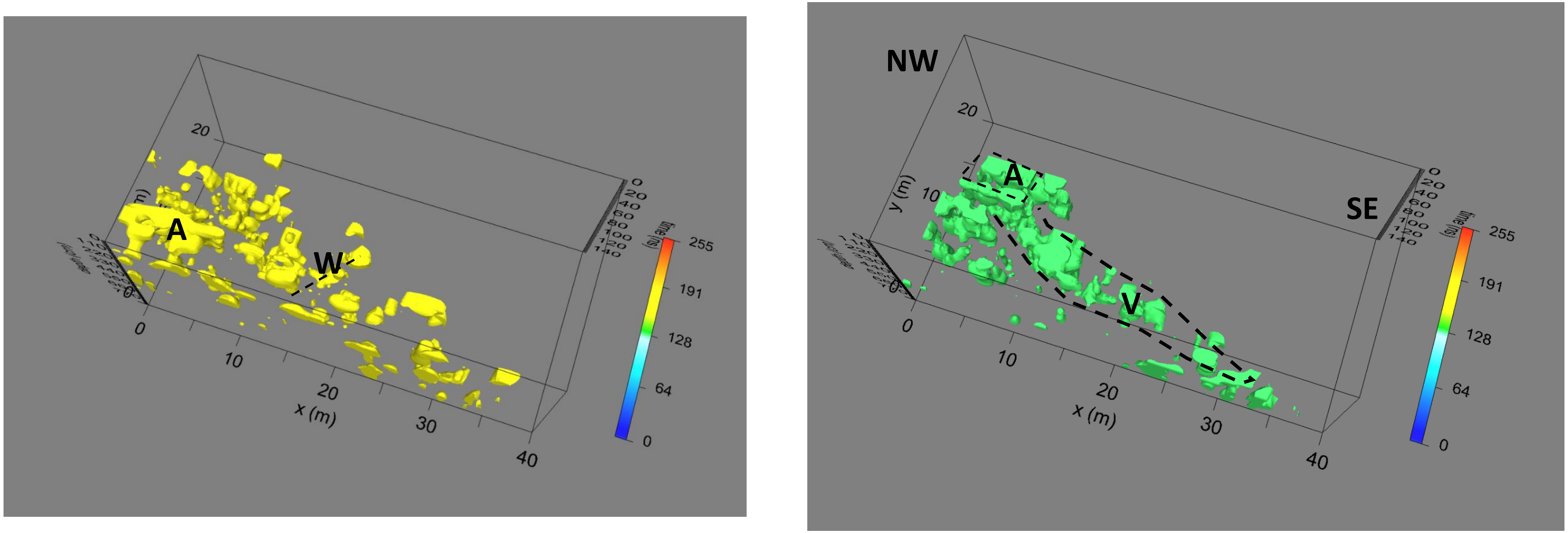

Figure 33: 200MHz antenna: the GPR iso – surfaces: W: walls; V: voids; A: archaeological structures

Area B-zone 3

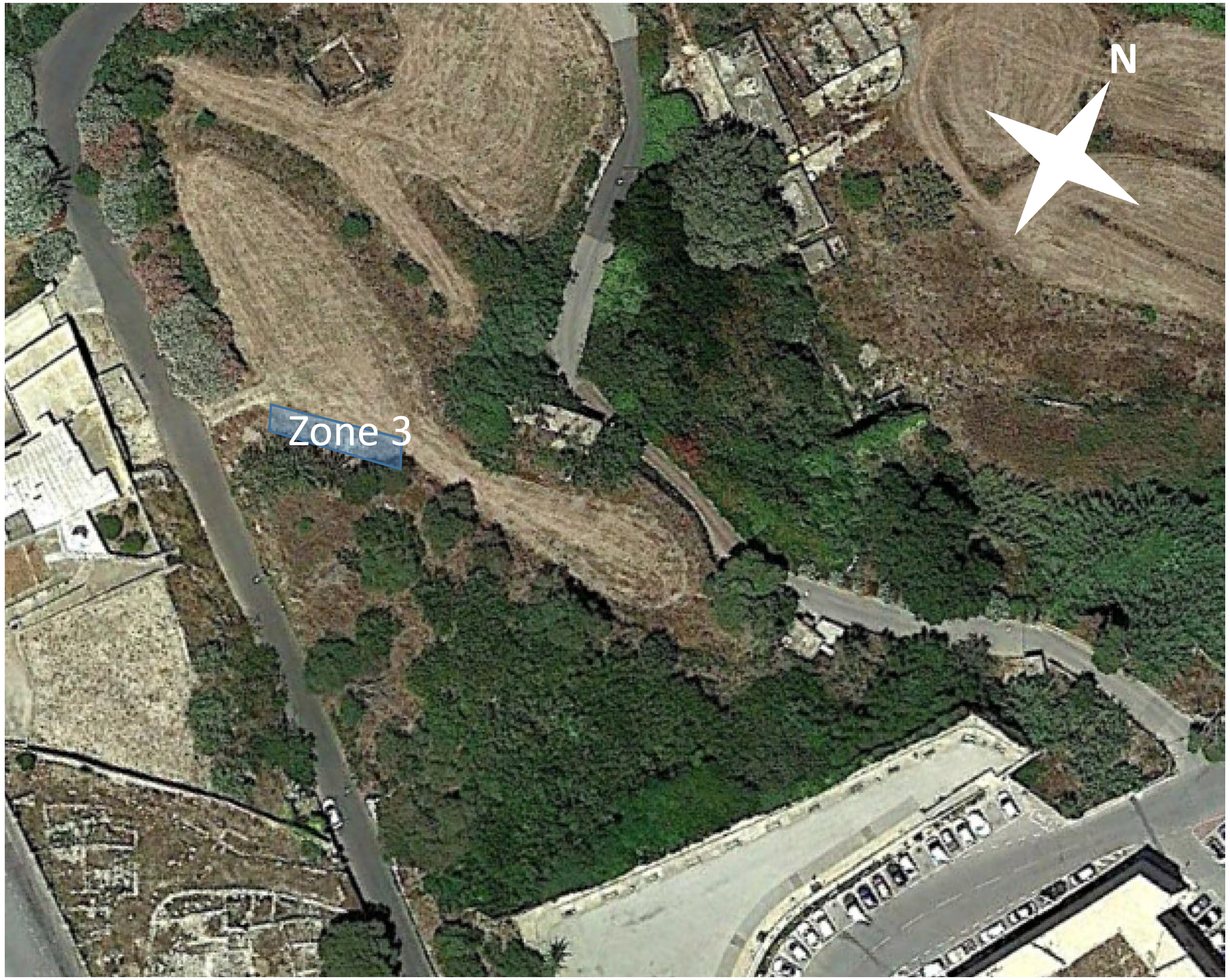

Figure 34: the surveyed area B: zone 3

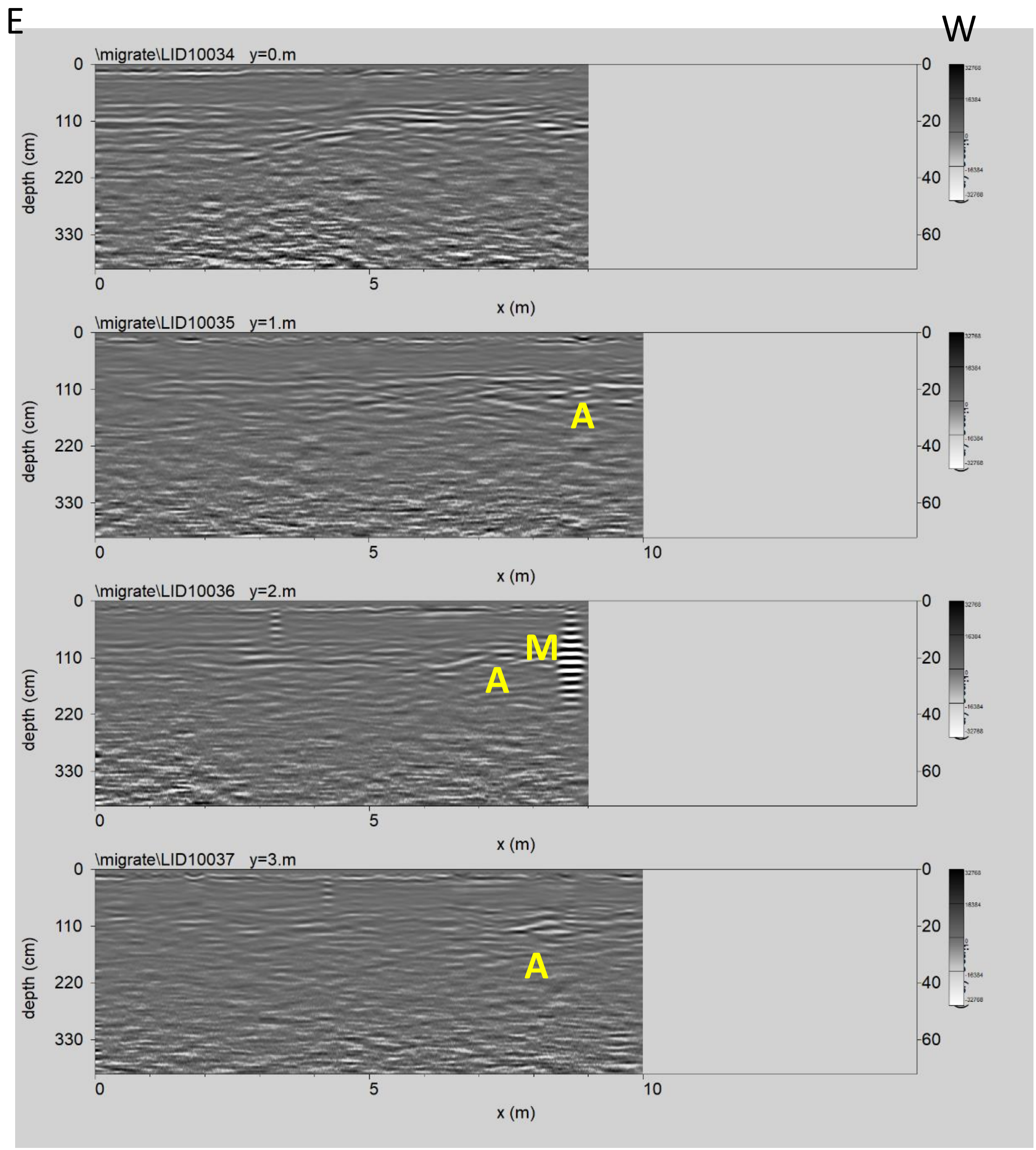

Figure 35: 600MHz antenna: the processed GPR profiles 34,…, 37.
A archaeological structures; M metal object

