From space to ground. Digital techniques for the investigation of monuments and sites

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Abstract

The scope of this work is to present an integrated methodological multi-scale and multi-temporal approach for the study of ancient monuments in their environmental context. The presented work showcases the interdisciplinary research experience gained during the last years by the Remote Sensing and Geo-Environment Lab (ERATOSTHENES Research Centre) of the Cyprus University of Technology. The developed capabilities of the Eratosthenes Research Centre derived from the successful implementation of various national and European research projects within the wider area of architectural heritage study and protection. In this framework geospatial tools, earth observation and in situ monitoring and measurements were merged and further investigated. The case study concerns Paphos town in Cyprus and particularly the archaeological site of Nea Paphos and the Hellenistic necropolis “Tombs of the Kings”, a UNESCO World Heritage Site.

The study encompasses a variety of technological tools to approach the area of interest, moving from a landscape level (macro-scale) to isolated monument scale (micro-scale). For the macro-scale approach novel earth observation and aerial image (semi-macro scale) processing techniques have been employed, while in a micro-scale level the study extents from the geometric documentation of the tombs to the image processing mapping surface weathering features, as well as seismic performance of single monuments. The overall results demonstrate that such geospatial data linked to the individual characteristics of each monument can assist towards the implementation of various directives and conventions, while offering an integrate understanding of the monuments state of preservation, not seen as an isolated unit, but as part of its natural and anthropogenic environment, inevitably affecting its viability in time and place.

Keywords

Architectural heritage; remote sensing; aerial images; Paphos; monitoring

I. INTRODUCTION

The paper aims to present a holistic framework based on various digital technologies for the investigation of monuments in different scales and levels. In the last years, research activities and projects have given the opportunity to implement different methodologies to an UNESCO World Heritage Site, in Cyprus (see section 2), targeting towards the further investigation and multi-temporal monitoring of the site as well as hazard detection and mapping. The overall results and their synthesis are here presented, targeting to demonstrate and highlight the potentialities offered by integrating space and ground technologies, for other important monuments and sites on the island and beyond.

Monuments and sites are systematically threatened by various anthropogenic and natural hazards such as climate change, urban sprawl, seismic activity, soil erosion etc. The complexity of the archaeological context itself, as well as the various types of occurring threats, makes the overall approach for preservation and protection of cultural heritage very complicated. To overcome several barriers, economic tightness included, innovative technologies and methods are needed to be implemented for acquiring reliable results in various scales: from a territorial level to the level of the monument itself. Several examples are found in the literature related to the use of non-contact and non-destructive techniques for monitoring cultural heritage sites [1]. In [2], earth observation was applied to detect illegal looting actions taken place in the historical city of Uruk, while in [3] earth observation was applied to map and monitor changes in the type and extent of land cover/use and habitat classes, which can be related to human pressures in cultural heritage sites over time.

II. CASE STUDY AREA

The area under investigation is located in the western part of Cyprus. The "Nea Paphos" archaeological site along with the "Tombs of the Kings" are listed as UNESCO World Heritage monuments since 1980. Both sites are found near the coastline on the western part of the modern city of Paphos (Fig. 1). The sites are considered amongst the most attractive sites for tourism in the island, with more than 200,000 visitors per year. The protected sites cover more than 1 square kilometer, a matter that implies the necessity of a landscape and environmental monitoring.

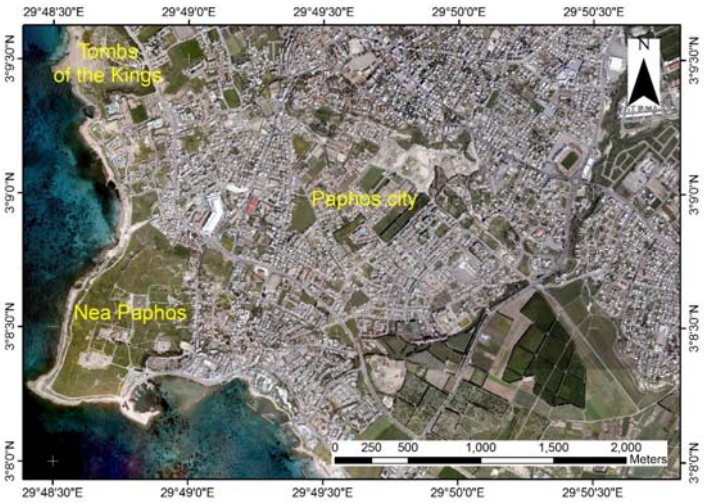


Fig. 1. Area of interest: "Nea Paphos" and "Tombs of the Kings" archaeological sites

