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ARCHAEOGEOPHYSICAL BASED APPROACH FOR INCA ARCHAEOLOGY: OVERVIEW AND ONE OPERATIONAL APPLICATION

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ARCHAEOGEOPHYSICAL BASED APPROACH FOR INCA ARCHAEOLOGY: OVERVIEW AND ~~AN~~ ONE OPERATIONAL APPLICATION

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1. Introduction

In the last decades the use of remote sensing technologies (from satellite, aerial and ground) for archaeology are stepping in a golden age characterized by an increasing growth of both classical and emerging multidisciplinary methodologies, addressed to the study, documentation and conservation of cultural property (Kvamme 2003; Lasaponara & Masini 2008; Lasaponara et al. 2016; Cuca & Hadjimitsis 2017; Opitz & Hermann 2018; Masini et al. 2018). The digital tools nowadays available for archaeology enable us to get extremely precise results in a non invasive way and to speed up the work during the diverse phases of archaeological investigations ranging from survey, mapping, excavation, and monitoring at diverse scales of interest, moving from small artefacts to architectural structures and landscape reconstruction. This has totally revolutionised the classical approach of studying human past and activities, before mainly based on the recovery and analysis of material culture, field recognition, survey, test pits, and, finally, excavation campaigns. All of these activities are time consuming, expensive, and can produce destructive impacts. Time, costs and invasive impact can be reduced or optimized through archaeological prediction tools and methods, as earth observation technologies including remote sensing and geophysics. The use of these technologies is particularly important in absence of historical sources, as in the case of prehistoric archaeology or for studies of civilizations that did not have writing and did not leave any documentation. This is the case of pre-Hispanic civilizations in Peru and in other countries of Southern America, from the most ancient cultures, as Chavin, Nasca and Moche, to the most recent ones including Inca. Despite this and the fact that the first pioneering geophysical application in Southern America date to 1985 (Gumaer1985), the geophysics for the study of the Andean civilizations is still today generally not used in the operational activities of preventive archaeology.

However, it must be considered that even in Europe and North America, the use of geophysics in archaeology has strongly increased only in the last two decades thanks to the technological advances of instrumentation, availability of friendly data processing tools, improvements in data visualization which facilitate the interpretation of the results.

In Southern America, the use of geophysics for archaeological prospection started at the end of the first decade of the 2000s. The most popular geophysical techniques used for preventive archaeological research, are geomagnetometry, Ground Penetrating Radar (GPR) and Electrical Resistivity Tomography (ERT), selected according to the expected characteristics of both buried archaeological features and soils.

Geomagnetometry methods, based on the measuring and recording of spatial variations in the Earth's magnetic field, have been mainly used to detect and map (i) ring ditches of the prehistoric sites in the lowlands of the Llanos de Moxos in the Bolivian Amazonia (Prümers 2006) and (ii) buried earthen city walls of the ceremonial center of Pachacamac in Peru (Lasaponara et al. 2017).

GPR, based on the analysis of radar signal reflection in the presence of subsoil discontinuities, has been mainly exploited to detect: (i) stone masonry structures, as those in andesite identified in Tiwanaku (Henderson 2004), and (ii) naturally dried-earth settlements, from the Formative age in the northwest of Argentina to the colonial period in Patagonia (Bonomo et al. 2010; Lascano et al.

2003). GPR has been also fruitfully employed in Peru for the characterization of looted areas in Ventarron (Lasaponara et al. 2014).

Integrated geophysical methods, including ERT, are adopted where and when the use of a single geophysical method is not suitable and effective in terms of information quality, data resolution and penetration capability. For sake of brevity, we cite the discovery in 2012 of a Nasca pyramid in the ceremonial center of Cahuachi made by integrating GPR and ERT (Masini et al. 2016). The joint use of GPR and Magnetic methods proved to be complementary in detecting several different archaeological features from (i) the buried foundation trenches of quincha (a construction system using wood and cane) walls of the colonial villages in the Zaña Valley (North Peru) (Vanvalkenburgh et al. 2015), to (ii) the Nasca tombs and ritual offerings in Cahuachi (Rizzo et al. 2010).

Related to Peru, it must be considered that paradoxically geophysical investigations were mostly performed along the arid coast areas to detect raw earth material settlements, which still today represents a technical challenge due to the very low geophysical difference/contrast between the targets and the neighbouring areas. On the contrary, in the highland of Peru very few archaeo-geophysical investigations have been performed to investigate settlements in stone, easier to be detected compared to those in earth material. In particular in the Urubamba valley, the origin region of the Incas, which includes Machu Picchu (the most famous and visited pre-Hispanic sites of Peru geophysical prospections were only performed for the monitoring of the landslide hazard to map fractures and zones of weakness in crystalline bedrock (Best et al. 2009).

In Machu Picchu as also in the Urubamba valley, up to now no significant archaeological studies have been performed using geophysical methods or other earth observations techniques. To fill this gap, a specific archaeological project in Urubamba valley started in 2017 as bilateral cooperation between the ITACA Mission of Italian CNR and the University of Warsaw in the framework of an agreement with Ministerio de Cultura del Peru. The aim of these joint research activities is to explore new approaches and investigation tools using the most advanced earth observation sciences and technologies to advance our knowledge on the Inca civilization, to improve our understanding of the Inca sites and their relationship with environment.

In this paper, we discuss the preliminary results obtained from the investigations conducted in Chachabamba. It is located on a strategic terrace overlooking three Inca roads, which served the most important ceremonial centres (including Machu Picchu) of the Urubamba Valley also known as the Sacred Valley. In particular, Chachabamba investigations were conducted with two principal aims :

1) to give new impetus to archaeological research with targeted investigations aimed at improving and completing the site's knowledge framework;

2) to experiment and validate an archeogeophysical approach to be reapplied in other sites of the Urubamba valley, including Machu Picchu, having similar characteristics as those typically found in Chachabamba, i.e. typical Inca walls, with their constructive features, terracing systems, and water channeling.

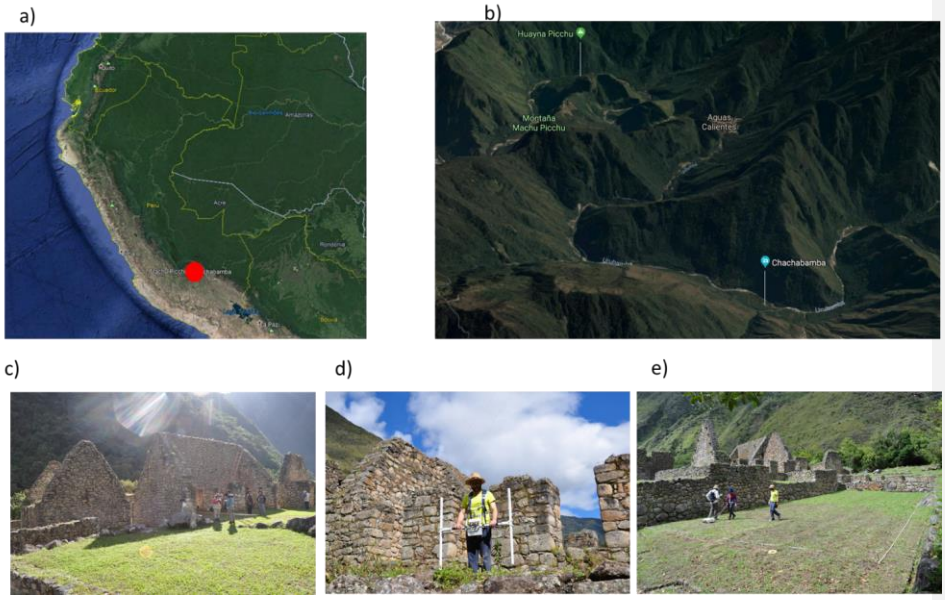

Figure 1. a: Peru with location of Chachabamba in Peru; b: location of Chachabamba in Urubamba valley where important Inca ceremonial and administrative centers, including Machu Picchu, overlook; c-d-e: geophysical data acquisition including geomagnetic (d) and georadar (e).

2 Study area

2.1 Geographical context

The Chachabamba archaeological site is part of the Historic Sanctuary of Machu Picchu and is located over an alluvial terrace at an altitude of 2170 m , on the left side of the Vilcanota River and the right bank of the Chachabamba basin. Three Inca roads connect the site to the most important ceremonial and administrative centers in the area, such as Wiñaywayna, Condorpata, Choqesuysuy, Chaskapata, Killapata and Machu Picchu. Chachabamba covers approximately 19,000 m^2 and develops in a reduced slope area that is located along the bottom of the Urubamba river valley, an alluvial surface of Quaternary origin.