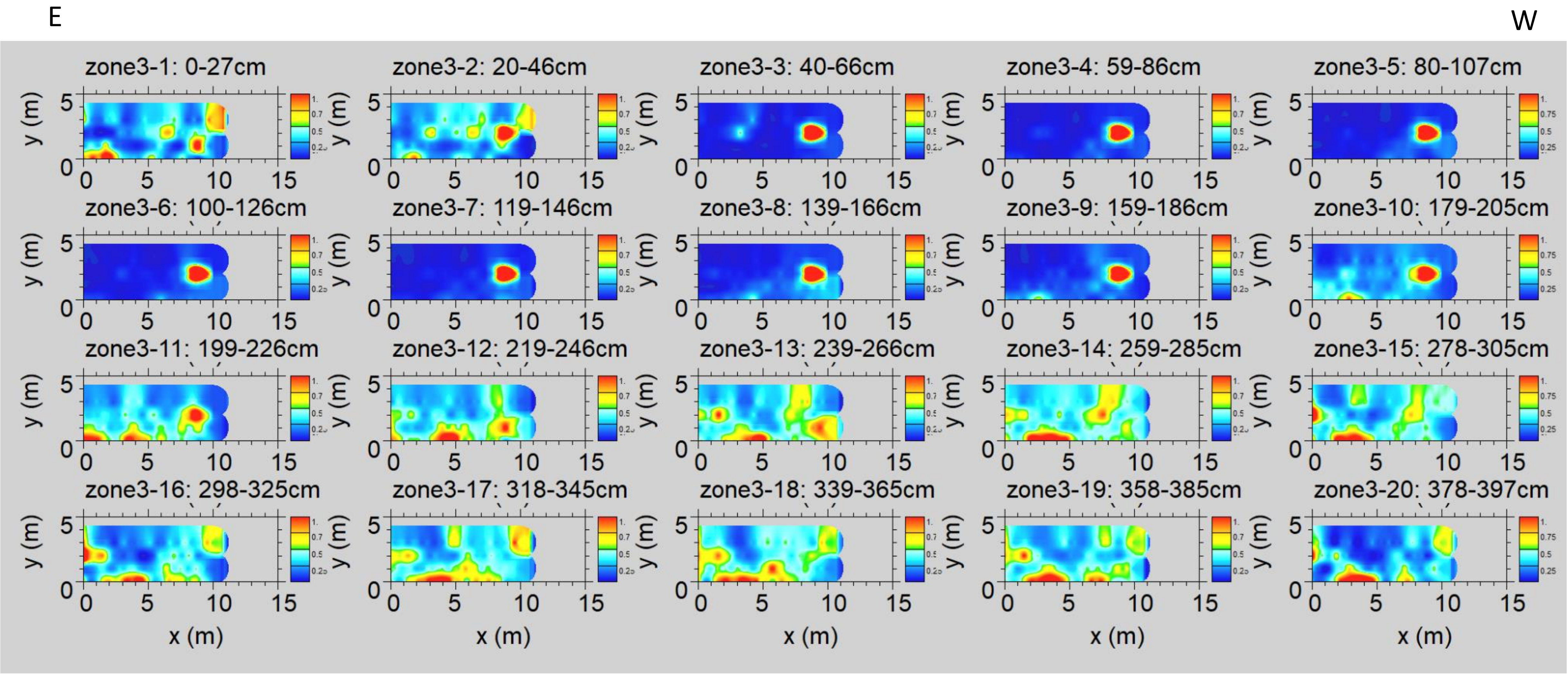

Figure 36: 600MHz antenna: the GPR depth slices

Figure 37: 600MHz antenna: the GPR depth slices overlapped to google earth photo. A: archaeological structures

E

W

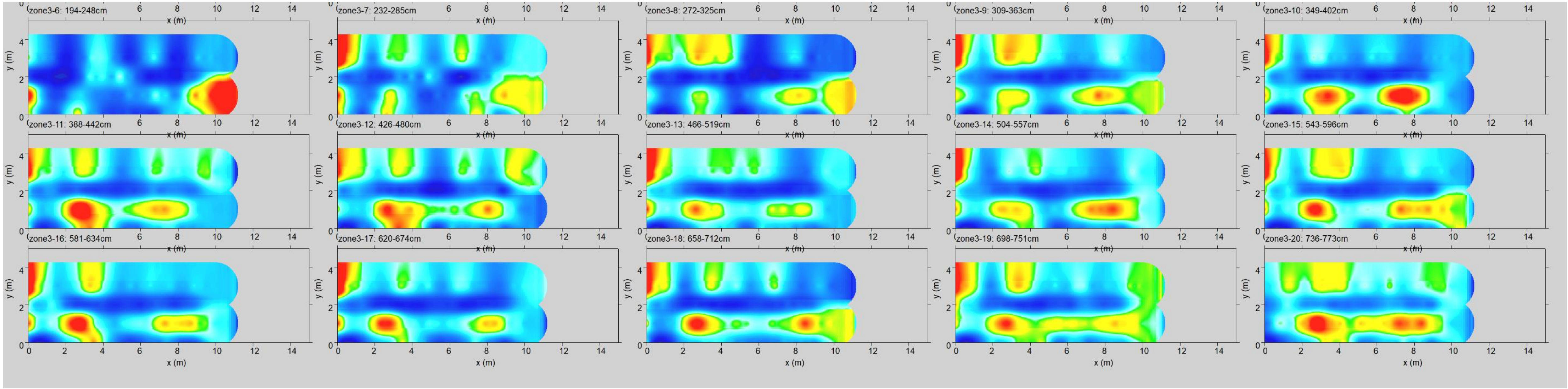

Figure 38: 200MHz antenna: the GPR depth slices

Figure 39: 200MHz antenna: the GPR depth slices overlapped to google earth photo. A: archaeological structures

Area E zone 1

Figure 40: the surveyed area E: zone 1

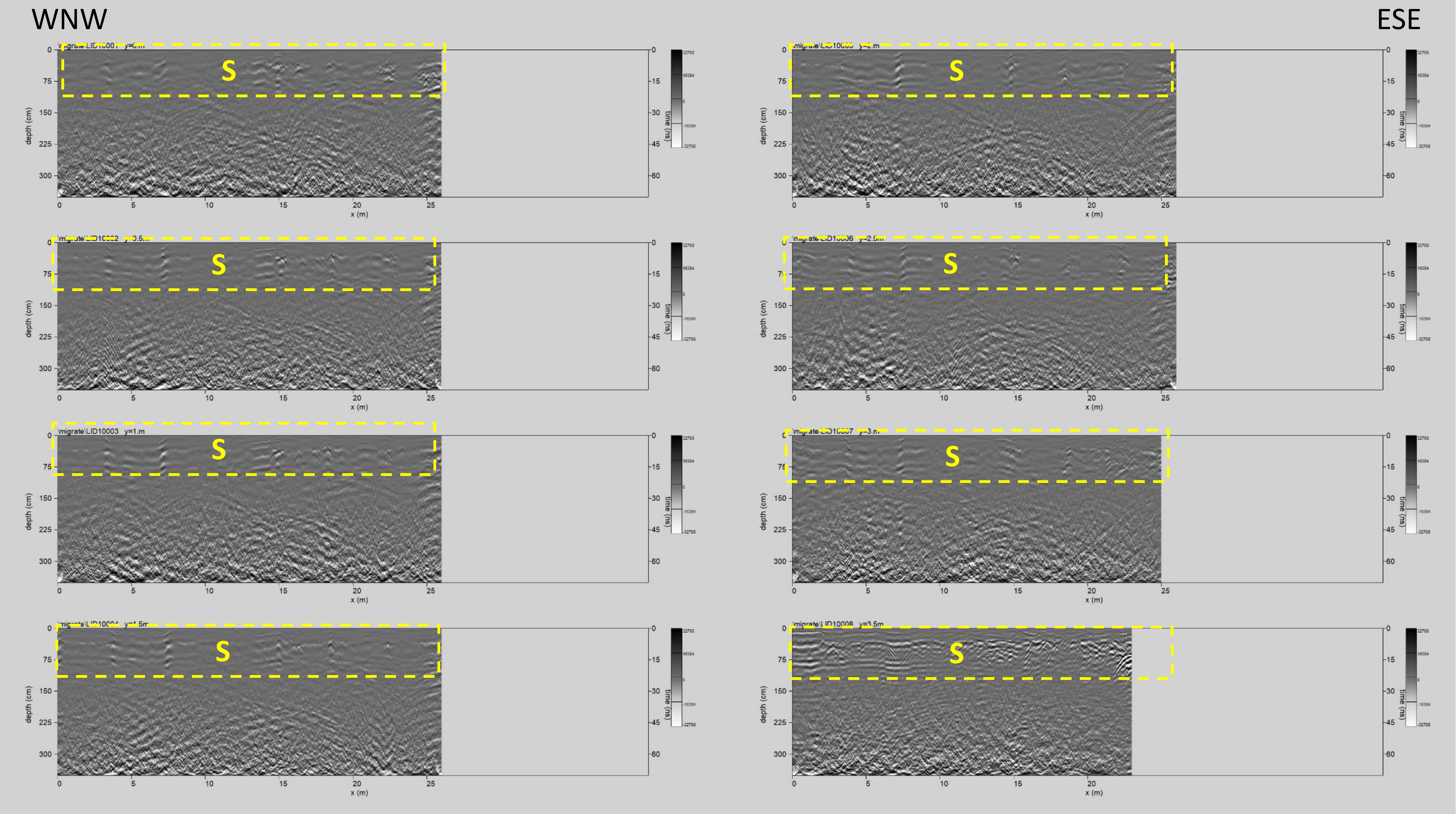

Figure 41: 600MHz antenna: the processed GPR profiles 1,…, 8. S: man-made area with the presence of underground services;

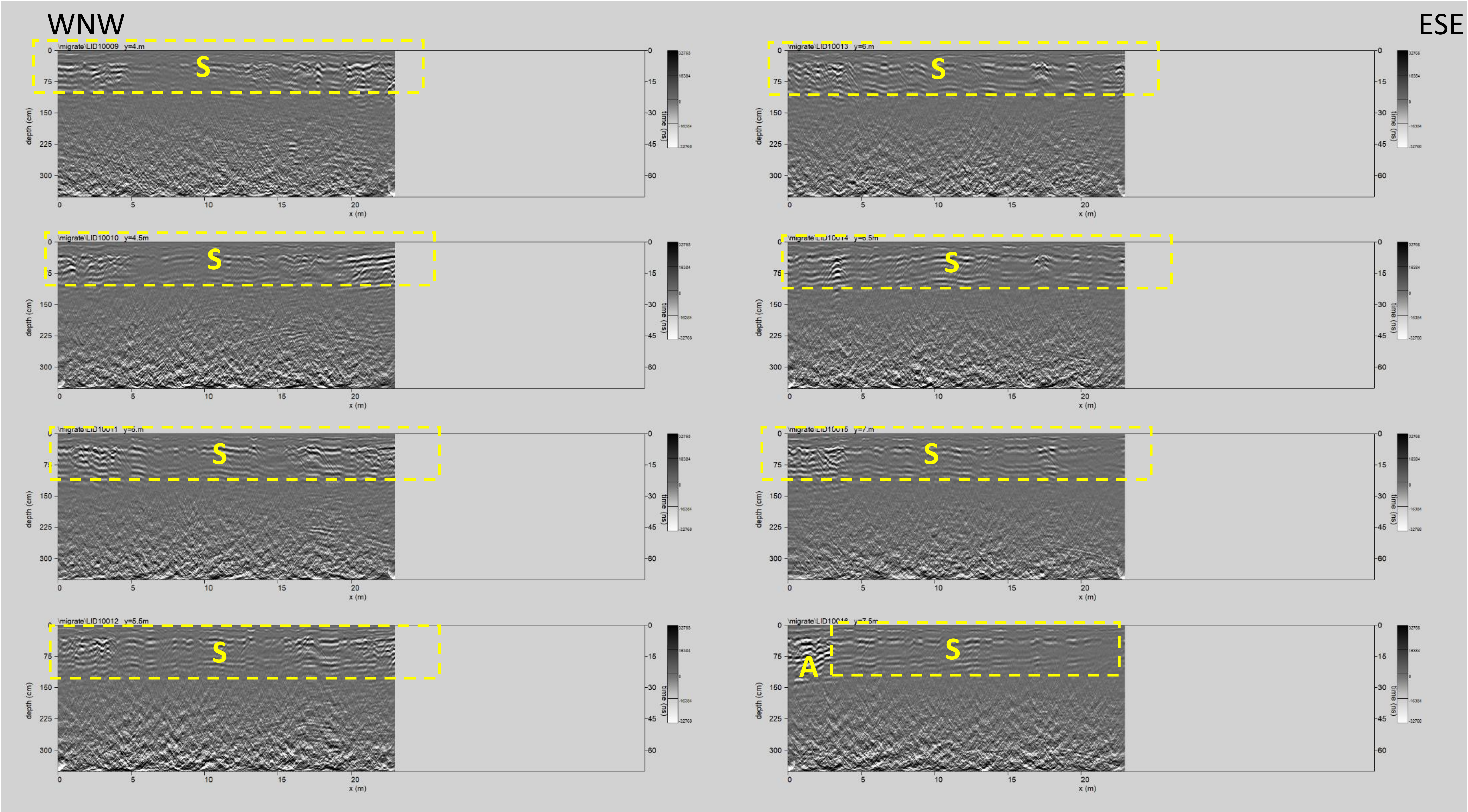

Figure 42: 600MHz antenna: the processed GPR profiles 9,…, 16. S: man-made area with the presence of underground services; A: archaeological structures

