Surface deformation data in the archaeological site of Petra from medium-resolution satellite radar images and SqueeSAR™ algorithm

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A B S T R A C T

Petra is a famous archaeological Nabataean city, carved out of stone, hidden by towering sandstone mountains in Jordan. Slopes are continuously affected by rock falls and local sliding events, involving volumes from less than 1 m³ to few hundreds m³. To investigate long-term cliff evolution and the impact on monuments, an area of about 50 km², including Petra Archaeological Park and its surroundings, was analysed with the SqueeSAR technique, an advanced Interferometric Synthetic Aperture Radar (InSAR) algorithm. The analysis of 38 satellite radar images, acquired between 2003 and 2010, allowed the identification of about 62,000 Measurement Points (MPs) for which it was possible to estimate the displacement time series along the satellite Line Of Sight (LOS). A close up to relevant monuments and comparison with ground-based geotechnical monitoring was implemented, revealing a major stability against medium-large potential rock falls, detectable with present method.

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1. Introduction

Petra is the famous ancient Nabataean city carved out of stone, hidden by towering sandstone mountains in Jordan. Although uninhabited today, during ancient times it was a wealthy trading town, capital of the Nabataean kingdom. Petra is one of the world’s most famous archaeological sites, where ancient Eastern traditions blend with Hellenistic architecture. In 1994, the UNESCO Management Plan highlighted Petra’s cultural, natural and socio-anthropological value, as well as its “striking varied geological features and landscapes”. From a geological point of view, the whole area of Petra is characterised by outcropping rocks belonging to the Cambrian-Ordovician sandstone of Disi and Umm Ishrin formations. The hand-carved rock monuments of Petra and the narrow access canyon (the Siq) are almost entirely cut in the Umm Ishrin sandstone that can be sub-divided into three main units, according to their texture, mineralogical composition and geotechnical characteristics [1]. The geomorphology of the site is the result of long and short-term factors affecting this part of its territory such as tectonic uplift, erosion due to runoff, differential erosion and weathering of sandstone materials. The slopes generally presents a rupestral aspect, mainly massive [2]. Nevertheless, discontinuities of various types are in place, mainly related to bedding (generally horizontal), tectonic activity (faults, master joints, mainly sub-vertical), geomorphological activity (from vertical to medium-inclined joints). Sub-vertical and medium-angle dipping joints intersecting horizontal bedding are quite frequent and observed during field investigation. Furthermore, stresses that act on the slopes and blocks that form Petra can cause progressive enlargement of fractures and consequently unstable conditions that may lead to collapses with potentially hazardous consequences to tourists that crowd daily the Siq and other areas, during their visits to Petra [3]. Dimensions of sliding/falling blocks are depending on local orientation, density and persistence of discontinuities, varying from few cubic meters till hundreds.

In this context, the present study aims to contributing to the investigation of ground’s deformation by generating ground motion mapping over the whole archaeological site through the use of multi-temporal satellite radar images, in some areas integrated with ground-based geotechnical sensors [4].

Finally, the current space technologies and new achievements, also including ground-based monitoring and expert field survey, can be considered as a main tool for management plan of UNESCO sites located in geo-hazardous areas.
2. Method and applicability

In the last few years, obtained results have shown how satellite radar monitoring is contributing to improve the level of understanding of ground instability and landslide phenomena [5], thanks to the quantitative information provided about their movements, the ability to perform wide area surveys and to measure displacements with the accuracy of mm. Nevertheless, the success of SAR landslide and ground deformation analysis depends not only on the type of sensor, acquisition strategy, and processing method but also on the area characteristics, including the size, slope and orientation of inclination, land use, displacement rate, and temporal and spatial variability of the movement [5].

In many cases, interferometric synthetic aperture radar (InSAR) results have determined the boundaries of landslides, characterised the state of movement and identified new phenomena that were not detected using other techniques [6–10]. InSAR data are quite effective in mapping slow landslides [11] that can then trigger faster and more disruptive events.

