Damage associated with geological discontinuities on rock-cut monuments in Petra / Jordan

Schäden im Zusammenhang mit Gesteinstrennflächen an den Felsmonumenten in Petra / Jordanien

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Abstract

The ancient Nabataean city of Petra in southwest Jordan represents outstanding world cultural heritage. Many hundred monuments were carved from Cambrian and Ordovician sedimentary bedrocks about 2000 years ago. A very characteristic feature of the Petra region is the net-like joint system with several intersecting joint sets resulting from post-Ordovician / pre-Cretaceous and Tertiary tectonic activity. Joints can be observed on many rock-cut monuments in Petra. Orientation, extension and aperture vary. The joints may represent paths for biological colonization and especially for increased ingress of rain water, thus triggering processes like frost wedging, root wedging or salt weathering. Weathering along the joints weakens the rock mass of the monuments. Moreover, in dependence on monument location, orientation of monument surface, monument architecture and orientation of joints, failure processes such as plane failure, wedge failure and toppling have caused damage on many monuments in terms of loss of rock material. Intensity of damage varies from loss of smaller rock blocks up to complete collapse of monuments at worst. With regard to preventive intervention for monument protection, studies on the orientation of joints and its relation to monument exposure characteristics are recommended for a first estimation of possibility, probability and damage potential of such failure processes and, thus, for rather fast identification of Petra monuments under this threat.

Keywords: Rock monuments, geological discontinuities, failure processes, damage, risk assessment

Zusammenfassung

Die Felsmonumente der alten Nabatäerstadt Petra in Südwestjordanien gehören zu den bedeutendsten Weltkulturdenkmälern. Viele hundert Monumente wurden um die Zeitwende aus anstehenden altpaläozoischen Sedimentgesteinen herausgearbeitet. Charakteristisch für die Gesteine in der Petra-Region ist ein intensives Trennflächennetzwerk, das aus dem postordovizisch-präkretazischen und tertiären tektonischen Geschehen resultierte. Auch an vielen Felsmonumenten sind Trennflächen erkennbar. Versagensmechanismen wie ebenes Gleiten, räumliches Gleiten oder Kippen haben teilweise schon zu Schäden geführt, die vom Verlust kleinerer Felsblöcke bis hin zum Einsturz ganzer Bauwerke reichen. Im Hinblick auf vorbeugende Schutzmaßnahmen wird eine systematische Erfassung der Raumlage der an den Felsbauten auftretenden Trennflächen und ihres räumlichen Verhältnisses zur Bauwerksexposition für eine erste Einschätzung von Möglichkeit, Wahrscheinlichkeit und Schadenspotential der verschiedenen Versagensmechanismen und damit für die Identifizierung bedrohter Monumente empfohlen.

Schlüsselworte: Felsmonumente, Gesteinstrennflächen, Versagensmechanismen, Schäden, Risikoanalyse

1 Introduction

Ancient Petra is situated in the Shera mountains of Southwest Jordan, a mountain ridge east of the Wadi Araba Valley (Fig. 1). In Petra more than eight hundred monuments such as tombs, sanctuaries and places of worship were carved by the Nabataeans from bedrocks about 2.000 years ago (Fig. 2). In 1985 UNESCO inscribed Petra on the list of World Heritage. In 2007 Petra was elected as one of the 'New Seven Wonders of the World'. Petra represents the most prominent historical site in Jordan and is of great importance for tourism in Jordan. All rock monuments show damage due to weathering. Salt weathering was identified as major cause of this damage (HEINRICHS 2008). Moreover, many monuments have suffered damage from failure processes associated with geological discontinuities, especially joints. The collapse of monument No. 609 in March 2010 has risen again the awareness of this persistent threat (Fig. 3).

2 Geological background

The Petra region is mainly composed of sedimentary rocks of Lower Paleozoic age. The relevant stratigraphic units with respect to the rock-cut monuments are the middle and upper part of the Cambrian Umm Ishrin Sandstone Formation (mIN, uIN) and the Ordovician Disi Sandstone Formation (DI) (JASER & BARJOUS 1992, JORDAN NATIONAL RESOURCES AUTHORITY 1991) (Figs. 4-7).

The original sediments were deposited in a braided river system. The rocks are characterized by an extensive joint system of net-like nature resulting from post-Ordovician / pre-Cretaceous and Tertiary tectonic activity in the region in context with the development of the Wadi Araba – Jordan Valley rift.

