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Remote sensing and GIS techniques for reconstructing the military fort system on the Roman boundary (Tunisian section) and identifying archaeological sites

Nabil Bachagha[a,b,c], Xinyuan Wang[a,b,*], Lei Luo[a,b,**], Li Li[a,b], Houcine Khatteli[d], Rosa Lasaponara[a,e]

[a] Key Laboratory of Digital Earth Science, Institute of Remote Sensing and Digital Earth (RADI), Chinese Academy of Sciences (CAS), 100094, Beijing, China
[b] International Centre on Space Technologies for Natural and Cultural Heritage Under the Auspices of UNESCO, 100094, Beijing, China
[c] University of Chinese Academy of Sciences (UCAS), 100094, Beijing, China
[d] Institut des RégionsArides (IRA), 4119, Médenine, Tunisia
[e] Institute of Methodologies for EnvironmentalAnalysis (IMAA), CNR, C.da Santa Loja, 85050, Tito Scalo (PZ), Italy

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ABSTRACT

Southern Tunisia is one of the most significant areas of historical and archaeological interest as, since the Roman period, it has played a key role as a land bridge controlling the passage from the Saharan plain to plateaus and to the north of the mountain range between Chebika and Metlaoui. Because of the difficult geography, the investigation of ancient sites in this region is not easy and, therefore, satellite-based investigation can play an important role in the detection and documentation of archaeological sites. In this study, we combined high-resolution remote sensing (RS) imagery with in situ investigations to assess the suspected archaeological sites detected using satellite data and historical documentation. The suspected sites were confirmed according to the geometric features of the sites as they appeared in the remotely sensed imagery these sites had not been detected during earlier field investigations. In particular, we aimed to use 1-m spatial resolution WorldView-2 (WV2) imagery of the Wadi El-MelahValley (WMV) in Gafsa (also named Capsa). The satellite data were processed using statistical analysis and unsupervised classification.WV2 satellite imagery of WMV, Southwestern Tunisia, was processed within ArcGIS 10.2 to identify spatial features linked to the sites. The study outlines three different feature-extraction methods (GIS-based, unsupervised classification-based and statistical analysis-based). The satellite-based analysis and archaeological records were evaluated by RS and GIS prospecting in the area of the field survey to confirm the new discoveries. The results of remotely sensed data combined with field survey enabled us to reconstruct the military defense system consisting of is a linear defensive structure (limes) and forts related to the Imperial Roman period. Taken together, the results of our investigations provide new insights into some important sections of the Roman limes in the southern part of the empire. Other concealed remains are still to be found and explored.

1. Introduction

1.1. Background: archaeological context

During the Roman period, Tunisia was known as Africa in fact, at this time, 'Africa' referred not to the whole continent but just to the small corner of Tunisia jutting out into the Mediterranean Sea. This historic name indicates just hints at the importance of Tunisia during the Roman Empire; proof of it can be seen in the country's many imposing, and well-guarded Roman sites (Florence, 1998). These sites are closely interwoven with the area's complex frontier and postcolonial history. Many records from the Roman period have survived, but tend to be biased towards the Roman Period at the expense of earlier periods (Fenwick, 2012). In fact, the Roman Empire was very influential in

* Corresponding author. Key Laboratory of Digital Earth Science, Institute of Remote Sensing and Digital Earth (RADI), Chinese Academy of Sciences (CAS), 100094, Beijing, China.
** Corresponding author. Key Laboratory of Digital Earth Science, Institute of Remote Sensing and Digital Earth (RADI), Chinese Academy of Sciences (CAS), 100094, Beijing, China.
E-mail addresses: wangxy@aircas.ac.cn (X. Wang), luolei@radi.ac.cn (L. Luo).

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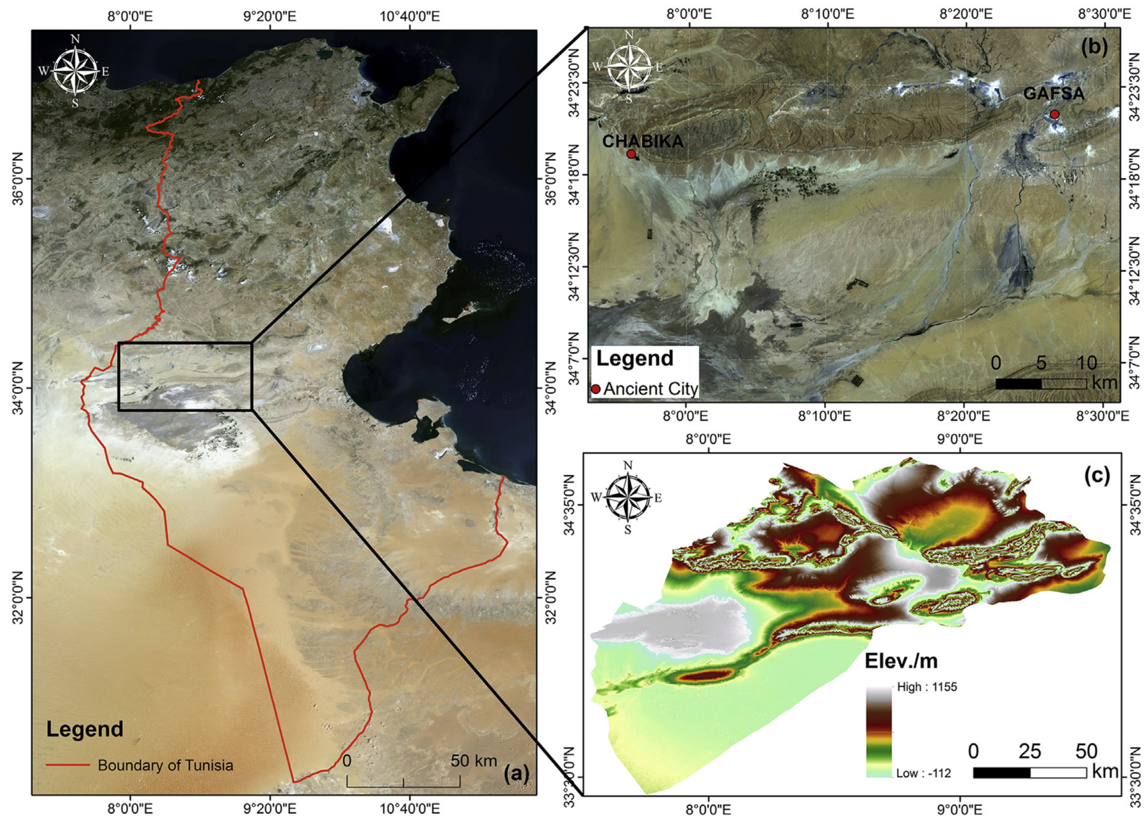

Fig. 1. (a) Landsat 8 OLI data composites (RGB: 7(SWIR-2), 4(NIR), 3(red)) of Tunisia showing the location of the study area; (b) location of the WMV; (c) ASTER GDEM map of the study area. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Tunisia and was endowed with a variety of defensive and agricultural installations; the area was also more densely populated than it is today.

In ancient Tunisia during the Roman period, the southern part was viewed as an example of the development of agricultural in arid areas. The area was a part of a huge military defense system located along the desert border and acted as a land bridge used to control the passage from the Saharan plain to the plateaus to the north of the mountain range. In these arid and semi-arid conditions, ancient Rome made a great effort to construct limes, forts, irrigation systems and oases to "dominate" the arid environment. An example is the southern Tunisian border area, where one of the most impressive Roman limes can be found.