2.2 Geological and geomorphological setting

From the geological point of view, ~~it~~ the site is characterized by the outcrop of granitic intrusive materials that are part of the eastern Cordillera of southern Peru. In particular, intrusive

permotriassic rocks and intrusive igneous rocks, part of the so-called Machul Pictu Batolite, are essentially consisting of granites and granodioritics (Carlotto et al 2009) which develop for a very large area of the Chachabamba site, including the slopes to the north and south.

The batholitic complex of Permian / Triassic age in the Eastern Cordillera (between the High Plateau and Subandine Zones of the Peruvian Andes- consists essentially of white to gray-colored granite which are characterized by abundance of quartz, feldspar and mica, predominantly biotite. There are also local rocks as granodiorites and serpentinites.

The Urubamba River crosses the eastern Cordillera of southern Peru (Fig. 2), locally called Cordillera Vilcabamba, and forms the canyon of Urubamba. The south-west and north-eastern slopes of the valley are rather steep and have important mountain peaks including the Salcantay (6,264 m asl) and Huamantay (5,459 m asl) to the southwest of Nevada Veronica (5,750 m asl) and Bonanta (5,024 ~~mmmmm~~m asl) to the northeast (Carlotto et al 2009). At the foot of the snow-covered glaciers, U-shaped valleys, moraines and other of recent and ancient glaciations are present, while along the Urubamba river there are widespread deposits of the eluvial, colluvial and alluvial deposits dated back to the Quaternary.

The archaeological site of Chacabamba is built right on alluvial deposits formed by accumulation resulting from the dismantling of the Machu Picchu batholith. In particular, it is settled in an area where the tributary Chachabamba flows and has a large recharge area inside the Urubamba. In fact, in this area essentially quaternary deposits of disassembly of the batholith emerge. The latter, in its last section starting from Chachabamba, is imposed on colluvial deposits and sometimes on granites or alluvial soils as showed in the geological map from Carlotto et al 2011.

The colluvial deposits have several meters of thickness and are located on the slopes of the Wiñaywayna hill and form a surface mantle characterized by the mixture of rock fragments of gravel granulometry up to the size of the blocks. Alluvial deposits are recognized at the mouths of the Chachabamba and Choquesuysuy rivers, with greater development at Chachabamba and are formed by large blocks of granite in a clayey and sandy clayey matrix. These deposits are very unstable, especially in the presence of heavy rains as they immediately reach saturation status.

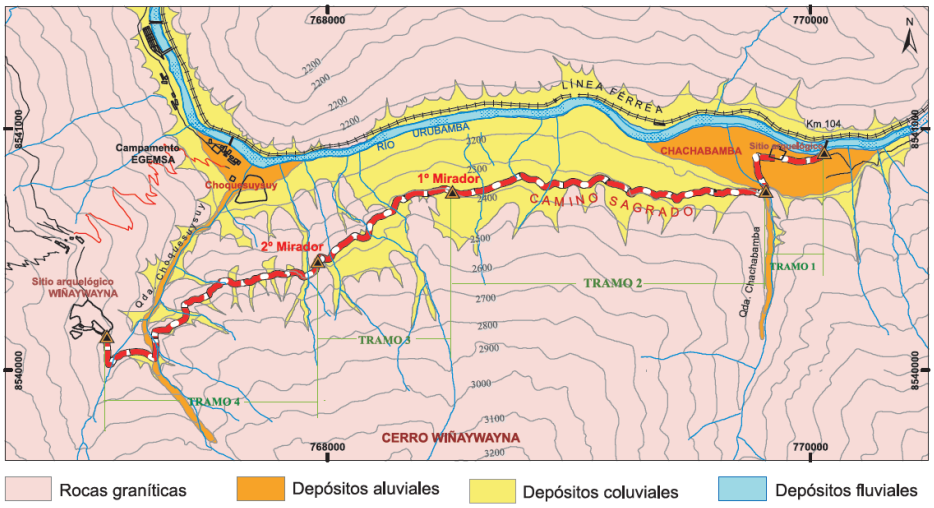

Fig 2 – Geologic map of Chahabamba site (from Oviedo et al 2011)

2.3 Archaeological context and state-of-the art of investigations

Chachabamba was investigated for the first time in 1941 by Wenner Gren who unearthed terraces, baths and water channels supplying the baths (Fejos 1944). These findings suggested that Chachabamba was an important religious place for the worshipping of water and fertility goddesses. The Inca had a functional and mystic connection with the nature. They were able to develop innovative agricultural techniques for plant adaptation taking into account climate and microclimate conditions, as in the case of the Moray site (Plachetka 2015), and the Mother Earth (Pachamama) and water were founding elements in the Incas cult and worldview.

After the excavations that took place in 1941, other investigations were carried out in 1996-97 only with the purpose of the restoration of the site conducted by the Instituto Nacional de Cultura. Finally, in 2016, first scientific excavations were conducted in the framework of the "Programa de Investigaciones Arqueológicas e Interdisciplinarias en el Santuario Histórico de Machupicchu and Centro de Estudios Andinos de la Universidad de Varsovia en el Cusco". These investigations provided invaluable information on the use and function of the architectural spaces. In particular, the investigated area (see figure 2) is the typical *kancha*, that develops around a central open space (with buildings facing inside) enclosed by walls to form small courtyards in the junction areas (Gavazzi 2010). In Chachabamba the kancha is structured around two squares (plaza 1 and plaza 2) flanked by buildings, known as *wayranas*, laid out symmetrically along north-south and east-west axes. The two squares are divided by a central building. The *wayranas* are built with a masonry

consisting of carefully laid field granite stones with finished corners and adobe binders and characterized, in some cases (at south of the central building), by niches (Fejos 1944). They are composed of two or more rectangular rooms which served to host pilgrims. In fact, Chachabamba was also a checkpoint for people on route to other sanctuaries, among which *in primis*, the sanctuary of Machu Picchu.

A 'boulder shrine' (named *huaca* in quechua) borders the north side of plaza 1 and overlooks the river below. It is a partially worked granite outcrop serving as an altar, smoothed off on the top, with two seats cut into it as well as a little flight of four stairs at one side of the seats (Fejos 1944) .Regarding the construction materials, the survey showed that in the vast majority of cases the walls were made in granite, extracted on site.

The architectural complex of *plazas* and *wayranas* is flanked to the east and west side by two broad terraces, which were '*plazas undidas*' (sunken squares) characterized by the presence of ceremonial baths on the north and south side (see map in Figure 2).

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Chachabamba presents all the typical architectural and functional features which could be found in the ceremonial and administrative sites of Urubamba valley, as the two plazas which recall the 'sacred-plaza' at Machu Picchu, the boulder shrine and the baths with ceremonial significance which are similar to those in one of the plaza of Phuyu Pata Marka (Fejos 1944).

3. Material and methods

The archaeogeophysical investigations have been focused on some areas of Chachabamba archaeological site (figure 3), including the *plazas hundidas*, the central square, the surroundings of the ceremonial baths and the altar. The aim is to provide an archaeological prediction map to guide future excavations and investigations and to detect the presence of past constructive phases hidden or reworked, related to masonry structures, canals, ceremonial baths. Finally, another expected result is the setup and validation of a geophysics-based investigation approach to be used in other sites of Urubamba valley which will be soon investigated by the Italian-Polish mission. To the aim of our purposes, magnetometry and ground penetrating radar were used: i) the first one was adopted to detect ditches, shallow canals and walls, ii) the second one to identify deeper walls (up to 2m depth), canals, buried earthworks and terraces.

The results from magnetometric and GPR investigations have been jointly analyzed and interpreted in a comparative way in order to maximize the information content exploiting their complementarities in detecting features of archeological interest.

