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figg. 16

Petra and Beida (Jordan): two adjacent archaeological sites up to an exploitation of geomorphology-related topics for a cultural and touristic development

Petra e Beida (Giordania): due siti archeologici confinanti idonei per una valorizzazione di temi connessi con la geomorfologia nel quadro di un loro potenziamento turistico - culturale

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ABSTRACT – Petra and Beida are two adjacent archaeological sites in southern Jordan characterised by both a striking monumental heritage, and an imposing geomorphologic landscape. These sites, besides preserving important remainders of protohistorical cultures, contain the most important Nabatean vestiges of the entire Middle-East and have more recent, Roman, Crusade and Islamic, significant remains as well. On account of the importance of their archaeological and monumental heritage, the two sites are included in the UNESCO's World Heritage list and are the heart sites of a National Archaeologic Park. Less known, yet not less interesting, is the rich and striking geomorphologic heritage of the Petra-Beida area, characterised by tectonic troughs alternating with steep mountains riddled by canyons and passages to form a town of rocks. The intrinsic beauty and significance of landforms and landscapes could be the driving elements for touristic and educational aims, towards an integration of the geomorphologic heritage with the archaeological-monumental one. In this connection, both Nabatean water management systems and historical burials of monumental areas by flood events are primary links to an integrated approach, suitable for being exploited for tourism and cultural goals. Ongoing researches by means of GPS systems and laser scanning allowed us the detailed reconstruction of both parts of the Nabatean water systems and historical alluvial fills. The digital elaboration and modellisation, as well as computer simulations and reconstructions, besides their intrinsic scientific meaning, can be powerful tools for tourism improvement and educational work.

KEY WORDS: Geoarchaeology, Geotourism, Hydraulic System, Alluvial fill, Petra, Jordan.

RIASSUNTO – Petra e Beida sono due siti archeologici adiacenti del sud della Giordania caratterizzati da uno straordinario patrimonio monumentale e da uno straordinario paesaggio geomorfologico. Questi siti, oltre a conservare importanti resti delle culture protostoriche, includono le più importanti vestigia dei Nabatei dell'intero Medio Oriente. Comprendendo inoltre significativi resti crociati romani e islamici. In considerazione dell'importanza del loro patrimonio archeologico e monumentale, i due siti sono stati inclusi nella Word Heritage List dell'UESCO e sono i siti principali del Parco Archeologico Nazionale giordano. Meno conosciuto, ma certo non meno interessante, è il ricco e straordinario patrimonio geomorfologico dell'area di Petra-Beida, caratterizzato da valli tettoniche alternate a ripide montagne intagliate da un intrico di stretti canyon e fenditure a formare città di roccia. La bellezza intrinseca e l'importanza delle forme del rilievo e del paesaggio possono rappresentare elementi trainanti ai fini turistici e didattici verso un integrazione del patrimonio geomorfologico con quello

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archeologico-monumentale. In tale contesto, sia i sistemi Nabatei di gestione delle acque sia le testimonianze storiche di aree monumentali seppellite da eventi di piena sono elementi chiave per un approccio integrato archeo-geomorfologico adatto anche a scopi turistici e culturali. Ricerche tuttora in corso con sistemi GPS e laser scanner hanno permesso di ottenere una dettagliata ricostruzione sia dei sistemi di approvigionamento idrico dei nabatei, sia delle colmate alluvionali. L'eleborazione digitale e la modelizzazione, così come simulazioni virtuali e ricostruzioni al computer, accanto al loro significato scientifico intrinseco, possono rappresentare anche efficaci strumenti per la valorizzazione turistica e per la didattica.

PAROLE CHIAVE: Geoarcheologicia, Geoturismo, Sistemi Idraulici, Riempimenti alluvionali, Petra, Giordania.

1. – INTRODUCTION

Petra - UNESCO World Heritage Site since 1985, National Archaeological Park established in 1993 by the Jordanian Department of Antiquity and the District of Ma'an under the UNESCO's auspices (UNESCO, 1991) - is a unique place for the splendid blend of landforms and architectural elements evocatively complementing one another. On a smaller scale, the same elements characterise the near Beida -not by chance known with the telling name of "*Little Petra*"- which, besides being an important protohistorical site (COMER, 2003), is part of the same World Heritage Site of Petra itself.

Being it the destination of a crowd of tourists, the Petra-Beida site is justly famous all over the world: nevertheless, only the aesthetic beauty rather than the intrinsic significance of its notable geologic-geomorphologic heritage is well known and exploited. Indeed quite every touristic guide or leaflet reports about issues as the impressive physical landscape, the astonishing chromatism of Petra and Beida sandstones, the imposing Nabatean water system, the deviation of the Siq in order to prevent flooding and, not least, the serious problem of monument weathering. The geomorphologic importance of this site is somehow implicit in the first denomination of "*Naturalistic and Archaeological Park*" already given by Jordan authorities to the initial protected area. Indeed, the importance –also for cultural and touristic purposes- of geologic-geomorphologic features is substantiated by several papers both by earth scientists (*e.g.* PANIZZA & PIACENTE, 2003; FRANCHI *et alii*, 2004 and 2005) and archaeologists (*e.g.* LUBICK, 2004 ZAYADINE, 1992; PALUMBO *et alii*, 1995). Specifically, several places in the Petra-Beida territory could be regarded as sites of specific geologic and geomorphologic interest (*i.e.* geosites or geomorphosites): namely, the Siq (*cf.* PANIZZA & PIACENTE, 2003, p. 289) and the canyon housing the monumental area of Beida are both suitable for being improved as geomorphosites (*sensu* PANIZZA, 2001). Nevertheless, being the area included in an already formalized (year 1985) UNESCO site of major monumental, archaeological and historical value, the geologic-geomorphologic elements are suitable for being improved and exploited as primary value-added components in an integrated cultural and touristic framework. A key to such integration is how the Nabatean and Roman cultures adapted to a hard physical environment, a topic already known to and attractive for many visitors. Indeed, a first major issue is the impressive Nabatean-Roman water-system, consisting of thousands of channels chiselled into the rocky slopes and flowing to cisterns and fountains. A further attractive issue is concerned with historical flood-evidence throughout the entire Petra-Beida territory and the impressive Nabatean works addressed to flooding prevention.

The aim of this paper is a concise description of the geologic and geomorphologic framework of the Petra-Beida area (fig. 1) in connection with both the exploitation of the physical environment by the ancient cultures and the modern weathering and conservation problems. Ongoing surveys and 3-D modelling of both the Petra-Beida hydraulic system and the alluvial fill in the Siq, performed in the framework of an international co-operation between Urbino University, Italian CNR and French CNRS, are also briefly reported. Actually, the results of such studies, besides their intrinsic scientific meaning, could give an innovative impulse to a better popularisation –for tourism purposes as well- of both the fascinating topic of skilful water exploitation by the inhabitants of Petra and Beida, and the flooding impact on this territory during historical times (HENRY, 1985; RAIKES, 1985).

2. – GEOLOGIC AND GEOMORPHOLOGIC OUTLINE

Petra and Beida (fig. 1) are situated on the eastern side of the Dead Sea-Wadi Araba tectonic depression (Dead Sea rift, according to BENDER, 1968; MART, 1991 *cum bibl.*; a transform valley, according to GARFUNKEL & BEN AVRAHAM, 1996), a *c.ca* 15 km-wide topographic low formed by shearing along the transform separating the Arabian and Sinai plates (*cf.* SNEH, 1996; GINAT *et alii*, 1998, *cum bibl*). Petra and Beida are placed in a rugged mountain area, characterised by heights ranging from c.ca 850 m to over 1.000 m a.s.l. Such mountain

