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New discoveries in the Piramide Naranjada in Cahuachi (Peru) using satellite, Ground Probing Radar and magnetic investigations

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ABSTRACT

The detection of buried earthen structures by using remote sensing techniques is still an open issue and a strategic challenge as crucial as it is complex. It is crucial because earthen archaeological remains are widely present thoughtout the world (in South America, Asia, Africa) and it is complex due to the subtle physical contrast between earthen remains and the surrounding subsoil.

This paper presents the results from investigations based on Very High Resolution (VHR) satellite imagery (2002, 2005, 2008), geomagnetic surveys (November 2008) and Ground Probing Radar (GPR) (April 2008), we conducted on a mound named Piramide Naranjada. It is located in Cahuachi (Nasca, Southern Peru), the largest adobe Ceremonial Centre in the World.

The studies were performed on two sides of this pyramid: (i) North-Eastern side, not yet excavated, using satellite data and magnetic prospection; (ii) and Eastern side using GPR to support the ongoing excavation activity.

In the North-eastern side, results from the analysis of satellite images allowed the identification of shallow and outcropping adobe (earthen material) walls related to terraced platforms which compose the trunk-pyramidal structure of the Piramide Naranjada. These archaeological features were further investigated by high resolution geomagnetic surveys. The gradiometric maps enabled the identification of magnetic anomalies with different shapes: (i) linear shape features linked to buried, shallow and outcropping walls (the latter two already detected from the optical dataset); (ii) and circular shape anomalies linked to tombs and ceremonial offerings.

In the Eastern side, where the excavations are in progress, radargrams allowed the discovery of a rich ceremonial offering made up mainly of ceramics, textiles, and painted pumpkins.

1. Introduction

In the past two decades the improvement in space, aerial and ground technologies have yielded significant advances in remote sensing for archaeology not only for discovery but also for feature analysis and interpretation (see for example, Lasaponara and Masini, 2006, 2007; De Laet et al., 2007; Casana and Cothren, 2008; Garrison et al., 2008; Parcak, 2009; Trier et al., 2009; Ross et al., 2009; Lasaponara et al., in press). Moreover, the combined information gained from disparate non-destructive sources do offer great potential for the identification and interpretation of cultural features (Piro et al., 2003; Chianese et al., 2004; Rizzo et al., 2005). In particular, space and aerial technologies provide large-area survey coverage which facilitates recognition of broadly distributed cultural patterns. Therefore, the integration of different remote sensing technologies advances the evaluation and interpretation of cultural features and improves the understanding of the relationships between archaeological features and landscapes (Masini and Lasaponara, 2006; Ciminale et al., 2009).

Nevertheless, the application of remote sensing technologies to study earthen archaeological remains is still an open issue mainly because of its complexity and a limited number of prior works (Abbott et al., 1997; Masini et al., 2008; Lasaponara et al., in press).

The detection of buried earthen structures by using non-invasive techniques is a strategic challenge as crucial as it is complex. It is complex due to the subtle physical contrast between earthen remains and the surrounding subsoil, as evident by comparing aerial images of adobe archaeological sites taken before and after the excavation (Masini et al., 2008; Lasaponara et al., in press).

It is a crucial challenge due to the widespread use of earthen material to build homes, communities and temples, mainly in arid

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and semi-arid lands where generally other building materials were quite scarce. In particular, in the arid regions of Peru, from the 3rd millennium B.C to the 15th century AD, several civilizations (such as, Mochica in Northern desert coast of Peru, Nasca near the Southern coast of Peru; see Moseley, 2001;) shaped sand, clay and water into bricks (known as adobe) to build villages, pyramids and ceremonial centres.

This paper presents the results from investigations based on Very High Resolution (VHR) satellite imagery, geomagnetic surveys and Ground Probing Radar (GPR), we conducted on a mound named Piramide Naranjada. It is located in Cahuachi (Nasca, Southern Peru), the largest adobe Ceremonial Centre in the World (around 24 km^2). It was built between 200 BC and 400 AD by the Nasca, recognized as one of the most important and evolved pre-Columbian civilizations. (Orefici, 1992; Orefici and Drusini, 2003; Orefici et al., 2009). The archaeological structures to be unearthed are walls, platforms and terraces in adobe. The excavations carried out during the last 25 years have often shown overlaid structures, ground refilling, vegetable fibres and ceramics, covered by alluvial deposits. This complex archaeological stratigraphy, the low spectral and geophysical contrast between adobe structures and alluvial subsoil and the arid environment make the detection of buried remains very critical.

To cope with this challenge, the integration of satellite, geomagnetometry and GPR has been exploited.

2. Study area: archaeological research in the Ceremonial Centre of Cahuachi

The study area is inside the Nasca ceremonial centre of Cahuachi, situated at an elevation of 365 m a.s.l. in the drainage basin of Rio Grande in Southern Peru.

The archaeological evidence, characterized by around forty tells (earthen mounds), spread out on a large desolate area situated on the left of the Nasca river (see south side in Fig. 1).

This territory has been characterized by a long and intense human activity since the Formative Period (which is generally divided in two different historical phases known as Initial Period, 1800–800 BC; and Paracas culture, 800–200 BC) to the Early Intermediate Period (dated back to 200 BC–600 AD) when the region flourished under the Nasca Culture and Cahuachi was founded and developed (Orefici, 1992; Masini et al., 2008; Lasaponara et al., in press).

Since 1984, archaeological investigations have been in progress under an Italian-Peruvian Mission directed by G. Orefici, who focused on two sectors, named A (0.16 km^2) and B (0.10 km^2) (Fig. 1). The results of archaeological investigations (Orefici, 1992; Orefici et al., 2009) allowed the identification of five historical building phases, which reflect the functional and cultural evolution of the site. At the beginning (200 BC) it was a sanctuary (*Huaca*), then it became a ceremonial centre (1st century AD) and finally the religious Capital of the Nasca State. Each historical phase was characterized by the enlargement and reshaping of pre-existent temples and platforms by filling the walls with earth, vegetable fibres, ceramics and offerings.