The SqueeSARSTM algorithm [12] is an advanced InSAR technique capable of identifying a larger number of Measurement Points (MPs) in non-urban areas compared to other InSAR techniques based on the Permanent (or Persistent) Scatterer (PSS) approach, such as the PSInSARTM technology [13,14]. By exploiting different kinds of natural radar targets and applying a statistical analysis of the radar returns at different times, this technique is capable of detecting millimeter-scale changes of the ground surface.

The PS technique [14] was introduced in the late 1990s to overcome the limitations of conventional InSAR analysis, making it possible for satellite radar data to detect mm-scale displacements affecting a special set of radar targets, called PSS. SqueeSARSTM analysis can be seen as the natural development of the PS approach, taking advantage of two types of ground reflectors: point-wise PSS and Distributed Scatters (DSs). PSs correspond to point-wise, high reflectivity, radar targets (e.g. buildings, rocky outcrops, linear structures, etc.), while DSs correspond to homogeneous areas of at least a few dozens of pixels, sharing very similar reflectivity values and exhibiting some level of coherence (e.g. areas of short vegetation, debris, desert areas, etc.). The use of both families of MPs allows SqueeSARSTM to significantly improve the spatial density of MPs and the precision of the interferometric measurements, compared to PSInSARSTM. In fact, the larger the density of MPs, the more effective the filtering of spurious atmospheric phase components [15]. Recently, [16] and [17] have investigated the benefits of the PSS InSAR processing techniques, for multi-temporal deformation analyses of built heritage sited within urban contexts, with critical discussion of the limits that these approaches encounter when used over vegetated and bare areas. According to the authors, significant advances can be achieved with the use of SqueeSARSTM analysis [12], as implemented in the present paper.

For all MPs, it is possible to estimate their average displacement rate and time history of movement along the satellite line of sight. Common to all InSAR data, the displacement measurements provided by SqueeSARSTM are differential in space and in time: they are spatially related to a reference point identified within the area of interest (AOI) and temporally to the date of the first satellite acquisition of the dataset. Whenever the average displacement rate of a MP is computed, an a posteriori standard deviation of the Line of Sight (LOS) velocity value is estimated as well, providing a very useful tool for precision assessment and data analysis.

Finally, the application of medium-resolution InSAR technique can be, in the case of Petra site, fully justified to understand large deformation patterns (i.e. tectonic) as well as local deformation of mass movements at a precursory stage, showing slow velocity and a reflecting area, theoretically, higher than 100 m², which actually is much less. This can be achieved only with the use of SqueeSARSTM analysis [12] and the presence of many MPs close to each other that can help in reducing uncertainty. The technique was then applied to verify the ground stability of the main monuments in Petra, the behaviour of large blocks potentially unstable and, finally, to verify the potentiality of the techniques and possible precursory stages, in occasion of large collapse of monuments occurred during the time-window covered by satellite data. Minor rock falls cannot clearly be investigated with medium-resolution InSar techniques.

Finally, some of the sites and large blocks investigated in this study are also equipped and monitored with traditional geotechnical sensors. As a consequence, the average displacement rate and time history of movement from MPs were compared with ground-based geotechnical instruments, providing a reliable validation of satellite data.

2.1. Area of interest and satellite dataset

The AOI has an extension of about 50 km² and it includes the archaeological area of Petra and surrounding areas. Fig. 1 shows the location of the AOI on Google Earth. From a morphological point of view, the AOI is a rocky desert mountainous zone without vegetation, with few villages and buildings. In particular, the Petra area is located in a valley surrounded by cliffs, close to the Wadi Musa village.

The dataset used in this study is composed of 38 radar images acquired by the ASAR C-Band radar sensor mounted on board the ENVISAT satellite operated by the European Space Agency from 2002 to 2012. Thirty-eight radar images over Petra were acquired along a descending orbit (Track 78-Frame 2997), from January 19th, 2003 to June 6th, 2010, with satellite swath S2 and polarization VV. The incidence angle was approximately 23°.

2.2. Data density and distribution

The spatial density of the MPs turned out to be very high in built-up and rocky areas, exceeding 1500 MPs/km². In areas characterized by a thicker layer of moving sand, however, reflectivity changes reduce the temporal coherence of the observations, leading to a lower density of radar targets. This can be easily recognized by comparing the density of MPs and the slope. Due to the missing of a detail geological map at local scale, it was assumed that flat area are mainly covered by sand then a lower density of radar targets. Steep slope are mainly considered as constituted by exposed rock.