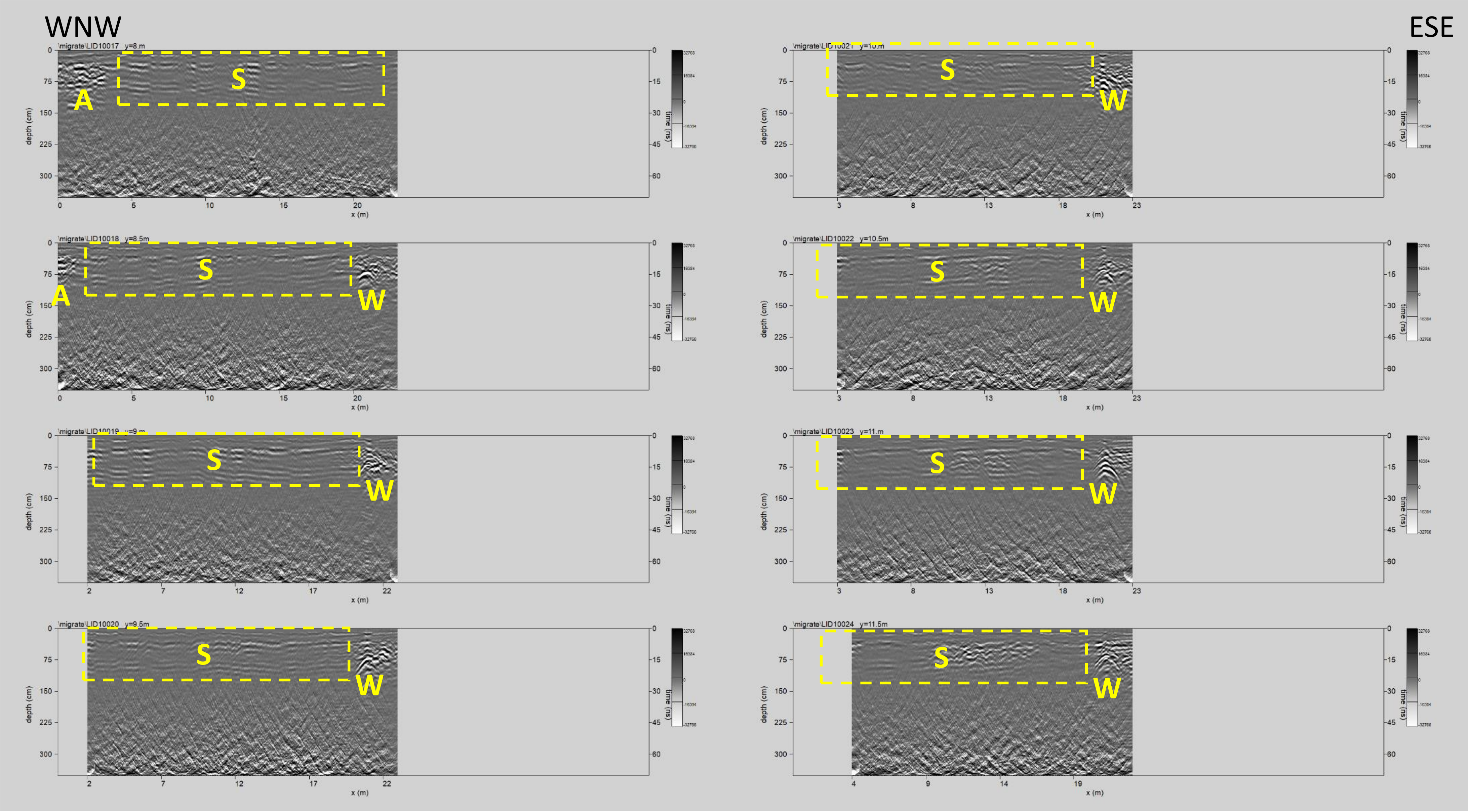

Figure 43: 600MHz antenna: the processed GPR profiles 17,…, 24. S: man-made area with the presence of underground services; A: archaeological structures; W: walls

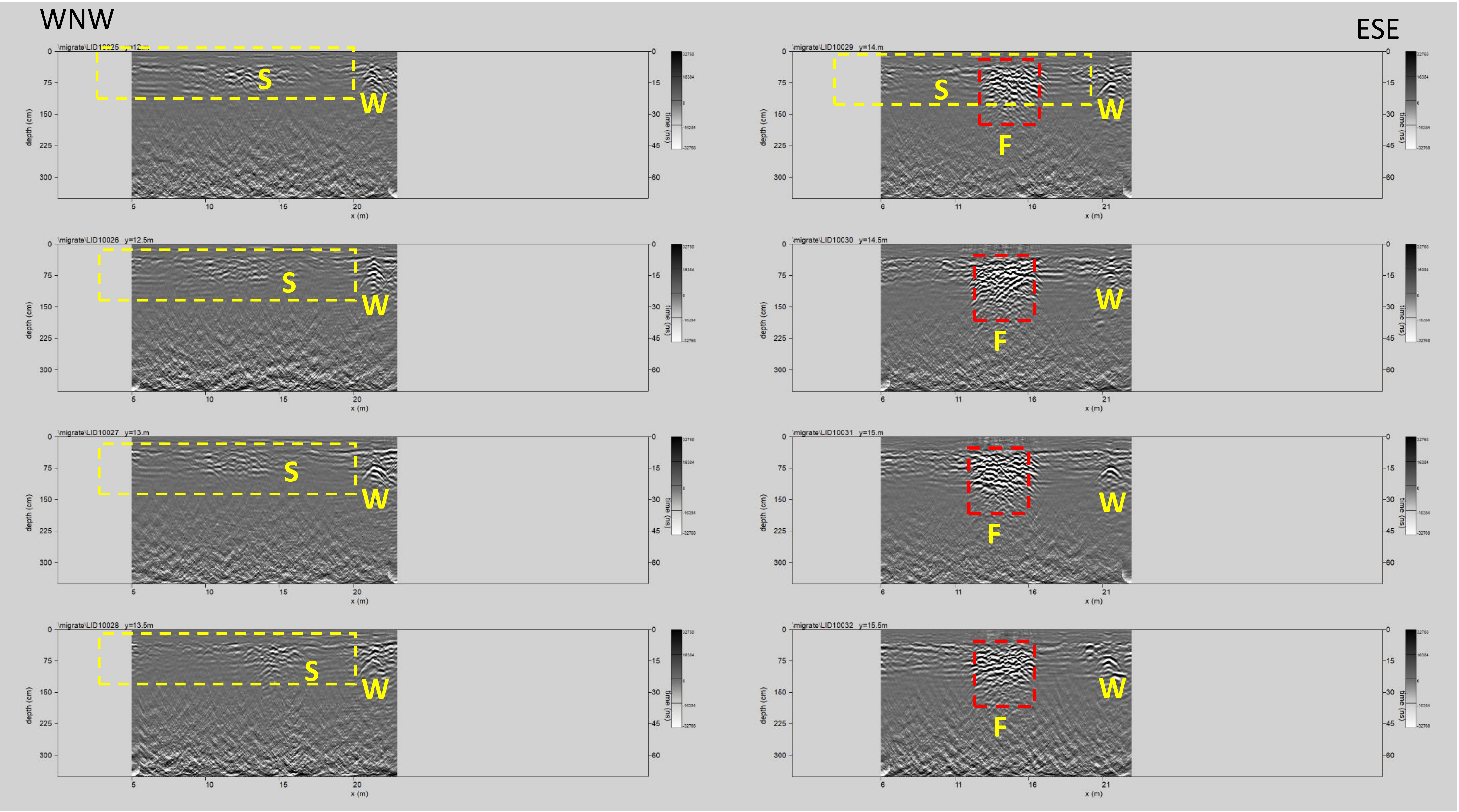

Figure 44: 600MHz antenna: the processed GPR profiles 25,…, 32. S: man-made area with the presence of underground services; F: filled room; W: walls