The excavations have been only concentrated on sector A considered to be the core of the entire ceremonial settlement (Orefici and Drusini, 2003; Orefici et al., 2009). So far, about half of sector A has been brought to light, including the Gran Piramide (see A1, in Fig. 1), Grande Templo (see A2, in Fig. 1) and part of Pirámide Naranjada (see A3, in Fig. 1).

In this paper, we focus on the Pirámide Naranjada mainly built during the fourth historical phase (4th–5th century AD) which was a very critical period for Cahuachi due to violent flooding and a strong earthquake. These environmental disasters strongly affected the ceremonial centre and modified the religious rituals which were made to propitiate the gods and stop the natural disasters. People gave precious offerings and made human sacrifices to the gods, in order to appease their anger and restore the broken relationship. But further violent flooding affected the area

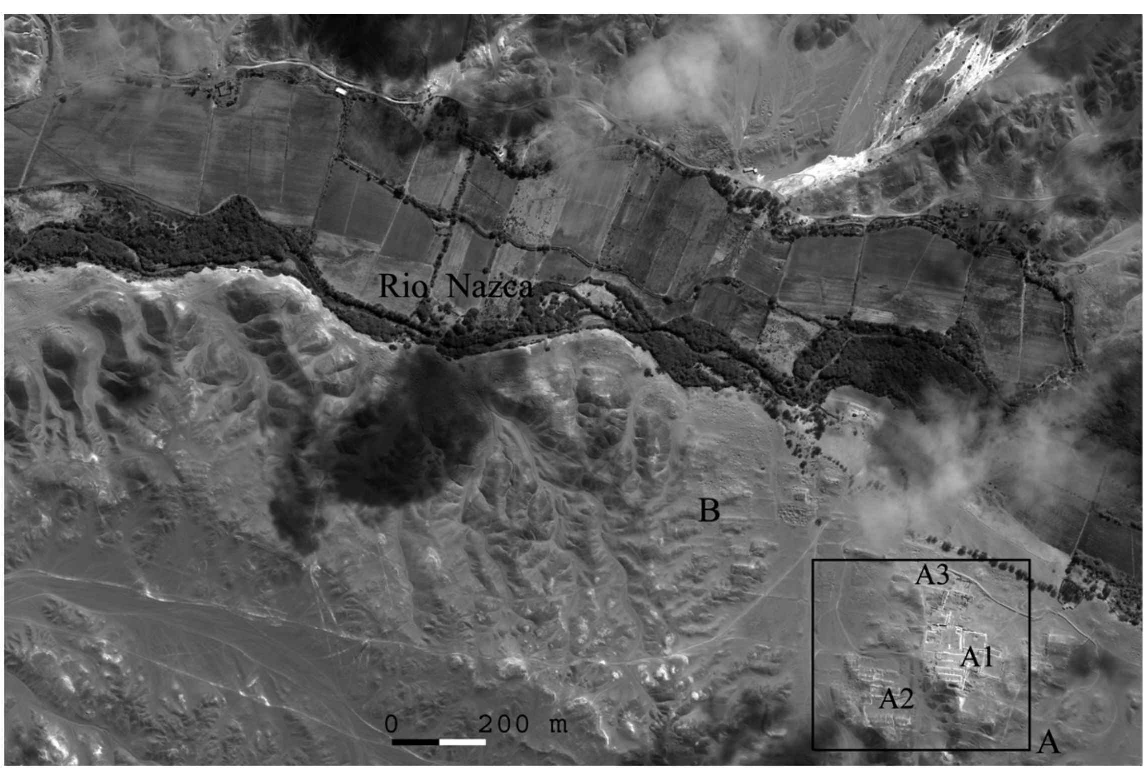

Fig. 1. Location of the sectors (A and B) investigated by an Italian-Peruvian Mission since 1984. A1, A2 and A3 indicate the Gran Piramide, Grande Templo and Piramide Naranjada, respectively.

and caused the abandonment of most of the pyramids and temples of the ceremonial centre. The archaeological investigations on Piramide Naranjada represent a key issue to improve our knowledge on the end of Cahuachi. Although important findings have been recorded, we still know very little. Important information can be continuously extracted and recorded and, in such a context, Earth Observation techniques have been used.

3. Integrated non-invasive survey: approach and aims

VHR satellite remote sensing, GPR and geomagnetic techniques have been applied to identify and evaluate archaeological features on the North-Eastern and Eastern sides of the Piramide Naranjada.

On the North-Eastern side, which is not yet excavated, VHR satellite and magnetic techniques, have been used to detect and map features linked to outcropping and shallow walls, buried tombs and/or ceremonial offerings.

On the Eastern side, GPR has been carried out where the excavations were planned and scheduled but not yet carried out at the time of GPR prospection. Such excavations were actually completed after the geophysical survey to check the reliability of results from GPR based investigations.

4. Investigations on North-Eastern side

4.1. Satellite data

VHR satellite images from QuickBird (QB) and WorldView-1 (WV1) have been used for this study. QB has panchromatic and multispectral sensors with resolutions of 61–72 cm and 2.44–2.88 m, respectively, depending upon the off-nadir viewing angle (0–25°). The panchromatic sensor provides images in a bandwidth ranging from 450 nm to 900 nm. The multispectral sensor acquires data in four spectral bands from blue to near infrared (NIR). For any additional details the reader is referred to http://www.satimagingcorp.com/satellite-sensors/quickbird.html.