Such distribution is also depending from slope exposure. Due to the rough topography of the AOI and the geometry of acquisition of the ASAR Envisat sensor, some areas could not be illuminated by the radar beam (shadowing effect), while others are characterized by foreshortening and layover effects [18], limiting the amount of information that can be extracted over very rough topography. As a confirmation of the above, most of detected MPs in the Petra area are located on W facing slopes due the effects of geometric distortion. The comparison of MPs density on flat and steep slopes as well as the polar plot distribution of MPs according to slope exposure are reported in the following Fig. 2, confirming the previous assumption.

The reason for a better data density in West exposed slopes lies in the modality of radar acquisition. Envisat images have been acquired along descending orbits (from North to South) with the radar sensor looking west, therefore the system is almost insensitive to North-South displacements, since they cannot create any range variations. In the mean time, the satellite acquisition mode, which is not orthogonal to the ground, causes a perspective deformation in the images due to land’s topography. In Fig. 3, a set of points evenly sampled in range direction for an undulating
2.3. Data processing

The SqueeSARTM analysis over Petra, patent by the company of two involved authors, identified about 62,000 MPs, with an average spatial density of ~1200 MPs/km², comparable to what can be obtained in desert areas. Despite the nominal repeat-cycle of the ENVISAT satellite was 35 days, the dataset exhibited much larger temporal gaps between two successive acquisitions, with a maximum of 280 days. In InSAR applications, the uneven sampling of the temporal axis can create severe limitations to InSAR analyses increasing the probability of phase unwrapping errors. However, it has a weak impact on projects where the areas of interest are affected by slow or very slow deformation rates, though temporal decorrelation phenomena can limit the quality of the results [18].

Since just one acquisition geometry was available, only one component of the 3D displacement vector affecting the identified MPs within the AOI was estimated. Therefore, pure horizontal and vertical components could not be discriminated. However, given the geometry of acquisition, the system was more sensitive to vertical, rather than horizontal, displacements. The pixel resolution of ENVISAT Strip-Map data is 20 × 5m, therefore, deformation pro-
cesses involving surfaces lower than 100 m² are difficult to detect, although PSSs can correspond to an object much smaller than the resolution cell [14] and SqueeSAR™ analysis [12] can significantly increase the accuracy.

The C-band SAR sensor mounted onboard the ENVISAT satellite operated at a central frequency of 5.405 GHz with a wavelength of 5.66 cm. This sensor allowed the measurement of unambiguous InSAR measurements of a single, isolated, target if displacement is lower than about 1 cm between two successive SAR acquisitions (to allow for proper phase unwrapping procedures). Typically, local deformation phenomena largely exceeding such a threshold creates a loss of coherence that no longer creates a MP.

2.4. Data precision

Results obtained from multi-interferogram techniques, such as SqueeSAR™, are essentially a set of MPs. As far as their precision and accuracy is concerned, we should distinguish between:

• the geographic (or UTM) coordinates of each MP;
• the displacement data (i.e. how this point is moving in time);
• the size of the investigated area for each MP.

Without going into the details of different geocoding procedures or reporting a long list with different precision figures for different sensors and acquisition modes, Table 1 provides some typical values for C-band Strip-Map ENVISAT acquisitions.

<table>
<thead>
<tr>
<th>Deformation rate</th>
<th>± 1 mm/y</th>
</tr>
</thead>
<tbody>
<tr>
<td>Displacement error</td>
<td>± 5 mm</td>
</tr>
<tr>
<td>Elevation</td>
<td>± 1.5 m</td>
</tr>
<tr>
<td>Positioning error (East direction)</td>
<td>± 7 m</td>
</tr>
<tr>
<td>Positioning error (North direction)</td>
<td>± 2 m</td>
</tr>
</tbody>
</table>

The present ground-based monitoring techniques have been analysed to calibrate and verify the displacement detected from satellite radar interferometry, in the case studies discussed below.