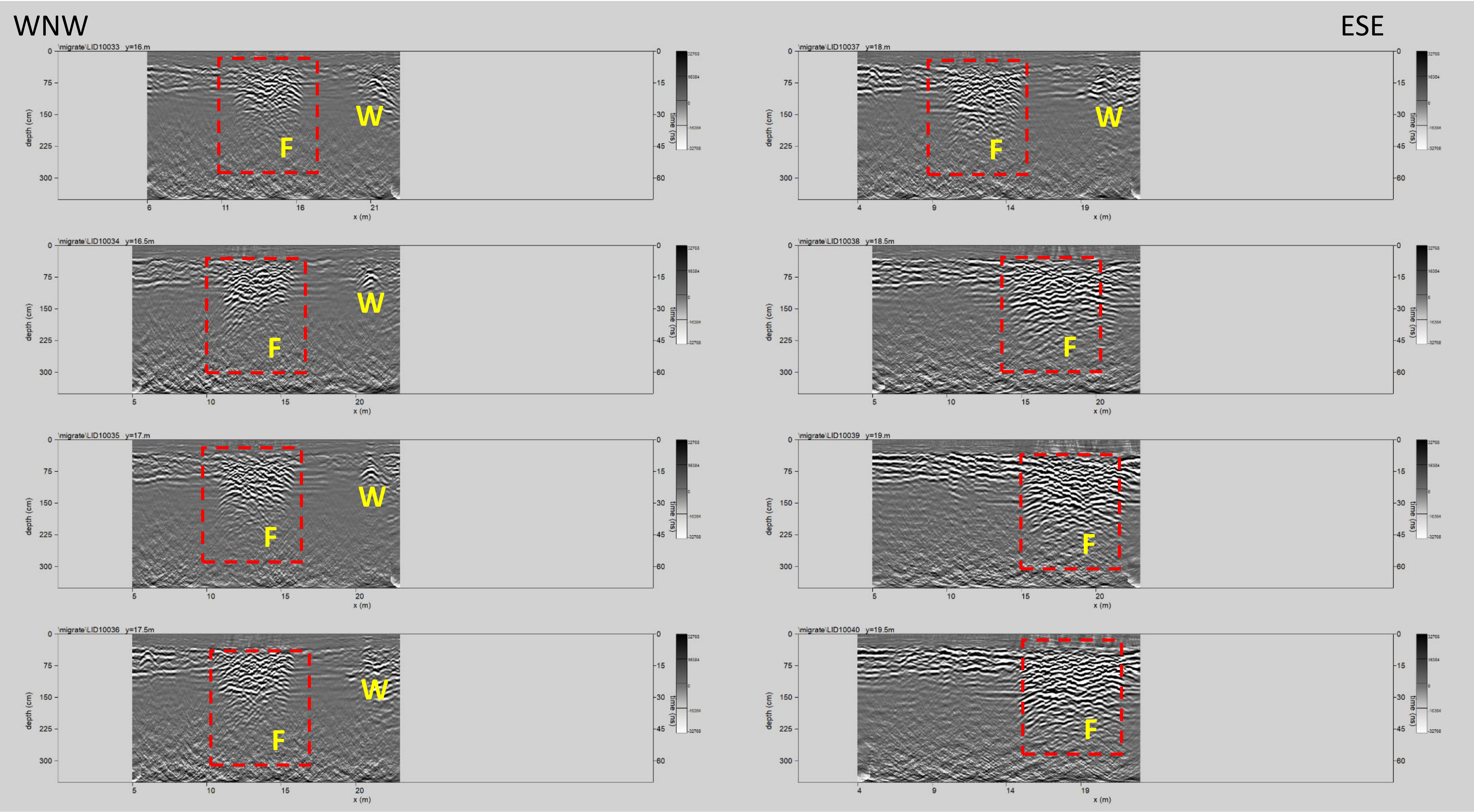

Figure 45: 600MHz antenna: the processed GPR profiles 33,…, 40. F: filled room; W: walls

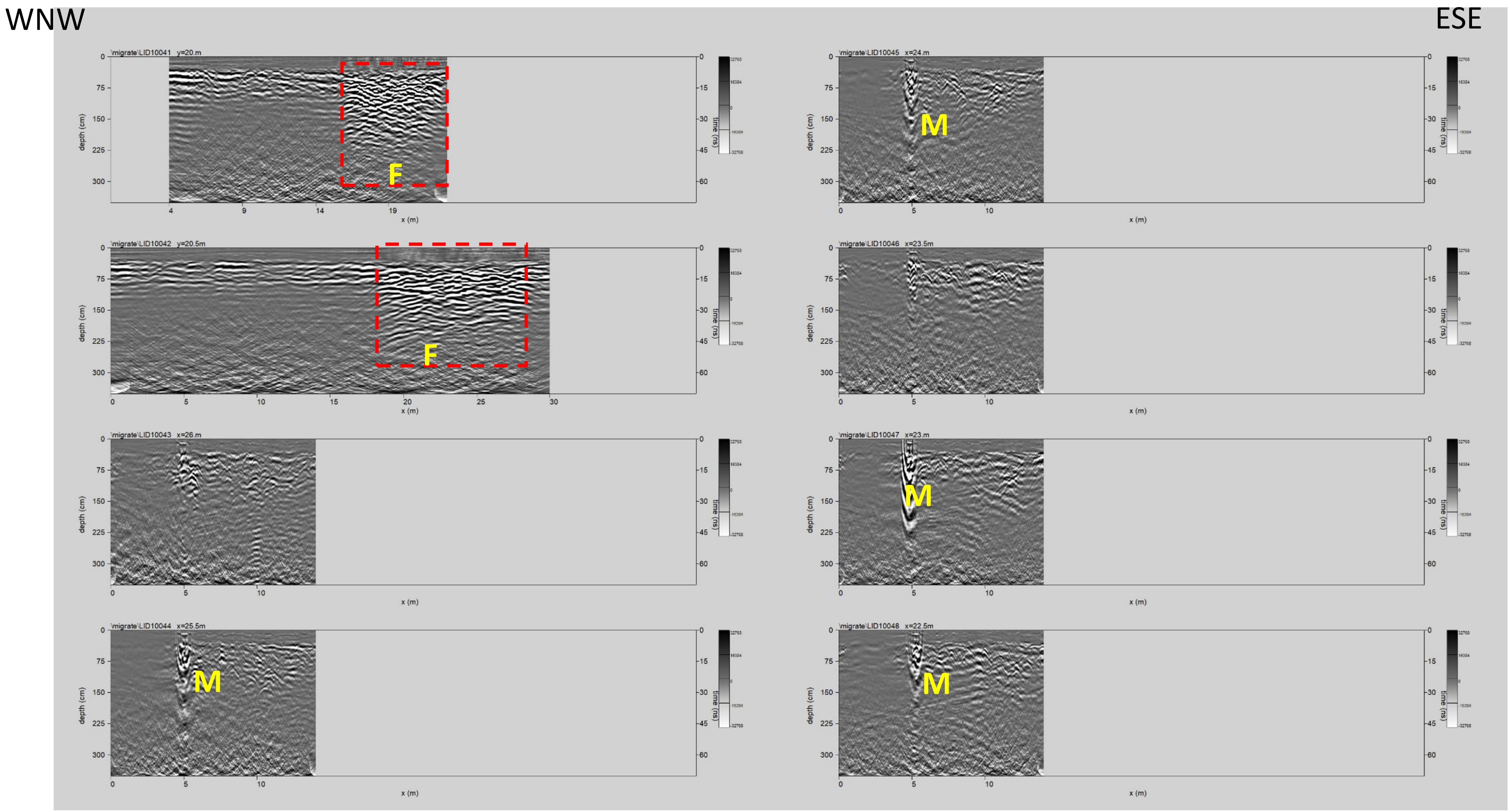

Figure 46: 600MHz antenna: the processed GPR profiles 41,…, 48. F: filled room; M: metal object