In Roman times, the WMV (Fig. 1) formed part of the interprovincial border and controlled movement between the desert areas in the south and Gafsa and the steppe areas. In the middle of the twentieth century, Colonel Baradez demonstrated the importance of this area to the Roman defensive system (Euzennat, 1971, 1972). The Romans built a road network to protect the communication between their domains as well as to monitor their territories and control the seasonal movements of nomads (Salama, 1989). According to Trousset (1980), these strategic routes of constituent of the Limes witch a frontier road lined with a series of military works, namely forts, fire towers, look-outs and watchtowers. These sites appear to have been directly related to major traffic axes. They constituted a surveillance network that allowed extensive views of the plains and passes.

In addition, there are natural obstacles to entering the region that could be augmented by organized defenses. Thus, the existence of a series of Roman forts in this sector has been shown to control the passage from the Saharan plain to the plateaus to the north of this mountain range between Chebika and Metlaoui. This may explain the possibility of finding the Fossatum in this defensive sector (Ben Ouezdou, 1994). Overall, this study focussed on the Roman military defense system in the arid and semi-arid regions of the northern Saharan as this is crucial to understanding how the Romans had the capacity to dominate these frontier areas.

A large number of archaeologists, experts and historians have carried out research in southern Tunisia (Euzennat, 1972). In their work, they found indications of the archaeological sites surveyed in our study area; these sites have also attracted the attention of archaeologists such as Euzennat (1972) and Trousset (1980). These studies focused on land use in this sector since antiquity, and the present study benefited from the identification as well as the descriptions of the sites studied. Today, the main remnants consist of wind-weathered landforms and sand dunes.In order to answer these mysteries, integrated RS and GIS methods were used to prospect and study the archaeological site in southern Tunisia.

1.2. Role of remote sensing in archaeological studies

The investigation of ancient sites in southern Tunisia is not easy due to the harsh geography and also safety concerns, which means that it is hard to find archaeological remains and sites using conventional archaeological techniques in this unexplored district. Archaeological remote sensing (Luo et al., 2012, 2019) provides a new viewpoint for investigating, discovering, reconstructing and documenting archaeological sites and cultural heritage at various scales. This study aims to show the great advantages and potential of remote sensing for understanding the ancient Roman Empire and to delineate the Roman boundary in southern Tunisia.

Satellite remote sensing, the most popular technique used in aarchaeological remote sensing, has been successfully applied in almost every field related to archaeology and cultural heritage (Luo et al., 2019; Pringle, 2010). Using satellite remote sensing, images of difficult-to-reach regions can be acquired at regular intervals with little effort and have been used in archaeological prospecting and monitoring. At present, today, a vast array of active and passive remote sensing techniques are accessible to archaeologists (Luo et al., 2017a; Christopher et al., 2018). To produce the best outcome, many researches will in general utilize a combination of satellite remote sensing, geophysics, excavation, coring and analysis (Luo et al., 2019; Sarris et al., 2013). For example, archaeologists found a fortified early Roman structure in northeastern Italy using a combination of LiDAR, GPR, and ground investigation.

In Central Europe (Austria), using airborne imaging spectroscopy, electromagnetic induction and GPR, archaeologists mapped large parts of the Roman town of Corundum and used these data in town reconstruction (Neubauer, 2014). Roman sites are often very large and located in landscapes where the use of combined methods is feasible. Combined methods can also be beneficial in regions where sites cover several different time periods given that different methods are better at finding different types of site (Fall et al., 2012).

Documented remote sensing information can play a key part: 1950s aerial photographs, Landsat and historical QuickBird imagery were used to distinguish a chinampa system in Mexico's northern basin (Morehart, 2012). The utility of SAR remote sensing to identify subsurface objects in regions covered by sand has long been known and has attracted particular attention since the Shuttle Imaging Radar (SIR-A) monitoring of ancient paleochannels that was carried out in the Sahara in November 1981(Christopher et al., 2018). Old survey data together with satellite remote sensing and GIS data can be used to detect ephemeral structures such as road networks (Luo et al., 2014a). Remote sensing has alsohelped archaeologists to discover and understand archaeological sites, find new hidden areas and to settle real archaeological problems.

RS, GIS and the Global Navigation Satellite System (GNSS) are collectively called 3S by Luo et al. (2014a). These form the basis of Earth observation and have been extremely important in helping archaeologists to explore and interpret archaeological sites, and to resolve real archaeological problems. In our previous study (Luo et al., 2014b), five medieval sites at Dunhuang were discovered using integrated remote sensing and GIS analysis. Additionally, remote sensing archaeology makes use of multisource remote sensing imagery as data, analyses the spatial patterns of archaeological sites and studies their structures, anticipates the discovery of unknown sites and mapped ancient ruins, and can be used to assist with the digital rebuilding of ancient monuments and their environmental backgrounds (Lasaponara et al., 2018).

This paper focuses on two issues that are fundamental to the understanding of the Roman military defenses in southern Tunisia and examines the possibility and extent to which remote sensing archaeology can be used in large-scale investigations of ancient Rome. In this study, we use satellite remote sensing to detect possible undiscovered structures that are covered by sand.

2. Materials and methods

2.1. Study area

The WMV is formed by a series of high plains that are encircled by mountains with the highest elevation (1479 m) and gradually descends towards the south. It is located in the southwest of the Gafsa Region (southern Tunisia) between 34°05′52″ N and 35°06′19″ N and 8°30′06″ E and 9°30′26″ E (Fig. 1). This region is also known as a developing bioclimatic region; it has a Saharan desert climate. Nevertheless, a small part of the WMV is in the desert zone where the yearly precipitation is less than 20 mm. In Roman times, this area was a part of a huge military defense system located along the desert border.

2.2. Historical materials

The general landscape of the WMV shows that the Roman interest in this border area was largely defensive, although the archaeological record shows the existence of agriculture, particularly in the northern plain to the southwest of the Gafsa Oasis. It can be concluded that this is the reason the WMV was a particularly important part of the African Limes (Tissot, 1888).

The ancient Roman Empire was described by an effective system of aqueducts that spanned the whole province of Africa (known as Africa Proconsularis), which included present-day Tunisia (Toutain, 1895). In these desert and semi-arid conditions, the Romans made great efforts to construct forts and cities to "dominate" the arid environment, as in the case of the south Tunisia border area, where one of the most impressive Limes of the Roman Empire can be found (Khanoussi, 2010). Until now, archaeological research in this area has focused more on the Roman roads that traverse the pre-Saharan and Saharan districts as this is considered crucial to understanding how the Romans had the capacity to dominate these remote border countries. In the Roman period, this space constituted an area where the Roman and Berber worlds came into contact (Euzennat, 1990).

In ancient Tunisia, a large number of historical records related to the south of the country dating from Roman times were collected and preserved. These materials are a key resource for investigations in a wide range of fields, including historical studies. The historical – geographical studies by Euzennat et al. (1972) and Trousset (1980) concern the Roman border in the south of Tunisia and are now held by the National Library of France and the National Institute of the Heritage of Tunisia. The latter institution holds key sources of data for archaeological prospecting in Gafsa and provides information about Roman sites, which is a valuable resource for finding new sites. For example, the ancient city of Gafsa was an important city in Roman Africa located near the Fossatum Africae (Limes) – Roman cisterns are still evident in the city ruins. In this study, Both the historical records and ancient topographic and thematic maps of archaeological sites were combined with high-resolution remote sensing data and field work to detect the new archaeological sites and presented as base maps in a GIS environment.