Abb. 1: Zentraler und westlicher Teil des Petra-Gebietes.

Fig. 1: Central and western part of the Petra region.

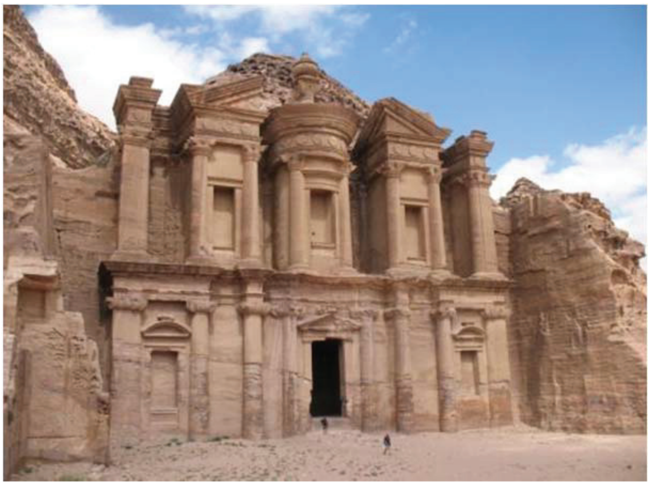

Abb. 2: Monument Nr. 762 (Ed-Der).

Fig. 2: Monument No. 762 (Ed-Der).

Abb. 3: Monument Nr. 609. Einsturz im März 2010.

Fig. 3: Monument No. 609. Collapse in March 2010.

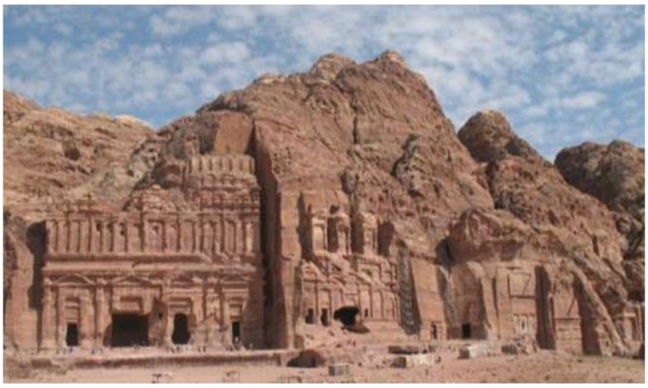

Abb. 4: Westflanke des Khubtha-Massivs mit den 'Königsgräbern', Umm Ishrin Sandstein Formation (Kambrium).

Fig. 4: Western slope of the Khubtha ridge with the 'Royal Tombs', Umm Ishrin Sandstone Formation (Cambrian).

Abb. 5: Buntgebänderter Sandstein,mittlerer Teil der Umm Ishrin Sandstein Formation (Kambrium).

Fig. 5: Multi-coloured sandstone, middle part of the Umm Ishrin Sandstone Formation (Cambrian).

Abb. 6: Bab el-Siq Region mit dem Turmgrab Nr. 9 (rechts), Disi Sandstein Formation (Ordovizium).

Fig. 6: Bab el-Siq region with Djinn Block No. 9, Disi Sandstone Formation (Ordovician).

Abb. 7: Weißer Sandstein, Disi Sandstein Formation (Ordovizium).

Fig. 7: White sandstone, Disi Sandstone Formation (Ordovician).

3 Failure processes associated with geological discontinuities

Three common modes of failure processes along discontinuities can be distinguished, namely plane, wedge and toppling failure (PRICE 2009). All of them can be observed on rock-cut monuments in Petra.

3.1 Plane failure

Plane failure, also called translational failure, describes the sliding of a mass of rock along a single discontinuity. The plane on which sliding occurs strikes parallel or nearly parallel to the monument surface. The dip of the failure plane is smaller than the dip of the monument surface. Two examples are presented in Figs. 8-11.

Abb. 8: Monument Nr. 831 (rechts). Einsturz infolge ebenen Gleitens entlang einer Kluft.

Fig. 8: Monument No. 831 (right). Collapse due to plane failure along a joint.