III. Methodology

The methodology followed suggests a non-contact monitoring and investigation of the sites, based on a multi-level approach as shown in Fig. 2. In the macro-scale level earth observation space sensors have been used to map the various threats occurred through time (from 1980s' until today). Satellite data included low, medium and high resolution multi-spectral images, such as MODIS and Landsat series (Landsat 5 TM, Landsat 7 ETM+ and Landsat 8 LDCM sensors), used to examine and map potential hazards (such as urban sprawl, air pollution, landslides, fires, soil erosion) of the wider area of Paphos town. Technically, the images received the necessary pre-processing operations (i.e. geometric and radiometric corrections). Thereafter, various post-processing image analyses occurred separately for each hazardous parameter under investigation [4]. An overall hazard map of the area produced based upon the Analytical Hierarchy Process (AHP). The results evidenced critical areas of Paphos Region marked as high-risk zones.

Shifting to a middle range observation level, archive and recent aerial photographs (up to 20 cm spatial resolution), provided by the Department of Land and Surveys of Cyprus, have been processed and analyzed. In addition, archived Royal Air Force (RAF) photographs capturing the area under investigation during the 1940s, have been merged with modern orthophotos, aiding the detection of old traces and crop / soil marks in the area. Such marks have been lost during the last decades mainly due to soil erosion of the archaeological sites, and can be retrieved only through image enhancement.

Changing scale and moving to ground level, the research focused on the terrestrial investigation of a single monument (tomb). To this end, a geometric documentation of the monument has been carried out and various scenarios for its seismic performance were applied. In addition, digital image processing of rectified images of the monument's facades to map and quantify surface deterioration have been produced.

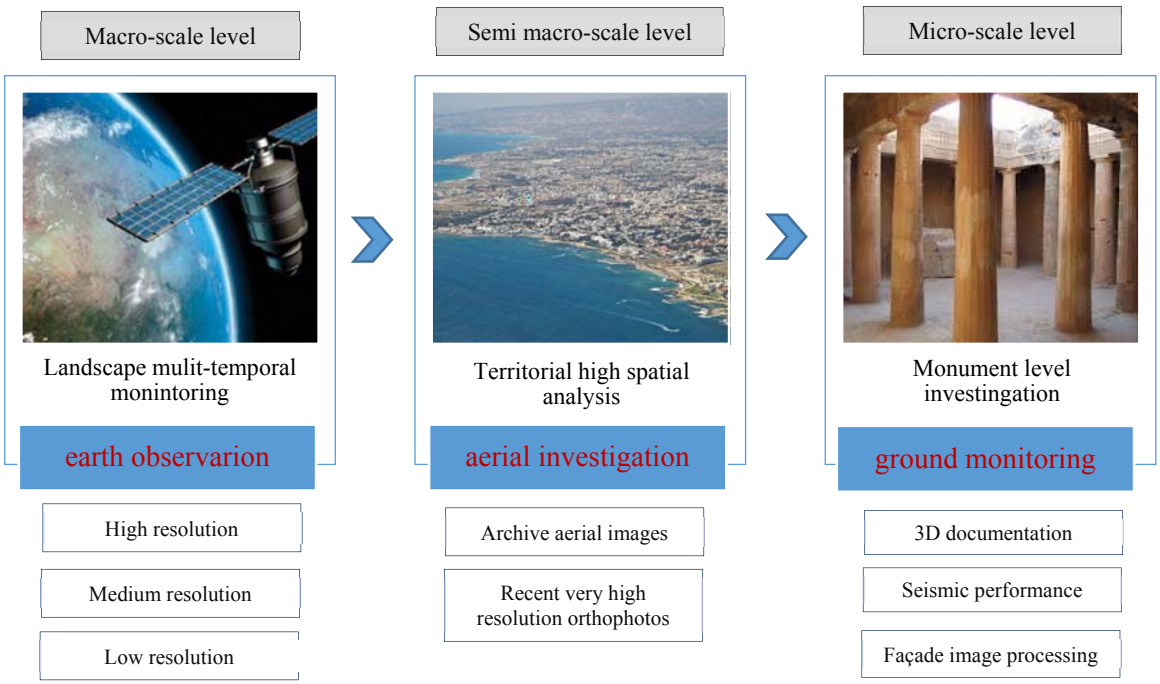
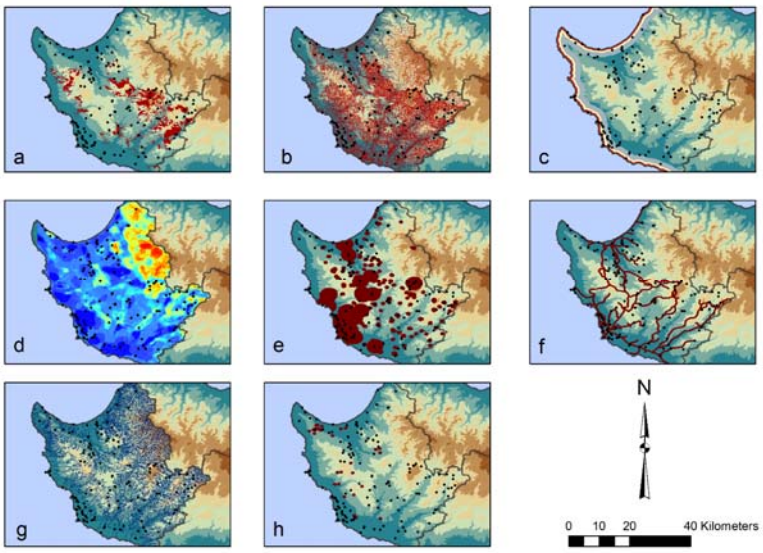