2.3. Remote sensing data

Archaeologists interested in recognizing sites of archaeological interest are increasingly using VHR commercial satellite imagery. In the past, data from the Ikonos and QuickBird satellites were the most commonly used (Bernardinia et al., 2015; Challis, 2007; Lasaponara et al., 2016; Lasaponara and Masini, 2011; Parcak, 2007, 2009) and these will continue to play an important role in the detection of sites of archaeological interest in the future (Luo et al., 2017b). WV2 has two imaging sensors: a panchromatic (PAN) sensor with a spatial resolution of 0.46 m and a multispectral (MS) sensor that obtains information in eight spectral bands from 0.4 mm to 1.04 mm and has a spatial resolution of 1.84 m.

In the present study, the dataset analysed was a WV2 image of a chosen study area obtained from Digital Globe. This scene, acquired on 13 November 2016, includes the region known as the "Wadi el Melah Valley", a generally wet and marshy area located in the south-east of the Gafsa region in the south of Tunisia. Freely accessible remote sensing data with different coverage and spatial resolutions, including Google Earth imagery and GDEM data, were employed and analysed together with the WV2 data.

2.4. Data processing

The approach devised and used in this study consisted of the following steps.

The first step in the data processing was pan-sharpening, which allowed the PAN and MS data to be combined to create new MS images with a higher spatial resolution than the original MS data. In this study, the Gram – Schmidt pan-sharpening method was tested on the WV2 images (i.e. the four bands of the WV2 data). The application of pan-sharpening techniques to VHR satellite data can enhance archaeological markings and facilitate their detection. Several studies have presented the results of applying this method for better detection of covered structures (e.g. Lasaponara and Masini, 2014; Beck et al., 2007; De Laet et al., 2007; Lasaponara and Masini, 2007).

In order to further improve the visibility of archaeological features, we also used the Local Index for Statistical Analyses (LISA), as described in Lasaponara et al. (2018). For the identification of archaeological features, unsupervised and supervised classifications were performed using both (i) the pan-sharpened scenes and (ii) the data set consisting of all the pan-sharpened scenes and the LISA images. This was done because the maximum spectral separability of the site boundaries occurred in the pan-sharpened scenes and the statistical analysis of these based on LISA indices (as in Lasaponara et al., 2018). The feature-extraction approach was applied twice: once at a global and once at a local scale. The global feature extraction was used to detect anomalies of archaeological interest and the later reapplication of the procedure at the local scale (as in Lasaponara et al., 2016) was intended to refine the anomalies extracted using the global approach.

There are many indicators of spatial autocorrelation, generally denoted as global indicators or local indicators. The latter are more suitable for identifying second-order effects (Anselin et al., 2006). Global statistics give information (as single values) about the size of the autocorrelation for the whole region under investigation. Local statistics give information about local clusters and are based on the distance information captured in the distance matrix. These indicators measure if and by how much the dataset is auto-correlated on the basis of the distance used to describe the neighborhood of a given region. For the most common local indicators of spatial autocorrelation denoted as LISA see Lasaponara et al. (2018). For digital images, global indicators indicate the extent of spatial affiliation for the whole image whereas the neighborhood indicators give an estimation of the autocorrelation for every pixel in the new image. Thus, local indicators can recognize discrete spatial patterns (Gatrell et al., 1996) that may not generally be obvious in global statistics. Local indicators produce an image which gives the size of the autocorrelation around each pixel.

One of the key globalmarkers of autocorrelation is Moran's index, I (Moran, 1948) described in equation (1):

$$\mathrm{I}= \frac{\mathrm{N}\sum_i \sum_j \mathrm{w_{ij}}(\mathrm{X_i}-\bar{\mathrm{X}})(\mathrm{X_j}-\bar{\mathrm{X}})}{\left(\sum_i \sum_j \mathrm{w_{ij}}\right)\sum_i (\mathrm{X_i}-\bar{\mathrm{X}})^2} \tag{1}$$

where N is the total number of pixels, X_i and $X_j$are the intensity at points I and j, respectively (with $i \neq j$), X is the average value and w_{ij} is a component of the weight matrix. $I \in [-1; 1]$: if $I \in [-1; 0)$, the autocorrelation is negative; if $I \in (0; 1]$, the autocorrelation is positive. Hypothetically, if I converges to 0, there is null autocorrelation; however, in most cases, rather than 0, the value used to certify the presence of invalid I autocorrelation is given by equation. (2):

$$E(I) = -\frac{1}{\mathrm{N}-1} \tag{2}$$

where N is the number of events in the whole distribution. The second global indicator of spatial autocorrelation is Geary's C (Geary 1954), represented by equation (3):

$$\mathrm{c}= \frac{(\mathrm{N}-1)\sum_i \sum_j \mathrm{w_{ij}}\,(\mathrm{X_i}-\mathrm{X_j})^2}{2\mathrm{w_{ij}}(\sum_i (\mathrm{X_i}-\bar{\mathrm{X}})^2)} \tag{3}$$

where the symbols have similar meanings to those in equation (1). $\mathrm{C} \in [0; 2]$: here, if $\mathrm{C} \in [0; 1)$, the autocorrelation is positive and if $\mathrm{C} \in (0; 2]$, it is negative. If C converges to 1, there is an invalid autocorrelation.

The most common local markers of spatial autocorrelation, known as LISA, are local Moran's I (Anselin, 1995), local Geary's C (Cliff and Ord, 1981), and Getis–Ord local Gi (Getis and Ord 1992). Thelocal Moran's I index is given by equation (4).

The local Moran's I index is defined as

$$\mathrm{I_i} = \frac{(\mathrm{X_i}-\bar{\mathrm{X}})}{\mathrm{S_X^2}} \sum_{j=1}^{N} (\mathrm{w_{ij}}(\mathrm{X_j}-\bar{\mathrm{X}})) \tag{4}$$

the Local Geary's C Index is given by

$$\mathrm{C}= \frac{\mathrm{n}-1}{\sum_{i=1}^{n}(\mathrm{X_i}-\bar{\mathrm{X}})^2}\,\frac{\sum_{i=1}^{n}\sum_{j=1}^{n}\mathrm{w_{ij}}(\mathrm{X_i}-\mathrm{X_j})^2}{2\sum_{i=1}^{n}\sum_{j=1}^{n}\mathrm{w_{ij}}} \tag{5}$$

and Getis and Ord's Gi is defined as

$$\mathrm{G_i(d)} = \frac{\sum_{i=1}^{n}(\mathrm{d})\mathrm{x_i} - \overline{\mathrm{x_i}\sum_{i=1}^{n}\mathrm{w_i(d)}}}{\mathrm{S(i)}\sqrt{\frac{[\mathrm{N}-1)\sum_{i=1}^{n}\mathrm{w_i(d)}-(\sum_{i=1}^{n}\mathrm{w_i\,(d)})^2]}{\mathrm{N}-2}}} \tag{6}$$

Geo-statistical analysis tools such as those described above are accessible through several open source devices (R for example), as well as in commercial software ranging from Geographic Information Systems (GIS) to image processing software.