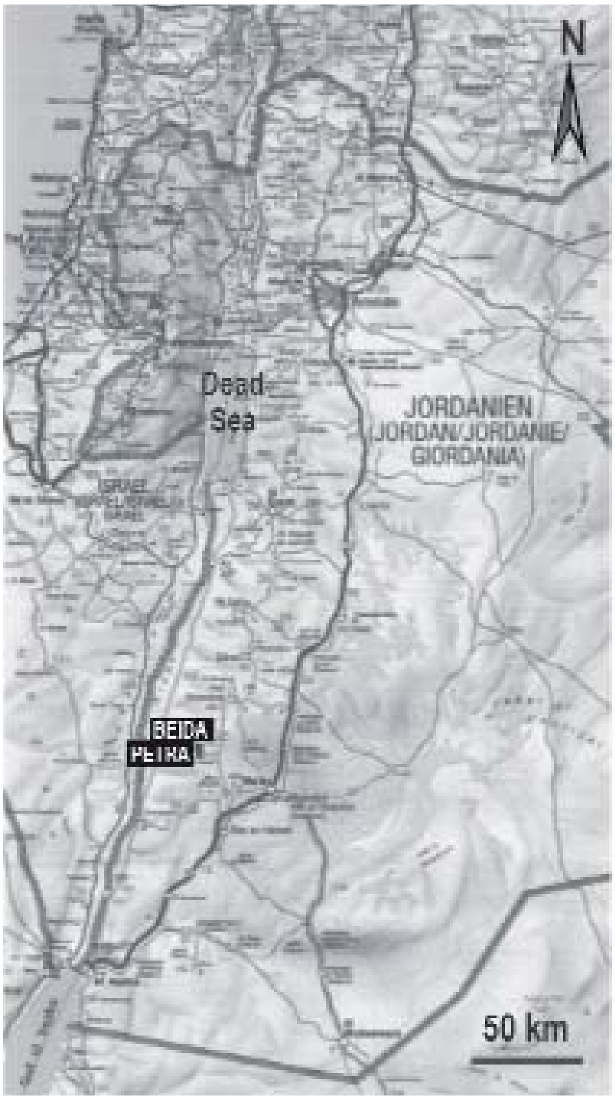

Fig. 1 – Location map.
– *Inquadramento dell'area.*

territory corresponds to the regional escarpment separating the Wadi Araba tectonic trough (south of the Dead Sea, RAIKES, 1985) from a regionally-extended high carbonate *plateau* (Qa' Al Jafr, to the East). The Petra-Beida area as a whole is part of the Seil Wadi Musa hydrographic basin, which drains from the eastern margin of the carbonate *plateau* to Wadi Araba with an overall E-W stream flow-direction. The main stream (*i.e.* Seil Wadi Musa) results from the junction of two main tributaries -namely Wadi es Siq and Wadi Siq el Ghurab-Wadi Beida- flowing across Petra and Beida, respectively.

In the Petra-Beida area, the Precambrian crystalline rocks of the Arabian-Nubian shield are cut by an almost flat late precambrian–early Cambrian peneplain unconformably overlain (fig. 2) by Cambro-Ordovician, mostly quartz-rich arenitic, terrains (BENDER, 1974) accounting for the weathering and erosion of the basement itself (*cf.* AVIGAD *et alii*, 2005 *cum bibl.*). The local stratigraphic succession (*cf.* QUENNEL, 1951; BENDER, 1974) starts (fig 2) with the thin (locally less than 50 m in thickness) *Salib Arkose* arenitic formation, overlain by a thick (locally more than 500 m in thickness) suite of both paralic and shallow-water (*e.g.* SELLEY, 1972; AMIREH *et alii*, 1994), massive and/or poorly stratified Cambrian-Ordovician quartzarenites belonging to the *Umm Ishrin* and *Disi* formations (BENDER, 1974 *cum bibl.*; FRANCHI, 2002). An important -although hardly detectable at the outcrop in the Petra-Beida area - regional unconformity separates the latter from the overlying, entirely fluvial (AMIREH, 1997), quartzarenites of the Early Cretaceous *Kurnub* formation. The local succession is closed by the *Ajlun Group* (QUENNEL, 1951), consisting of marly-calcareous platform formations (SCHULZE *et alii*, 2005 *cum bibl.*) over 500 m thick.

The hand-carved rock monuments of Petra and Beida (*cf.* figures 6B, 10, 16) are entirely cut in the sandstones of *Umm Ishrin* and *Disi* formations (AMIREH *et alii*, 2001; FRANCHI, 2002); moreover, many quarries in use in different historical period attest to the fact that the same sandstones were employed as construction material (FRANCHI, 2002). Since the rock characters largely account for weathering-related conservation problems, it is worth emphasizing some lithologic and petrographic attributes of the two formations above (fig. 2). The *Umm Ishrin* formation is mostly composed of medium-coarse grained, well-sorted quartz (in percentage as high as 80%) combined with highly variable proportions of cements consisting (*cf.* AMIREH, 1991) of authigenic kaolinite, hematite, goethite and subordinate poikilotopic calcite (FRANCHI & PALLECCHI, 1995). Cementation by both quartz overgrowths and pressure solutions is rather frequent. Quite common are needle-shaped, not always identifiable, mineral inclusions. The most common detrital grains recognised under optical microscope are zircon, tourmaline, titanite and occasional crandallite (FRANCHI & PALLECCHI,1995). The occurrence of several 10-15 cm-tick arenaceous lenses/layers with amounts of hematite cement as high as 50%, is a peculiarity of the *Umm Ishrin* formation. Diaclases filled with fibrous-radial hematite have also been observed. The first occurrence of whitish, thin-bedded arenites marks the rather uncertain boundary between the sandstones of the *Umm Ishirin* formation and those of the overlying *Disi* formation. This latter consists entirely of light grey, fine to medium-coarse grained quartzarenites, characterised by recurrent lenses of well

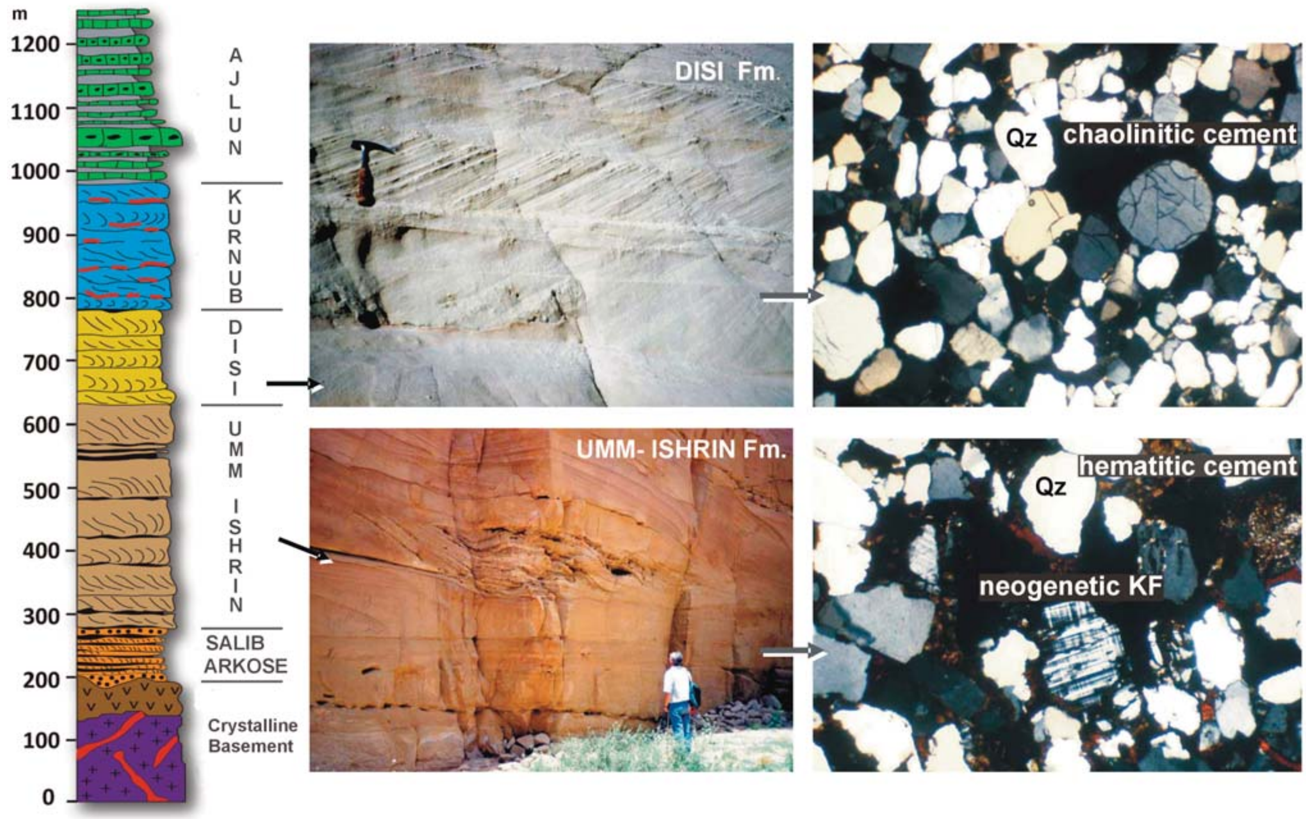

Fig 2 – Lithostratigraphy of the Petra-Beida area and view at the outcrop and in thin section of typical sandstones from the *Umm Ishrin* and *Disi* formation in which main part of the rock monuments are carved.
– *Colonna litostratigrafica dell'area di Petra-Beida e immagini degli affioramento e delle sezioni sottili delle arenarie delle formazioni dell'Umm Ishrin e del Disi. In queste rocce sono scavati i principali monumenti.*

rounded centimetric quartz pebbles. From a petrographic standpoint, the sandstones of the *Umm Ishrin* and *Disi* formations are quite similar, except for a considerable decrease of both iron oxides and hydroxides cements. The *Disi* accessory minerals are the same as for the *Umm Ishrin* and are generally found with the same frequency.