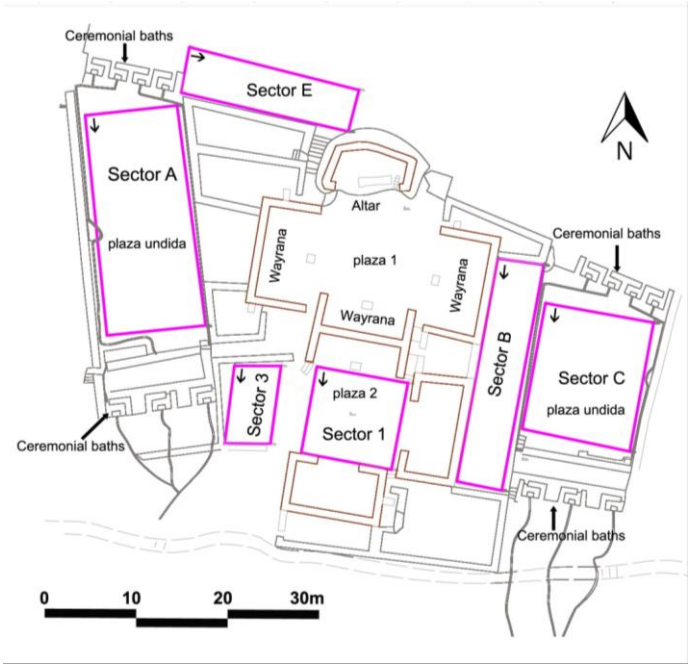

Figure 3. Chachabamba: investigated areas. The arrows in the corners of the investigated areas indicate the starting point and the direction of the geophysical data-acquisition. The map includes the most important functions of the sacred areas.

3.1 Geophysical methods used for the study area

3.1.1 Ground penetrating radar (GPR)

GPR is a non-invasive methodology used in geophysics to detect and characterize electromagnetic (e.m.) impedance contrasts in a medium. It is based on the analysis of the reflections of electromagnetic waves transmitted into the ground. This method provides information on subsoil from a depth of some meters up to a few tens of meters according to the frequency of the electromagnetic waves and the electrical characteristics of the potential targets and surrounding soil (permittivity and electrical conductivity). The use of different antennas and frequencies enables the imaging of subsoil at different penetration depths and with different details. Lower the frequency greater the penetration, for this the operating frequency is always a trade-off between resolution and penetration. Moreover, the use of different antennas and frequencies enables multiple imaging at different resolutions and penetration capabilities and for different purposes and application fields ranging from civil and geotechnical engineering; geological and sedimentological studies, environmental contamination, monitoring of monuments and artifacts, and archaeological research.

The use of GPR in archeology dated back to the 1970s, and more recently (from 1990) it has been quite systematically adopted to detect and map subsurface archaeological artifacts, features, and patterning, changes in material properties, and voids. Indeed, its success in the archaeological prospection field is showed by the great number of researches where the method is used in order to detect buried structures in urban and rural areas and discover archaeological features in a great number of scenarios, such as to identify ancient settlements (Trinks 2014), locate unearthed burials and ceremonial offering (Leucci et al. 2016; Pipan et al. 2001) reconstruct the history of ancient buildings (Goodmann and Piro 2008; Masini et al. 2017), image structures and infrastructure (Malfitana et al. 2015; Florit et al. 2018), identify sub-water structures (Qin et al. 2018; Ludeno et al. 2018).

From the technical point of view, GPR device is made up of (i) an antenna (operating in both transmitting and receiving mode), (ii) a control unit, (iii) battery supply and (iv) a survey cart. The antenna (operating in transmitting mode) propagates e.m. wave in the subsoil and receives (operating in receiving mode) the e.m. wave back reflected by discontinuities i.e. depositional layers and/or buried “objects” in order to define a mono-dimensional description of e.m. impedance contrasts encountered by the generated signal called A-Scan. The emitted signal is repeated, according to a defined cadence and the GPR is moved progressively along a predetermined path on the surface, so that a two-dimensional representation is obtained ("B-scan or Radargram"). To calculate the depth of the reflections, it is necessary to determine the propagation speed of the radar waves in the investigated levels. This is mainly related to the physical-electrical characteristics of the investigated medium (in particular it is inversely proportional to the square root of the dielectric constant ε) and is estimated or calculated through various possibilities of signal analysis or with experimental calibration tests. The data processing enables us to convert the propagation speed of the radar waves into the subsoil depth. Finally, the digital acquisition allows us to represent the acquired data in 2d-profiles that can be filtered and enhanced to detect and locate archaeological features or changes in the matrix referable to different historical phases of the site.

For the detailed characterization of the target it is necessary to analyze the lines of GPR data which represent a sectional (profile) view of the subsurface usually acquired at 0. 50 to 1.0m of distance between each other (defined according to the size of the expected target).

The use of multiple lines of data, systematically collected over the investigated area, is generally used to obtain three-dimensional representations of the scattering phenomena occurring within the subsoil. Data can be visualized as three-dimensional blocks, or as horizontal or vertical slices. In particular, horizontal slices generally indicated as "depth slices" or "time slices", are maps related to specific depths. In archaeological applications, time-slicing is usually adopted because the presence of horizontal patterning is an important indicator of antrophogenic/cultural activities. Nevertheless, even if horizontal sections are the most common and easy way to visualize the pattern of targets, especially for large areas, sometimes, this visualization can compromise the reliability of the information, especially for morphologically irregular surfaces and complex structures located at different depths (Masini et al. 2017).

3.1.2 Magnetic method

In non-destructive archaeological explorations the magnetic survey is one of the most important and widely applied geophysical techniques (Larson et al. 2003). The aim of a magnetic survey is to investigate the subsurface on the basis of the anomalies in Earth's magnetic field resulting from the magnetic properties of the underlying rocks or buried artifacts.

The origin of Magnetic anomalies within the Earth's magnetic field can be related either to the induced or the remanent magnetism. With the term induced magnetism it is indicated the properties according to which an unmagnetized magnetic material within the earth's magnetic field becomes magnetized. The induced magnetization is directly proportional to the intensity of the ambient field and to the magnetic susceptibility of the magnetized material. The remanent magnetism, on the contrary, is the magnetism that an object has also in absence of a magnetic field. The remanent magnetism is the results of several processes (i.e. thermal or chemical) and it may differ radically from induced field (always the same direction of the inducing field).

In archaeological explorations, both the induced and the remanent magnetization are very important (Aspinall et al. 2008). The former is useful to highlight the variations in magnetic susceptibility between topsoil, subsoil and rocks; induced magnetization allows hence to detect the possible presence of ditches, pits and other silted-up features which were excavated in ancient times and then silted or backfilled with topsoil. The remanent magnetization, on the other hand, makes possible to sense the presence of man-made objects which were heated (pottery kiln, hearth), of volcanic or metamorphic stones or of bricks.

The range of magnetic anomalies (related both to the induced and the remanent magnetization) generated by buried archaeological features spams form few nT (1–20 nT) for remains up to thousands of nT for fired' structures (hearths, kilns, crockery, pottery) and ferrous objects (Piro et al. 2007).

For the aforementioned reasons, and being that the magnetic method is characterized by a (i) considerable cost-effectiveness and (ii) extreme speed in the use compared to other survey methods (as GPR and ERT), it has been widely applied in archeology, from the small-scale site characterization (Aitken al. 1958) to the surveying of large scale areas (i.e. Keay et al. 2014).

3.2 Geophysical data acquisition and processing

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3.2.1 GPR data acquisition and processing

GPR surveys were performed with a RIS MF Hi-Mod GPR System of IDS equipped with an array of two multi-frequency antennas using simultaneously 200 and 600 MHz antennas mounted on a survey cart equipped with an incremental encoder. The 200 MHz and 600 MHz data were acquired in continuous and reflection mode with a time window of 130 ns and 160 ns respectively, samples per scan set at 512 with a resolution of 16 bits and a transmit rate of 100 KHz.

The data processing is based on several steps addressed to (i) improve the signal noise ratio and (ii) enhance the discontinuities to make the interpretation easier. The data were processed using standard two-dimensional processing techniques by means of the Reflex-W software [Sandmeier, 2016].

Accurate three-dimensional representations were obtained at different frequencies in order to image potential archaeological targets. The adopted data processing can be summarized as follows:

1) Normalization of the amplitude (performed on the mean amplitude value of the complete profile) in order to de-clip saturated traces using a polynomial interpolation procedure;
2) Dewow filter to leave out potential low frequency part of the signal;
3) Removal of background made (i) summing all the amplitudes of reflections (recorded at the same time along a profile) and (ii) dividing by the number of traces summed. In this way the average of all background noise is subtracted from the data;
4) Energy decay based on a mean amplitude decay curve determined from all existing traces;
5) Declipping step to reduce too high amplitudes values;
6) Bandpass filter to reduce the noise affecting the radargram linked to the gain function previously adopted;
7) Kirchhoff 2D-velocity migration with a velocity estimated quantitatively using the diffraction hyperbolas generated by potential archaeological features. The adopted velocity is equal to 0.060-0.065 m.~~sn~~ns^{-1} that is coherent with a scenario characterized by a high water content.