3. Results and discussion

The distribution of the MPs is shown in Fig. 4. Different colours of the MPs correspond to different velocity values in mm/y. As already mentioned, the incidence angle of the radar beam was about 23°; therefore, InSAR data are very sensitive to vertical displacement components.

The colorbar associated to MP velocity values was selected so that green points correspond to stable areas, yellow and red points highlight MPs affected by a displacement away from the sensor, while blue dots move towards the sensor. Other conventions can be found in the scientific literature. Data have been saturated between ± 5 mm/y for visualization purposes, although larger displacement rates are present and affect many MPs.

Apart from the spatial distribution of the MPs identified by the radar and their LOS velocity, it is possible to visualize a time series of displacement data for each MP. Multi-interferogram InSAR results provide not only a synoptic view of the displacement field affecting the AOI in the period of time covered by the radar scenes, but also precise information concerning the motion of each MP identified by the radar.

Common to any InSAR measurements, SqueeSAR™ results measure the projection along the satellite LOS of the relative displacement of a point P with respect to a reference point P₀, supposed motionless or with known motion. In time, data are relative as well and, although the master image used in the processing was different, the reference instant of the final results (i.e. when all time series equal zero) is the acquisition time of the first radar image of the dataset.

The reference point is usually selected on the basis of two criteria:

• the consistency of its radar return, i.e. the point should exhibit a very stable reflectivity value in all available images;
• geological properties, i.e. the point should be selected in an area presumably stable.

It should be noted that the time series of P₀ will reflect on all MPs as a signal common to all time series. This is why the selection of the reference point is not as delicate as it is in conventional geodetic networks, where the number of MPs is typically orders of magnitude lower than for SqueeSAR™ data. Any "wrong choice" can be detected and fixed quite easily: the mean value of all time series (typically thousands) is computed by automatic quality check procedures, highlighting any common mode characterized by a significant signal power. If that is the case, the reference point is changed until the quality check is passed successfully, taking into account the statistical analysis of the radar returns for ranking the possible candidates [15].
Fig. 4. Average LOS displacement rate of the MPs identified from the ENVISAT descending dataset (A) and average LOS displacement rate standard deviation plot of the MPs identified with the ENVISAT descending elaboration (B).

To understand the potential variability in each MP, Fig. 4 also shows the estimated standard deviation of the velocity values. Values range from 0.2 to 0.6 mm/y. Apart from decorrelation phenomena, phase spurious components are largely dependent on atmospheric effects [15]. These are independent of the wavelength of the sensor and generate spatially correlated phase components. Therefore, the precision of the InSAR results depends on the distance between the MP under analysis and the reference point: the shorter the distance, the better the precision (Fig. 4). It should be noted that relative accuracy is higher whenever point P and point P0 share very similar elevations and this was confirmed in our results.

The main deformation phenomena in the area of Petra can be related to either regional trends of local movements such as rock falls.

From a regional point of view, available data do not show a major distributed pattern. Only a strip in the central part of investigated area is showing an increasing of distance from the satellite (lowering of the topographic surface up to −5 mm/y in the map of Fig. 4). The reason for such a trend is not very clear; a possible interpretation can be related to the weathering and surface erosion of a local geological formations, as can be seen from the overlap of geological map with the available MPs. Also the nearby presence of the expanding village of Wadi Musa and the Kings Highway 35 could play some role.

Among the largest archaeological structures, the Siq of Petra is playing a major role and then requiring high attention [19]. The Siq is a 1.2 km long natural structure formed by very steep slopes with variable heights by the ground level, from few meters, at the entrance, to several tens of meters at the end of the path. Outcropping rocks belong to the Cambrian-Ordovician sandstone of Disi and Umm Ishrin formations [1].

The rock falls are generally located at the border of the Siq, with a small surface extension that is, likely, far behind the resolution of MP technique. As a matter of fact, no significant surface deformation phenomena were detected in this area, at least for those exhibiting a surface potentially detectable with InSAR technique (Fig. 4).