(1) Local Moran's I: a high value means that there is a positive correlation both for high and low values of the intensity.
(2) Local Geary's C: this recognizes zones of dissimilarity between occurrences.
(3) Getis and Ord's Gi: a high value means a positive correlation for high estimates of the intensity while a low value means a positive correlation for low values of the intensity.

We used the Iterative self-planning information studies system (ISODATA) in the ENVI 5.3 software, which assigns pixels to classes depending on the degree of similarity in the multidimensional space formed by the stacked images (Lasaponara et al., 2018; Keeney and Hickey, 2015).

The importance of using unsupervised classification in archaeological applications is that: (i) it is an automatic process; namely, it normally requires only a minimal amount of initial input compared to supervised datasets; (ii) classes do not have to be defined a priori; and (iii) unknown classes may be discovered. We therefore had to assume that an archaeologically exclusive signature would likely occur outside the boundaries of known sites and the contexts of unknown sites. The image analysis software extracts the spectral statistics from the training data for each site; we also applied a supervised classification in order to quantitatively estimate the accuracy, which is not possible with an unsupervised classification.

3. Results

3.1. WV2 data processing and interpretation

It can be seen that the pan-sharpening that was applied increased the spectral resolution of the PAN image, which had a higher spatial resolution (Fig. 2), and also that the use of LISA statistical analysis significantly improved the enhancement (Fig. 3).

Fig. 3a-c shows the results of a LISA performed on channel 2 (green spectral channel) applied using both lag 1 and lag 2. In particular, from the zoom and the profiles shown in Fig. 3c, it is clear that both the Geary and Moran indices allow good discrimination of archaeological features from the surrounding areas. Fig. 3c the shows the LISA results as R (Geary), G (Gates) and B (Moran) (computed using lag1). The right-hand side shows the results as R(Getis), G (Geary) and B (Moran) (computed using lag 2); on the left, the two graphs show the values along the two transects crossing the archaeological features denoted as anomaly 1. Both clearly show that Geary and Moran (the red and blue lines, respectively) allow good discrimination of the archaeological features from the surroundings. In particular, Fig. 3c shows the values

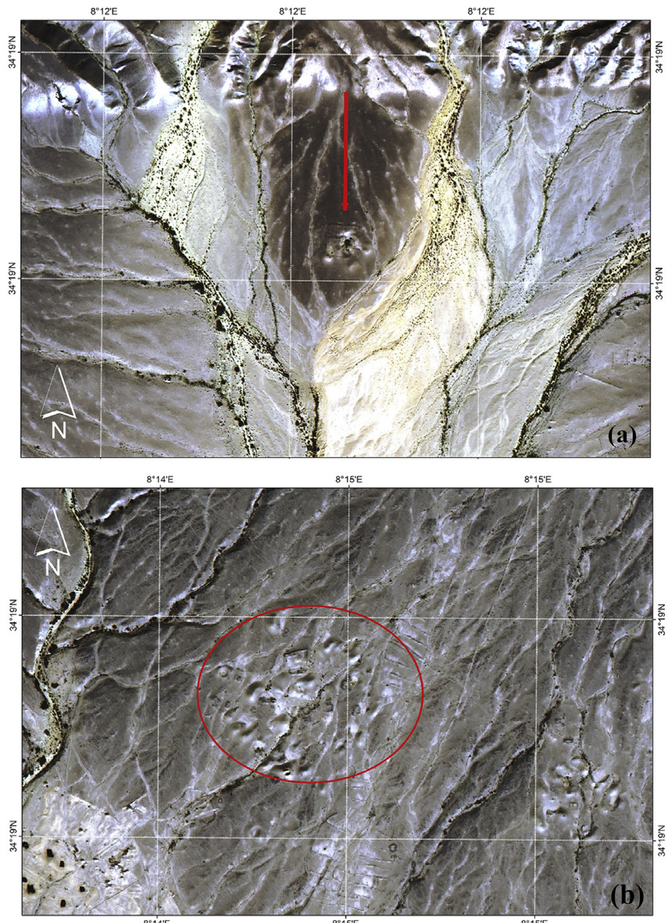

Fig. 2. Results obtained from pan-sharpened of WV2 MS data (RGB: 321): the red arrow in the top part marks anomaly 1(a) and the red circle in the lower part indicates anomaly 2(b). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

for a transect crossing the archaeological feature marked as anomaly 1 in Fig. 2 (a and c).

Considering both PAN and MS scenes along with other quite massive areas to separate the polygon and square shape geometric example region expected to be of archaeological sites interest. In particular, the classification of PAN image classifies the areas into four classes, and the highlighted areas of archaeological interest belong to the yellow class (Fig. 4 (b − c)). Note that the analysis of the ISODATA results (Fig. 5) was carried out on the data definitely known to be related to archaeological remains within the ROI (Fig. 4a).

Comparing the PAN and MSS data,it can be seen that the microrelief is more clearly visible in the PAN scenes and a quadrangular shaped-anomaly related to a buried structure can be seen. However, as expected, the best discrimination was obtained from the LISA analysis. As the microrelief was clearer in the PAN image than in the MS scene, the feature extraction based on the MS scene produced poorer results. In the other area within the ROI that was investigated, linear soil markings probably associated with a channel were detected. The unsupervised classification improved significantly when it was performed using both pan-sharpened scenes and a statistical analysis based on the Geary, Gates and Moran indices (Fig. 4b and c).

As expected, significant improvement was obtained from the unsupervised classification performed using the spectral channels together with the maps obtained from applying LISA to channel 2 using both lag 1 and lag 2. These results were considered to be much more useful than those obtained from supervised classification because they enabled previously unknown sites to be found without the need for any a priori knowledge.