After these steps, a 3D representation was built interpolating data of the processed 2D-lines. A linear interpolation was made analyzing an area equal to two times the minimum distance between the radargrams. Then the envelope of each trace of the 3D-file was calculated and showed in horizontal depth slices where the reflections with greater amplitude are highlighted with the aim to support the identification of archaeological features.

3.2.2 **Magnetic data acquisition and processing**

The magnetometer used for the investigations carried out at Chachabamba is the Grad601-Bartington. It is a high-resolution fluxgate gradiometer, used to measure minimal variations in the magnetic field that are caused by anomalies hidden in the soil, as archaeological features, tubes, cables or unexploded ordnance. The system includes a data logger, a battery, two Grad-01-1000l sensors mounted on a rigid carrier bar. The instrumental sensitivity is ± 1 nT (nano Tesla). Calibration is performed on-site prior to acquisition through an automated procedure which allows to correct possible misalignment in the sensors measurements.

The magnetic gradiometry acquisition technique, compared to the single-sensor measurements, has a reduced depth resolution linked to the fact that gradient field decays with the fourth power of the distance but it allows a simplification of the measuring and analysis of the magnetic data by making them not dependent from magnetic field temporal variations, from the regional background field and from cultural noise.

The surveyed area location (13°09′47″S 72°32′44″W) imposes some considerations on the expected results of the magnetic surveys. Since near the equator, the Earth's field is almost horizontal, the way in which the magnetic anomalies can be detected varies according to their orientation. In particular, for a survey performed closer to the equator, the anomalies from north-south oriented object can decrease until they become invisible (Radhakrishna Murthy 1998), therefore, features that extend in a north-south direction may not be detected. Thus considering, the integration with GPR data will be far more important for the detection of N-S elongated features.

In the present paper, the magnetic data have been collected in unidirectional mode (considering the relative small extension of the surveyed area, zig-zag mode was not adopted to increase data quality), along parallel profiles 1 m apart. With a walking speed of about $1ms^{-1}$, the spatial resolution was about 1 m× 0.1 m.

i) The data processing was based on the filtering of the rough magnetic data to obtain the best S/N ratio using the following steps: despike made using a uniform weighted window to search for and leave out outlier valued replace by the mean;

ii) destripe to remove the striping effect between grids caused by directional effects;

~~ii)~~iii) pass-band filter, to remove high or low frequency components;

~~iii) destripe to remove the striping effect between grids caused by directional effects;~~

iv) Kringing interpolator with a linear variogram to highlight the main geomagnetic linear anomalies.

4. Archaeogeophysical investigations: results and discussion

The following paragraphs show and discuss some of the results obtained from the GPR and Magnetic prospection (MAG in what follow). It has to be considered that: (i) the GPR slices provide information at different depths, whereas (ii) the gradiometric data only give indication of the maximum possible depth of the source of magnetic anomalies. Therefore, any magnetic anomaly may have a counterpart in all, none or in some of the GPR time-slices. Figure 2 shows the investigated areas. In particular, the archaeogeophysical areas have been indicated with A, B, C, D, E, F, 1 and 3. For sake of brevity only the results on five sectors will be described and discussed.

4.1 Sector A: the west *plaza undida*

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The MAG survey was carried out according to pre-established grids and profile spacing of 1 meter. The measures involved an area of size 24x10m following an acquisition direction of N-S. In the same area, the GPR surveys were carried out according to the two directions E-W and N-S with a spacing between the profiles of 0.5 m. GPR investigations were conducted using marker placed every meter.

MAG map is shown in fig. 3a. The range of magnetic anomalies, relatively small (10 nT), and on the absence of regular or elongated patterns, make difficult the identification of buried archaeological features 'sic et simpliciter'. The most relevant anomaly located on the west side (a1) of the magnetic map is due to the presence of a rock formation emerging from the field and also mapped in figure 2. Thus, anomaly a1 was generated by a reduction of the distance between the magnetic sensors and the investigated surface; this reduction occurred during the MAG data acquisition when the magnetic sensor passed over this elevated rock formation. Other magnetic anomalies observable on the west side of the magnetic map can be ascribed to the presence of archeological remains such as walls and the channel flanking the west side of the *plaza undida*, which feed the ceremonial baths (see figure 3).

Anomalies a3 and a4 seem to converge in a common point and could be associated to the presence of drainage channel. It is worth to note the presence of linear anomalies, indicated with a2, that transversely cross the area, and other anomalies indicated with a5 in the north east corner of the *plaza undida*.

At first sight, results obtained with GPR are very hard to interpret because of the presence of reflections distributed without break in continuity. To simplify the identification of significant structures from an archaeological point of view some depth slices are extracted by the 3D model generated using the radargrams. The slices highlight the presence of some interesting alignments and reflective areas imputable to archaeological or geological features that confirm geomagnetic results and identify other relevant anomalies. In particular, at a depth of 0.30 m (Fig.4b) some shallow linear structures are detected (a1 and a8) that correspond presumable to some drainage channels. At this depth some reflective areas, a6 and a7, are detected and oriented as the nearest walls and could be associated to archaeological features. A7 anomaly is also detectable at a depth of 0.90 m. Anomaly a2, already detected by magnetometric acquisition, is confirmed by the GPR acquisition that identifies it at 90cm depth. Magnetic anomalies a3 and a4 well fit with GPR reflectors at depths of 0.90 and 1.50 meters, respectively.

Finally, chaotic and not regular reflections are due to outcropping rocks, as confirmed by trial excavations conducted by archaeologists coauthors of this paper (Ziolkowski 2016; 2017), refered a huanca. For the Inca builder of Chachabamba, the huanca was a sacred monolithic rock with the function as altar (for additional detail about the huanca see Nair 2015, in particular p. 42) . Similar examples of huanca have been found in other Inca ceremonial centers, among which Macchi Picchu where in recent excavations conducted in 2016 a huanca has been found in a plaza hundida (Ziolkowski 2016).

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Figure 4e-f shows B-scans, acquired at the frequency of 600 and 200 MHz, respectively. They image the presence of two main stratigraphic units highlighted with red and yellow arrows at different depths that likely correspond to different archaeological phases of the site. It is remarkable the strong pseudo-horizontal reflectors that across the whole radargrams, at depths approximately ranging between 0.50 and 1.00 m (visible both at 600 both 200 MHz), and 2.0 and 3.0 m (detectable only within data at 200 MHz). It is possible that the first one (see red arrows in figures 4e and 4f) is related to the presence of anthropic soil while the second one (see yellow arrows in figure 4f) identifies the expected bedrock.