Local deformation phenomena in the area of Petra are mainly related to rock falls. Collapses are caused by different factors: expansion-contraction phenomena caused by temperature variations, freeze-thaw cycles, erosion and enlargements of fractures caused by rainfalls or vegetation growth, seismic events, etc. Rock falls cause abrupt changes in the land surface, leading to phase decorrelation phenomena. In other words, InSAR data should be used to detect possible precursory motion, rather than to study the rock fall itself.

3.1. Discussions over specific areas

The entire archaeological areas of Petra were studied, with a greater detail in some close up such as relevant monuments, ground-based monitored sites or sites with recent collapse. They include relevant monuments (Royal Tombs, the Great Temple, the Monastery-Deir, the Treasury-Khazneh), sites with potential large instabilities (huge block along the Siq, huge block in the Treasury valley) and sites, also with ancient and recent rock fall, that are not exhibiting deformation or even MPs (the Theatre, the newly discovered archaeological site in 2016, the collapse near steps leading to High Place of Sacrifice, the Street of Facades, the collapsed Muesra tomb).

The analysis highlighted that no major surface deformation phenomena were affecting Petra valley neither on the monuments nor on the cliffs during the monitored period (2003–2010), for the adopted methodology. Only some limited lowering trends have been discovered in the Royal tombs area and on two unstable blocks in the treasury area and on the Siq. Following are the details of the above described specific areas.
3.2. Royal Tombs

The Royal Tombs of Petra are made of four distinct tombs: the Urn Tomb, the Silk Tomb, the Corinthian Tomb, and the Palace Tomb. The four tombs lie on the Western cliff of Facades streets, after passing the Roman theatre and overlook the main walkway of Petra (the colonnade street). They have been named “Royal Tombs” because of their size and decoration. Despite their relevance, they cannot be linked to any Nabateean King in particular.

The tombs are located in a vertical cliff, with an irregular and plateaux on top.

The performed investigation revealed a large number of MPs almost stable but also seven PSs showing a lowering trend, with a velocity of about 1.5 mm/y (Fig. 5). Considering that some of these MPs are positioned on top of the facades, close to the vertical cliff, a periodical verification is required and, may be, the installation of a proper ground-based geotechnical monitoring system would be necessary.

3.3. Great Temple

The Great Temple is the largest free-standing structure in central Petra. This is a two-level structure that was discovered in 1992. Based on the style of fragments found at the site, archaeologists believe the Great Temple was built in the last quarter of the 1st century BC and further enlarged in the 1st century AD. It continued to be used until the Byzantine period (5th century). Although the excavators believe that the building had a religious use, the sorts of activities that might have taken place here, such as cultic rituals, sacred dramas or musical performances, remain a mystery [20].
According to available MPs, in the period 2003–2010, no significant deformations were affecting the Great Temple in Petra. Some examples of MPs are reported in the following Fig. 6.

3.4. Monastery (ad-Deir)

The Monastery is the largest monument of the archaeological Park, carved into the sandstone hill by the Nabataeans in the second century A.D., with a huge ancient building’s entrance. It measures some 44 m high by 51 m wide with the doorway over 6 m high. The ad-Deir or Monastery, produced for the Nabataean King Obodas III who died around 85 BC but continued to have a cult following long after, which is why many archaeologists believe his tomb was completed around the mid - first century AD. [21]

The MPs (2003–2010) investigation is not revealing significant deformations affecting the archaeological structure (Fig. 6). Interesting is also the cluster of lowering MPs in the Northern corner, in an area with important water infiltration in that period, later on stabilised by the Petra Archaeological Park.

3.5. Treasury (al-Khazneh)

One of the most widely known monuments in Petra is the Khazne (Khaznet Fir‘aun i.e. Pharaoh’s Treasury). It measures some 44 m high by 51 m wide with a doorway over 6 m high. The Treasury is one of the most elaborate temples in the ancient Arab Nabatean Kingdom in the city of Petra. As with most of the other buildings in this ancient town, this structure was carved out of a sandstone facade. It has an architecture with classical Greek-influence [23].