WV1 has a panchromatic sensor with a resolution varying from 50 cm to 59 cm, depending on the off-nadir viewing angle (0–25°). Additional details can be found in http://www.satimagingcorp.com/satellite-sensors/worldview-1.html.

The QB data used for this study were acquired: (i) on the 16th September 2002 at 15:17 with an off-nadir of 7°.90 and Ground sample distance (GSD) of 61.90 cm; (ii) on the 25th March 2005 at around 15:29 with an off-nadir view angle of 11°.90 and GSD = 63.40.

WV1 data were acquired on the 31st July 2008 at 15:26 with an off-nadir of 23°.90 and Ground sample distance (GSD) of 58.10 cm.

Satellite VHR data have been used to update the survey of the excavated structures as well as to detect unknown buried and outcropping walls in adobe. In order to enhance the low contrast between the adobe walls (buried and/or partially outcropping) and the surrounding areas, we computed Principal Component Analysis (PCA) and spatial autocorrelation statistics (see sections 4.2 and 4.3, respectively), which were successfully applied in archaeology by the same author group (Masini et al., 2008; Ciminale et al., 2009).

4.1.1. Satellite data analysis based on PCA

The identification of archaeological features related to buried, outcropping and shallow adobe structures was performed considering both QB and WV1 images.

Both QB and panchromatic multispectral images were analysed. They were first investigated individually and then combined by using pan-sharpening and PCA. Pan-sharpening algorithm was applied to integrate the geometric detail of panchromatic with the spectral information of the multispectral images. The benefits achievable from pan-sharpening algorithms have been specifically assessed in the case of archaeological remains (Lasaponara et al., 2007). The pan-sharpening was performed by using Grahm Schmidt algorithm available in ENVI software. It was selected because, in the current case, it performed better than the other algorithms according to our visual analysis.

PCA is a powerful tool for analysing data and identifying patterns. It is a linear combination that transforms the data into a new coordinate system that highlights data similarities and differences. PCA involves a mathematical procedure that transforms a number of possibly correlated variables into a smaller number of uncorrelated variables called principal components. The first principal component accounts for as much of the variability in the data as possible, and each succeeding component accounts for as much of the remaining variability as possible. PCA reveals the internal structure of the data in a way which best explains the variance in the dataset. This generally makes the identification of archaeological features easier.

4.1.2. Satellite data analysis based on spatial autocorrelation statistics

Spatial autocorrelation statistics measure and analyze the degree of dependency among spectral features looking for specific

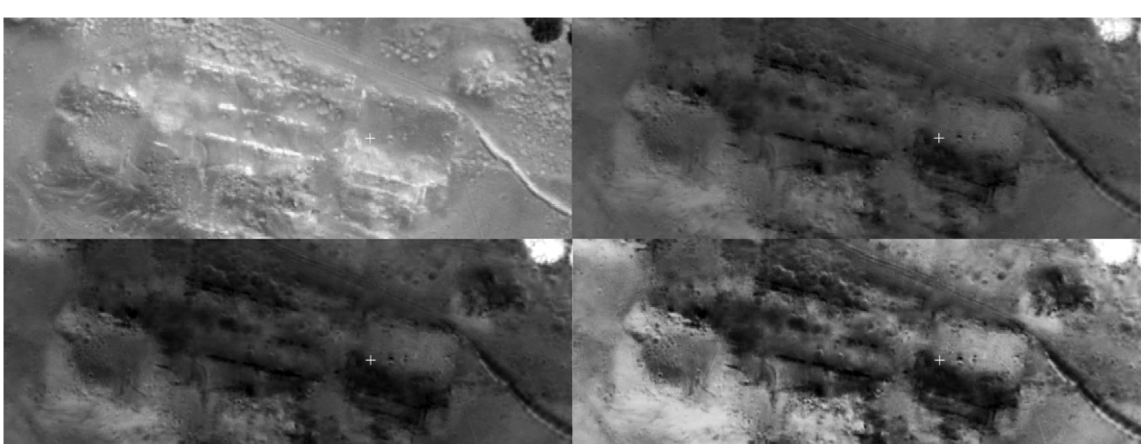

Fig. 2. (Upper left) 2005 QuickBird Panchromatic image of North-Eastern side of the Piramide Naranjada; (upper right) PC2; (lower left) PC2 linear enhancement; (lower right) PC2 adaptive enhancement.