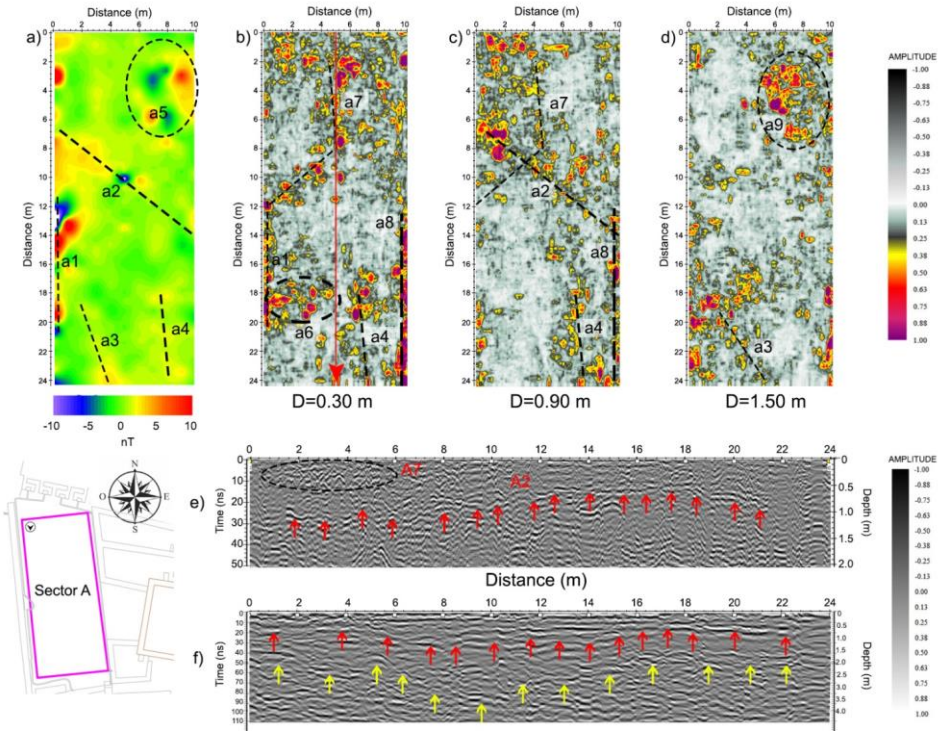

Figure 4. Sector A. (a) Z gradiometric map; (b-c-d) GPR depth slices (600 MHz frequency) at theoretical depths of 30, 90 cm and 150 cm respectively (red and purple colours indicate reflections with higher amplitude); (e-f) radargrams acquired at 600 and 200 MHz frequencies respectively in correspondence of the profile indicated with the red arrow in figure 3b. Red and yellow arrows mark the presence of two main stratigraphic units likely corresponding to different archaeological phases of the site

4.2 Sector B

MAG survey was carried out according to a grid of 24x5 meters (Fig. 5a) following a north-south acquisition direction and with a distance between measurements of one meter. In the same area, GPR surveys only in the longitudinal direction were carried out from north to south and with a spacing between the profiles of 0.5 m.

MAG results, as showed in figure 4a, have identified the possible presence of an anomaly b1 perpendicular aligned with an existing wall located at west of the map; further some disorganized anomalies are recorded near the south edge of the area (b5) that could be associated to removed material or collapsed structures. In this zone also a linear anomaly (b4) characterized by an orientation not compatible with that of existing structures was also recorded.

GPR results have identified the presence of some aligned reflections (b1) in continuity with the near walls that confirm the MAG results. Further a perpendicular structure, indicated with b3, is also recorded at the depths of 0.90 and 1.30 m (see figure 5c and d).

The presence of not homogeneous material or collapsed structures could justify the reflective areas, indicated with b2 and b5 in the southern part of the map. Furthermore, GPR map at 1.10m depth puts in evidence a linearly oriented reflective area consistent with magnetic anomaly b4.

GPR B-scan show three sub-horizontal layers (see figure 5e and 5f) of archaeological interest. In particular, it is possible to note the presence of a continuous sub-horizontal reflector at a depth ranging between 0.50 and 1 m. It is due to a recent earthmoving works (red arrows) which probably cover the cause of strong reflector visible at a depth of about 1.5 meter and better detectable in the b-scan acquired at the frequency of 200 MHz (see fig. 5f).

Finally, at a depth greater than 3 m another reflective layer was recorded that could correspond to the geological soil. The presence of this behaviour leads to hypothesize the presence of some terraces enclosed by walls that are the continuation of the closer ones. This hypothesis is also confirmed by the presence of the reflective alignments b1 and b2 detectable in the depth slices of figure 5b-c-d.

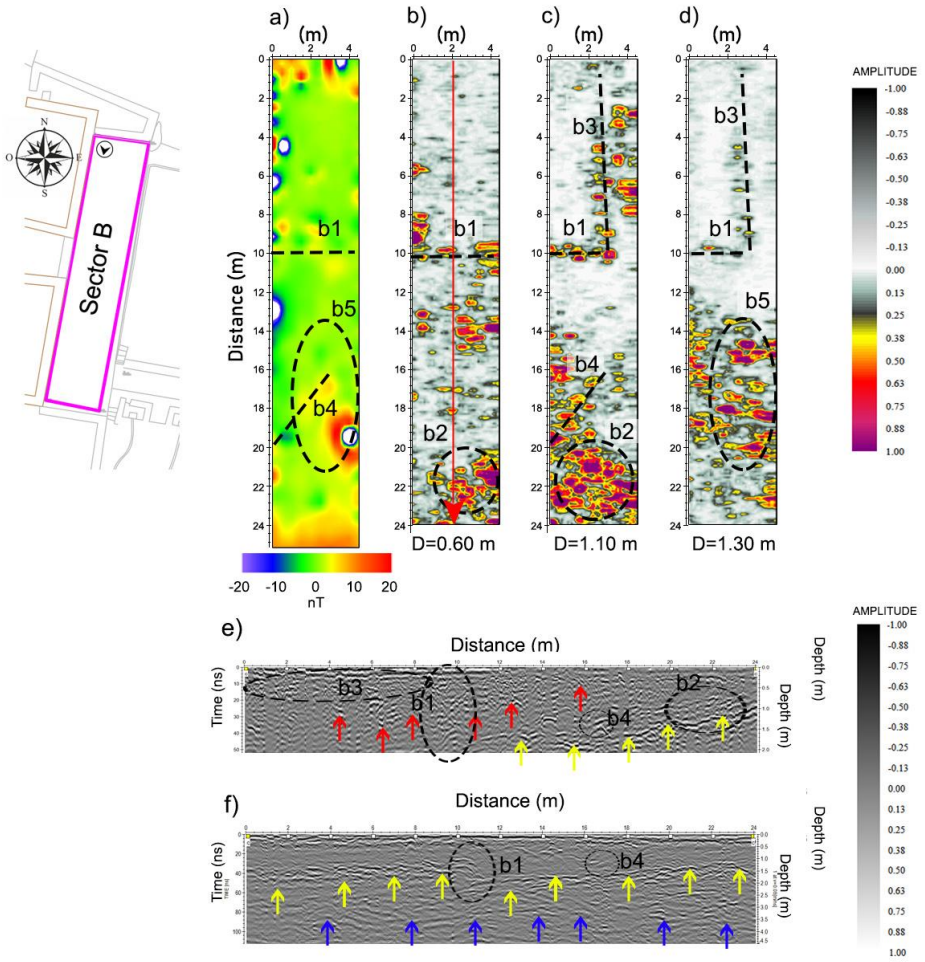

Figure 5. Sector B: (a) Z gradiometric map; (b-c-d), Depth slices (200 MHz frequency) at depth of about 60 cm, 110 cm, and 130 cm respectively; (e) b-scan acquired at 600 MHz frequency in correspondence of the profile indicated with the red arrow in Fig.5b; f) b-scan acquired at 200 MHz frequency along the same profile. Red arrows indicate the position of sub-horizontal reflector due to a recent earthmoving works. Yellow and blue arrows mark the presence of reflective layers of anthropogenic layers, as confirmed by trial excavations made close to this area (Ziolkowski 2017)

4.3 Sector C

Magnetometric measurements were be made according a grid with a size of 12x14m and acquisitions longitudinal with a distance of 1 meter. GPR surveys were acquired with the same scheme adopted for the magnetometric techniques but in this case the distance between the investigated lines was halved to obtain a better resolution. The presence of furrows for soil irrigation have strongly complicated the acquisition because the investigated surface was not flat and regular and this is the reasons that the surveys were carried out only in parallel to the channel direction.

MAG map (Fig.5a) shows the absence of any relevant magnetic alignment. The most significant feature is located along the Southern and the Eastern edges of the map and can be likely related to the perimeter walls presence (anomaly xc). Another anomaly is c1 that is located inside the area where the presence of furrows for soil irrigation have been reported. For this reason it cannot be excluded that c1 is generated by "modern" man-made artefact.

The GPR depth slice seems to confirm the absence of relevant reflective areas of archaeological interest. At a depth of 0.40 m, possible alignments are detected (c2 and c3 in Fig. 6b). Considering the discontinuity of the observed anomalies and their limited extension in depth, they could be associated to the presence of drainage channel. Anomalies c4, c5, c6 and c8 possibly identify the presence of collapsed structures, stone blocks and/or rocks.

More interesting is c7 that could be generated by archaeological remains or by an elongated geological body.

The B-scan showed in figure 5f, acquired at the frequency of 600 MHz, identifies the presence of three main stratigraphic units highlighted in green, black and red arrows at different depths that likely correspond to different archaeological phases of the site. The top and the bottom units (green and red arrows) are mainly horizontal. The intermediate one shows a depression in correspondence of c4. The B-scan also shows the amplitude of the reflection associated to the anomaly c4 and the more chaotic and smaller ones related to anomaly c6.