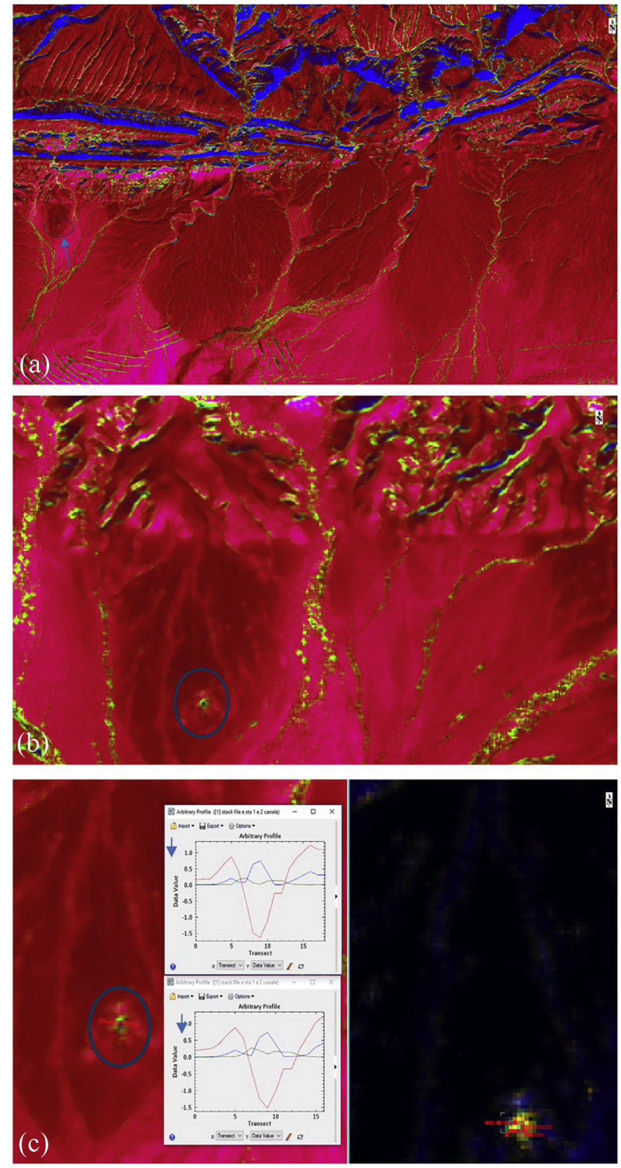

Fig. 3. (a) Results obtained from LISA statistical analysis applied to the green channel of WV2 MS data (channel 2) (RGB: Geary (R), Getis (G) and Moran (B), as in Lasaponara et al. (2018)); **(b)** zoomed detail of Fig. 3a; **(c)** zoomed details of Fig. 3a and b (See also Table 1). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3.2. Observations: analysis of suspected sites combined with field investigations

3.2.1. GNSS-based field investigation

The GNSS-based field survey performed within the study area was effective at confirming suspected sites that had been detected in the pansharpened VHR WV2 images. Furthermore, ground-truth data from the study area was used to confirm and complement the information obtained using the proposed GIS methods. In addition, the archaeological prospection based on the RS and GNSS that was carried out enabled the detection of unknown sites, providing new insights for future archaeological surveys of Roman southern Tunisia. In September 2017, the first author of this article took part in an expedition to obtain ground-truth data for suspected sites within the prospective sub-area.

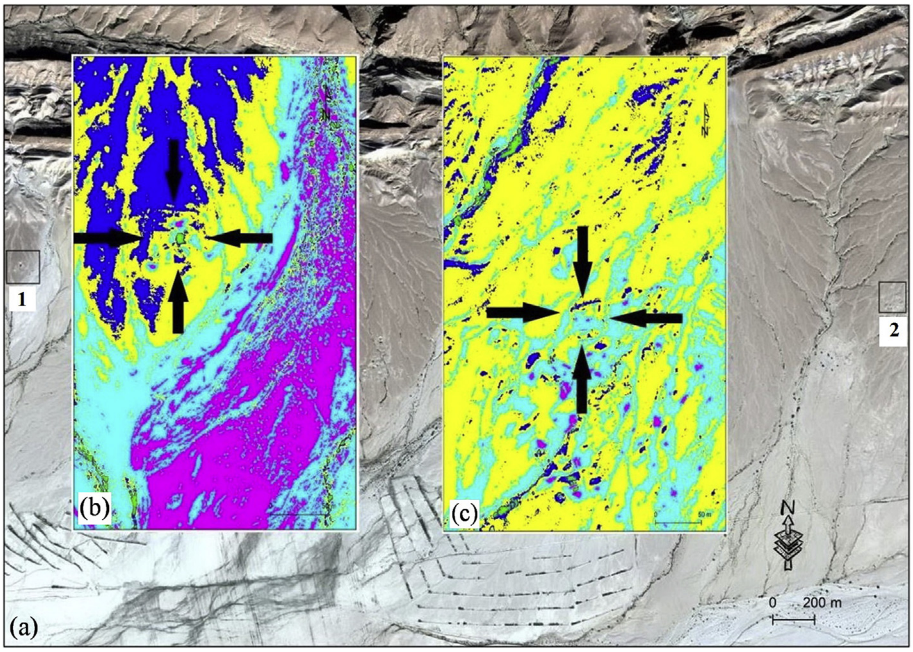

Fig. 4. ROI. Results of feature extraction from the WV2 green channel (channel 2) image: **(a)** ISODATA and **(b, c)**, locations of the rectangular patterns at sites 1 and 2, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

The integrated scientific investigation conducted in December 2017 led to the discovery of two ancient sites located in the southwest of Tunisia. The investigating group went directly to the suspected sites that could be seen clearly in the satellite imagery, taking full advantage of the ancient road based on historic maps from Tacape to Capsa. When analyzing WV2 high-resolution satellite imagery of one of these key areas in southern Tunisia, our team discovered two new sites. In some cases, the findings represented entirely new sections of previously uncharted Roman roads (Fig. 6), or showed that the scale of roads that were already known had an even greater extent than previously thought. The newly discovered forts located in the south of Tunisia helped to answer a long standing question about how remote areas could have supported long-term settlement. Previous archaeological surveys in this region had discovered forts and other settlement sites, accompanied by much pottery evidence.

3.2.2. New discoveries

3.2.2.1. Newly discovered site no. 1. This site is situated in Gafsa, about 10 km from El-Metlaoui and 30 km from Chebika in Henchir Alima. From the WV2 VHR image of the prospective sub-area, a square-shaped mark can be seen northwest of the site (Fig. 7). Each side of the suspected area was measured as being~50 m long. In addition, on December 23, 2017, the exploration team arrived at another site about 10 km north of the first spot and, turning south to cross the wadi, found many pottery and brick fragments.

The suspected site had no complete walls; however, the remains of four wall piers were investigated. Pottery and brick fragments were scattered among the walls and their surroundings. Based on the remains that had been observed, we therefore confirmed this suspected site to be a Roman fort.

3.2.2.2. Newly discovered site no. 2. This site is located in Gafsa, about

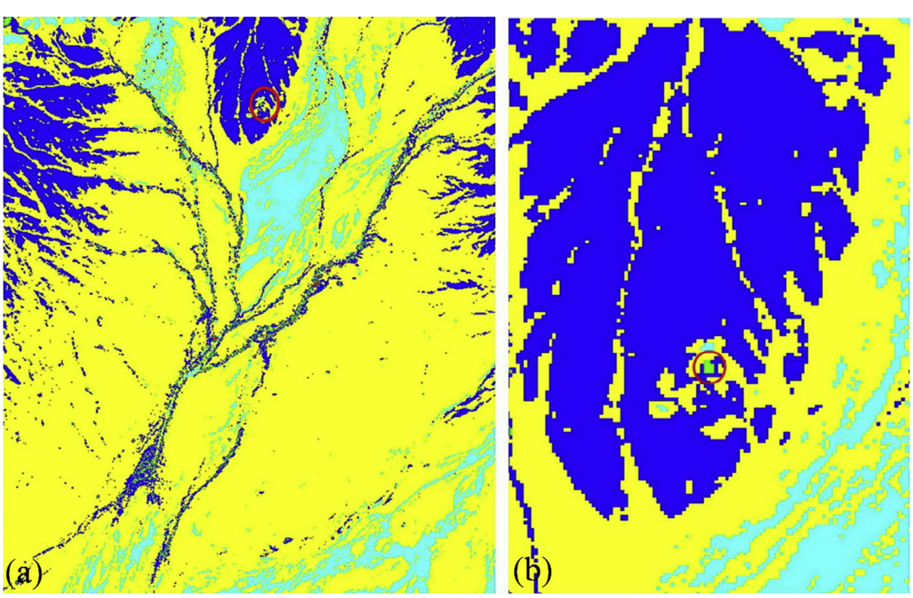

Fig. 5. (a). Results obtained from the unsupervised classification: the red circle is related to anomaly 1, which is highlighted in Figs. 2–4 a.**(b)** Zoomed in area of the results obtained from the unsupervised classification. The red circle is related to anomaly 1, highlighted in Figs. 2 and 3. The green pixels inside the red circle are also related to this anomaly. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