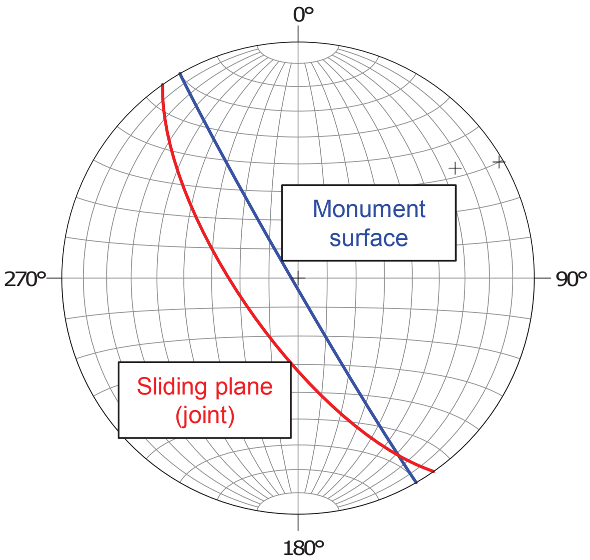

Abb. 9: Monument Nr. 831. Darstellung der Raumlagen von Bauwerksoberfläche (240/88) und Gleitfläche (Kluft, 235/70) im Schmidt´schen Netz.

Fig. 9: Monument No. 831. Illustration of the orientation of monument surface (240/88) and sliding plane (joint, 235/70) in the Schmidt net.

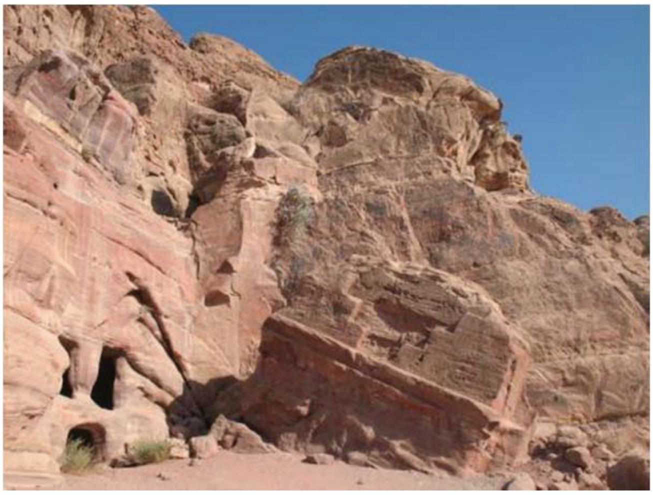

Abb. 10: Monument Nr. 198. Einsturz infolge ebenen Gleitens entlang einer Kluft.

Fig. 10: Monument No. 198. Collapse due to plane failure along a joint.

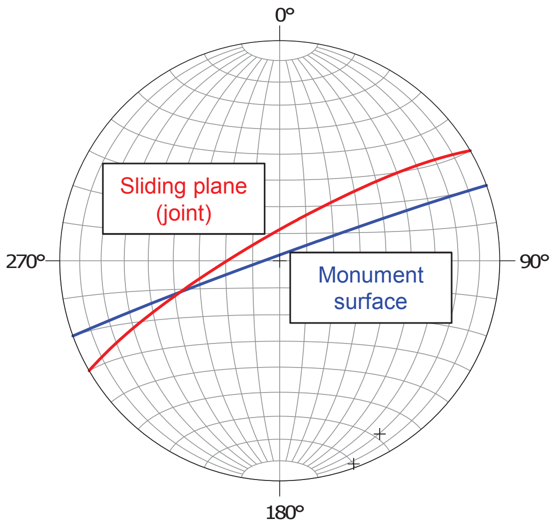

Abb. 11: Monument Nr. 198. Darstellung der Raumlagen von Bauwerksoberfläche (340/88) und Gleitfläche (Kluft, 330/80) im Schmidt´schen Netz.

Fig. 11: Monument No. 198. Illustration of the orientation of monument surface (340/88) and sliding plane (joint, 330/80) in the Schmidt net.

3.2 Wedge failure

Wedge failure describes the sliding of a mass of rock along two intersecting discontinuities. The discontinuities dip towards each other. The linear of their intersection dips out of the monument surface. In Petra the most common combination of such discontinuities resulting in wedge failure processes is that of two joints. An example is presented in Figs. 12 and 13.

3.3 Toppling failure

Toppling failures describes the fall of a rock block which is separated from the rock mass by a steeply inclined discontinuity, provided that the center of gravity of the block is brought outside its base. Toppling failure at Tomb No. 73 is shown as an example in Fig. 14.