Fig. 2. Multi-level approach for monintoring monuments and sites

IV. Results

A. *Macro-scale level*

In the macro-scale level, the potential hazards of the wider area of Paphos were defined and evaluated using satellite multi-temporal datasets. The hazards were divided into two main categories: (a) natural (landslides; erosion; salinity and neotectonic activity) and (b) anthropogenic (urban sprawl; modern road network; drainage network and fires) [4]. Low resolution space data like the Moderate Resolution Imaging Spectroradiometer (MODIS) Terra and Aqua platforms and Defense Meteorological Satellite Program (DMSP) - Operational Linescan System (OLS), medium resolution images from Landsat and ASTER sensors, as well as high resolution data from QuickBird have been processed separately. Results from the analysis of the low-resolution MODIS Terra and Aqua products regarding the Aerosol Optical Thickness (AOT) over the area of interest for the entire year of 2012 have shown the AOT fluctuations over the seasons [5]. AOT is linked to the air pollution, and therefore insights regarding the impact of the pollutants to the standing monuments can be investigated. In a similar way, all the above mentioned hazards have been mapped for this area of Paphos town and region, using a Geographical Information System (GIS) (Fig. 3).



(a)

Fig. 3. Map indicating anthropogenic and natural hazards over Paphos District as follow: (a) Landsides map: very high hazard and high hazard areas are indicated with red; (b) Erosion map: areas where the soil loss is greater than the mean value soil loss of the whole district are indicated with red ; (c) Salinity map: areas closesly to the sea are indicated with red; (d) Tectonic activity: high and very high hazard area are indicated with red; (e) Urban expansion; (f) Road network proximity (250 m); (g) Drainage network (50 meter buffer zone) and (h) Fires map observed during the period 2010-2013 (see more details in [4]).

The overall results, generated hazard maps for each type of threat which was then grouped together following the AHP methodology [4]. These results were then further improved [6], based on the clustering of the monuments prior to the AHP evaluation. The various archaeological sites under investigation (including those mentioned in this paper) have been grouped into five main categories based on their characteristics, susceptible to related risks:

Class 1: Monuments/sites located in low elevations, far from the coastline, within active tectonic regions; close to main road network and urban areas. Limited threats from soil erosion, but within areas with high possibility of fires.

Class 2: Monuments/sites located on hilly areas, far from the coastline, within active tectonic regions; away from main road network and urban areas. Limited threats from soil erosion, but within areas with high possibility of fires.