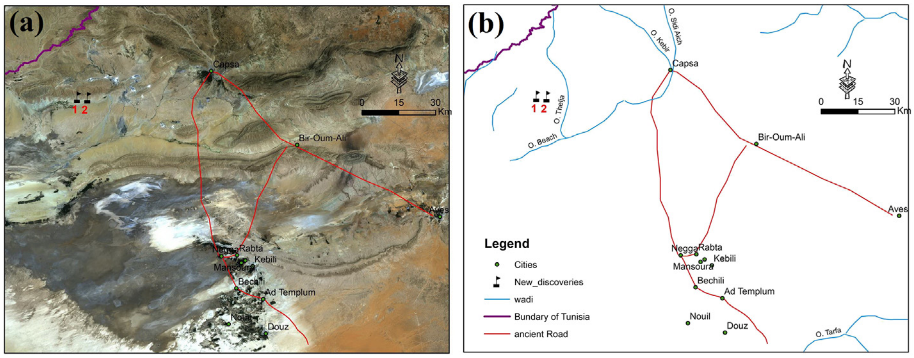

Fig. 6. **(a)** Landsat 8 image of suspected archaeological sites (discoveries 1 and 2); **(b)** comprehensive investigation map of the ancient road from Capsa to Tacape in southern Tunisia.

18 km from El-Metlaoui and 25 km from Chebika. From the WV2 VHR image of the prospective sub-area, a square-shaped mark can be seen northwest of the site (Fig. 8). Each side of the suspected spot was measured at ~60 m long.

On December 23, 2017, the exploration team arrived at a site about 10 km north of the first suspected site and turned south to cross the Melah Wadi. Across the site, many fragments of pottery and brick fragments from the Roman period were found (Fig. 8d). Ceramic and brick fragments were scattered among the walls and their surroundings. Thus, based on the observed ancient remains, we confirmed that this was the site of a Roman fort.

The two newly discovered sites were found by the authors in December 2017 by using GIS combined with historical records and satellite remote sensing; the discoveries were then confirmed by GNSS-supported ground-truth surveys. The strategic locations of the newly discovered sites have led to a lot of speculation about what these sites were in the past. By integrating our discoveries with GIS and remote sensing imagery, this article tries to address the spatio-temporal distribution of the archaeological sites and to reconstruct the Roman defensive system in this area.

3.3. Reconstructing the Roman military fort system

The use of geospatial analysis enabled us to improve the discrimination of the different buried structures (walls and roads) dating from the main Roman period in the WMV. This was possible using the methodological approach that was adopted, which made use of the sites of archaeological interest, their layouts and the surrounding areas. In particular, the results of the geospatial studies allowed us to: (1) detect unknown archaeological sites, (2) reconstruct the shape of Wadi El Melah during the main Roman period, and (3) detect and map newly discovered archaeological sites. In this study, currently, the spatial description of new archaeological sites detected using the WV2 images was processed by LISA. Generally, our research results showed that the WV2 data are flexible and valuable data sources that can be used in operational archaeological studies. The use of these data allowed us to not just address the complicated matters involved in detecting buried archaeological sites in a highly disturbed landscape but also to produce a spatial description of buried archaeological sites. Finally, it is important to highlight that the majority of the WV data, enhanced using LISA, is significant not only because it can provide more information about the areas of study but also because it can support feasible techniques for protecting invaluable archaeological sites.

During the Roman period, the Wadi el Melah valley was an area where large seasonal movements to and from the summer areas on the high steppe occurred – the area was firmly controlled by the Roman army. This control was achieved through a network of tracks and a

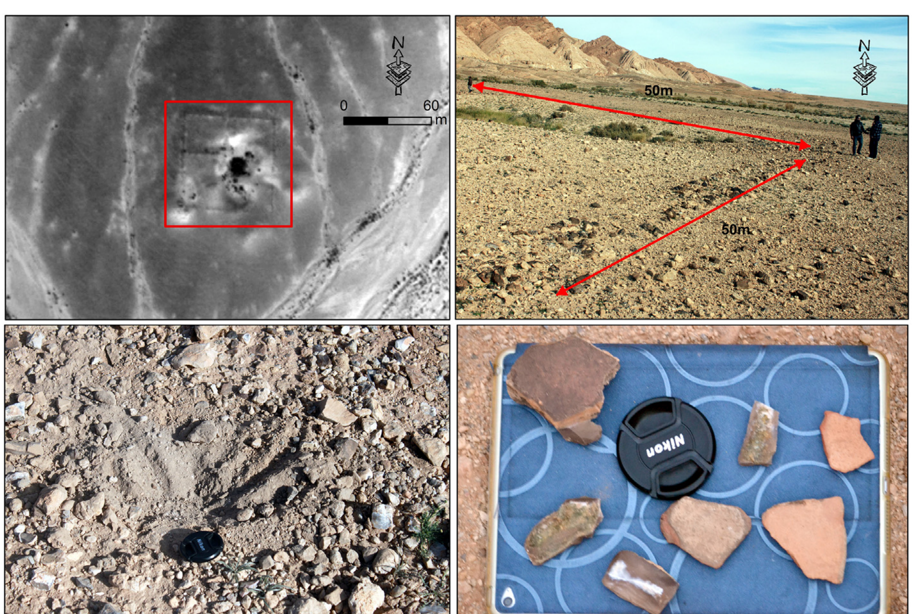

Fig. 7. **(a)** WV2 VHR PAN image of site 1, **(b)** field photos ofwall remains; **(c)** reddish burnt soils, and **(d)** pottery fragments.

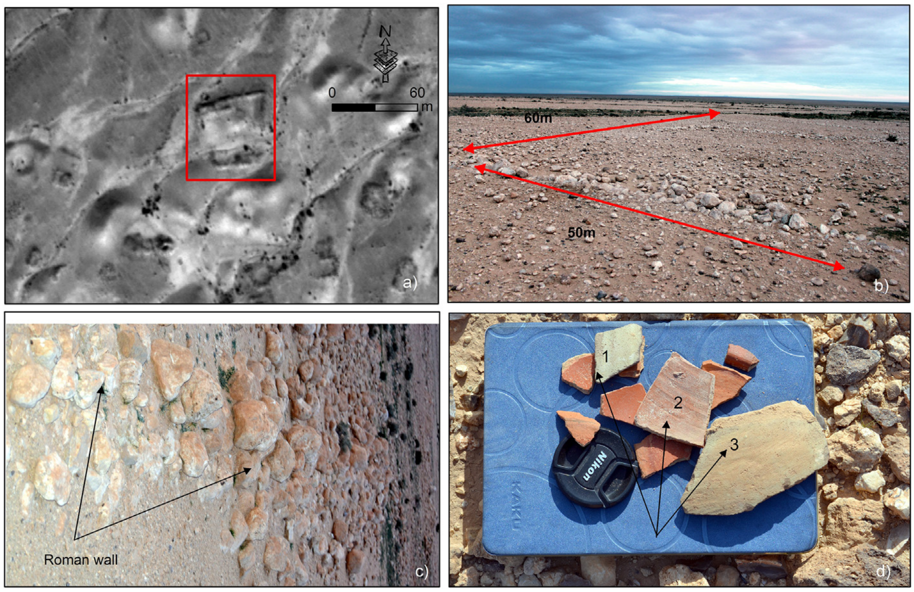

Fig. 8. (a). WV2 VHR PAN image of site 2; **(b and c)** Field photos of wall remains and **(d)** pottery fragments.