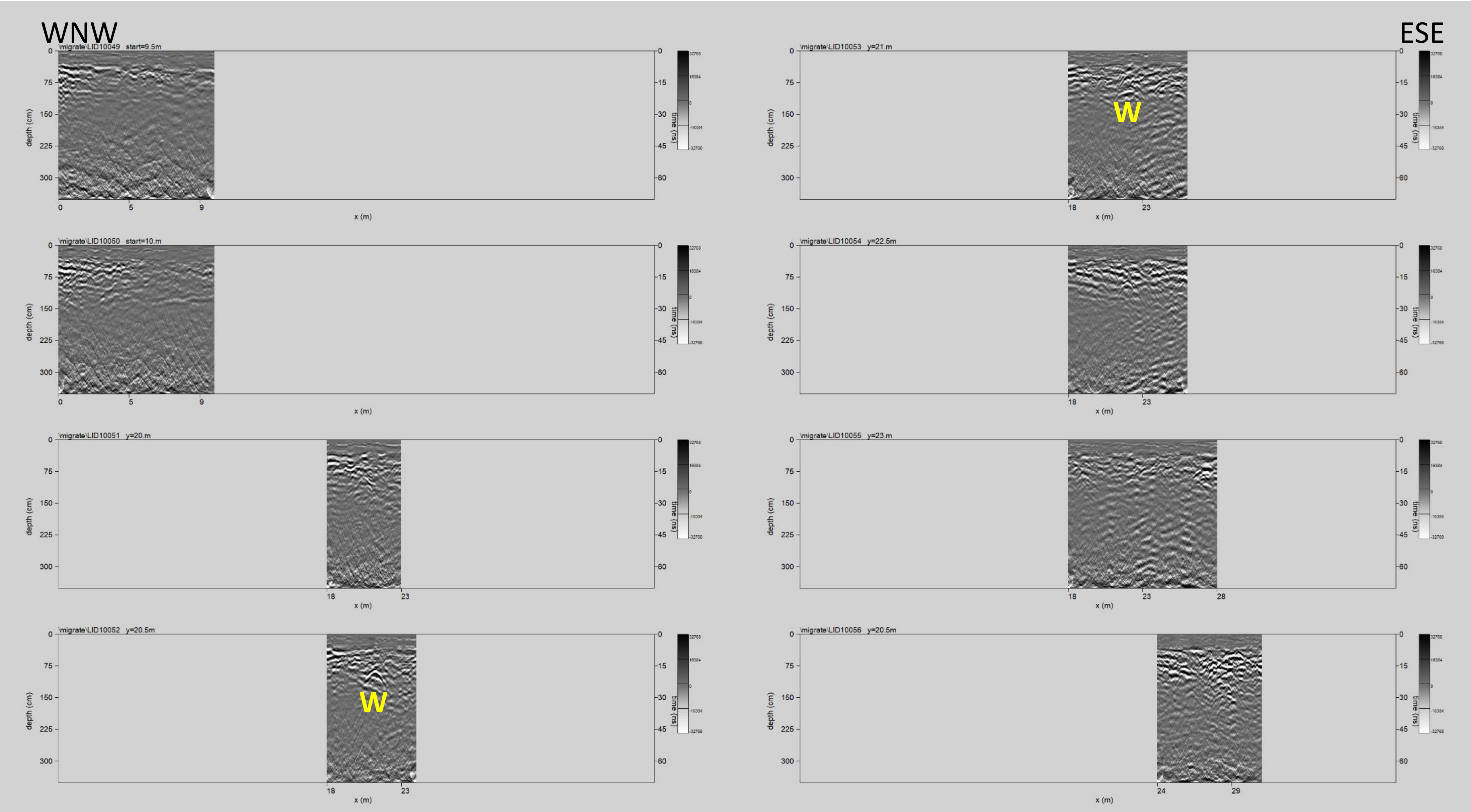

Figure 47: 600MHz antenna: the processed GPR profiles 49,…, 56. W: walls

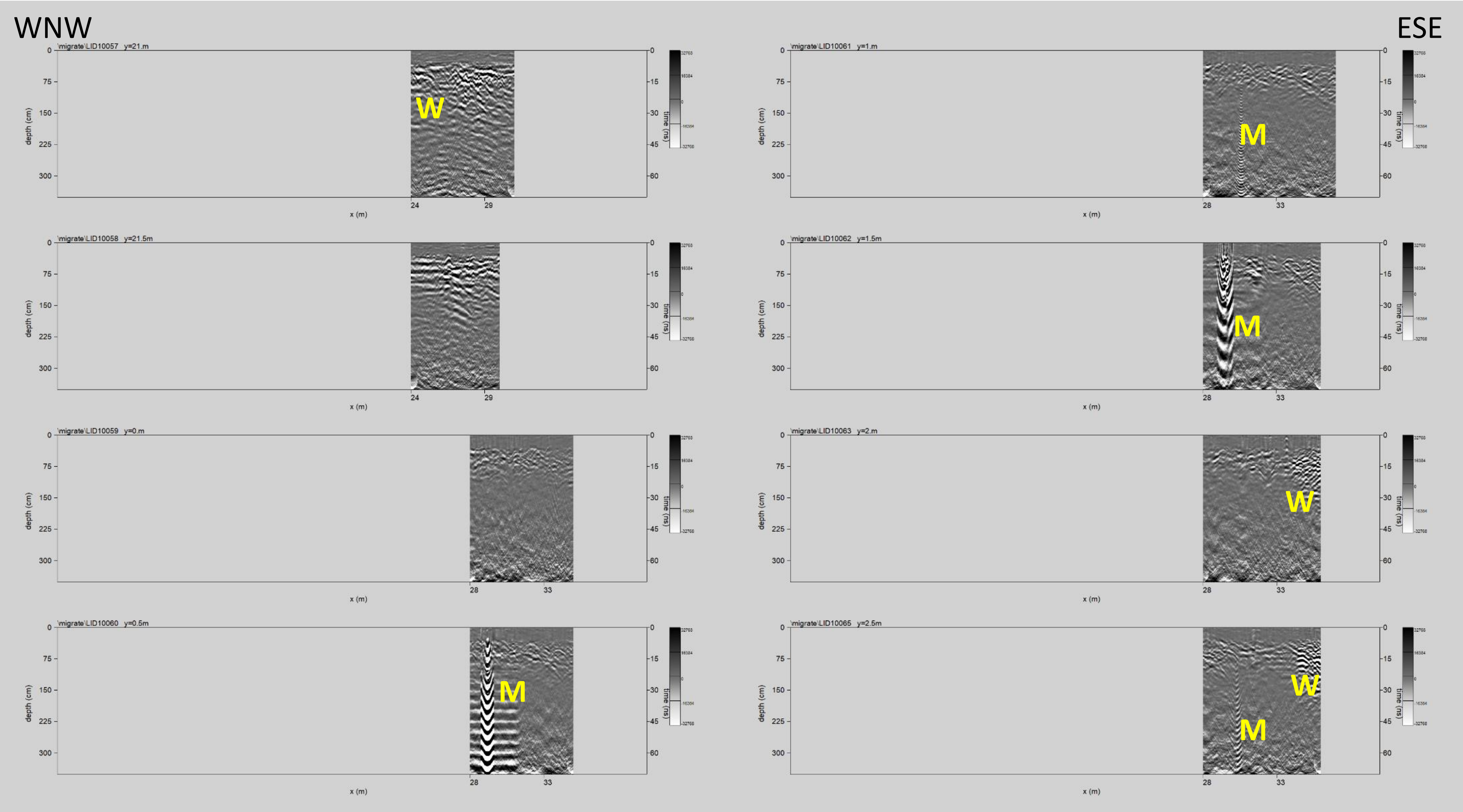

Figure 48: 600MHz antenna: the processed GPR profiles 57,…, 64. W: walls; M: metal object

ESE WNW

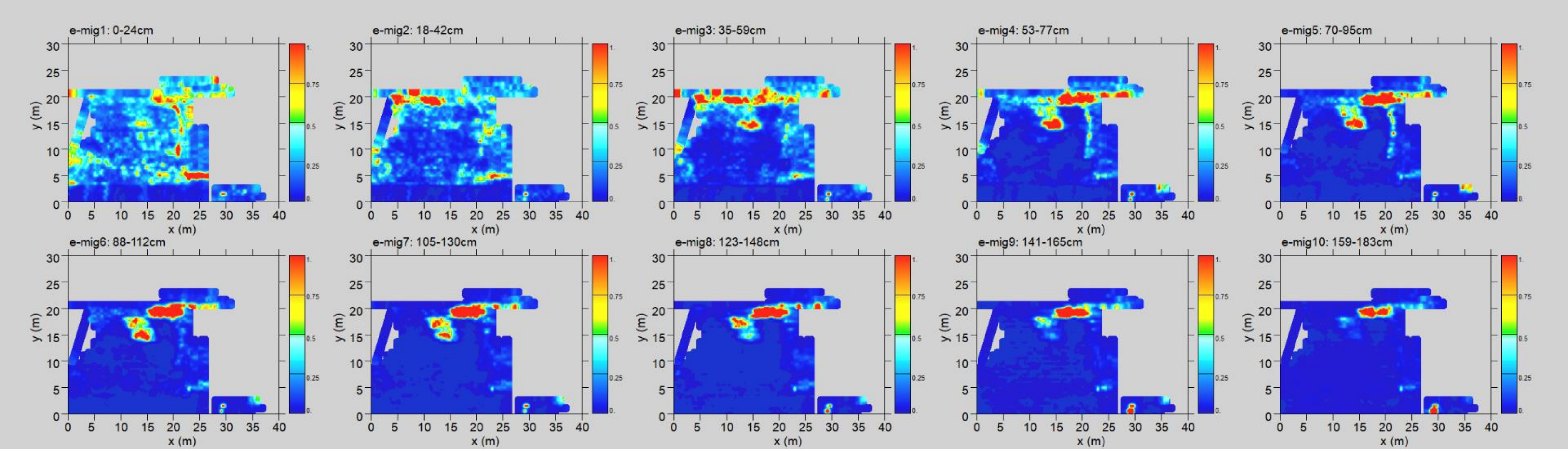

Figure 49: 600MHz antenna: the GPR depth slices

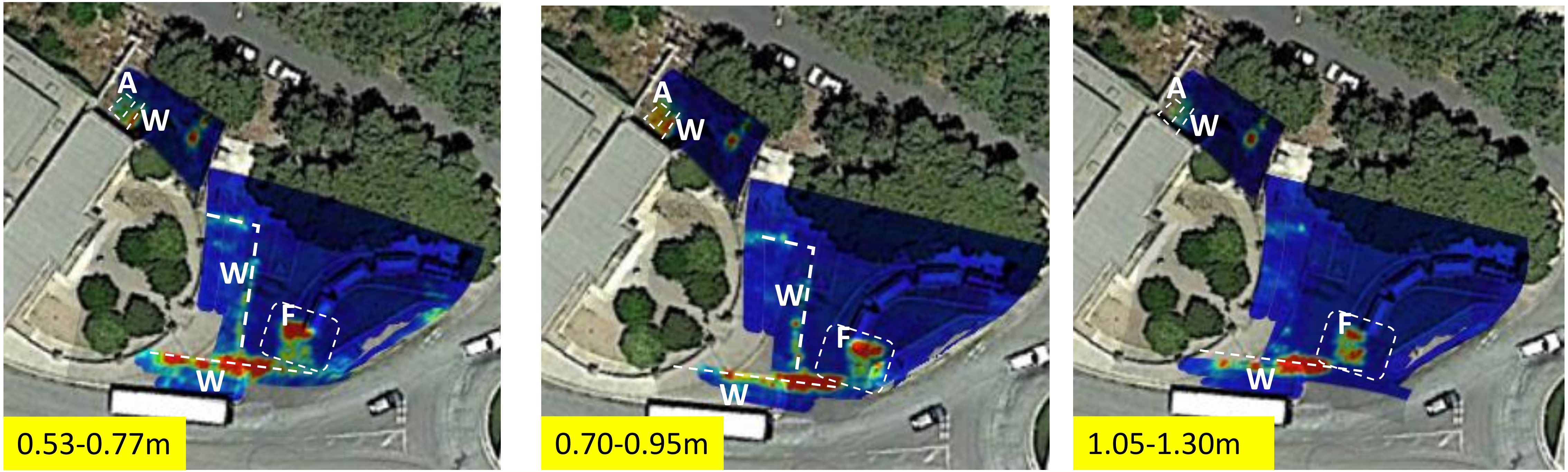

Figure 50: 600MHz antenna: the GPR depth slices overlapped to google earth photo. A: archaeological structures; W: walls; F: filled room

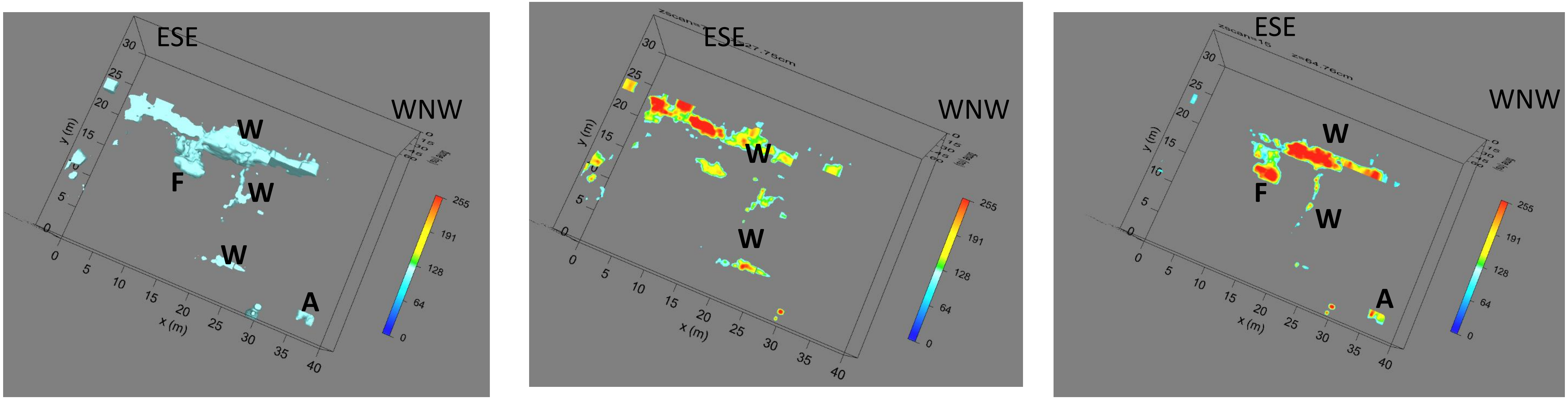

Figure 51: 600MHz antenna: the GPR iso – surfaces: W: walls; F: filled room; A: archaeological structures