Class 3: Monuments/sites located in very high elevations, far from the coastline, away from active tectonic regions; close to main road network and urban areas. Threats from soil erosion and limited threats from fires.

Class 4: Monuments/sites located nearby the coastline, in low altitude and in the vicinity of urban areas and main road network. Limited threats from soil erosion and limited threats from fires. Within active tectonic regions.

Class 5: Monuments/sites located in medium elevations, far from the coastline, within active tectonic regions; close to main road network and urban areas. Threats from soil erosion and limited threats from fires.

Paphos town with the ancient city and the necropolis ‘Tombs of the Kings’ enter in Class 4. The overall hazard map produced following the AHP methodology is shown in Fig. 4, evidencing that the area under investigation is marked as of “very high hazard”.

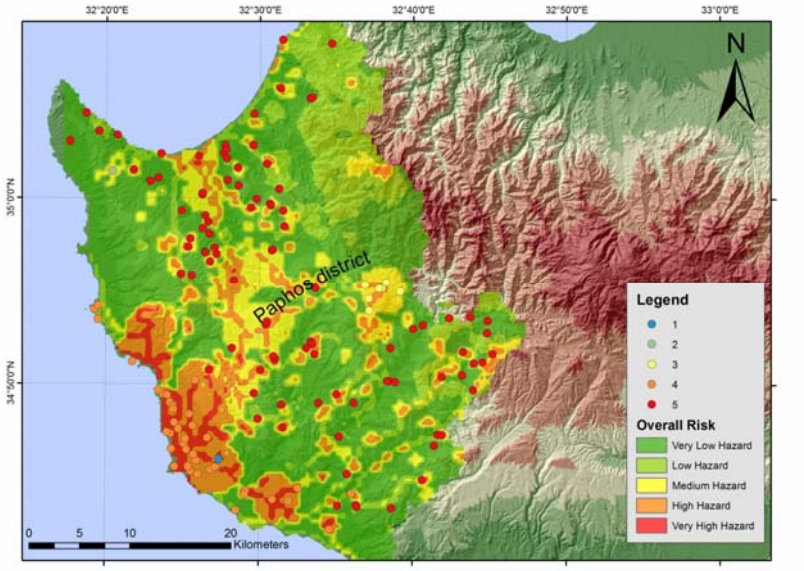


Fig. 4. Overall risk hazard map for the Paphos district, based on the clustering of the sites [6].

B. Semi macro-scale level

Beyond the known and standing monuments, these areas are also rich in terms of buried and still unexcavated archaeological remains (Fig. 5). To detect and map potential traces of the remains, archive and recent aerial photographs have been used. Towards this end, identification of potential crop and soil marks [7], which are considered as a proxy for buried archaeological remains was studied. Based on pan-sharpening techniques these marks could be enhanced and identified from recent orthophotos (see [7]). Several marks were also identified after photo-interpretation and *in situ* inspections, using Global Navigation Satellite Systems (GNSS). The rich context found at the archive aerial images indicates once again the important aspects of the cultural heritage that these sites are holding, which however can be threaten from various hazards, in this particular case, the soil erosion.

Fig. 5. High Pass Filter (HPF) transformation of archive aerial image (1945) and a more recent one (2014) over the archaeological site of Nea Paphos [9].

C. Micro-scale level

The micro-scale survey concerned a single monument, specifically Tomb 4 of the "Tombs' of the Kings" ancient cemetery. The geometric documentation was the backbone for all following digital and numerical elaborations accomplished in the micro-scale level. Various close-range techniques for the documentation of the site and its monuments have been carried out in recent years, mainly for research purposes. Terrestrial laser scanner (Fig. 6, left) and close-range photogrammetry have been processed in selected monuments to capture their geometry, decipher their architecture, as well as for future preservation and digital reconstruction research. Geometric documentation of Tomb 4, along with *in situ* inspection and mapping of the cracks observed, permitted its structural investigation. To correlate the monument's structural state of preservation to ancient or more recent earthquakes, a numerical finite element model of the structural resisting system of the tomb (geometry in a 3D space) including mapped wall crack pattern and the material properties was drawn and its seismic response to various time-history loading scenarios was simulated [8]. The overall results leaded to better understanding of the structure's behaviour (Fig. 6, right), while permitted speculation on other geo-environmental parameters that possibly caused material deterioration throughout the centuries. It was also concluded that frequent moderate seismic activity in the Eastern Mediterranean region increases the structural vulnerability of such monuments through increased cracking of

the stone wall material especially at the base level, and may lead to catastrophic collapse in case of low probability larger seismic events, with a recurrence rate greater than 2000 years. Therefore, the systematic monitoring, maintenance and retrofit of monuments accessible to the public should be amongst the general strategic priorities in a local level.