The area is showing geomorphological features that suggest potential slope instability. As a consequence, a wireless ground-based monitoring instrument constituted by a invar wire extensometer equipped with temperature and air humidity sensors, was installed in May 2013, on top of a large rocky block [4]. Measurements are executed every 15 minutes. Available MPs (2003–2010) are exhibiting a deformation rate less than 1 mm/y, suggesting a general stability of the site (Fig. 6). Similarly, the ground-based wire extensometer is not detecting any surface deformation in the monitored period 2013–2015, confirming the coherence between the two different monitoring techniques.

3.6. Huge block in the Siq

A large sandstone block, potentially unstable, is located in the northern sector of the Siq, isolated from the rear rock-mass by a sub-vertical fracture, partially eroded at the base in correspondence of a softer sandstone layer.

The rock block was equipped with a wireless ground-based geotechnical monitoring, composed by a wire extensometer located on the top, a biaxial tiltmeter installed on the East face and a temperature and air humidity sensors. Measurements are executed every 15 minutes, since May 2013 till now. The combined analysis of the measurements provided by the wire extensometer and by the tilt meter is suggesting a closure of the sub-vertical fracture. The total closure is, at the end of 2015, now equal to 5.5 mm [25].

Some MPs were identified on top of the block in the period 2003–2010 and two of them labelled as A and B in Fig. 7. These MPs show, respectively, an average velocity of −0.23 mm/y and −0.24 mm/y, close to zero and below the detectable threshold with the InSAR analysis. This is confirming the missing of any remarkable block deformation of the block, at least along the LOS. Considering the descending orbit of satellite, the surface topography and the
prominence of horizontal displacements as verified from geotechnical monitoring in the period 2013–2015, the combined evaluation of PSs data with ground-based ones, is in agreement with a model of a stable block, with a limited horizontal deformation.

As a confirmation, a preliminary two-dimensional stress-strain analysis was also carried out, using a commercial finite difference code software; the results show the global stability of the block in the present conditions and the possibility to become unstable only under seismic conditions [25].

A further monitoring is clearly required, especially to investigate possible changing in the present deformation trend.

3.7. Huge block in the Treasury valley

The Treasury area is an important canyon, perpendicular to the access Siq. In this area, despite of the Treasury monuments, there are vertical cliffs with several potential unstable blocks. A major block is located on the Northern part of the canyon, western side, apparently detached for the parent material and potentially unstable.

The MPs surveyed on the site are showing either stable surface displacement and lowering of about 1–1.2 mm/y, with a constant trend for the whole period. Considering the geomorphological conditions of the block a continuous ground-based monitoring is required, even if it is not affecting historical monuments but potential run out of displaced boulders may impact on visitors (Fig. 7).

3.8. Theatre

The “Theatre” in Petra, originally Hellenistic in design and dating back to the 1st century AD, was refurbished by the Romans after they annexed Nabatean in 106 AD. The seating extended to the orchestra’s floor level, typical of Hellenistic design. It was capable of seating of about 10,000 spectators. The entire seating, except for the extreme ends was carved out of the mountain and one whole street of facades was wiped out to form the back wall. The holes seen in the back wall are the interiors of the tombs destroyed when this was done. The stage backdrop was built up in stone but this was destroyed likely in the earthquake of 363 AD.

Fig. 7. View of a huge block in the Siq (A) and of a huge block in the Treasury valley (B) with average LOS yearly displacement rate of the MPs and selected time histories.
Petra’s theatre, cut out of sandstone cliff face, is presently badly deteriorated due to weathering and erosion [22]. The front of the theatre, including most of the stage was badly damaged by floods.

The remote sensing survey was not capable to detect MPs directly in theatre, likely because of the geometry of acquisition. The few points in the surroundings cliff are not showing movements in the investigated time-window (Fig. 8).

3.9. Newly discovered archaeological site in 2016

Recently, a large structure that had previously eluded detection was discovered in the area of Petra [24]. By combining data gathered by Google Earth and satellite sensors, they observed the shape of what may have once been a giant stone platform, located about 900 m outside Petra’s city centre. Image sharpening applied to the satellite views of the site revealed four areas with unusual features that could represent human-made structures, the researchers reported.