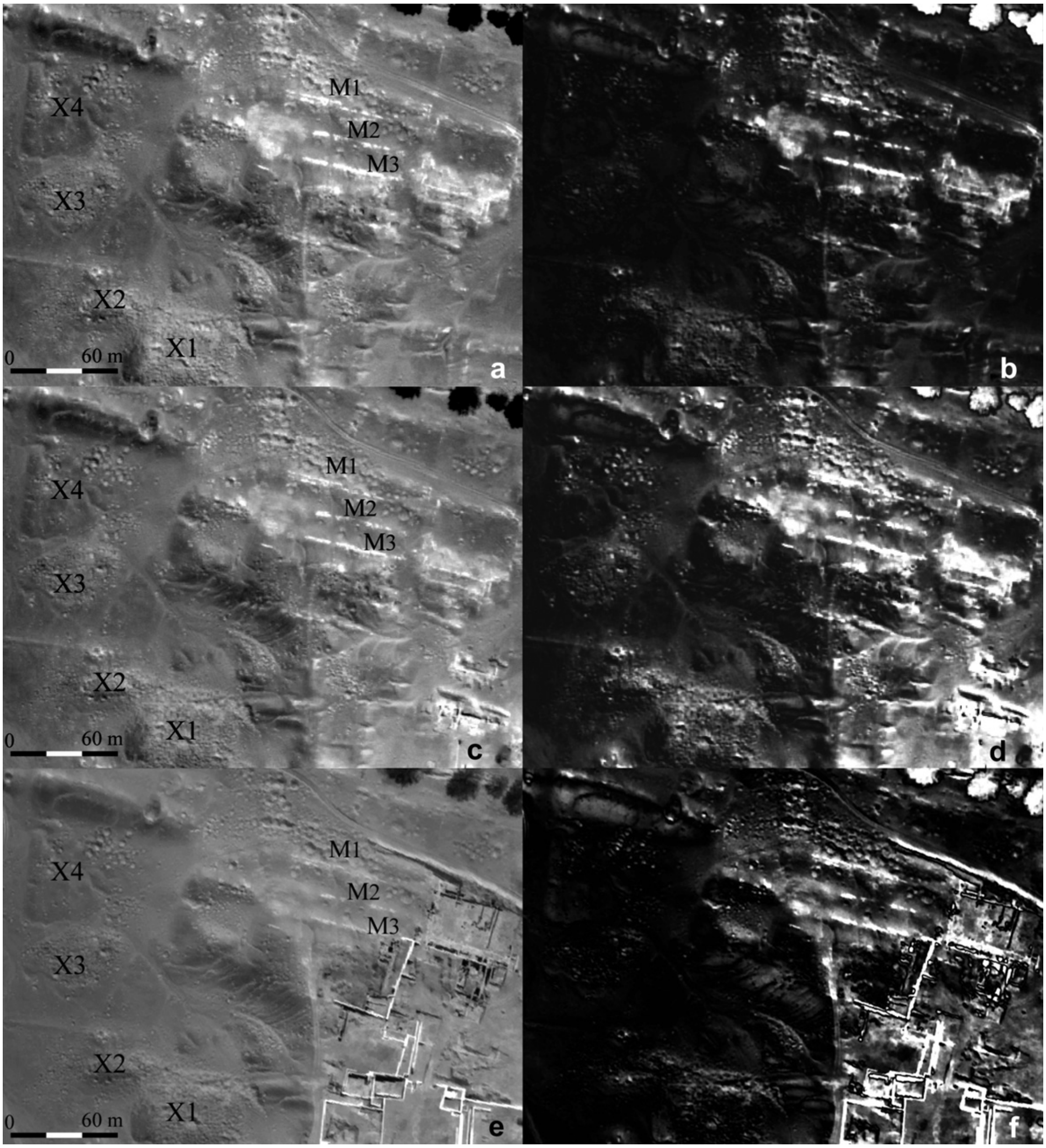

Fig. 3. (a) 2002 QB panchromatic image; (b) Moran product of image shown in (a); (c) 2005 QB panchromatic image; (d) Moran product of image shown in (c); (e) 2008 WW1; (f) Moran product of image shown in e. X1–X4 indicate mounds characterized by pits dug by grave looters. M1–M2–M3 denote outcropping and shallow walls.

areas within an image that have clusters of similar or dissimilar values. The use of classic spatial autocorrelation statistics such as Moran's I, Geary's C, and Getis-Ord Local Gi index (for more information see Anselin, 1995; Getis and Ord, 1992) enables the characterization within a user-defined distance. For each index, the output is a new image which contains a measure of autocorrelation around the given pixel. In particular:

(i) the Local Moran's I index identifies pixel clustering. Positive values imply the presence of a cluster of similar values which means low variability between neighboring pixels, whereas negative values indicate the absence of clustering which means high variability between neighboring pixels,
(ii) the Getis-Ord Gi index permits the identification of areas characterized by very high or very low values (hot spots) compared to those of neighboring pixels,
(iii) the Local Geary's C index allows us to identify edges and areas characterized by a high variability between a pixel value and its neighboring pixels.

All of these indices are available in commercial softwares for Geographical Information System (GIS) and image processing such as ENVI.

4.1.3. Results from satellite data analysis

A multitemporal dataset of satellite QB and WV1 images have been analysed. In particular: (i) all the four QB spectral bands (blue, green, red and near infrared) were investigated using pan-sharpening and PCA, whereas (ii) panchromatic images of QB and WV1 were processed using local spatial autocorrelation statistics, such as, Moran's I, Geary's C, and Getis-Ord Local Gi indices.