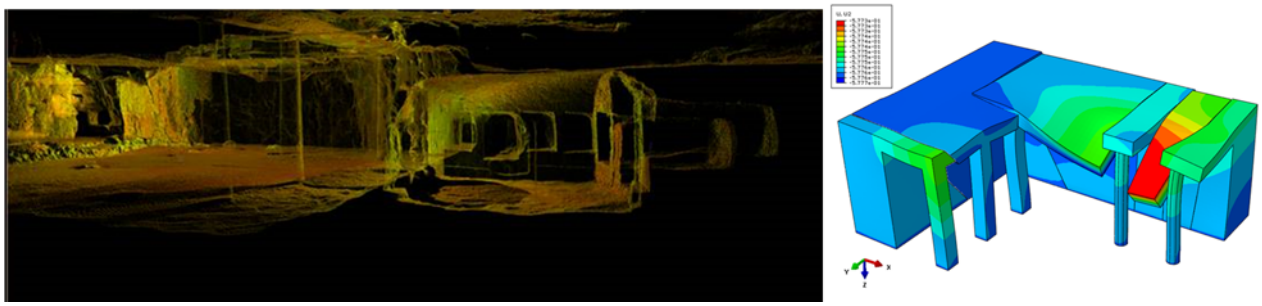


Fig. 6. Left: 3D documentation (points cloud) of one of the necropolis atrium tombs. Right: Distribution of maximum principal stresses [see more in 8].

A final application of the micro-scale analyses involved rectified Red-Green-Blue (RGB) photographs of the monuments' facades, using image classification techniques (Fig. 7). The orthophotos have been introduced, analyzed and processed using the ERDAS Imagine software. Supervised classification was applied using specific areas of the images as "training spots". In addition, a series of processing parameters, such as threshold filtering and image enhancement, have been implemented, resulting an overall mapping of the surface state of preservation of the tomb. Semi-automatic quantification of the individual weathering conditions on a larger scale on the monuments vertical walls was the overall result of the Digital Image Processing.

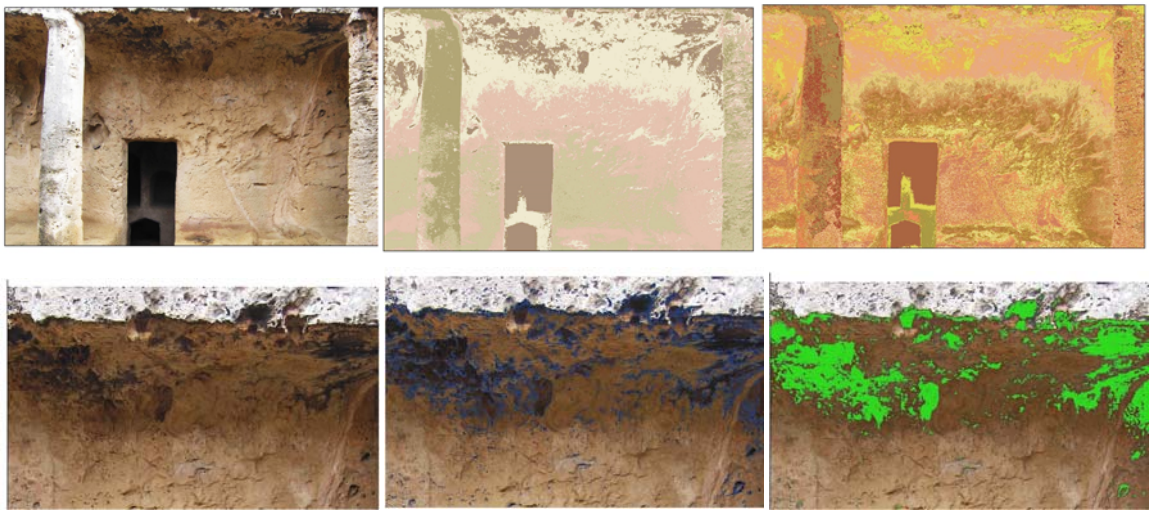


Fig. 7. Preliminary results of the Digital Image Processing. Above: Overall of the eastern internal wall of Tomb no 4, seen form the atrium. Below: Detail of the same wall highlighting voids or their contours.