The geomorphology of the Petra and Beida territory strongly reflects both differential erosion and recent tectonics. Several distinct landforms, such as sharp stream deflections and alignments of scarps, canyons and ridges, account for recent displacement along the structural fault-system affecting the area. On the contrary, a large number of examples in which the control on landforms by the tectonic structures must be regarded as passive -*i.e.* simply produced by differential erosion processes independent (or quite independent) from the recent deformation history of the region- are apparent. At a large scale, a *c.ca* N-S trending, high escarpment (fig. 3) accounts for a marked eastward erosional retreat of the western margin of the carbonate *plateau*, favoured by the thick weak layer represented by the arenites of the *Kurnub* formation and the marls of the *Naur* formation (base of the *Ajlun Group*, figures 2, 3). The escarpment faces a wide terrace-like area accounting for the resistant top of the Palaeozoic quartzarenites (*i.*e. *Umm Ishrin* and *Disi* formations), deeply dissected by an complex net of canyons and narrow throughs concealing the sites of Petra and Beida. Indeed, in such rocks the tectonics related to the Dead Sea-Wadi Araba transform system has produced steep, high rock-relieves, spaced out by fault-bordered narrow troughs as the "*Petra Valley*" (fig. 4) (*cf.* BARJOUS & MIKBEL, 1990; FRANCHI, 2002). Since the arenites are always intensely faulted and fractured (*cf.* figs. 3, 4), streams entrenching in deep, narrow gorges as well as weathering, aeolian, and runoff processes shaped such area in a tangle of cliffs, pillars and passages to form an imposing "*town of rocks*" (FRANCHI *et alii*, 2004). The intricate system of canyons and passages that characterise the area includes both the Siq, the c.ca 4-km narrow (in places less than 4 m wide and more than 60 m high), hidden way to Petra (*cf.* PANIZZA & PIACENTE, 2003; FRANCHI *et alii*, 2004) and the cramped canyon where the

Fig. 3 – Panoramic view of the Petra-Beida territory. Please note the dissected structural bench (t) corresponding to the top-surface of the Palaeozoic sandstones and the retreating escarpment (s) at the base of the Meso-Cenozoic terrains.
– *Panoramica del territorio di Petra-Beida. Da notare il terrazzo strutturale (t) corrispondente alla superficie superiore delle arenarie del Paleozoico e la scarpata in arretramento (s) alla base dei terreni del Mesozioico-Cenozoico.*

Fig. 4 – Panoramic view of the Petra Valley; dotted lines = principal fault traces.
– *Panoramica della Valle di Petra; le linee tratteggiate indicano le principali tracce di faglia.*

monumental area of Beida is placed (fig. 5). Such canyons belong to a riddled minor stream-net, controlled by the complex fault-fracture systems affecting the Palaeozoic quartzarenites and joining the Seil Wadi Musa main stream.

Weathering is certainly one of the most effective processes in the Petra-Beida area, able both to mould landforms and to deteriorate the monumental heritage (fig. 6). The weathering effectiveness on natural landforms is underlined by a large abundance of niches, honeycomb-structures and tafoni, and by rounded and spheroidal rock-surfaces as well (*cf.* figs. 3, 6A). On both monuments and natural surfaces, hardening of external rock-surfaces is a usual phenomenon. Liken generated oxalates, at least in the documented examples (*case hardening*, DORN, 2004) are responsible for such weathering-related biological action, able to exert a partial protection of the rock-surface itself from further degradation,

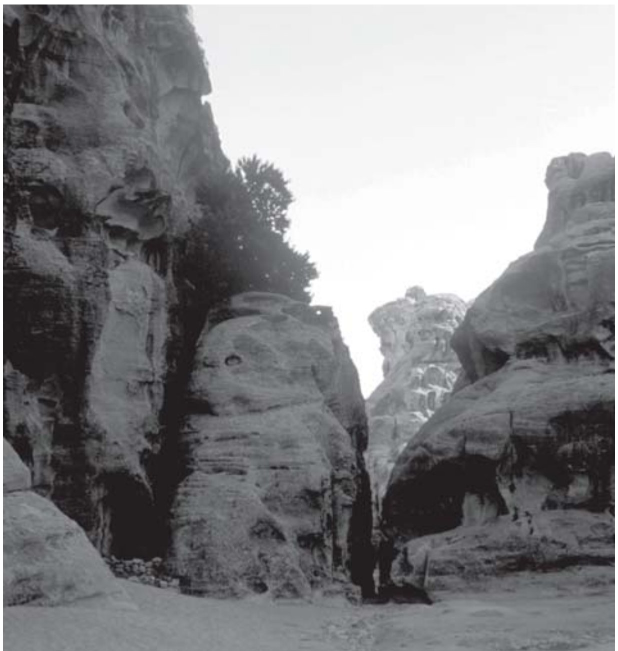

Fig. 5 – The entrance of the Beida canyon.
– *L'entrata al canyon di Beida.*

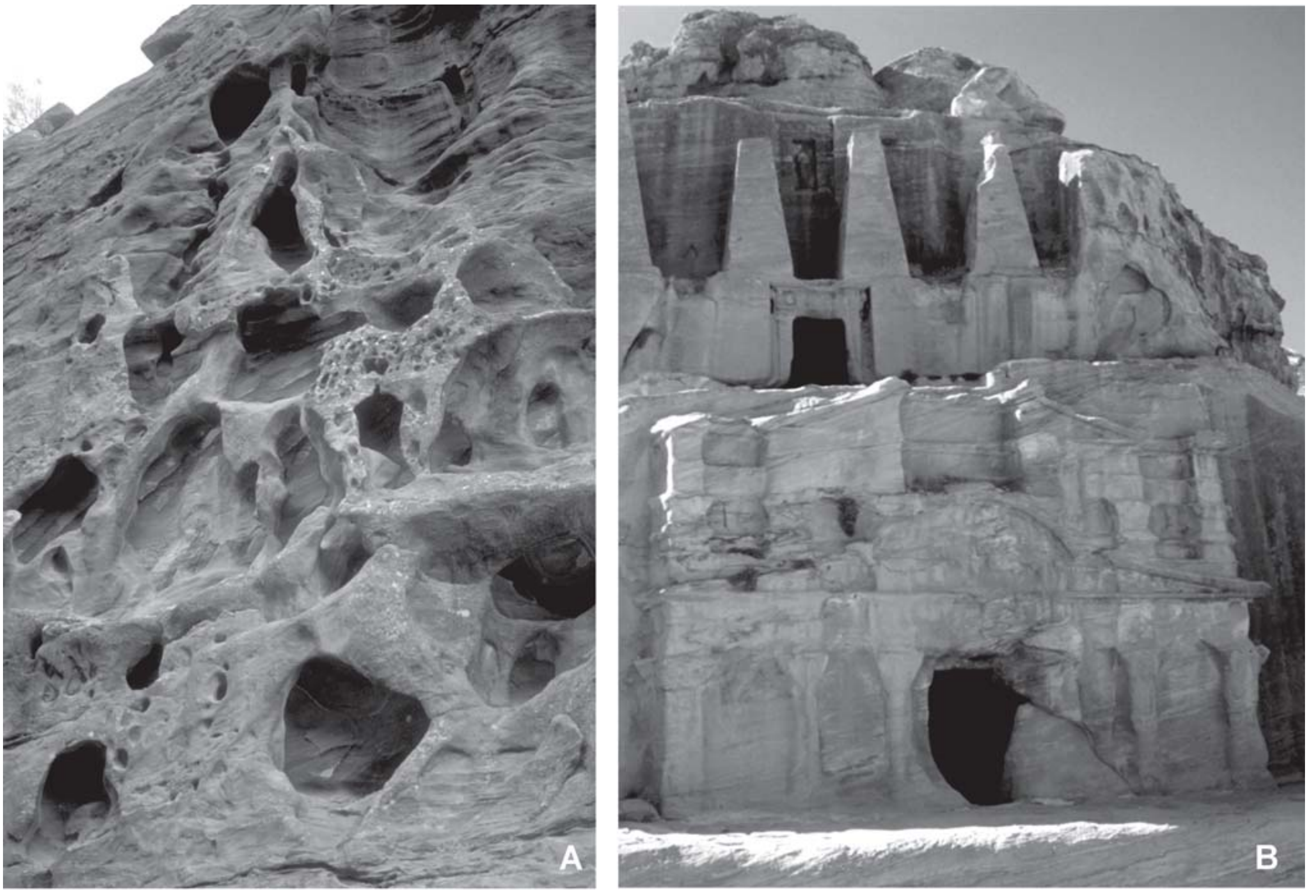

Fig. 6 – Weathering effects on the Paleozoic sandstones: A – tafoni, *Umm Ishrin* formation, Petra; B – facade of the Obelisk Tomb, *Disi* formation, Petra.
– *Effetti dell'alterazione delle arenarie paleozoiche: A – tafoni, Formazione dell'Umm Ishrin, Petra; B – facciata della Tomba degli Obelischi, Formazione del Disi, Petra.*