ESE

WNW

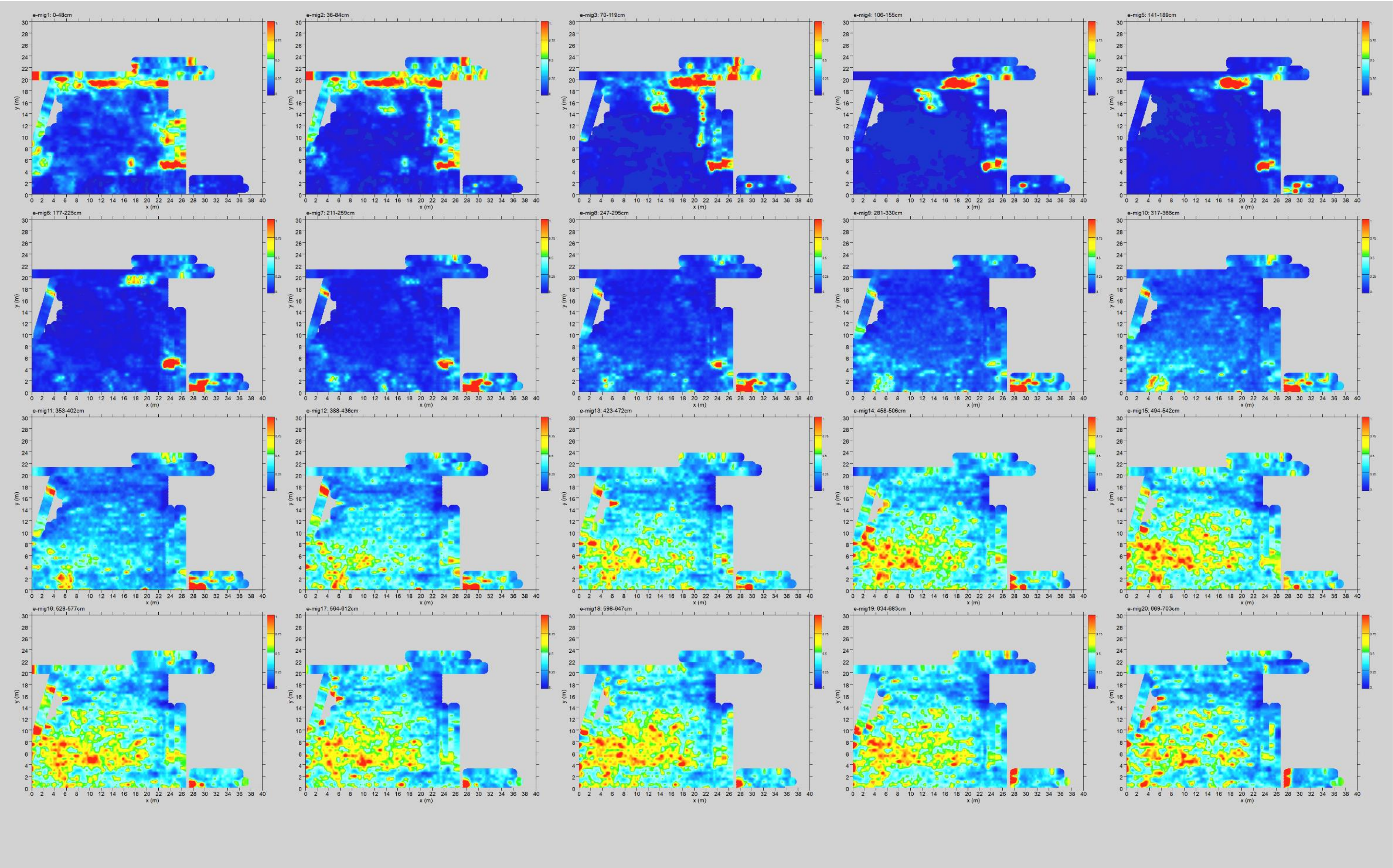

Figure 52: 200MHz antenna: the GPR depth slices

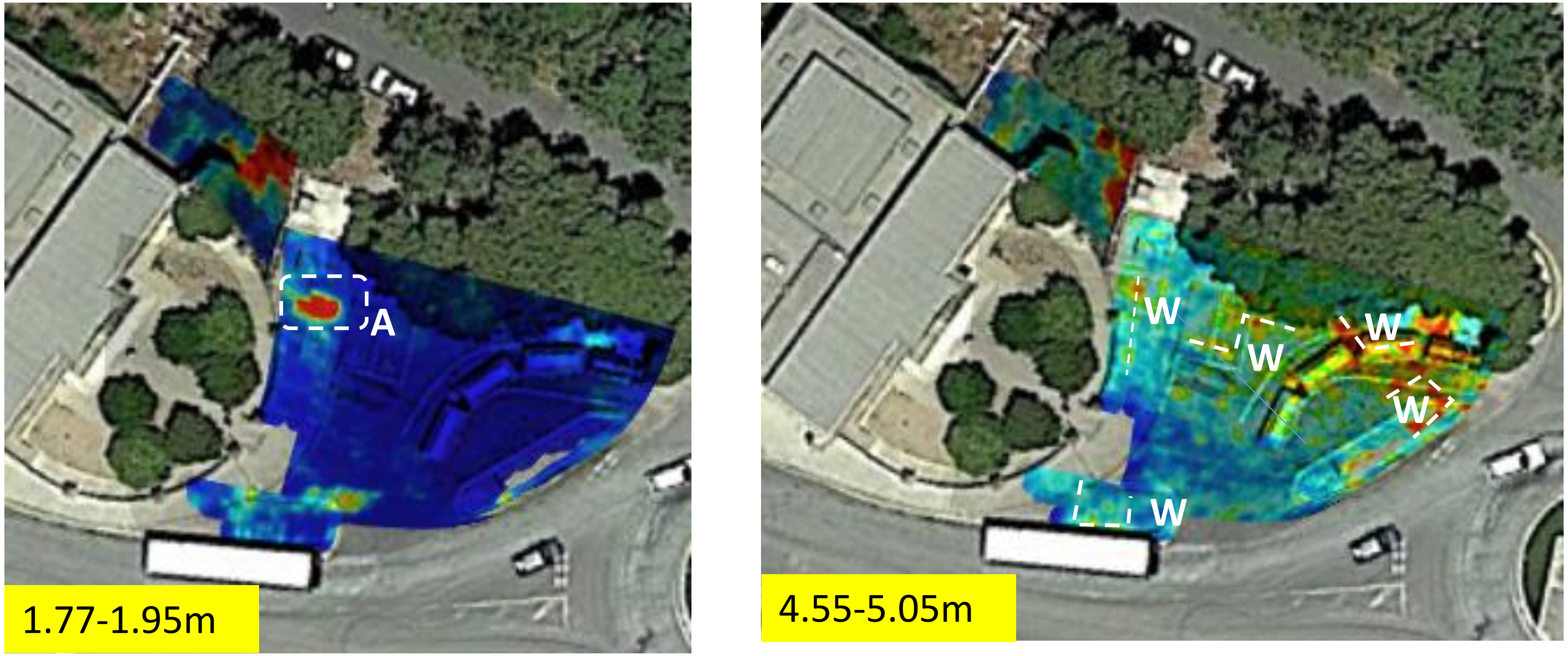

Figure 53: 200MHz antenna: the GPR depth slices overlapped to google earth photo. A: archaeological structures; W: walls

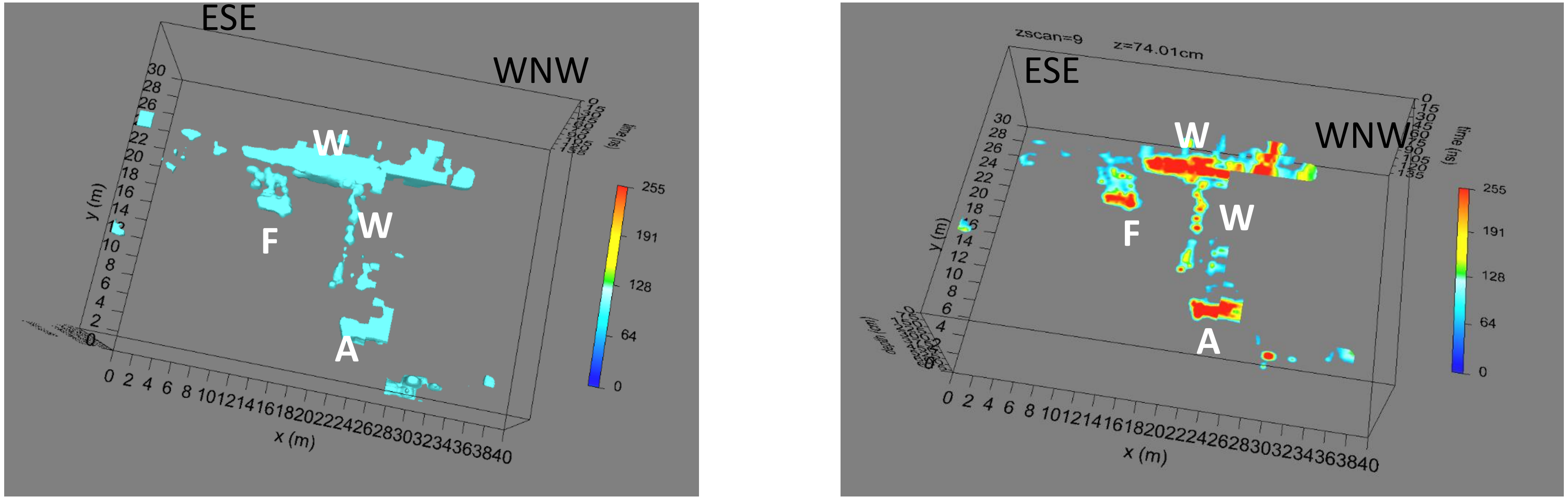

Figure 54: 200MHz antenna: the GPR iso - surfaces. A: archaeological structures; W: walls; F: filled room