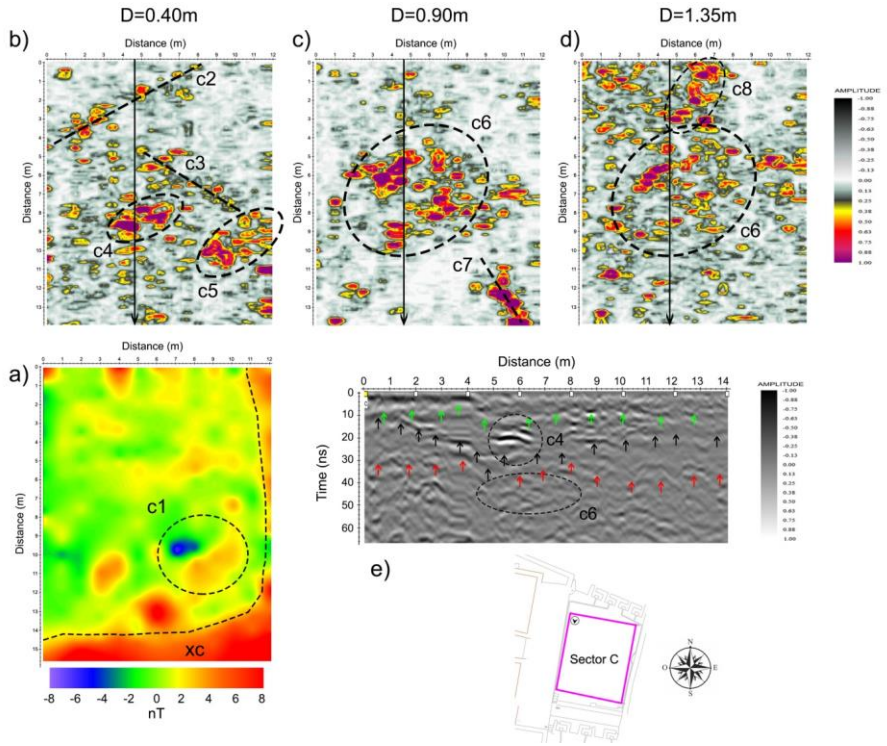

Fig.6 - Sector C: (a) Z gradiometric map; (b-c-d) GPR depth slices (600 MHz frequency) at theoretical depths of 40, 90 cm and 135 cm respectively; (e) radargram acquired at 200 MHz in correspondence of the profile indicated with the black arrows in figure 6b-c-d. . Green, black and red arrows indicate the presence of three anthropogenic layers (with this regard see caption of Fig. 5).

4.4 Sector E

The magnetometric investigation was carried out according to a grid of 4 x 18 m with longitudinal acquisitions towards the East and a spacing of 1 meter. In addition, GPR profiles were acquired only in the longitudinal direction using the same grid of 4x18m as for MAG with a spacing of the acquisitions every 0.5m and direction towards the East.

The lower part of the magnetic map (Fig. 7a) is significantly influenced by the presence of the confining wall (anomaly xe). Other anomalies are indicated as e1 – 4. Among these, e1 is the only clearly visible. It is mainly constituted by three dipolar anomalies thus suggesting that is not related to a continuous body (geological or archaeological). As regard as e2 – 4, they have been traced on the base of GPR data analysis (Fig. 7b-d) where they are associated to the presence of N-S

elongated anomalies, probably related to the presence of shallow remains such as channels. In addition, there are strong reflections in areas e5 and e6. These reflective areas clearly suggest the presence of functional and constructive relationships with the structures of the ceremonial baths of the plaza undida (sector A). In particular, the shapes of e5 and e6 imaged at depths from 30cm to 1.30m are very similar to the walls of the ritual baths of the western *plaza undida*. This suggests a different plant of the western plaza undida in the past before the current spatial configuration. As a consequence the building between the current western plaza undida and the central nucleus was added later so modifying the shape of the same plaza undida.

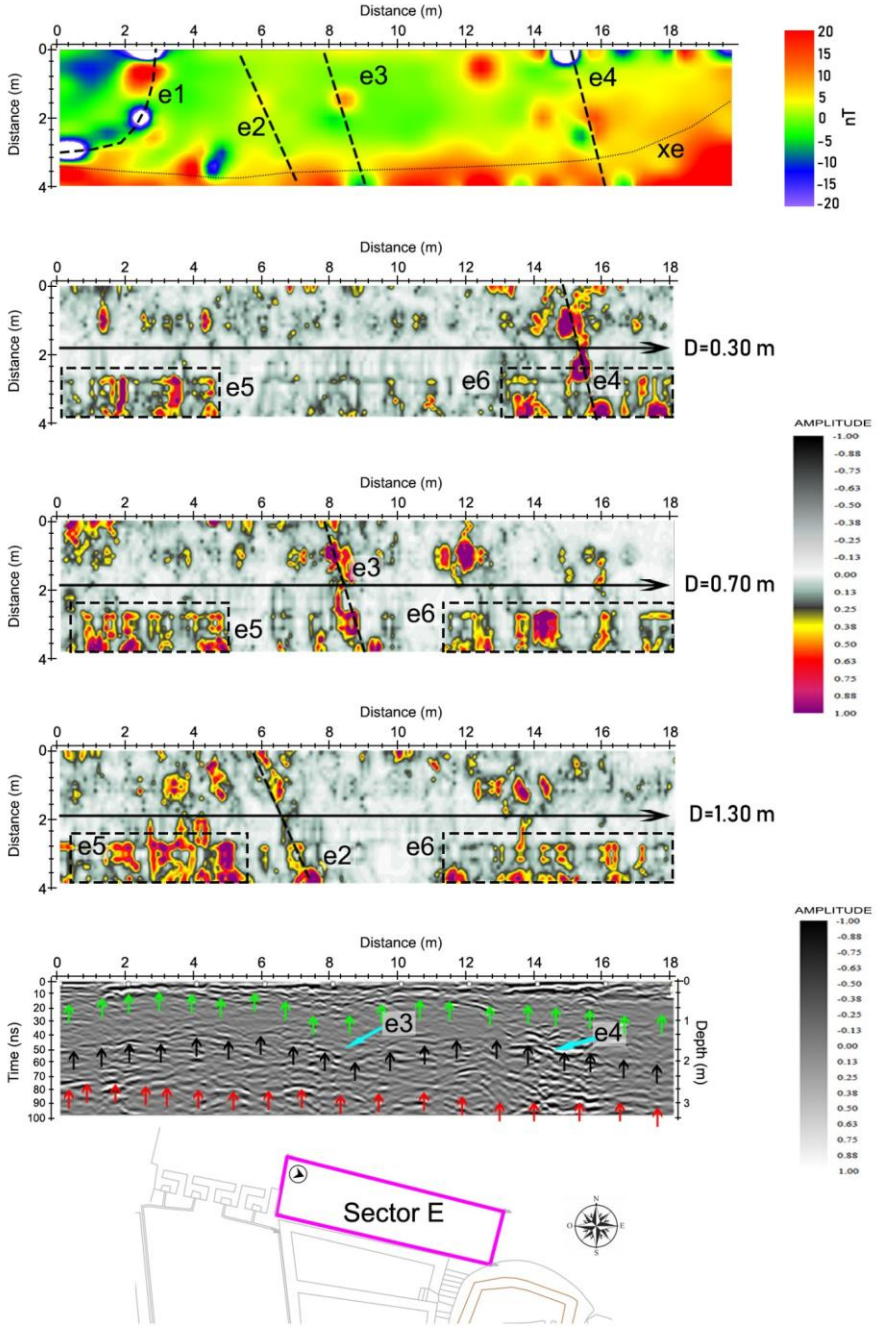
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Figure 7. Sector E. (a) The investigated area; (b) Z gradiometric map; (c-d-e) Georadar maps (600 MHz frequency) at depth of 50-17, 100-125cm, and 150-175cm respectively; (f) radargram acquired at 600 MHz frequency in correspondence of the profile indicated with the black arrow in Fig.7 cde. Green, black and red arrows identify the presence of three layers at different depths that correspond to different archaeological phases of the site as proved by some trial excavations conducted nearby (Ziolkowski 2016; 2017)