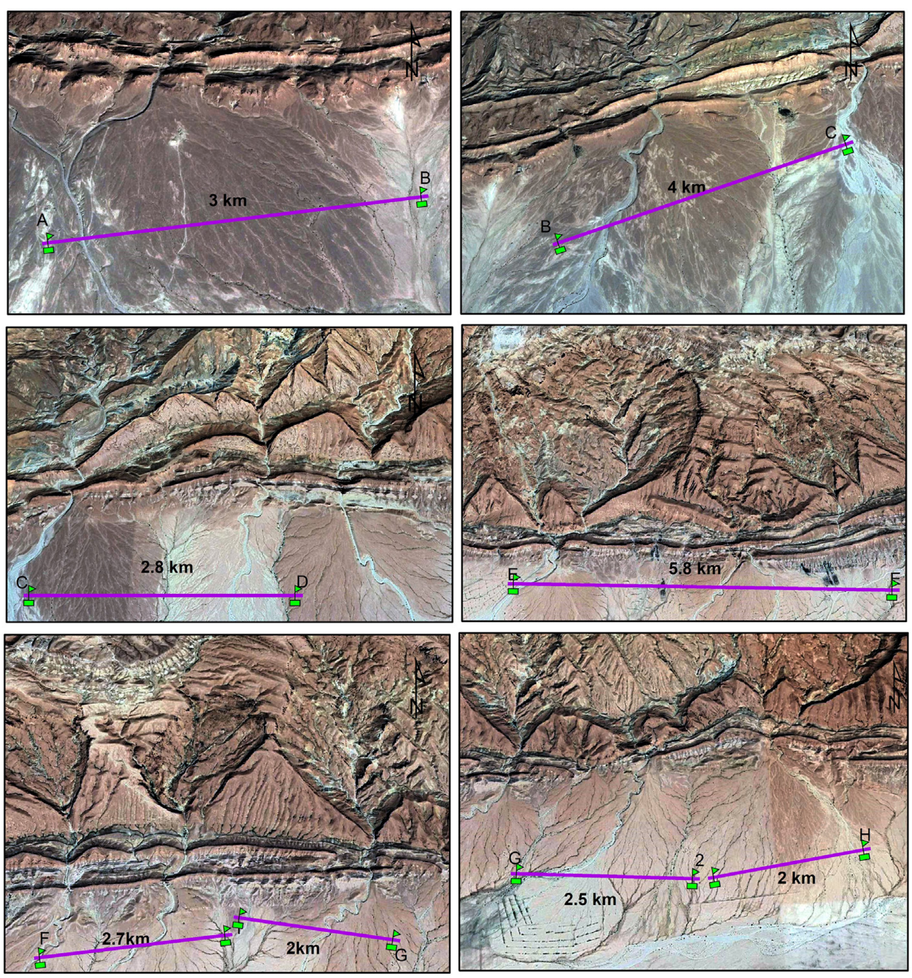

Fig. 9. Comprehensive interpretation map of Roman forts and the distance between them (The base map is Google Earth VHR imagery, acquired on 5 July 2013).

series of fortified positions. Many sites that appear to be military structures forts or towers of various sizes have been identified at these positions (Toussaint, 1906) based on their layout and the methods used to construct them, as well as their positions. The study area, the valley of the Wadi el Melah, was a region of vital importance in Roman times. It offered the possibility of well-developed irrigated agriculture on the one hand and the circulation of commercial exchange on the other hand. This commercial activity and its importance in this period must

Table 1
Characteristics of WV2 data.

Sensor	Band	Wavelength (μm)	Spatial Resolution (m)
PAN	–	0.45–0.80	0.46
MS	Blue	0.45–0.51	1.84
	Green	0.51–0.58	
	Red	0.63–0.69	
	NIR	0.77–0.89	

be studied in parallel with the strategic tracks and the military works created by the Romans. Thus, in this paper, we have revealed the existence of eight Roman forts (Fig. 9) in this area (sites A – H: see Table 2); these forts controlled the passage to the Saharan plateau located to the north of this mountain range between Chebika and Metaloui. This means that there was a possibility of finding this Fossatum within this defensive sector and, using remote sensing data, we discovered two Roman forts (site 1 and site 2) (Figs. 7 and 8). These fortifications were used by advance units as frontier posts. Small square fortresses with 50-m-long walls and a single gate were constructed through the Roman territories. These forts were related to the limes (Fossatum) or played a role in controlling the trade and travel corridor and were characterized by the long distance about 2.5 km between them (Table 2). These limes consisted of fortresses for use by legions as well as a system of roads used for the rapid transit of troops as well as, in some places, extensive walls, such as were built across the mountains of southern Tunisia to protect the area from attack. The so-called limes of southern Tunisia are perhaps the best example apart from the ultimate one the Great Wall of China, which was an attempt to construct a continuous man-made fortification along the length of an entire border a massive undertaking. This paper explains how we reconstructed the Roman military forts by using satellite analysis of Roman fort sites in southern Tunisia (Fig. 10). An appraisal of the data using a spreadsheet demonstrated an association between the Roman forts and the limes, which can be related to the likely course of events during the Roman conquest of the area. As result, according to our discoveries and the literature, we made a logical reconstruction of the Roman defenses in southern Tunisia, hence demonstrating that the fortifications in this area were a military project aimed at the defense, protection and control of the limes. These strategic, parallel or radial routes, which facilitated trade, were largely controlled by fortifications. This Romanised space was attached to the rest of the territory of the empire by a road network.

According to Trousset (Trousset, 1975; 1981, 1982, 1985a,b, 1986), the establishment of these defense structures in strategic positions expresses the will of the Romans to ensure order and protect their territory against nomadic incursions on the one hand, and their interest in controlling the main transport corridors as well as monitoring cultivable areas and points where water was available on the other hand. The potential sites I, J, K and L were carefully examined using both the WV2 VHR images and Google Earth imagery. However, no suspected spots were found. This was due to the complicated terrain and also the lack of high-resolution data for this sector.

In addition, the Roman army built fortifications along the empire's boundaries and within areas which required a permanent military presence to prevent indigenous uprisings. Although they possessed basic defensive features, these forts were never designed to withstand a sustained enemy attack, but rather to provide a protected living space as well as storage facilities for food, weapons, horses, and administrative records.

Over the centuries, Roman forts took on a remarkably standardized design, and impressive gates and forts were built in Tunisia during the 2nd century BCE. It was, in fact, during this time that Roman forts started to assume their standardized form. The limes consisted of fortresses for the legions as well as a system of roads for the rapid transit of troops and, in some places, extensive walls which were built across the mountains of southern Tunisia to protect the area from attack.