Area E zone 2

Figure 55: the surveyed area E: zone 2

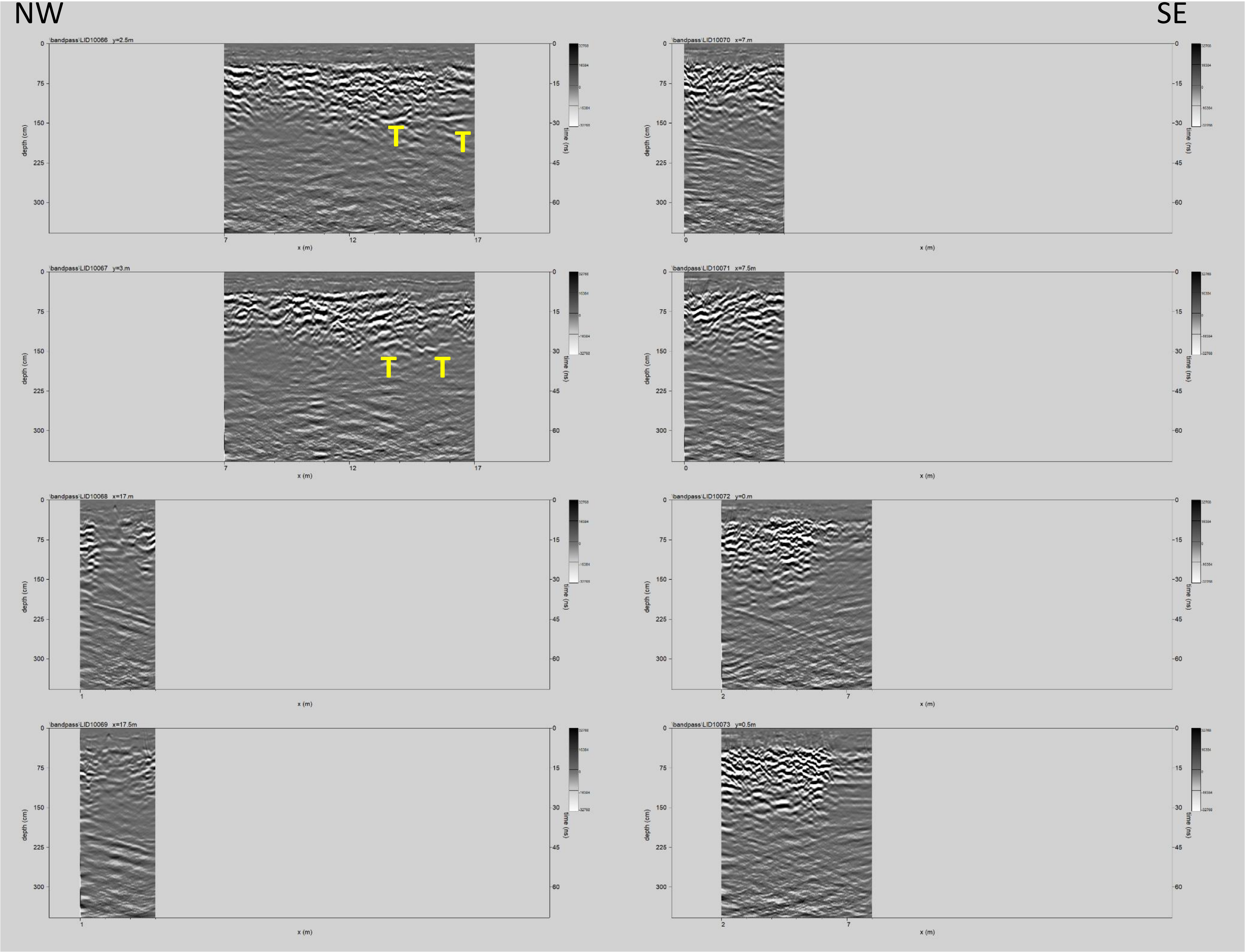

Figure 56: 600MHz antenna: the processed GPR profiles 66,…, 73. T: tombs

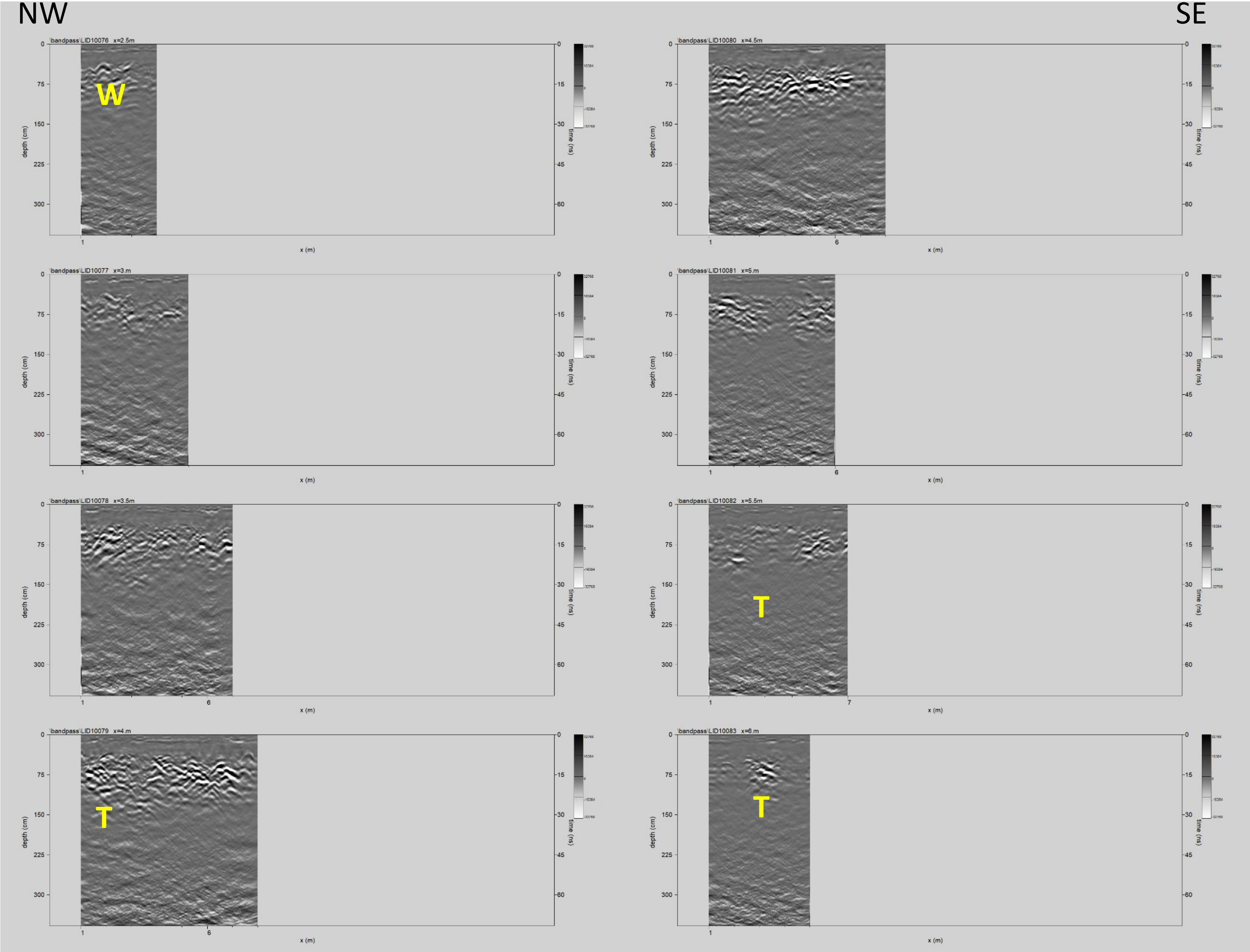

Figure 57: 600MHz antenna: the processed GPR profiles 76,…, 83. T: tombs; W: walls

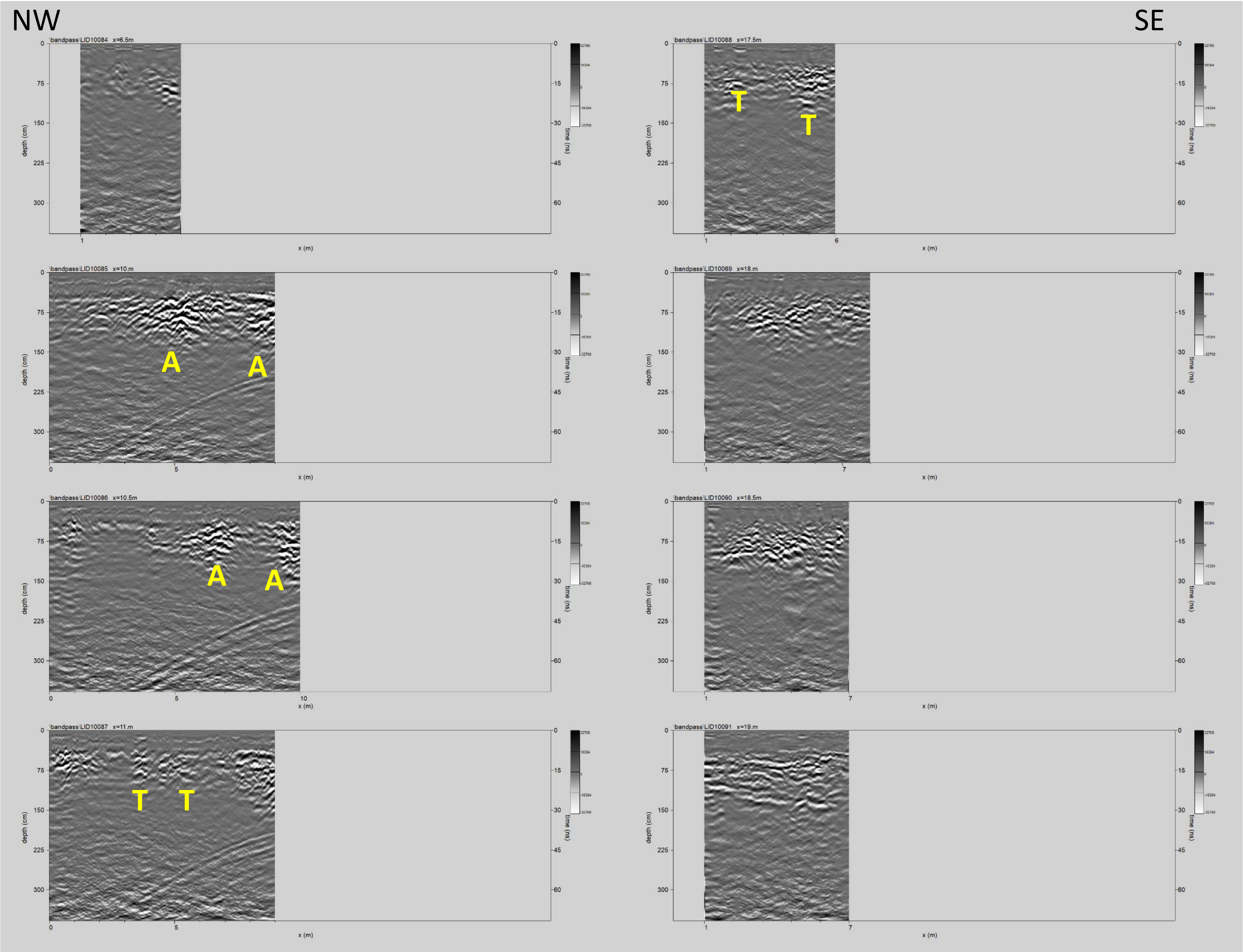

Figure 58: 600MHz antenna: the processed GPR profiles 84,…, 91. T: tombs; A: archaeological structures

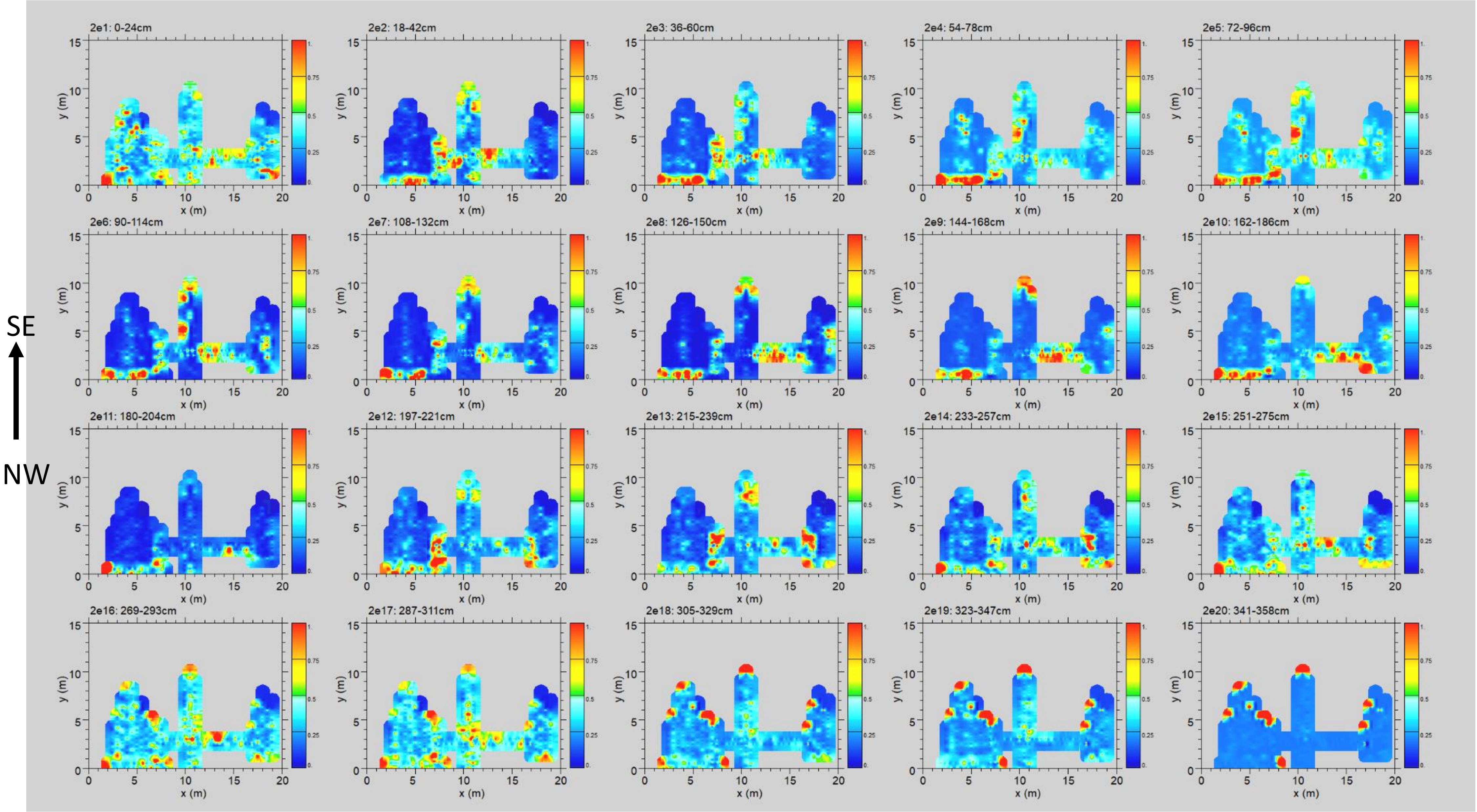

Figure 59: 600MHz antenna: the GPR depth slices

Figure 60: 600MHz antenna: the GPR depth slices overlapped to google earth photo. T: tombs; W: walls