4.6 Sector 1

In this sector magnetic survey was not performed due to the presence of rivets stuck in the ground. On the other hand, a GPR investigation was carried out in a 10x10m grid with longitudinal and transverse acquisitions spaced 50 cm and directions, respectively, from west to east and from north to south. 600 MHZ depth slices exhibit high values of amplitude, indicated with $s_1$3 and $s_1$4 in figure 8a-b-c, at depths between 70 and 120cm referable to stone accumulation to level the square which is more elevated respect to the square of the *huanca*. Being close to the corner of the *kancha* such stone accumulation could be related to collapse material, considering that the area of high radar amplitude increases with depth. At the same time the anomaly $s_1$3 could be due to a collapsed wall that intercepted two unearthed structures (identified by the anomalies $s_1$1 and $s_1$2) defining a quadrangular area. Similar interpretation could be made for the anomalies $s_1$6 and $s_1$7, found at a depth approximately equal to 1.50 m. These anomalies are oriented of about 15 degrees respect to the sides of the courtyard (Figure 8e). This leads to the hypothesis that these anomalies may refer to a construction phase preceding the courtyard. Such hypothesis is also confirmed by the B-scan showed in figure 8d intercepting the anomalies $s_1$3, $s_1$6 and $s_1$7 (indicated with red arrows in figure 8a). The radargram (figure 8d), acquired at a frequency of 200 MHz, evidences the presence of at least three separated layers associable to three distinct phases. The first one, indicated with green dashed line, should be related to a previous floor, the second and the third, indicated with the red and yellow lines, respectively, refer to two more ancient phases. Some reflectors with hyperbola shape, suggesting the presence of walls or ancient drainage channels, are also visible.

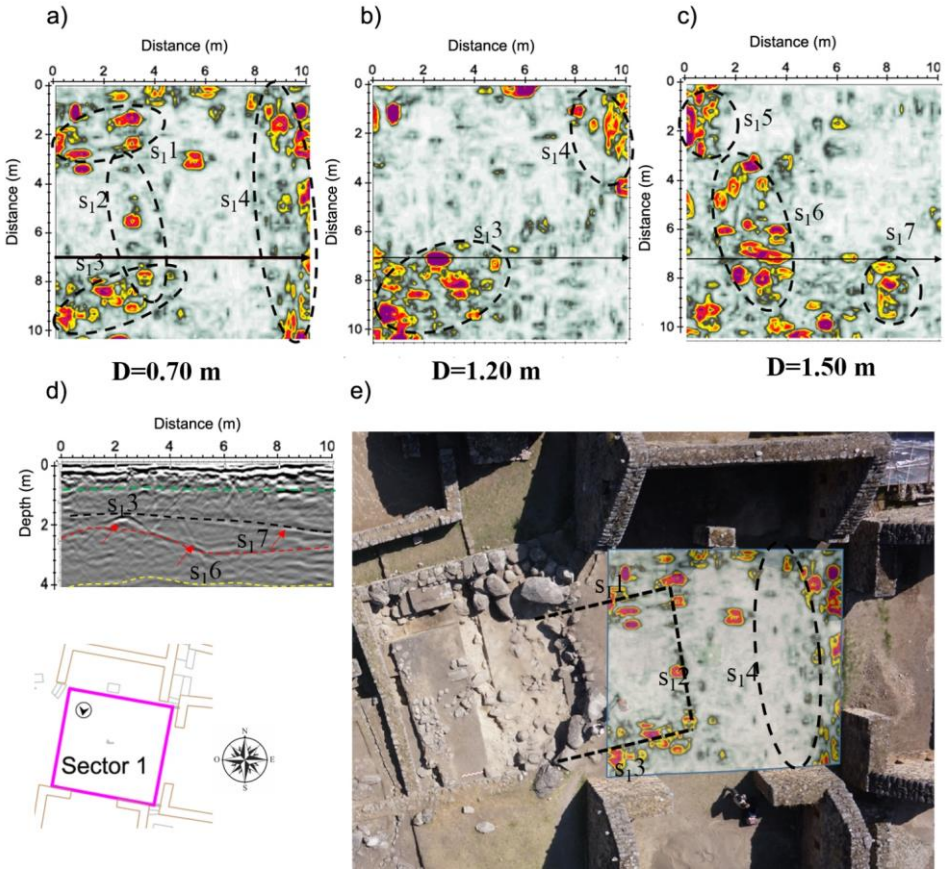

Figure 8. Sector 1: (a-b-c) GPR depth slices (600 MHz frequency) at depths of about 70, 120, and 150cm, respectively; (d) radargram acquired at 200 MHz frequency along the profile indicated with the black arrow in Fig.8 a-b-c-; The green, red and black dashed lines indicated the presence of different archaeological phases. The red arrows mark the presence of some reflectors with hyperbola shape, suggesting the presence of walls and drainage channels.

(e) overlapping of the depth slice placed at a depth of 70 cm on the aerial photo of the site characterized by the recently (and partially) excavated area of sector 3.

4.7 Sector 3: comparing archaeological finds with GPR results

575 The georadar survey was performed according to a 5x8m grid with longitudinal and transverse
576 acquisitions and 0.5 meter spacing. After a few months from the geophysical prospections sector 3
577 has been excavated to a depth of approximately 1 m. Therefore, the interpretation of the
578 investigations consists in the comparison between what has been unearthed and what is observed
579 from the geophysical maps.
580 In particular, it can be seen that some stones aligned to form a perpendicular orientation could
581 explain the anomalies $s_3$1, $s_3$2 and $s_3$3 plotted in figure 9(a-b); at the same time, the strong reflective
582 events indicated with $s_3$4 and $s_3$5 could be associated to the presence of linear structures (walls) of
583 which the second one only partially excavated.
584 The correspondence between the structures brought to light by archaeologists and the reflection of
585 the radar is more evident by observing the radar profiles in Fig. 9f-g where the B-scans at 600 and
586 200 MHz are showed. As in the case of sector 1, also here it is possible observe the presence of
587 three subparallel horizontal reflector due to the presence of different archaeological phases
588 (identified with red, yellow and blue lines in the radargrams), among them it is to be expected that
589 the first two are related to archaeological features while the other one is due to the geological
590 bedrock of the site.
591 The comparative analysis highlights both the potentials and limits of geophysical prospections in
592 detecting structures and artefacts of archaeological interest, especially in less regular contexts and
593 characterized by collapsed walls as in the case of sector 3.