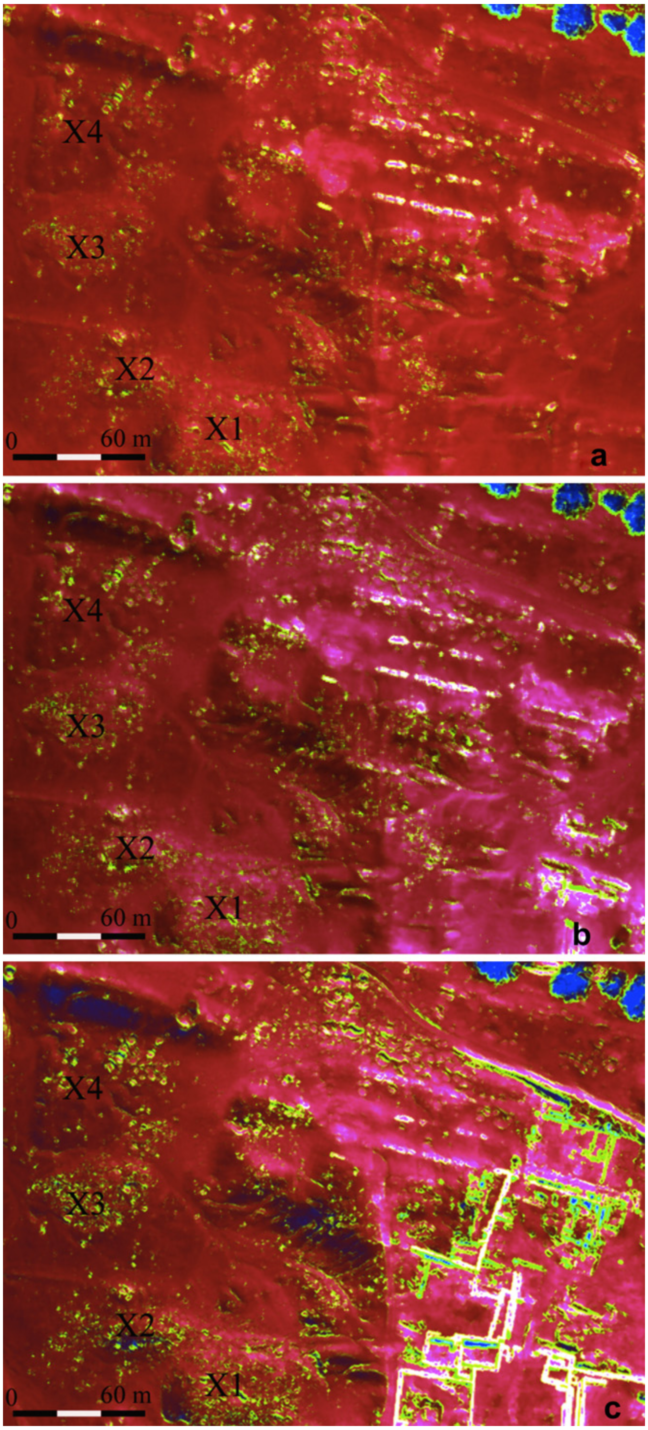

Fig. 4. RGB composition of Moran, Getis and Geary indices (R: Moran; G: Getis; B: Geary) applied to panchromatic images of 2002 QB (a), 2005 QB (b) and 2008 WW1 (c).

The comparative visual inspection of the available dataset put in evidence that the panchromatic images are more suitable than spectral bands to emphasize archaeological features. This is due to the fact that for the study area there are no significant spectral variations in the four bands for both 2002 and 2005 QB imagery. For the same reason also the results from PCA did not provide significant enhancement of archaeological features; an example is in Fig. 2, where QB panchromatic image (2005) is shown along with results from the second component of PCA (PC2). Also additional enhancement filtering did not provide any significant improvement, as shown in Fig. 2c and d.

On the basis of these results, we focused only on satellite panchromatic scenes which were further processed using local spatial autocorrelation statistics.

Fig. 3a, c, e shows QB (2002 and 2005) and WV1 (2008) panchromatic images (Fig. 3a, c, e) along with their corresponding maps obtained from Moran index (Fig. 3b, d, f).

The visual inspection of the panchromatic time series, clearly shows the excavations' progress made over the years. In particular, the comparison of satellite pictures taken before and after the excavations (see Fig. 3a,c,e) put in evidence three important facts: (1) the buried adobe structures are not visible from satellite images; this confirms our findings based on the comparison of aerial images taken before and after the excavations (Masini et al., 2008); (2) outcropping structures (M3, and part of M1 and M2) are easily identifiable due to the high contrast in brightness between the clay of the surface adobe walls and the surrounding alluvial deposits; (3) shallow walls (part of M1 and M2) are detected thanks to micro-relief which produce shadows on the ground.

Compared to the panchromatic scenes Moran index shows a general improvement in the feature enhancement. This is more evident for the WV1 image. Moran index emphasizes clustering, which for the study area, are corresponding to the excavated structures (in the southeast of the scene) and outcropping walls (M1, M2 and M3, in Fig. 3). Such walls are related to parallel terraced platforms which characterize the North-Eastern slope of the trunk-pyramidal structure of the Naranja Pyramid. These archaeological features were further investigated by high resolution geomagnetic surveys (see Section 4.2).

From satellite panchromatic scenes four mounds (see x1, x2, x3 and x4 in Fig. 3) can be identified at the west and southwest side of the Piramide Naranjada. These mounds are characterized by a number of circular anomalies, which are pits dug by grave looters (known as huajeros). Traces of looting are still visible thanks to the micro-relief, but the spatial resolution is not enough to map and measure them.

Compared to the panchromatic image, the RGB composition of Moran; Getis; and Geary indices, does emphasize these pits enhancing their edges (yellow coloured, see Fig. 4).

Finally, the multitemporal comparison of the three RGB images (see Fig. 4a–c) clearly show an increasing number of pits from 2002 to 2008 and, therefore, the intensification of the looting phenomenon over the years, as confirmed from in situ analysis. Looting is the greatest problem facing the Nasca Ceremonial site today. To contrast and limit this phenomenon a systematic monitoring is required. In this context, Earth Observation and clustering analyses techniques can play a fundamental role to identify and map looted areas.

4.2. Geomagnetic data acquisition and results

In order to evaluate the archaeological features linked to the presence of shallow and outcropping walls detected from satellite images, geomagnetic measurements were carried out on November 2008 in the area shown in Fig. 5 (upper).

The measurements were performed using an optical pumping magnetometer G-858 Geometrics in gradiometric configuration, with two magnetic probes set in vertical direction at a distance of around 1 m from each other. Such a configuration allowed the automatic removal of the diurnal variations of the natural magnetic field. As measurement acquisition modalities we selected the mapped survey mode, which allows us to define and visualize the survey area as well as to move around within it in a non-continuous fashion by means of regular grids.