so often allowing tafoni-like forms to develop. With respect to the historical and artistic heritage conservation, the principal causes of degradation depend on complex interactions of mechanical, chemical, and in part anthropical processes (*cf.* ALBOUY *et alii*, 1993; FRANCHI & PALLECCHI, 1995; FRANCHI *et alii*, 1999; PARADISE, 2005). Indeed, the principal –or in any case a primary- mechanism of weathering depends on the thermal stresses (*i.e.* thermoclastism) suffered by sandstone grains (quartz above all) for insolation changes, night drops in temperature, etc. The loosened grains can be removed from the rock-surface by gravity, wind, rain-splash, runoff etc. In this concern, it is worth emphasizing that both in Petra and Baida, running waters coming from higher areas usually flow all over the facades of the monuments, largely contributing to the decaying of the architectural elements (*e.g.* FRANCHI, 2002; WEDEKIND, 2005). A second important cause of weathering processes/monument decay peculiar to the area of Petra-Baida (*e.g.* Ed Dehir, Petra) is related to salts of varying chemism, abundant all along sandstone fractures and/or faults, and the origin of which is still matter of working hypothesis. Such salts, besides producing –also owing to the presence of iron sulphate hydrate (acid hydrolisis with pH 2)- a chemical corrosion on many sandstone cements, are responsible for mechanical aloclastic processes related to cycles of salt dissolution-precipitation (fig. 7). Chemical and mineralogical analyses carried out

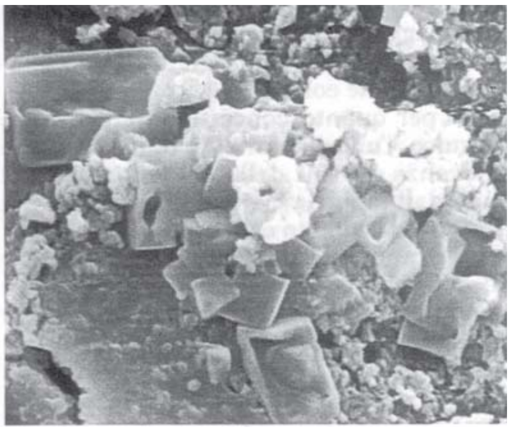

Fig. 7 – Microcrystals of chlorides and sulphates from weathered sandstones on the inside of a Nabatean tomb.
– *Microcristalli di cloruri e di solfati prodotti dal'alterazione delle arenarie nella parte interna di una tomba Nabatea.*

on a large number of samples has established (FRANCHI *et alii*, 1999) the presence in varying proportions of sodium chloride (predominant) together with potassium chloride, nitrates (deriving from the anthropisation of the tombs) and calcium sulphate.

Although largely controlled by the tectonic structure and lithology, the Petra-Beida area also shows a significant association of landforms (mainly depositional ones) related to climatic causes. The occurrence of aeolian products and landforms deriving from weathering processes typical of arid and semi-arid regions is rather obvious. Nevertheless, less obvious depositional landforms -often relic and related to past climatic conditions- are recognisable all over the Petra-Beida territory. In this connection, it is worth reporting several terrace-alluvium patches scattered on the hilltops and along the hillsides of the Petra Valley tectonic depression and partially correlatable with the remnants of ancient pedimentary surfaces. These latter are covered by more or less thick alluvial-fan deposits, sometimes deeply dissected and terraced, sometimes well preserved or only partially dissected (*e.g.* the piedmont area of Beida), anyhow likely to be related to upper Pleistocene relatively cold and humid depositional stages (FRANCHI, 2002).

3. – PHYSICAL ENVIRONMENT CONSTRAINTS AND CULTURAL OUTCOMES

The territory of Petra and Beida bears the remainders of very ancient cultures (*cf.* CLARK, 1987), every so often substantiated by important archaeological remains. Here, the remains of archaic cultures definitely co-exist and overlap with relatively recent vestiges, *e.g.* Crusader and Islamic. Petra is the crucial site of the Nabatean culture, known above all for a huge concentration of monumental tombs of Hellenistic inspiration (*cf.* fig. 16). Beida, in turn, is well known among archaeologists for its masonry architecture and other attributes of agricultural-farming settled village (fig. 8) dating back as long as the 9th millennium B.C., with older hunting occupations from about the 12th millennium B.C. (COMER, 2003).

The geomorphologic setting of the Petra-Beida territory has acted as an ideal background for the inhabitants to evolve from nomadic to resident conditions (*e.g.* BIENKUWSKI, 1995). This very change brought about the deep anthropogenic modifications which made this site unique. As a matter of fact, the prehistorical-protohistorical cultures –including the Edomite one– took advantage of landforms without significantly modifying them (*e.g.* KIRKBRIDE, 1985). Indeed, their settlement, mainly on the foothills, has been probably favoured by the vicinity of wadies and springs, although other morphologic factors such as good drainage conditions, positions out of both flash flooding and rock fall hazard must have been important in the ultimate settlement choice (*cf.* COMER, 2003). In this concern, it is worth emphasizing that Baida protohistorical settlement exploits an alluvial terrace (fig. 8), and still in its zenith (7th-6th millennium B.C.), the nearby stream has been its major water source. The Nabateans themselves –who gradually supplanted the Edomites between the 6th and the 4th century B.C.- got an undoubted advantage from the tangled geomorphology of the Petra-Beida area (*e.g.* PANIZZA AND PIACENTE, 2003; FRANCHI *et alii*, 2004). Indeed, the built Petra town is placed into a deep tectonic depression, out-of-the-way and easy to defend because flanked by cliffs (fig. 4) and reachable without difficulty only through a narrow and

Fig. 8 – The morphological setting of Beida protohistorical village (A) and a detail of the archaeological site (B).
– Localizzazione del villaggio protostorico di Beida (A) e dettaglio del sito archeologico (B).

hidden passage through the mountain (the "*Siq*", i.e. *crack in the rock*): it is worth emphasizing that the geomorphology of the area hindered in some degree also the Roman conquest of the town (*cf.* PARKER, 1987), dating to 106 A.D. The monumental Nabatean Beida, in turn, is set in a narrow, hidden canyon (fig. 5) cutting a steep rock relief riddled by canyons and crevices. Besides being an ideal place to live in because of its geomorphologic setting, the Petra-Beida area benefits from a favourable climate, since its mountains protect it from both north-eastern cold winds and south-western warm ones. Being water the primary need, both the first Nabatean settlement and the earlier stages of town development, were certainly favoured by springs fit to supply water to both the local community and caravans. The growth of Petra as a big caravan town (*e.g.* ZAYADINE, 1985) got the Nabateans, innately skilled at water exploitation (they came from the arid Arabian lands), to achieve an impressive system of watering, suitable for over 30.000 inhabitants living there in the 1st century B.C.-2nd century A.D. On the contrary, the neighbouring Beida valley, reproducing and emphasizing Petra's geomorphologic characteristics on a small scale, became the heartland of both Nabatean religion and politics.

The watering-system construction, the necessity to maintain the *Siq* passage free from debris as well as the development of a monumental "*town of deads*" obtained by chiselling a multitude of tombs out of the maze of rock walls all around the built-up town, are just the main reasons for the manifold landscape modifications which make the Petra-Beida site such an unique place. Nevertheless, the necessity to prevent natural hazards, as floods or the decay of in-use architectonic elements, compelled the Nabateans to implement flood-control works as well as to equip the majority of architectural structures with drainage systems (*e.g.* FRANCHI, 2002; WEDEKIND, 2005). In conclusion, although different geomorphologic processes (*e.g.* mass movements, weathering, aeolian activity) and tectonic factors (earthquakes) influenced the Nabatean culture, water was the primary one. Hence, the fascinating subject of water exploitation and water related hazard –an issue still today able to exert a great appeal on both scholars and tourists- is what we will focus on in the next pages.