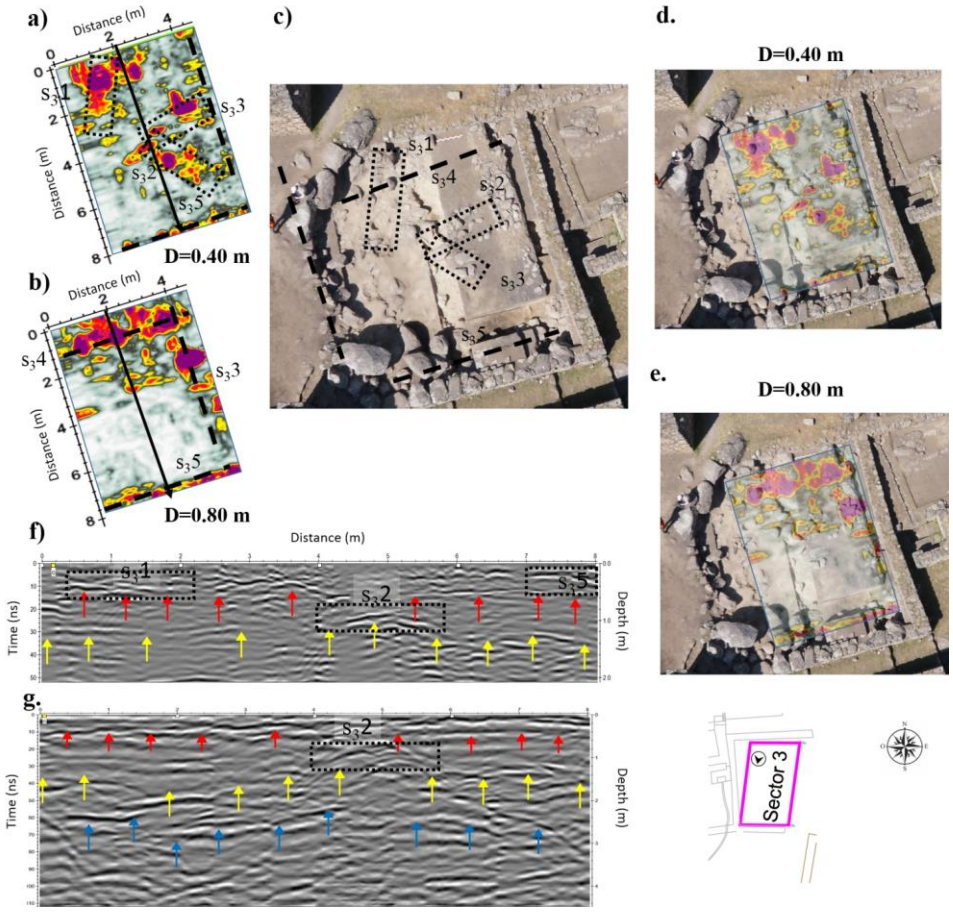

Fig. 9 - Sector 3: (a-b) GPR depth slices (600 MHz frequency) at depths of about 40 and 800cm respectively; (c) aerial photo of the excavated areas with identification of the most interesting GPR anomalies; (d-e) (e) overlapping of the depth slices showed in figure 8a-b on the aerial photo of the investigated area; (f-g) radargrams acquired at 600 and 200 MHz respectively with identification of the main layers associable supposedly to archaeological stratigraphic units (marked by red, yellow and blue arrows).

5 Resume and Final remarks.

Geophysics as other earth observation technologies only provide indirect data (proxy indicators) related to the presence of archaeological buried remains; therefore, the question is: how is it possible to recognize them? An aid in the interpretation process is given by: (i) the integration of

609 results from different geophysical techniques and (ii) the analysis of spatial relationships of the
610 potential archaeological remains, and their spatial and functional relation with emerging
611 architectural evidences. This was the approach adopted in Chachabamba, where the integration of
612 the results from the MAG and GPR survey enabled us to detect a large variety of archaeological
613 features (see figures 9up and 9bottom).
614 The interpretation process of geophysical surveys was possible thanks to the availability of ancillary
615 data related to previous excavations, which facilitated the identification of some archaeological
616 targets such as, walls, canals, morphological changes of terraces, stone blocks and rocks (see in
617 particular sections 4.1 and 4.2). In some cases, the GPR B-scans and time slices allowed the
618 identification of different anthropogenic layers. This confirmed the hypothesis of archaeologists,
619 also supported by trial excavations, according to which the current archaeological area of
620 Chachabamba has not been constructed in a single phase, but, it is the result of at least two or more
621 building phases.
622 Nevertheless, the results so far obtained pose still additional questions, among which that related to
623 the original plan of the *plaza undidas*. In particular, in the western side, the results obtained in
624 sector E put in evidence some reflective (radar) areas characterized by the same shapes as those of
625 the ceremonial baths, still well preserved. (see sector E in Figure 9bottom). Therefore, it is
626 reasonable to argue that, in the past, the western *plaza undida* was different from what it appears
627 today in both shape and dimensions. Moreover, observing the plan, it seems enough clear that the
628 oblique buildings B1 and B2 (in Figure 9bottom) were constructed after the *kancha*, that is the
629 architectural complex around plaza 1 and plaza 2. This suggests that in the original plan the western
630 *plaza undida* was symmetrically laid (as the eastern *plaza undida*), respect to the North-South axis.
631 Subsequently, the western *plaza undida* (see red rectangular block in Figure 9bottom) was moved
632 and rotated to make room to buildings B1 and B2 (see Fig.9bottom).
633 Additionally, the results from the integration of MAG and GPR show anomalies referable to: i)
634 structures (see red circle in Fig.9bottom) preceding plaza 2, ii) some canals in the western *plaza*
635 *undida*; iii) buried walls in continuity with emerging structures (see small red rectangular box in
636 sector B, Fig. 9bottom).
637 In conclusion, the geophysical results we obtained shed new light on the Chachabamba
638 archaeological area, where there are rich buried remains that still wait to be excavated and
639 numerous pieces of its puzzled history to be revealed. Moreover, Chachabamba presents all the
640 typical architectural and functional features that are also present in the ceremonial and
641 administrative sites of Urubamba valley. Therefore, the successful results we obtained in

Chachabamba encourage to adopt the same methodological approach for other sites in to the sacred valley which also includes Machu Picchu.

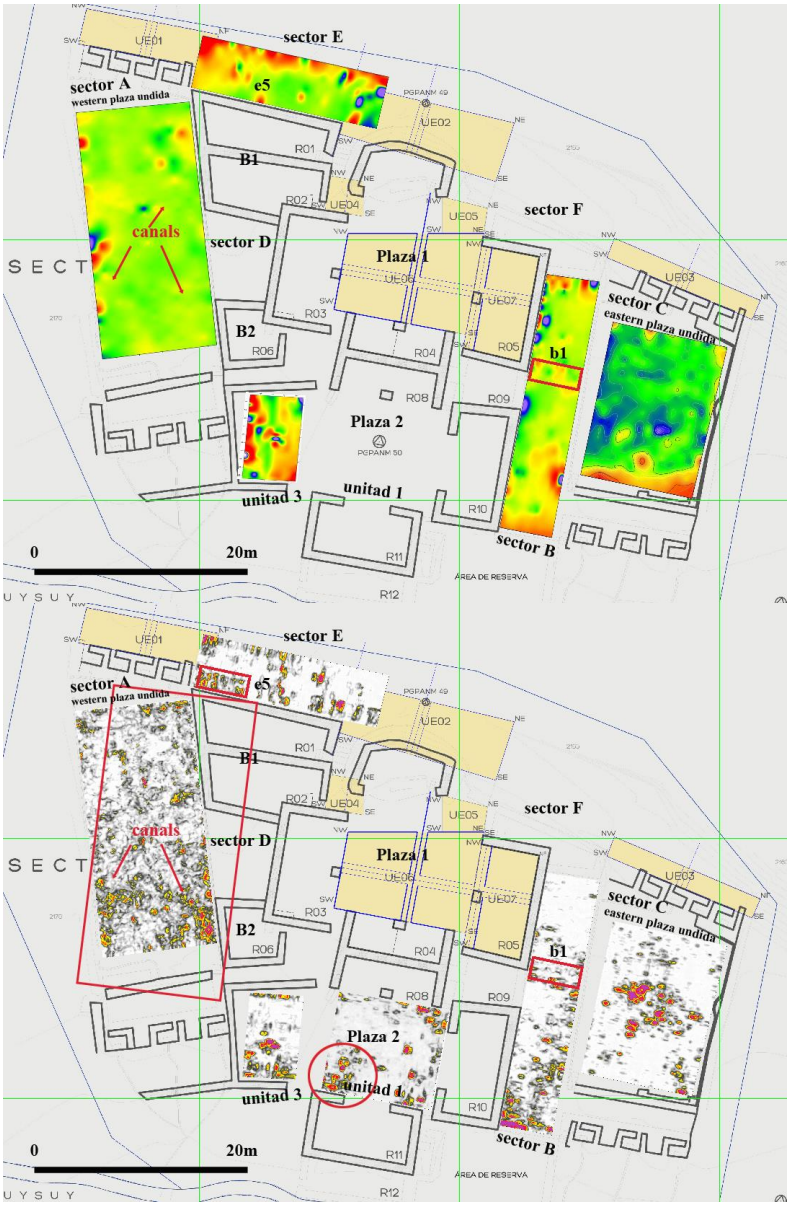

Figure 10. (up) magnetic maps; (bottom) georadar maps at depth of 75 cm.

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Author contributions

N. M. conceived and directed archaeo-geophysical investigations, wrote sections 1 and 5, coordinated sections 3 and 4, contributed to section 4 for archaeo-geophysical interpretation; L.C. acquired and processed GPR data and wrote section 3.2.1 and contributed to section 4 with particular reference to GPR results discussion; G.R. acquired and processed MAG data, wrote sections 3.2.2, contributed to section 4 with particular reference to GPR results discussion. M. S. contributed to GPR and MAG data acquisition, wrote section 2.2; D.S. contributed to section 2, with particular reference to state-of-the art of investigations, and the archaeological interpretation in section 4; F.A., J.B., M.Z. contributed to section 2 with particular reference to state-of-the art of investigations, R.L. revised the whole paper, wrote with N.M. section 1, contributed to sections 4 and 5.

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