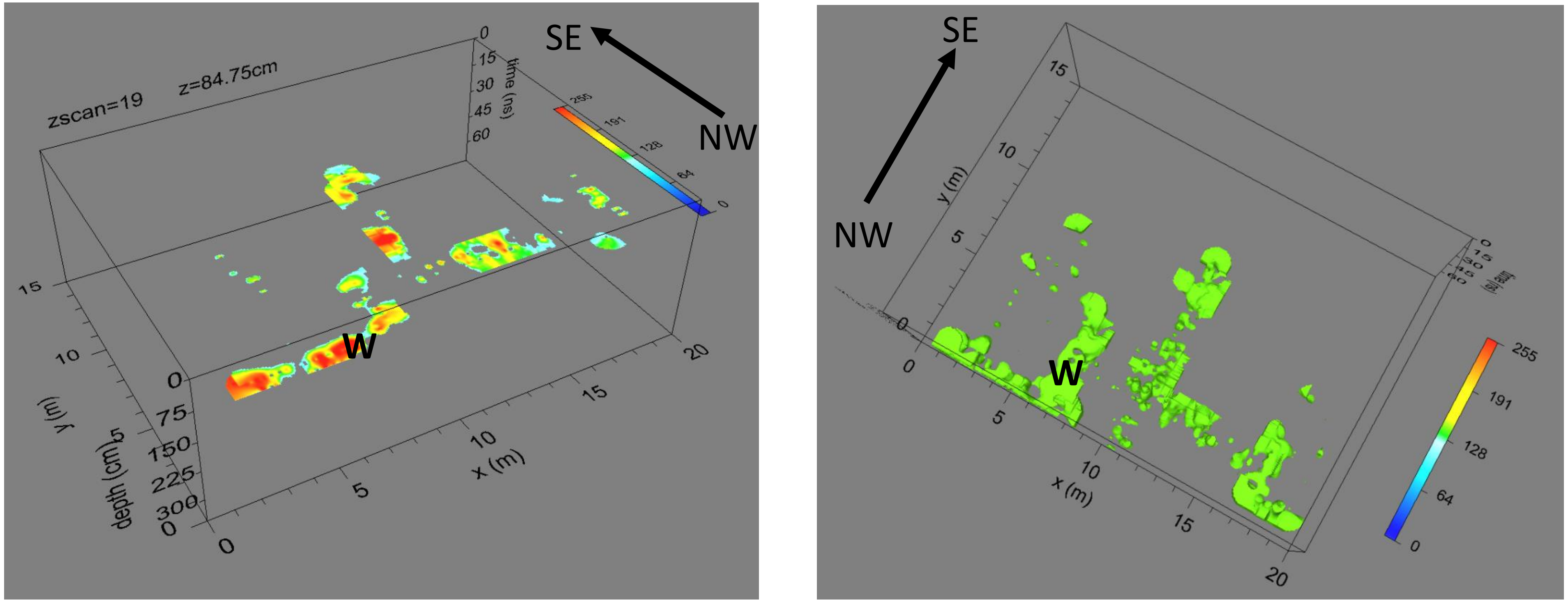

Figure 61: 600MHz antenna: the GPR iso-surfaces; the deeper structures, W: walls

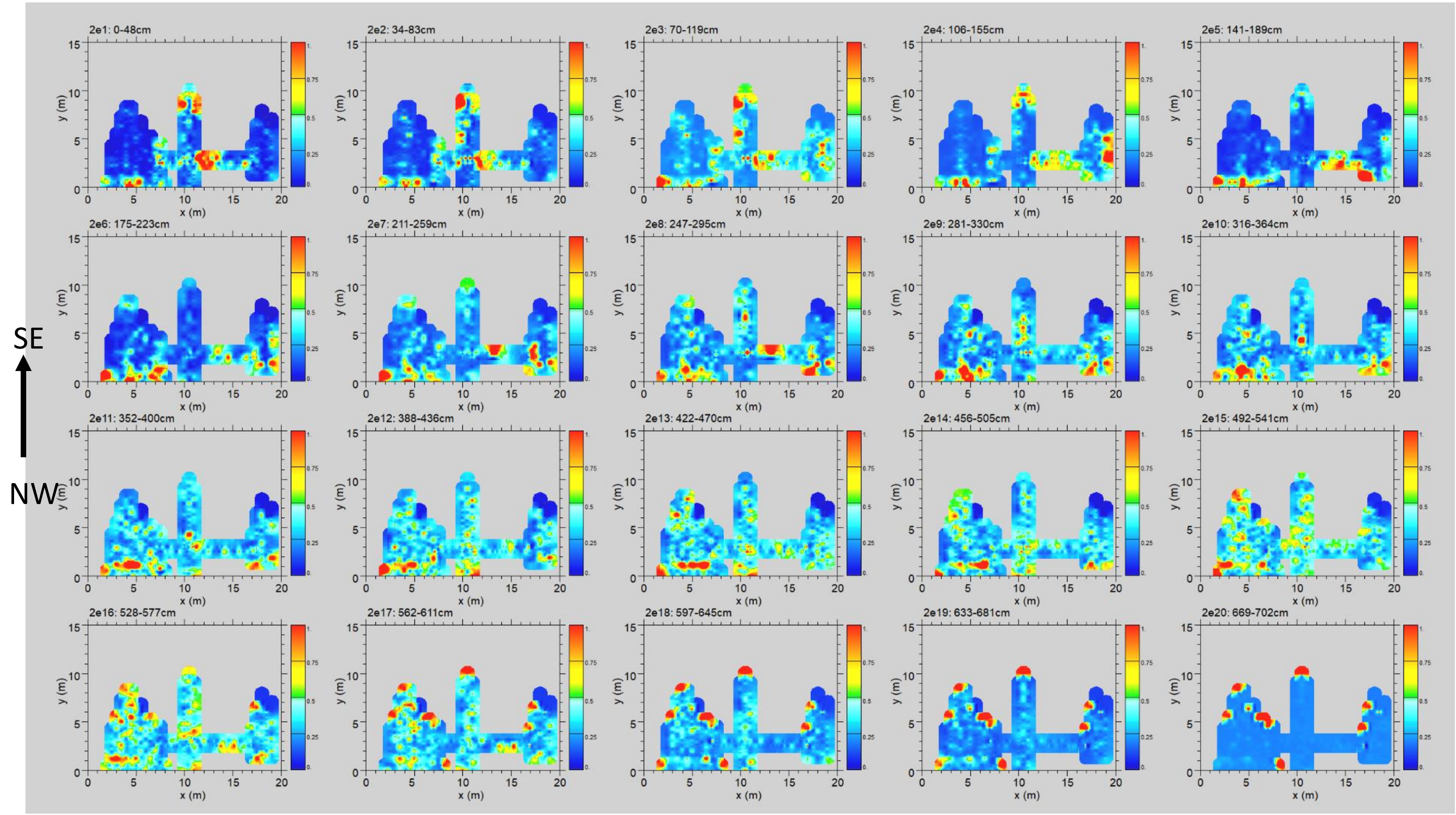

Figure 62: 200MHz antenna: the GPR depth slices

Figure 63: 200MHz antenna: the GPR depth slices overlapped to google earth photo. W: walls

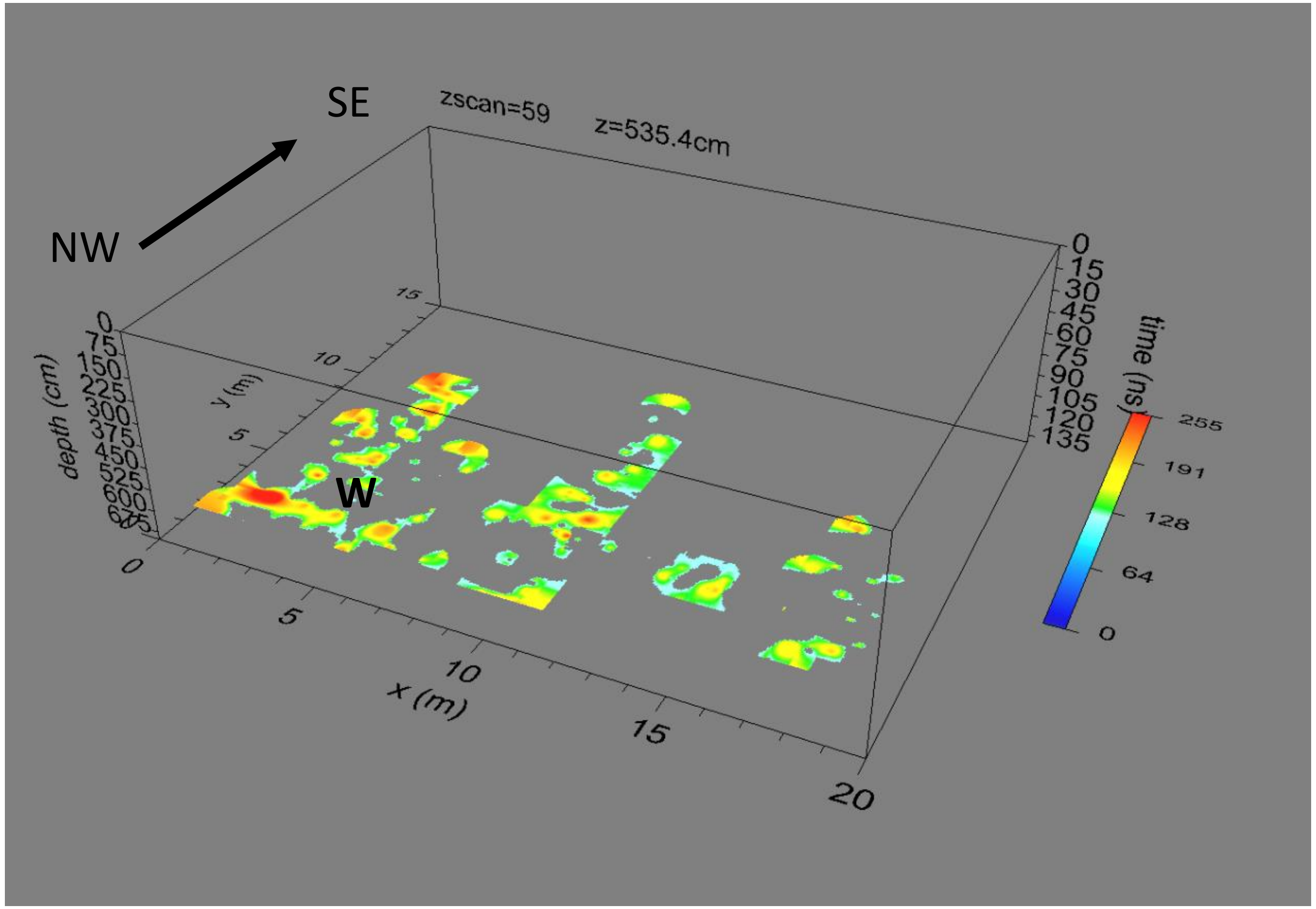

Figure 64: 200MHz antenna: the GPR iso-surfaces; the deeper structures, W: walls