4. – THE ANCIENT WATER SYSTEM OF PETRA AND BEIDA: THE AL HABIS SITE

Umm al Biyara – the name of which means "*Mother of the Cisterns"*– is the first example (probably Edomite) of large cisterns chiselled out of rock to collect rain water. Later on, Nabateans developed impressive water supply systems based on channels and cisterns. Specifically, the Nabatean water-system, inherited in a second time by Romans, consists of imposing cisterns, dams and hierarchized channel nets (figs. 9, 10). Indeed, taking advantage from both the topographic and lithologic characteristics of the area, the construction of a dense net of channels has delivered the scarce rainfall water into a multitude of cisterns chiselled

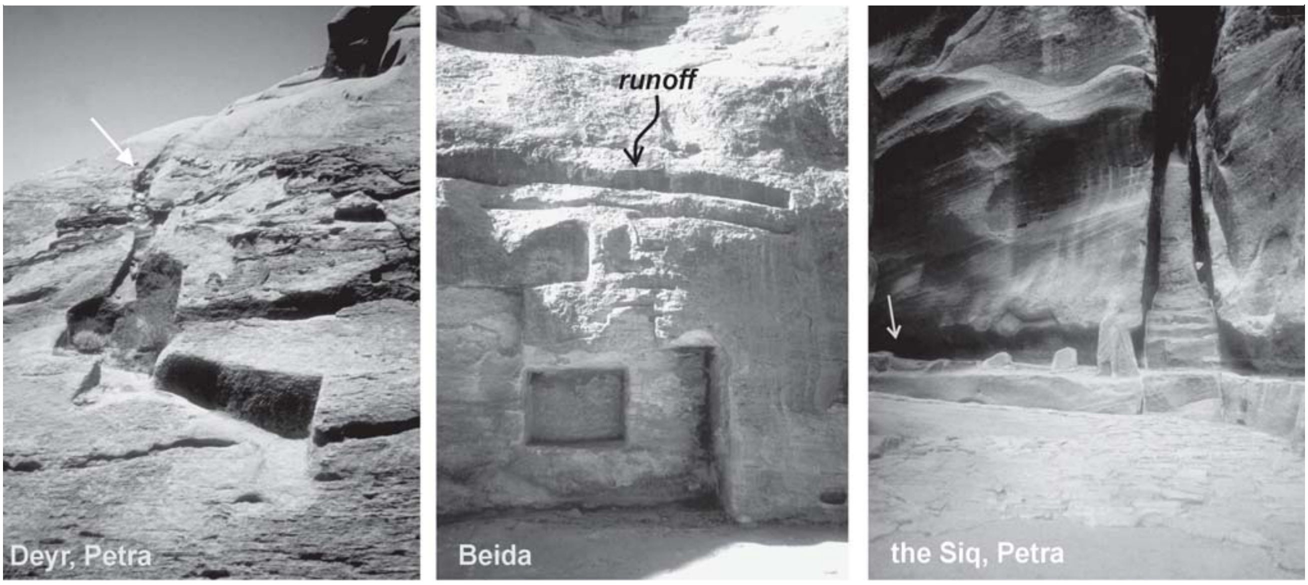

Fig. 9 – Examples of water channels and water collecting systems.
– *Esempi di canali e altri sistemi di raccolta delle acque.*

Fig. 10 – A cistern connected with a Nabatean sacral building in Beida.
– Cisterna sottastante un edificio sacro Nabateo a Beida.

out of sandstone slopes. Such complex hydraulic engineering works both ensured an adequate water supply for the local population and mitigated the effects of monument degradation produced by rainwater runoff down their facades (FRANCHI, 2002; LUBICK, 2004; WEDEKIND, 2005). Today, the drainage system is no longer operational, as it has been filled up with debris and broken up by landslides. Nevertheless, the elements constituting the water-supply system, often carved in rock, maintain even nowadays monumental characteristics and display an unquestionable skill both in hydraulics and in exploiting an unfavourable environment.

Taken into account the importance of the water providing system in both archaeological and geologic-geomorphologic studies, a detailed survey of the water collection system of Petra and Beida archaeological sites has been started in 2004 in order to ascertain the precise function of each single part of the system. Field work has been started in the sample-site of Al Habis (fig. 11), the choice of which accounts for both its small size and its effectiveness as a model system for testing an appropriate field surveying method. The most important water collection channels -chiselled out of the rocky slopes (*Umm-Ishrin* sandstones) and still visible today- run all around the Al Habis site, along the so-called "third bench" (fig. 11). Since the inaccessible nature of the site prevents the use of a GPS system, to rapidly acquire a cinematic view of the points, measurements were made using the Total Station Trimble 5600 (FRANCHI *et alii*, 2005). The employment of this equipment allowed both a quick survey of their course and mapping of their position on a 3-D model of the Al Habis rock-spur. 3-D reconstructions of the geometric shape of each single section of the channels was instead obtained by photogrammetry (DRAP *et alii*, 2001). The result of this operation is an extremely detailed and measurable 3-D model of the channels (fig. 12) that can be used both for classification and study purposes as well as for virtual tests and simulations on the flow of the waters.

The creation of such a detailed model allowed us to extract information on sections along the course of a channel and to estimate the degree of deterioration of the side walls of the water channel. A forthcoming development of this analyses is the spatial and functional survey of the water channeling system in order to gain an correct un-

Fig. 11 – The site of Al Habis where the water collection channels have been studied in detail. A: view from the south-east; the main water channel is found on the "third bench" (arrows). B: a detail of a channel.
– *Il sito di Al Habis dove i canali per la raccolta d'acqua sono stati studiati in dettaglio. A: panoramica da sud-est; il canale principale si trova sul "terzo gradino" (frecce). B: un dettaglio del canale.*

derstanding of the complex network of cisterns and channels. The model can be used for channel classification, flow simulation, virtual tests, and other scientific objectives as well as for to develop projects of restoration of parts of the water providing system with a consequent mitigation of runoff damages to the facades of the monuments. An exploitation in touristic and educational frameworks is also a natural development of scientific results and flow simulations.

5. – EVIDENCE OF HISTORICAL ALLUVIAL EVENTS IN PETRA

The Nabatean dependence on water is sanctioned in their rituals, thus mirroring its sacredness; such cultural trait is testified by the large number and size of cisterns and pools connected with sanctuaries and sacred places (fig. 10). Neither the more ephemeral and aesthetic forms of water employment were disregarded by the Nabateans; indeed they built up pools, fountains and gardens both in the urban area and in its neighbourhood (an aspect emphasised after 106 A.D. by the Romans). However, to Petra, water didn't mean just survival, aesthetics and rituality: it represented a natural hazard as well. It is well known how the Nabateans were obliged to divert the course of Wadi Musa stream (fig. 13), in order to prevent the recurrent flooding of the Siq, their main way to Petra (*e.g.* AL-WESHAH & EL-KHOURY, 1999; LUBICK, 2004; PANIZZA & PIACENTE, 2003, p. 289). A dam was built by Nabateans just downstream the deviation to prevent flood overflow (fig. 13); later, not only the Romans maintained the dam and the same tunnel, but they also enlarged this latter, 88 m long and 6 m wide at present time.