Located on a plateau within one of those areas was their most significant find a giant platform measuring about 56 by 49 m, topped with a smaller platform that was fronted with columns and crossed by a stairway. Terrace walls supported the large platform’s western side.

The newly discovered platform was probably built during the second century near the city centre when the Nabataean civilization was flourishing, and it appears “highly likely that the platform and structures were initially constructed to serve ceremonial purposes.” [24].

Not a large amount of MPs were detected on this site, likely because of the presence of sand that is limiting the reflectivity of radar waves. Thus, the almost nil vertical displacement in available MPs, is suggesting a limited sand erosion in the investigated time-window (Fig. 8).

3.10. Collapse near steps leading to High Place of Sacrifice

Out of the Siq and Treasury and before of the Theatre, some tombs on the Eastern cliff are exhibiting some collapses dated back on 1997 and on 14 October 2010 [3].

The remote sensing investigation was not revealing any deformation in the available time-window (January 2003–June 2010) suggesting that the collapse of October 2010 was not exhibiting remarkable precursory phenomena (Fig. 9), with a brittle rupture and sudden fall.

3.11. Street of Facades

Along the street of Facades, after the Theatre in the direction of Colonnade street, some minor rock fall affecting the Southern cliff are well evident.

Fig. 8. View of Theatre (A) and of the newly discovered archaeological site in 2016 (B) with the average LOS yearly displacement rate of the MPs and selected time histories.
No MPs have been detected in the period 2003–2010 (Fig. 9), likely due to the limited size of the block or exposure and low reflectivity of predominant sand material, all around the block.

3.12. Collapsed Mueesra tomb

Mueesra tomb is located in the Northern part of the Petra archaeological park. The tomb was collapsed on March 2009 with the mechanism of a vertical sliding.

The radar interferometry was not able to detect the collapse (Fig. 9), also considering that available algorithms generally do not maintain the signal after a huge break down in the survey.

4. Conclusion

The present research is dealing with the application of radar interferometric data (ENVISAT) elaborated by an advanced SqueeSAR™ algorithm, to investigate regional deformation and medium-large potential rock falls in the archaeological Park of Petra, also affecting rupesrian monuments.

The spatial density of identified MPs within the AOI is extremely good in built-up and rocky areas (higher than 1000 MPs/km²), while in areas characterized by a layer of moving sand it drops to a few MPs/km².

As a general conclusion, there is no evidence of major ground deformation phenomena in the Petra archaeological park, at least during the 2003–2010 period, covered by our satellite dataset.

Only a large block on the Siq is slightly tilting, according to ground-based geotechnical sensors, not confirmed from satellite interferometry due to missing of vertical displacement. Another large block in the Treasury area is exhibiting some sinking MPs, at the limit of resolution for the radar interferometry. Thus, in this case, considering the presence of wide cracks on surface, the implementation of a ground-based monitoring system will be useful. Also in the Royal tombs sector there are few MPs with a limited vertical sinking, surrounded by stable MPs, suggesting the need of a periodical inspection of such sites. The ancient rock falls in the Facades street are presently stable, for the adopted methodology.

From a methodological point of view, results obtained in this study confirmed the main advantage of remote sensing techniques: the ability to obtain a synoptic view of possible surface deformation phenomena affecting large areas and the possibility to then integrate this information with other in situ observations. In general, satellite InSAR measurements do not replace traditional ground monitoring instrumentations but are complementary to them, due to the much larger spatial distribution.

On the other hand, minor small rock falls, of the order of cubic meters, clearly recognizable on site are hardly detectable with medium-resolution interferometric data provided by the Envisat ASAR sensor due to decorrelation phenomena that might occur considering volumes/magnitude or involved surfaces of potentially unstable rocks with respect to the minimum detectable area of the technique (with ENVISAT about 20 m × 5 m) and the geotechnical behaviour of the Petra cliff and rock, characterized by a brittle rupture mode. In the latter case, the analysis could be better concentrated in a smaller time-window, generally prior to collapse).

Finally a further improvement of InSAR data should be based on satellite data with much higher temporal and spatial resolution, such as the X-band COSMO-SkyMed constellation or TerraSAR-X/Tandem-X sensors.

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