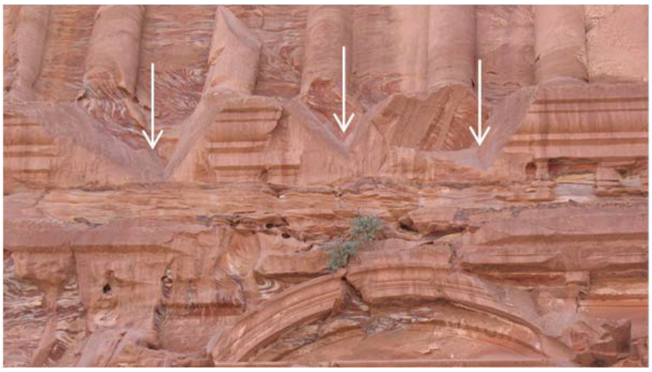

Abb. 12: Palastgrab (Nr. 765). Verlust von Gesteinsblöcken am Gesims infolge räumlichen Gleitens.

Fig. 12: Palace Tomb (No. 765). Loss of stone blocks at the moulding due to wedge failure.

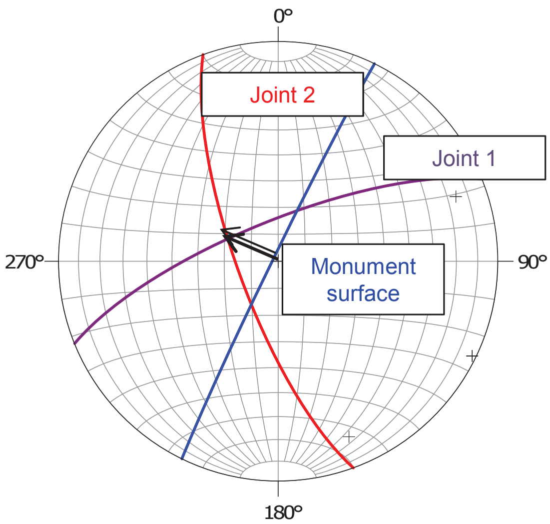

Abb. 13: Palastgrab (Nr. 765). Darstellung der Raumlagen von Bauwerksoberfläche (296/88) und Gleitflächen (Klüfte, 338/75 und 250/75) im Schmidt´schen Netz.

Fig. 13: Palace Tomb (No. 765). Illustration of the orientation of monument surface (296/88) and sliding planes (joints, 338/75 and 250/75) in the Schmidt net.

Abb. 14: Monument Nr. 73. Rechter Teil des freistehenden Monumentes infolge Kippens an einer steil einfallenden Kluft zerstört.

Fig. 14: Monument No. 73. Right part of the monument destroyed due to toppling failure along a steeply inclined joint.

4 Preliminary risk assessment

Discontinuities – especially joints – can be observed on many rock-cut monuments in Petra, either as individual discontinuities or intersecting discontinuities. Systematic studies for risk assessment have not been carried out until now. An inventory of the monuments with respect to the orientation of the discontinuities and its relation to monument exposure (orientation of the monument surface, geometry of the monument and its surrounding) is recommended, since it could make an important contribution to a first estimate of monuments that may be in risk of failure processes (Fig. 15).