Since Pleistocene times, the Petra Valley and the topographically low areas around Beida underwent repeated stages of alluvial accumulation and dissection because of climatic and perhaps tectonic control (FRANCHI, 2002). Nevertheless, also in historical times, when such areas experimented a generalised downcutting –or at least a vertical stability-stage of streams, several alluvial events occurred, perhaps in connection with late Holocene climatic fluctuations (*cf.* ENZEl *et alii*, 2003, *cum bibl.*) and/or

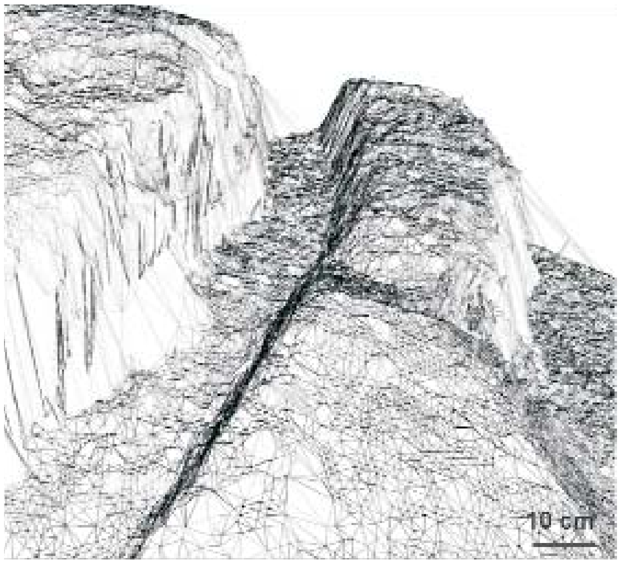

Fig. 12 – 3-D modelling of a water-channel.
– *Modellizzazione 3D di un canale.*

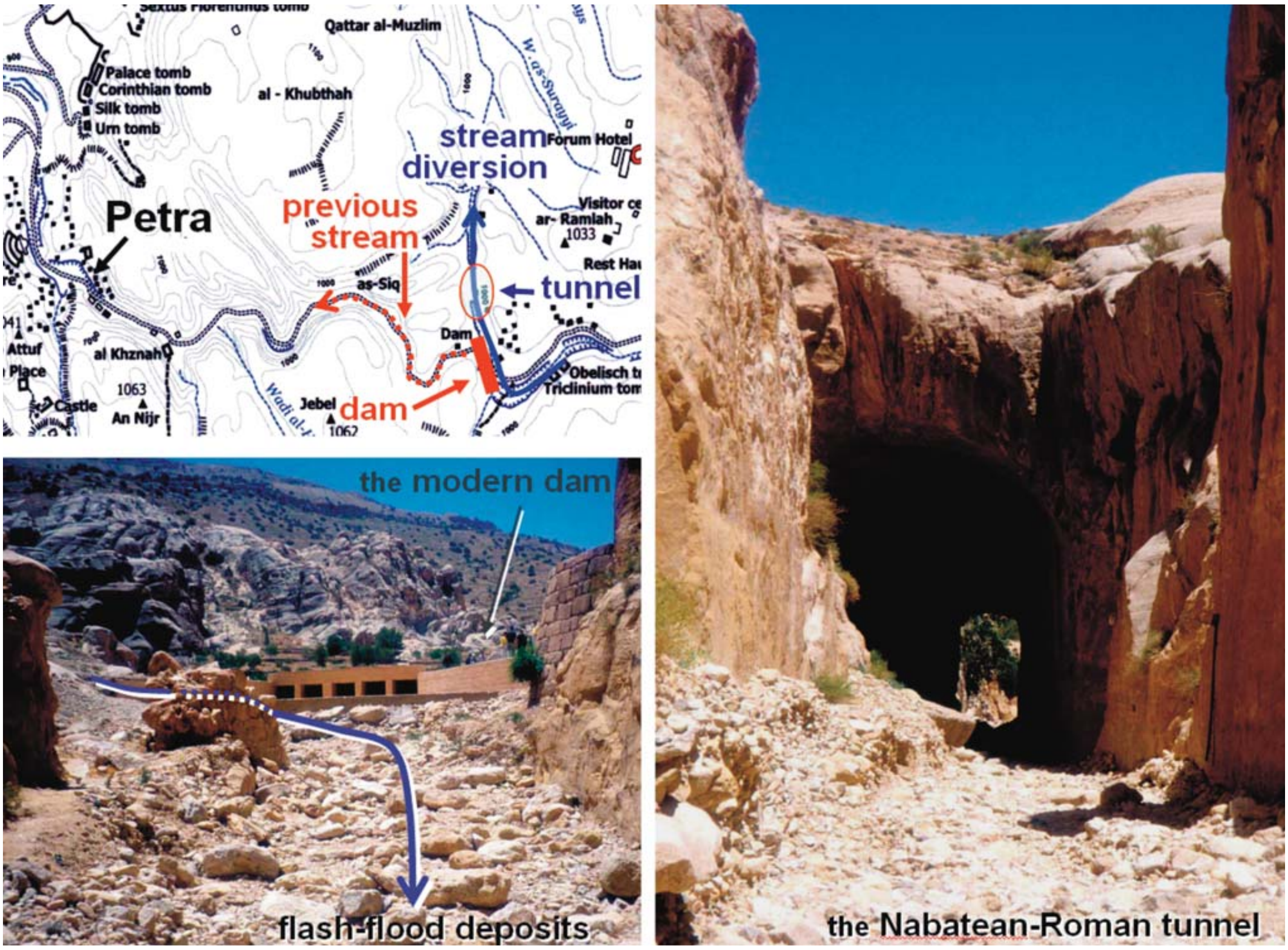

Fig. 13 – The diversion of Wadi Musa.
– *La deviazione del Wadi Musa.*

exceptional meteorological events (*cf.* Al-Weshah & El-Khoury, 1999). Actually, terrace alluvium containing fragments of pottery, monuments completely or partly buried by alluvium as well as alluvial patches on the canyon rock-walls of the Siq (fig. 14), highlight flooding events spanning from Nabatean to post-Roman age. Several architectural elements (*i.e.* tombs) have been probably buried before the construction of the dam: in this respect, some of the highest alluvial patches in the Siq (*c.ca* 3.5-4 m above the Roman paving), although "Nabatean" in age -as shown by included pottery fragments- could indicate flood events pre-dating the dam. Nevertheless, since the most part of both Nabatean and younger alluvial deposits hints at repeated flooding events of the Siq-Petra Valley, temporary inefficiencies of the upstream dam and/or overflow episodes can be stressed. It is worth emphasizing that some important alluvial stages burying Nabatean artefacts are recognisable both far downstream the channel diversion and along nearby wadies, thus hinting at rather generalized events, perhaps related to climatic changes or important storms. It is therefore possible that the dam constructions has mitigated the flood impact without completely removing the problem of floods, as indirectly indicated also by an extensive flooding event of the Siq occurred in January 2004. Anyhow, in Nabatean/Roman times important alluvial-fill episodes raised several metres the Siq valley floor burying entire monuments, as demonstrated by recent excavations beneath Al Khazneh (*i.e.* the Treasure), the most famous Petra's monument, and other tombs (figs. 15-16). Other important alluvial-fill episodes clearly postdate the town decline which followed 551 A.D. destructive earthquake and the 663 A.D. Arab conquest. Such decay produced hydraulic system and dam deterioration: floodwater entered again the Siq and both the Roman paving and several architectonic elements were definitively buried by alluvium (fig. 15).

Besides being a geomorphologic hazard for an area with high touristic impact (Al-Weshah & El-

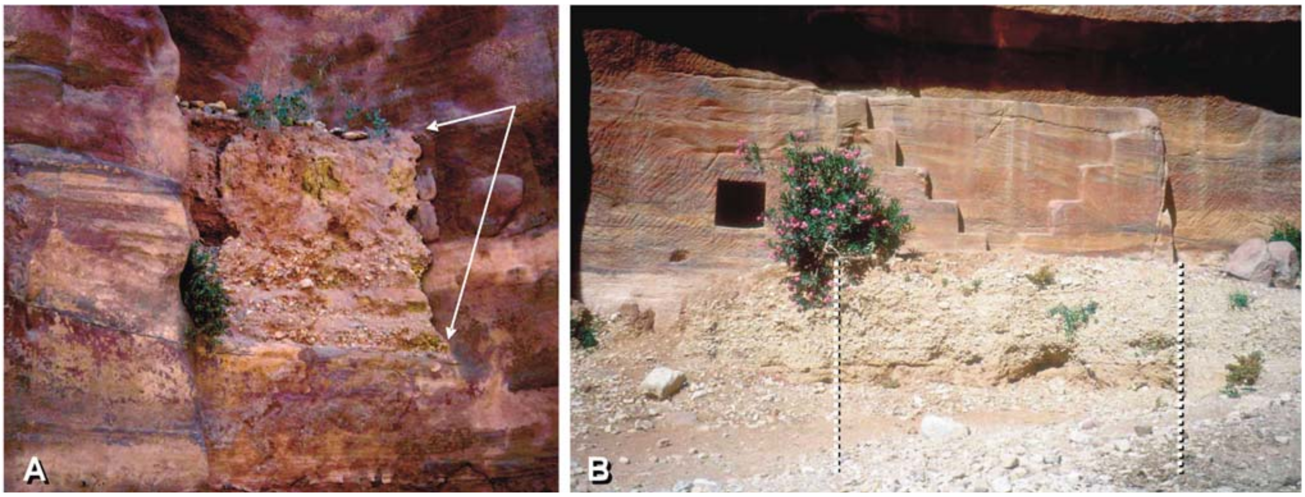

Fig. 14 – Evidence of historical alluvial events in the Siq, Petra. A: an alluvial patch hanging on the left wall of the canyon; B: archaic Nabatean tombs almost completely buried in alluvium.
– Evidenze di alluvionamenti storici di alluvione nel Siq, Petra. A: materiale alluvionale sulla parete di sinistra del canyon; B: tombe Nabatee arcaiche quasi completamente sepolte da materiale alluvionale.