The total map surveyed was around 56×60 m. In order to overcome logistic problems, due to the presence of excavation trials

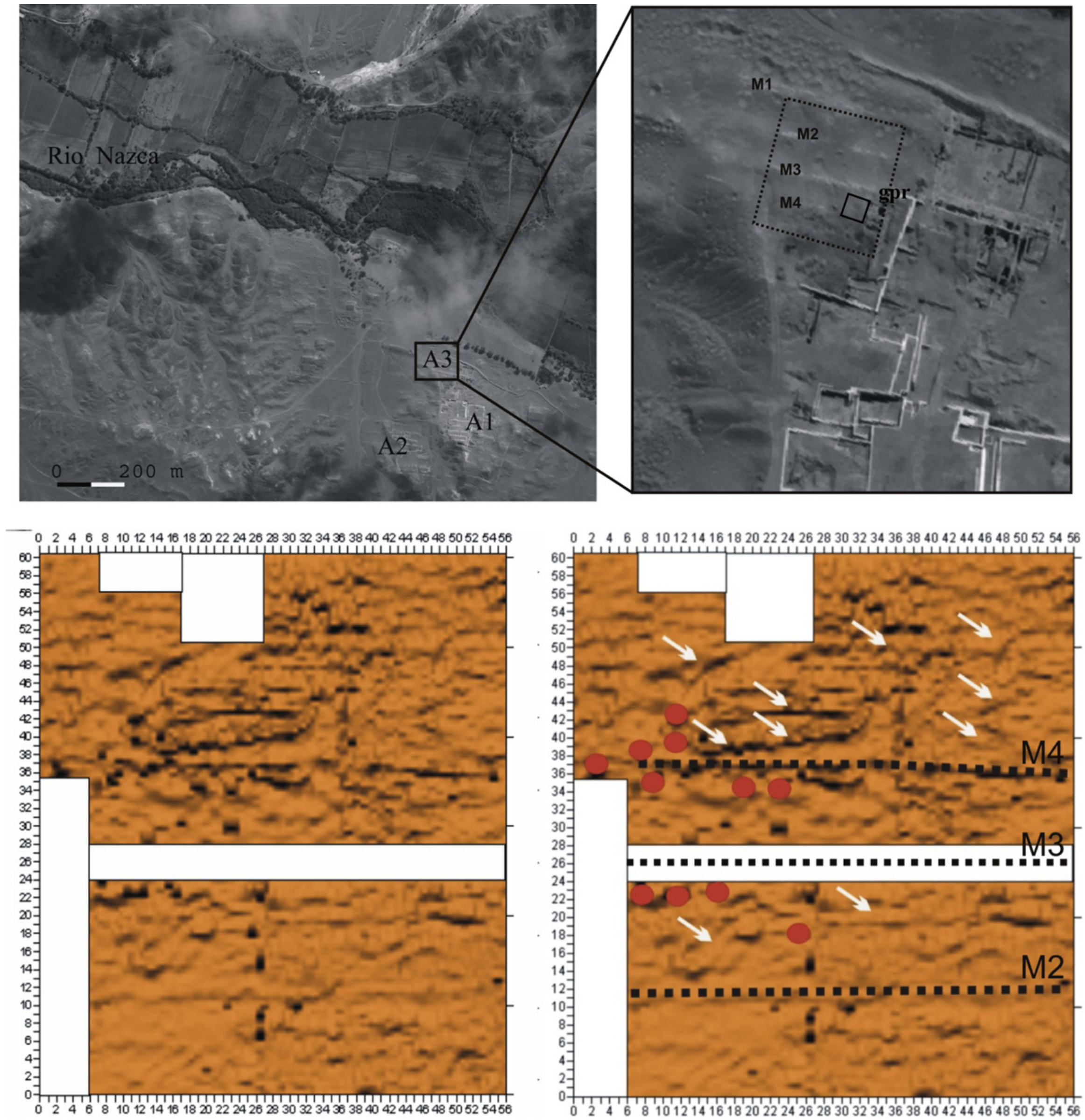

Fig. 5. (Upper) Location of the magnetic (dashed line square) and GPR survey (continuous line square). Lower: geomagnetic map (left) and its interpretation (right). The map puts in evidence linear anomalies in E–W direction linked to shallows and outcropping walls (black dotted line) and N–S direction (white arrows) likely referable to buried structures. Red circles denote anomalies related to potential buried tombs and ceremonial offerings. Finally white boxes are no data areas due to the presence of excavations, pits and morphological steps which prevented the geomagnetic survey.

and pits dug by grave looters, the investigated area was subdivided into ten sectors. The survey direction was always South-North. The software CSAZ by Geometrics was used to set the proper sensor orientation for Cahuachi.

Fig. 5 (lower left) shows the geomagnetic map obtained from gradient data. It was calculated from the magnetic values acquired by each sensor (top and bottom). The geomagnetic image is the product of filtering tools and imaging software (Surfer software). Two kinds of magnetic anomalies are visible in the gradiometric map: (i) linear type, linked to buried and surface walls, and (ii) small circular anomalies. A significant number of such circular anomalies were detected over pits partially dug by grave looters. Therefore other circular magnetic anomalies are very probably linked to buried tombs or ceremonial offerings.

The variations in the Earth's magnetic field could be due to the high quantity of ceramics generally found in tombs and ceremonial offerings (see Section 5.3), ash and charcoal, usually employed during the ceremonial rituals.

As regards the linear anomalies, most of them are oriented in the E–W direction, in continuum with the main visible wall structures (indicated with black lines in Fig. 5, lower right) which bear the terraced platforms of the pyramid. Other linear anomalies are oriented in N–S direction and this suggests the presence of walls related to ramps and corridors which connect the different levels of the terraced pyramid.