V. Conclusions

Natural and anthropogenic hazards on monuments are directly or indirectly connected to a series of parameters to be taken into consideration, tangling a considerable number of disciplines involved and means to be employed. The present study displayed a methodological approach for the investigation of ancient structures, their sites and environment, shifting from space to terrestrial level, but most importantly operating in a non-contact, non-destructive domain.

The overall results and the integration of the data obtained from the different types of analyses, provided a unified visibility of the site, single monuments included. This approach consists of an operational methodological framework for archaeological sites and their surroundings strategic monitoring and protection, considering not only the expected natural deterioration of monuments, but also eventual risks provoked by the changing environmental context of the sites due to modern life's needs and evolution [9]. Therefore, directly linked to what, we may say, the World Heritage Convention since the beginning clearly sets as "… the cultural heritage and the natural heritage are increasingly threatened with destruction not only by the traditional causes of decay, but also by changing social and economic conditions which aggravate the situation with even more formidable phenomena of damage or destruction".

Even though outdated, still in a timely manner is here recalled the suggestion of the Convention for the Protection of the Architectural Heritage of Europe [10], which, in terms of European co-ordination of conservation policies, stressed the investigation of "the possibilities afforded by new technologies for identifying and recording the architectural heritage and combating the deterioration of materials as well as in the fields of scientific research, restoration work and methods of managing and promoting the heritage" Article 17(3)]. Indeed, the possibilities provided by innovative technologies currently in use offer great potential for systematic observation of cultural heritage sites in different levels and most importantly these technologies can readily be used due to a variety of free access data, a crucial advancement particularly in the cases of emergency. Towards this direction the INSPIRE European legislation foresees the creation of an infrastructure for sharing spatial data information. Amongst its 34 spatial data themes, protected sites and natural risk zones are included, offer readily support for the implementation and monitoring of environmental policies, reporting and easy access of environmental information for the public, as well as for other policy areas (e.g. disaster management, Copernicus).

On 18th of June 2003 UNESCO and the European Space Agency (ESA) signed an agreement to encourage earth observation sensors for monitoring cultural and natural World Heritage sites. The signing of the Agreement officially launched the 'Open Initiative on the Use of Space Technologies to Support the World Heritage' convention [10]. This agreement was emanated from the Convention Concerning the Protection of the World Cultural and Natural Heritage to develop scientific and technical studies and research to work out operating methods capable of counteracting various dangers that threaten cultural or natural heritage. The convention also argues the necessary measures needed to be taken in legal, scientific, technical, administrative and financial aspect for the identification, protection, conservation, presentation and rehabilitation of this heritage (articles 5c and 5d). The Open Initiative "*aims to develop a framework of co-operation, open to space agencies, research institutions, non-governmental organizations (NGOs) and the private sector in order to assist developing countries, though, space technologies to improve their natural and cultural conservation activities*". On 8 July 2016 Cyprus became the 11th country to sign the European Cooperating State Agreement, strengthening its relations with ESA also towards this direction. Within this framework, systematic efforts have been made by the authors in the last years in order to exploit the capabilities of earth observation as well as to downscale the level of work in a monument scale.

Future work foresees more terrestrial analysis at a monument level, involving the ground penetrating radar for structural investigation and possible failures, since past restoration works are not documented. This will trigger a more thorough structural analyses of single monuments and their performance, while the properties of building materials will be further examined.

ACKNOWLEDGMENT

The present paper is under the ATHENA project. This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691936. Work programme H2020 under "Spreading Excellence and Widening Participation", call: H2020-TWINN-2015: Twinning (Coordination and Support Action). Acknowledgment is due to the Director of the Department of Antiquities Dr. Marina Solomidou-Ieronymidou for supporting research by granting all necessary permissions and access to the sites.

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