Khoury, 1999), the repeated occurrence of flood events is an intriguing matter scientific research and can be also of some concern in both educational and touristic purposes. Since a detailed reconstruction of the alluvial top-surfaces is needed, in order both to decipher at least a relative chronology of the events and to reconstruct the alluvial bodies, similarly to the Al Habis site, detailed surveys by means of laser scanning and GPS systems have been taken up, starting from the Siq, where the relationship between alluvium and architectural elements is clear enough. Preliminary surveys have allowed the reconstruction of two of the main historical alluvial top-surfaces, including the one shown in figure 15. Buried monuments and alluvial patches can be thus combined in 3-D reconstructions and explicative panels for both the popularisation of geomorphologic topics and their integration into the better-known archaeological context, also fostering new educational paths. Indeed, whatever the causes, timing and extension of the historical alluvial events, their evidence is so striking and so closely related to architectural elements of the monumental areas that both educated tourists and scholars cannot help wandering about such issue.

Fig. 15 – Recent excavation close to a Nabatean tomb, left downstram sector of the Siq, Petra. The highest alluvial patch (1) hints at a first alluvial event post-dating the monument; the monument weathering (2) likely predates both a second alluvial burial and the Roman channel (3) construction; weathering also stresses (4) the top-surface of the second alluvial fill, preserved in some patches (5) hanging on the tomb facade. In the foreground (6) the modern valley floor.
– Scavo recente di una tomba Nabatea, sinistra idrografica del Siq a Petra. Il pacco di strati alluvionali (1) fa pensare ad un primo evento alluvionale successivo al monumento; l'alterazione del monumento (2) verosimilmente pre-data sia un secondo evento alluvionale, sia la costruzione del canale Romano; l'alterazione evidenzia anche (4) la superficie superiore del secondo riempimento alluvionale, conservato in alcune tasche ghiaiose sulla facciata della tomba. In primo piano (6) il fondovalle alluvionale attuale.

6. – CONCLUDING REMARKS

Petra and Beida (Jordan), UNESCO sites, are two important adjacent archaeological areas deeply integrated in a striking geomorphologic landscape. The impressive historical, archaeological and monumental heritage as well as a somewhat "exotic" collocation of these sites, are unquestionably the main factors contributing to attract a huge number of tourists in such places. However, several geologic and geomorphologic features blending with monumental elements and appealing to both tourists and scholars are part of the overall indivisible heritage of these sites and suitable for being improved and popularised.

Both Nabatean water exploitation and flow

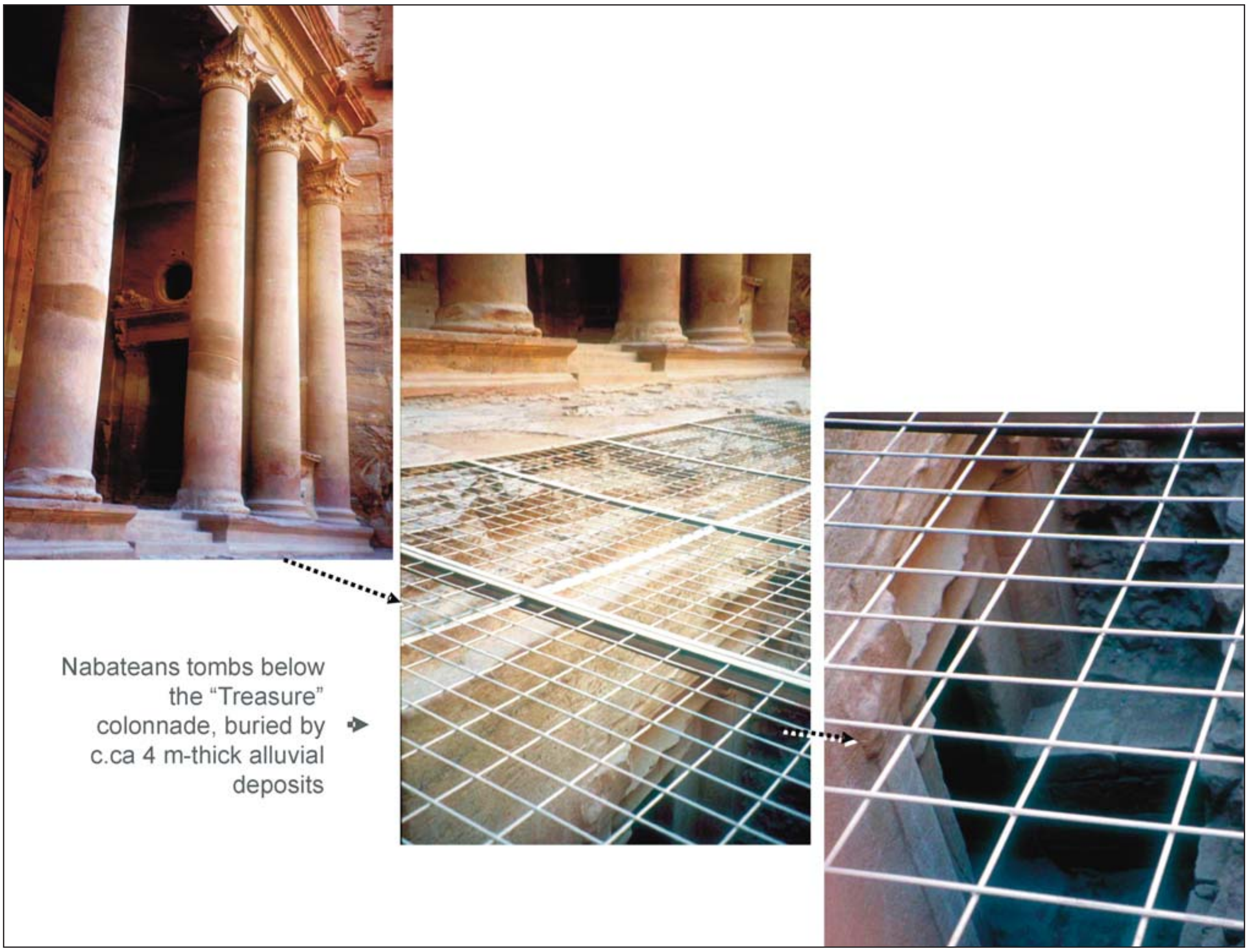

Fig. 16 – Recent archaeological excavation in the alluvial fill beneath Al Khazneh showing buried Nabatean tombs.
– *Recenti scavi archeologici nei depositi alluvionali sotto Al Khazneh mostrano tombe Nabatee sepolte.*

control are fascinating issues and, what's more, they are primary links between archaeological-monumental topics and geomorphologic ones. In this connection, ongoing researches about two topics directly related to both water and geomorphology of the Petra-Beida area –*viz.* water system reconstruction and historical alluvial-fill assessment- are suitable to promote a "geomorphologic culture" among both tourists and scholars. The analysis of both problems has been started by means of laser scanning and GPS systems, in order to obtain detailed measurements and reconstructions. The collected data make it possible to obtain 3D digital reconstruction and interactive models, flow models, alluvial fill modellisations etc., which are all appropriate for being improved as both educational and divulgation tools. Actually, they are suitable for being used in education rooms, employed as illustrative materials in guides, leaflets and explicative-panels and so on. Moreover, the singling out of additional topics could encourage the realization of new thematic touristic paths, able to lighten an overpressure along the usual touristic paths of an area the heritage of which is known to be at risk of decaying.

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REFERENCES

Albouy M., Deletie P., Haguenauer B., Nion S., Schreiner D., Rewerski J. & Seign J. (1993) – *Petra, la cité rose des sables. La pathologie des grès et leur traitement dans la perspective d'une préservation et d'une restauration des monuments*. In: Thiel M.-J. (Ed.): *Conservation of stone and other materials,* **1**. UNESCO/RILEM, E & FN Spon., London, 376-385.