5. Investigations on the Eastern side

5.1. Investigated area

On the eastern side of the Piramide Naranjada archaeological excavations, carried out on August and November 2007, unearthed

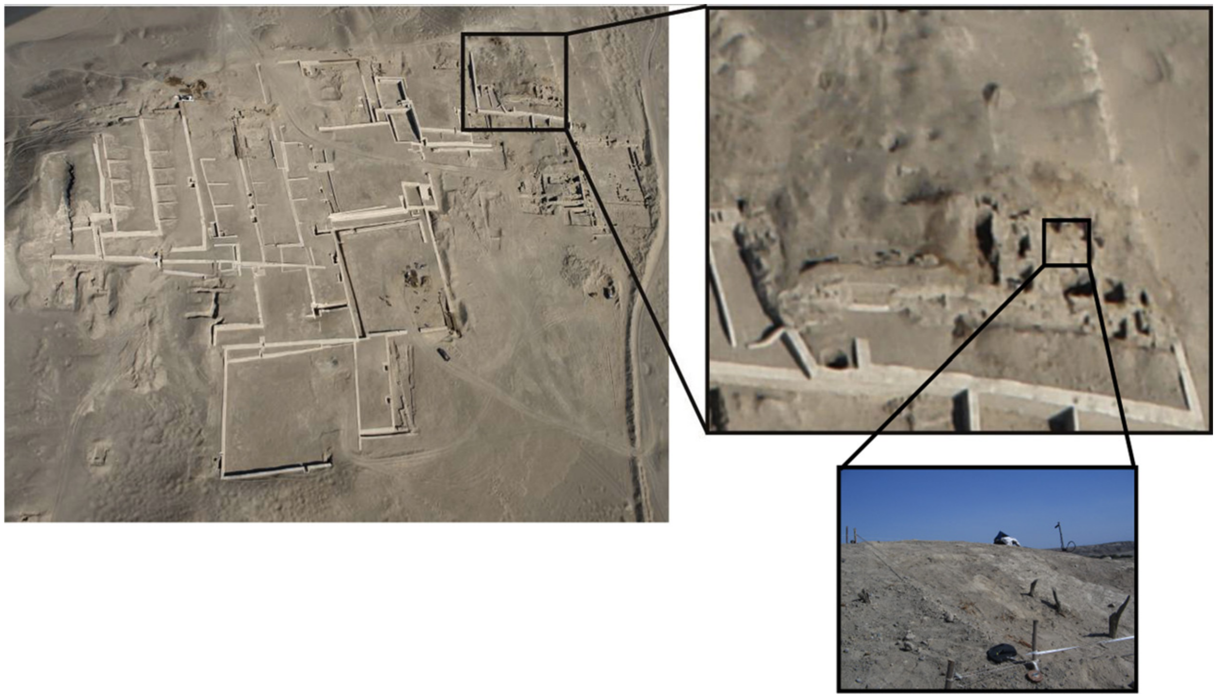

Fig. 6. Eastern side area investigated by GPR (see also Fig. 5, upper).

walls, tombs and ceremonial offerings related to the 4th historical phase of Cahuachi (4th–5th century AD). It was the last and most dramatic period for Cahuachi before its abandonment. To cast new light on this crucial historical period of the Ceremonial site, any finding can provide fundamental information. To this aim, GPR measurements were carried out (April 2008) on the eastern side of the pyramid in order to detect unknown archaeological remains connected with structures and tombs unearthed by the team of archaeologists during excavations of the previous year (2007).

5.2. Field data acquisition

On the eastern side of the Piramide Naranjada (Fig. 5, upper right, and Fig. 6), GPR profiles were carried out by using Subsurface Interface Radar (SIR) 3000 manufactured by Geophysical Survey Systems Incorporation (GSSI). The SIR 3000 has a digital control unit with keypad, VGA video screen and connector panel. The unit is backpack portable, requiring one or two operators, and the antenna used was the monostatic type 400 MHz (by GSSI). The GPR acquisitions were in continuous mode with a two-way time range of 40 ns, and an interval band pass filter of 100–800 ns. The survey was acquired without a “wheel accessory”, due to the complex topography.

To mitigate uncertainties on the antenna position, a reference meter rule was located along each profile and marked at each meter. Therefore, a distance normalization was adopted. The ReflexW software was used to process the data. The high quality of the traces only required standard analysis techniques for data

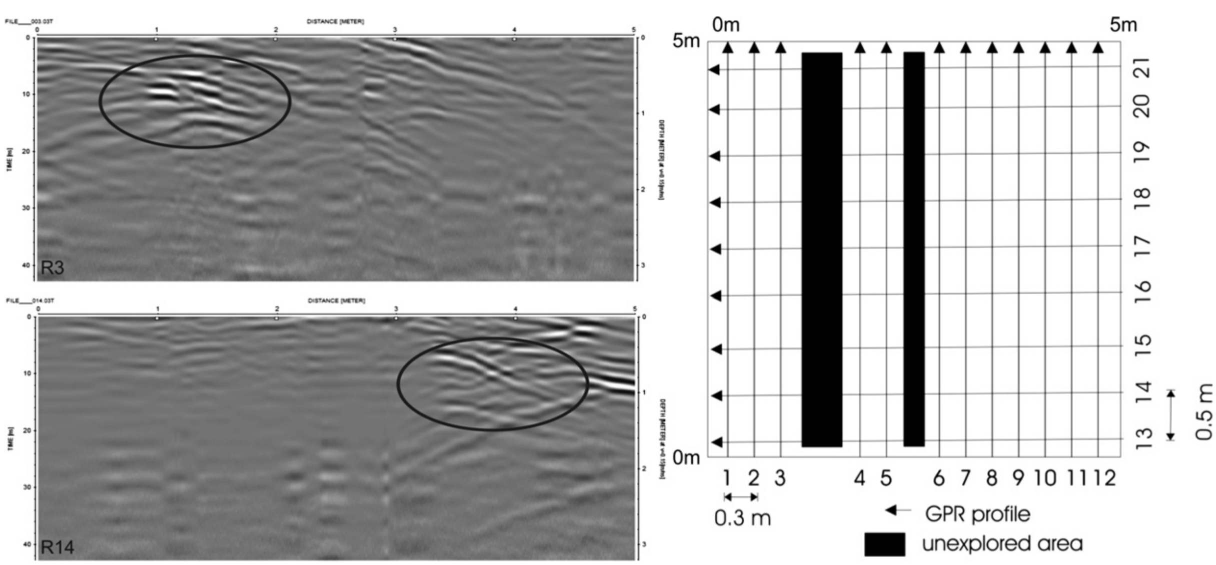

Fig. 7. Eastern side. Two GPR profiles (upper left and lower left) and grid of the investigated area (right). The black circles highlights the reflection zones.