4. Conclusions and perspectives

The results of this study suggest that the integrated application of RS is a powerful tool for the prospection of archaeological sites and can provide very detailed characterization (identification, localization and mapping of different types of site) of the Roman forts present within the study area. Pixel-based analysis together with spatial analysis methods (LISA approach) were able to locate these sites using 1-m resolution WV2 imagery, while the unsupervised classification reflected a unique spectral anomaly reflecting the ecotone between willow and bare, non-vegetated ground. The use of LISA prior to the classification greatly improved the results of the unsupervised classification and the identification of archaeological features. This method would be most useful when combined with predictive models and used in the planning of field surveys of archaeological sites.

This paper showed that the complementarity of information from remote sensing data can help with the detection of and, more importantly, the interpretation of reconstructions of archaeological sites. This is of particular interest to the reconstruction of Roman forts at newly discovered archaeological sites in remote areas. As a result, one of the benefits of this research is that it demonstrates, from the perspective of archaeologists, the ability of satellite data to detect buried archaeological sites and, in particular,the value of high spatial resolution data currently being acquired by numerous satellite platforms.

Future challenges in this field are mainly concerned with the full exploitation of currently available high spatial resolution data to construct potential buffers for sites I, J, K and L by using radar and LiDAR techniques together with high-precision DEMs to provide details about

Table 2
Distances between the archaeological sites (forts, cities) in the study area (unit: km).

	A	B	C	D	E	F	Site 1	G	Site 2	H	Chebika	Metlaoui
A	0	3.1	6.8	8.8	12.0	17.7	20.8	22.3	24.7	27.3	3.0	40.0
B	3.1	0	4.0	6.5	9.4	15.0	17.7	19.9	22.0	24.2	6.0	36.5
C	6.8	4.0	0	2.8	5.4	11.4	14.0	16.0	18.5	20.8	8.8	33.7
D	8.8	6.5	2.8	0	4.2	8.5	12.6	14.5	16.5	18.0	12.7	31.0
E	12.0	9.4	2.8	4.2	0	5.8	7.2	10.5	12.8	14.9	15.4	27.4
F	17.7	15	11.4	8.5	5.8	0	2.7	4.7	7.0	9.0	21.8	21.3
Site 1	20.8	17.7	14.0	12.6	7.2	2.7	0	2.0	4.5	6.2	23.6	19.6
G	22.3	19.9	16.0	14.5	10.5	4.7	2.0	0	2.5	4.5	25.6	17.4
Site 2	24.7	22.0	18.5	16.5	12.8	7.0	4.5	2.5	0	2.0	28.5	14.6
H	27.3	24.3	20.8	18	14.9	9.0	6.2	4.5	2.0	0	30	12.5
Chebika	3.0	6.0	8.8	12.7	15.4	21.8	23.6	25.6	28.5	30	0	45.0
Metlaoui	40.0	36.5	33.7	31.0	27.4	21.3	19.6	17.4	14.6	12.5	45.0	0

A: Henchir Dghima, **B:** Henchir el Blida, **C:** Henchir Merchene, **D:**Henchir Wadi Hamda, **E:** Aioun Ameur, **F:** Henchir Segdoud, **G:** Henchir Rass Alima, **H:** Khanguet Thelja.

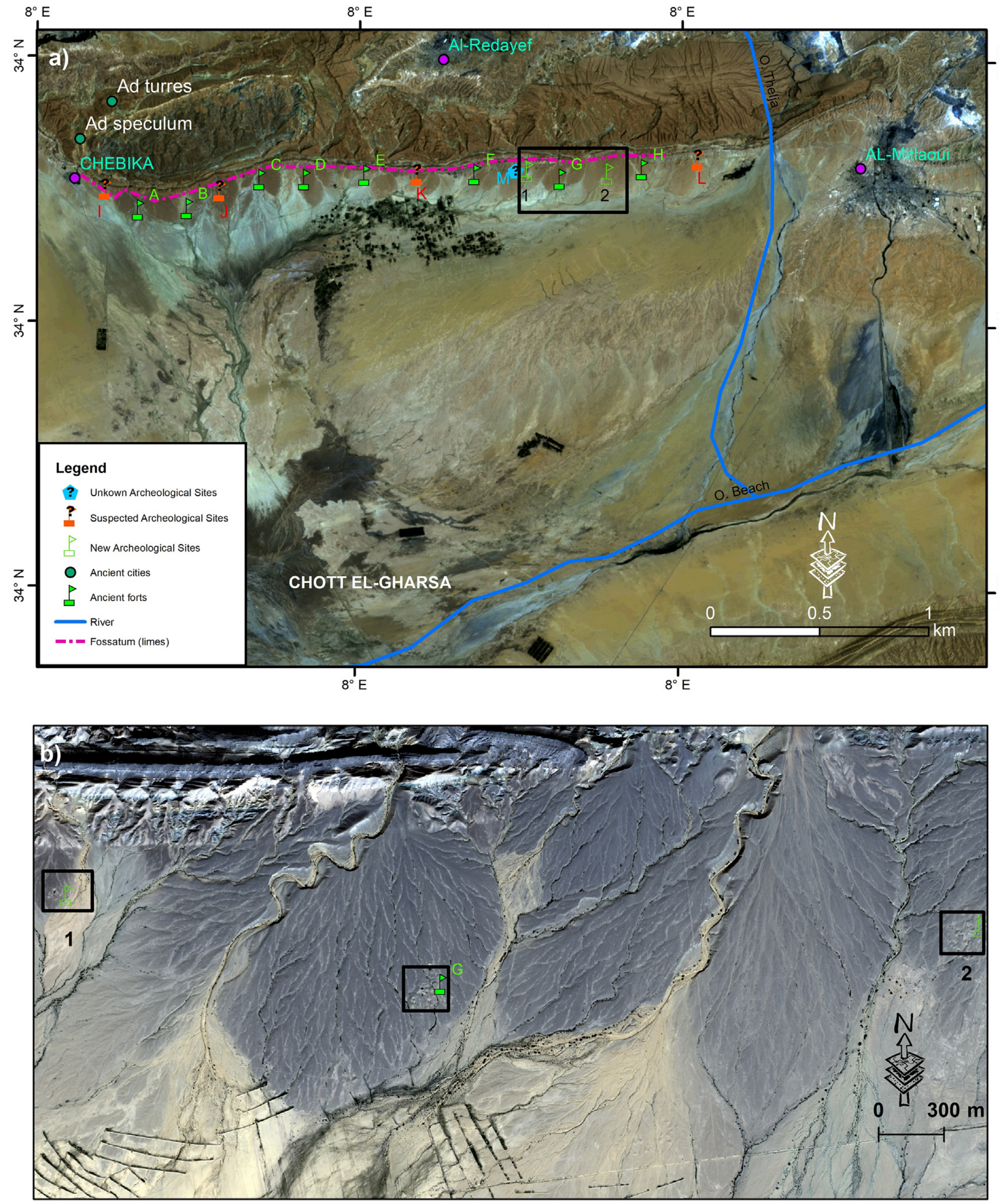

Fig. 10. (a) Comprehensive interpretation map of Roman limes and forts based on archaeological remote sensing; (b) sub-image corresponding to the area marked by the white box in a, showing the location of new discoveries.

the sub-surface conditions. Additionally, the same methods can be also applied to aerial photographs, including historical records and declassified satellite images. In the future, it will also be possible to apply these techniques to geophysical investigations of the arid desert areas of southern Tunisia.

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