Al-Weshah R. A. & El-Khoury F. (1999) – *Flood analysis and mitigation for Petra area in Jordan*. J. Water Res. Planning and Management, **125**, 170-177.

AMIREH B.S. (1991) – *Mineral composition of Cambrian-cretaceous Nubian Series of Jordan: provenance, tectonic setting and climatological implications*. Sedim. Geol., **78**, 267-283.

AMIREH B. S. (1997) – *Sedimentology and paleogeography of the regressive-transgressive Kurnub Group (Early Cretaceous) of Jordan*. Sedim. Geol., **112**, 67-88.

AMIREH B. S., SCHNEIDER W. & ABED A. M. (1994) – *Evolving Fluvial-transitional-marine Deposition through the Cambrian Sequence of Jordan*. Sedim. Geol., **89**, 65-90.

AMIREH B. S., SCHNEIDER W. & ABED A. M. (2001) – *Fluvial-shallow marine-glaciofluvial depositional environments of the Ordovician System in Jordan*. J. Asian Earth Sci., **19**, 45-60.

AVIGAD D., SANDLER A, KOLODNER K., STERN R. J., MC WILLIAMS M., MILLER N. & BEYTH M. (2005) – *Mass-production of Cambro-Ordovician quartz-rich sandstone as a consequence of chemical weathering of Pan-African terranes: Environmental implications*. Earth and Planetary Sci. Lett., **240**, 818-826.

BARJOUS M. & MIKBEL S. (1990) – *Tectonic Evolution of the Gulf of Aqaba-Dead Sea Transform Fault System*. Tectonophysics, **180**, 49-59.

BENDER F. (1974) – *Geology of Jordan*. Gebrueder Bornstraeger, Berlin, pp. 196.

BIENKUWSKI P. (1995) – *The architecture of Edom*. In: HADIDI A. (Ed.): *Studies in the History of Jordan*. Bath Press, Avon, **5**, 87-99.

CLARK G. A. (1987) – *Paleolithic Archaeology in the Southern Levant*. Annnual Dept. Antiquities of Jordan, **31**, 19-78.

COMER D.C. (2003) – *Environmental history at an early prehistoric village: an application of cultural site analysis at Beidha, in southern Jordan*. J. of GIS in Archaeology, **1**, 103-115.

DORN R. J. (2004) – *Case hardening*. In: GOUDIE A. S. (Ed.): *Encyclopedia of Geomorphology*. Routledge, London, 118-119.

DRAP P., GRUSSENMEYER A. & GAILLARD G. (2001) – *Simple photogrammetric methods with ARPENTEUR. 3-d plotting and orthoimage generation*. The I-MAGE Process, CIPA 2001 International Symposium, Postsdam University (Germany), 18-21.

ENZEL Y., BOOKMAN R., SHARON D., GVIRTZMAN H., DAYAN U, ZIV B. & STEIN M. (2003) – *Late Holocene climates of the Near East deduced from Dead Sea level variations and modern regional winter rainfall*. Quat. Res., **60**, 263-273.

FRANCHI R. (2002) – *A study of the natural environment and of the problems of conservation of the Historical-artistic heritage in the area of Petra*. In: JEDRKIEWICZ S. (Ed.): *Civilizations of the Past, Dialogue of the Present: Italian Research Mission in Jordan*. Ambasciata d'Italia, Amman, 67-92.

FRANCHI R. & PALLECCHI P. (1995) – *The sandstone of Petra, Petrography and problems in conservation*. In: PANCELLA R. (Ed.): *Preservation and restoration of cultural heritage*. Pancella, Losanna, 679-689.

FRANCHI R., CAPACCIONI B., PECCHIOLI E. & VASELLI O. (1999) – *Indagini chimico-mineralogiche sull'arenaria cambrica dell'Um Ishrin (sito archeologico dell'area di Petra -Giordania-): una nuova ipotesi sui meccanismi di degrado*. Geoitalia 99 - FIST.

FRANCHI R., SAVELLI D. & MORETTI E. (2004) – *Petra and Beida (Jordan): two adjacent archaeological sites deeply integrated in an impressive geomorphologic landscape*. 32nd International Geological Congress, Florence – Italy, August 20-28 2004, Scientific Sessions: Abstracts (part 1), 27-4, 38.

FRANCHI R., SAVELLI D., COLOSI F., GABRIELLI G., LAZZARI A., PELOSO D. & DRAPP P. (2005) – *The ancient water supply system of Petra (Jordan): a link between monumental and geomorphologic heritage*. IV International Symposium ProGEO on the Conservation of Geological Heritage, 13-16 sept. 2005, Braga, Portugal, abstract, 70.

GARFUNKEL Z. & BEN AVRAHAM Z. (1996) – *The structure of the Dead Sea basin*. Tectonophysics, 226, 155-176.

GINAT H., ENZEL Y. & AVNI Y. (1998) – *Translocated Plio-Pleistocene drainage systems along the Arava Fault of the Dead Sea transform*. Tectonophysics, **284**, 151-160.

HENRY O. D. (1985) – *Late Pleistocene environment and Paleolithic adaptation in southern Jordan*. In: HADIDI A. (Ed.): *Studies in the History of Jordan*. Bath Press, Avon, **2**, 67-79.

KIRKBRIDE D. (1985) – *The Environment of the Petra Region during the Pre-pottery Neolithic*. In: HADIDI A. (Ed.): *Studies in the History of Jordan*. Bath Press, Avon, **2**, 117-124.

LUBICK N. (2004) – *Petra: an eroding ancient city*. Geotimes, **49**, 22-27.

MART Y. (1991) – *The Dead Sea Rift: from continental rift to incipient ocean*. Tectonophysics, **197**, 155-179.

PALUMBO G., QUSSOUS A. S. K., WAHEEB M. (1995) – *Cultural resources management and national inventory of archaeological and historic sites: the Jordanian experience*. In: HADIDI A. (Ed.): *Studies in the History of Jordan*. Bath Press, Avon, **5**, 83-91.

PANIZZA M. (2001) – *Geomorphosites: concepts, methods and examples of geomorphological survey*. Chinese Sci. Bull., **46**, 4-6.

PANIZZA M. & PIACENTE S. (2003) – *Geomorfologia Culturale*. Pitagora, Bologna, pp. 350.

PARADISE T. R. (2005) – *Petra revisited: An examination of sandstone weathering research in Petra, Jordan*. In: TURKINGTON A. V. (Ed.): *Stone Decay in Architectural Environment*. GSA Spec. Pap., 390, 39-49.

PARKER S. T. (1987) – *The Roman* Limes *in Jordan*. In: HADIDI A. (Ed.): *Studies in the History of Jordan*. Bath Press, Avon, **3**, 151-164.

QUENNEL A. M. (1951) – *The geology and mineral resources of (former) Trans-Jordan*. Colonial Geology and Mineral Resources, London, **2**, 85-115.

RAIKES L. R. (1985) – *The climate and hydrogeological background to the post-glacial. Introduction of farming in the Middle-East and its subsequent spread, with examples from Jordan*. In: HADIDI A. (Ed.): *Studies in the History of Jordan*. Bath Press, Avon, **2**, 267-273.

RAIKES T. (1985) – *The character of Wadi Araba*. In: HADIDI A. (Ed.): *Studies in the History of Jordan*. Bath Press, Avon, **2**, 95-101.

SCHULZE F., KUSS J. & MARZOUK A. (2005) – *Platform configuration, microfacies and cyclicities of the upper Albian to Turonian of west-central Jordan*. Facies, **50**, 505-527.

SELLEY R.C. (1972) – *Diagnosis of Marine and Non-marine Environments from the Cambro-Ordovician sandstones of Jordan*. J. Geol. Soc., **128**, 135-150.

SNEH A. (1996) – *The Dead sea Rift: lateral displacement and downfaulting phases*. Tectonophysics, **263**, 277-292.

UNESCO (1993) – *A plan to safeguard Petra and its surroundings*. The World Heritage Newsletter, World Heritage Center, UNESCO, English Version, 2.

WEDEKIND W. (2005) – *Jordan, Petra*. In: *ICOMOS World Report 2004/2005, Heritage at Risk*. München, 151-156.

ZAYADINE F. (1985) – *Caravan Routes Between Egypt and Nabatea and the Voyage of Sultan Baibars to Petra* in 1276. In: HADIDI A. (Ed.): *Studies in the History of Jordan*. Bath Press, Avon, **2**, 159-174.

ZAYADINE F. (1992) – *L'espace urbain du grand Petra, les routes et les stations caravanières*. Annuals Dept. Antiquities of Jor dan, 36, 217-241.