Fig. 8. Photo of the excavation carried out on the area investigated by GPR. Archaeologists unearthed a rich and extraordinary ceremonial offering, including ceramics, painted textiles, basketry artifacts, metal objects and painted pumpkins.

processing and for reducing background noise (normalization, zero time correction, background removal processing).

The average electromagnetic (e.m.) wave velocity (V_{em}) was estimated at around 0.1 m/ns using this strategy: a metallic plate was situated behind a wall, with a well-know thickness, in order to have a maximum reflection of the e.m. waves.

The average electromagnetic wave velocity was estimate by hyperbola analysis and the value was 0.15 m/ns. Therefore, by exploiting the estimated V_{em} for the 400 MHz antenna, the time range of 30 ns corresponds to a maximum investigated depth around to 2 m.

5.3. GPR results and archaeological findings

Several GPR profiles were carried out in the area of Fig. 6 divided into several grids of 5 m × 5 m, selected according to the dimension of each square excavated by the archaeologists.

Each grid was investigated by several parallel profiles The number of these profiles and their interlinear distance were selected on the basis of logistic reasons due to the presence of wood branches (see Fig. 6, lower). In this paper, we focus our attention on one grid 5 m × 5 m, whose excavation was scheduled and carried out immediately after the GPR prospection (see Fig. 7, right).

The square area was investigated by 21 profiles carried out along two directions (12 E–W and 9 N–S direction).

For seek of brevity, herein we focuses on some profiles, representatives of the final results: profiles R3 and R14 (shown in Fig. 7, upper left and lower left), which are long 5 m. The profiles are perpendicular to each other and have an investigation depth around 2 m (with $V_{em} = 0.15$ m/ns).

The GPR profiles point out very well several reflections up to 15 ns (about 1 m). In detail, several mean reflections are visible in the profile R3 (Fig. 7, upper left) between $x = 1$ m and $x = 3$ m at depth between 6 and 16 ns (0.45 m and 1 m, respectively). The same results are visible in the R14 profile (Fig. 7, lower left) but between $x = 3.5$ m and $x = 5$ m. This reflected area is in correspondence with R3, because the two profiles are perpendicular. Fig. 7 (lower left) shows the presence of a strong reflector, ascribed to buried objects.

The excavation of the first 50 cm unearthed remains of *huarango* trunks and branches belonging to a wood framework, which typically covers a ceremonial offering or a tomb, thus confirming the reflector of the radargram (Fig. 7, upper left and lower left).

The excavation of the subsequent layers revealed the existence of a rich and extraordinary ceremonial offering (see Fig. 8), which included eighty undamaged ceramics, painted textiles, basketry artefacts, precious metal objects and above all painted pumpkins which are up to now unique examples only from the Nasca Culture. Archaeologists also found balls in well preserved red cotton (thanks to the hyper-arid climate), ornamental sculptures in bone and shell representing birds and necklaces in *chrysocolla* (a semi-precious bright green or bluish stone widely used in Peru). Finally, the archaeological deposit also revealed two human bodies belonging to a child and to an adult. Both of them were sacrificed and formed part of the ceremonial offering.

6. Conclusion

In this paper we focused on the detection of earthen archaeological deposits using non-invasive techniques. This is a crucial challenge especially for arid environmental settings, complex hydro- geological and geo-morphological conditions, as in the case of Cahuachi near Nasca, in Peru.

To address this challenge the integration of diverse remote sensing techniques has been adopted.

The investigations were performed on two sides of the Piramide Naranjada: (i) North-Eastern side, not yet excavated, using satellite data and magnetic prospection, and (ii) Eastern side, where GPR has been used to support the ongoing excavation activity.

In the North-Eastern side, results from the analysis of satellite images based on spatial autocorrelation statistics such as Moran's I, Geary's C, and Getis-Ord Local Gi indices, allowed the identification of unknown shallow and outcropping adobe walls, related to terraced platforms which compose the trunk-pyramidal structure. Moreover, the multitemporal analysis of RGB composition of the above mentioned indices put in evidence the dramatic increasing of the looting phenomenon over the years. Additional information on the presence of buried and shallow walls were provided by geomagnetic surveys. The gradiometric map enabled the identification of magnetic anomalies linked to tombs and ceremonial offerings.

In the eastern side of the Piramide Naranjada, GPR allowed the discovery of an unknown rich ceremonial offering according to results from geophysical prospection. Such excavations unearthed precious items, among them craftwork (ceramics, painted textiles, basketry artefacts, precious metal objects), painted pumpkins, unique examples of the Nasca culture, sculptures in bone and shell and two human remains of a child and an adult. Both of them were sacrificed and formed part of the ceremonial offering.

Our results pointed out that the use of different remote sensing technologies can open new perspectives for the detection and documentation of adobe archaeological remains, not only for the ancient Andean civilizations but also for the earthen archaeology in Middle East, Northern Africa and Asia. Finally, Earth Observation can significantly contribute to the monitoring of the fragile earthen archaeological heritage, whose conservation policies must also address looting activity.

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