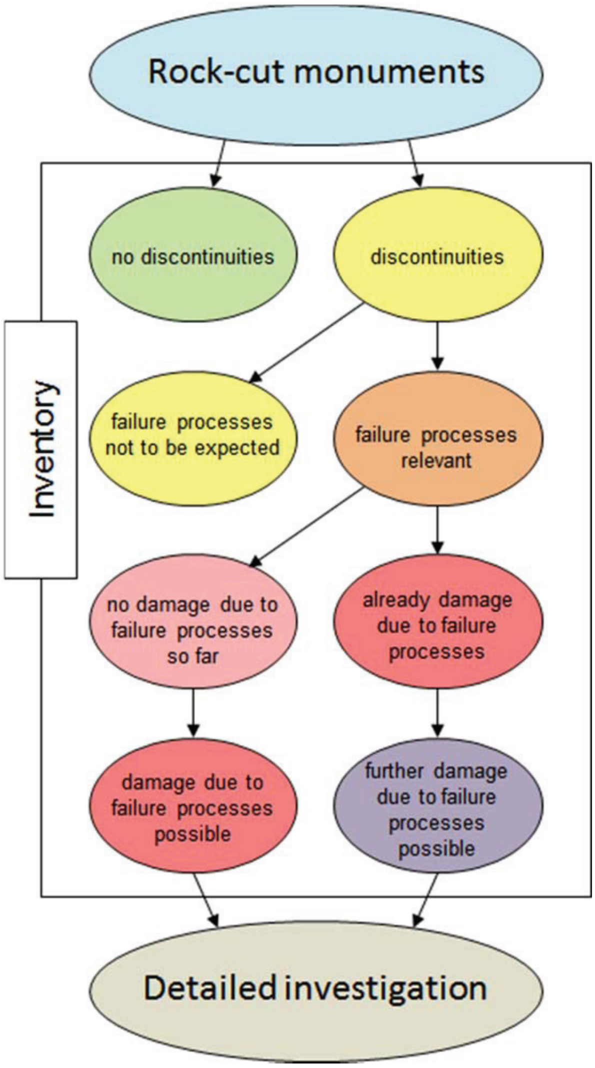

Abb. 15: Teilaspekte der empfohlenen Bestandsaufnahme bezogen auf Trennflächen und ihre Relevanz hinsichtlich Versagensmechanismen und daraus resultierender Bauwerksschäden.

Fig. 15: Aspects of the recommended inventory in terms of discontinuities and their relevance with respect to failure processes and resulting monument damage.

Figs. 16-20 document the situations with respect to discontinuities and potential failure processes for the monuments No. 808 (potential failure process: plane failure), No. 69 (potential failure process: wedge failure) and No. 138 (potential failure process: toppling) as examples.

The findings obtained from such an inventory would provide the possibility of a first valuation of risk and damage potential of failure processes. In combination with an accompanying photo-documentation of the monuments, the inventory would provide a suitable basis for the long-term monitoring. Re-observation of the monuments in regular intervals could be made easily and rather fast.

Abb. 16: Monument Nr. 808 mit markanter Kluft.

Fig. 16: Monument No. 808 with significant joint.

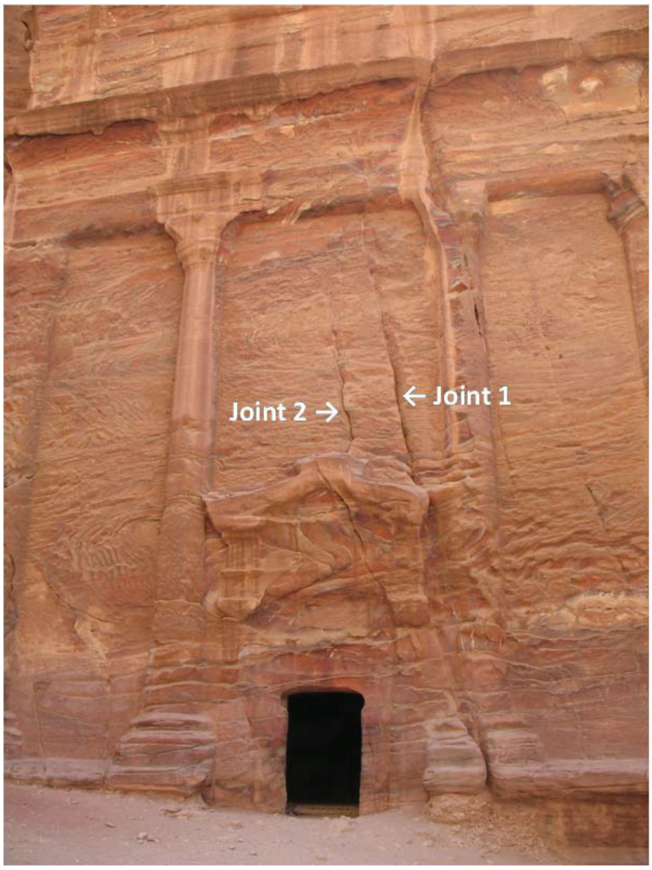

Abb. 18: Monument Nr. 69 mit sich verschneidenden Klüften. Das Verschnittlinear der Klüfte fällt steil aus der Bauwerksoberfläche heraus.

Fig. 18: Monument No. 69 with intersecting joints. The linear of their intersection dips steeply out of the monument surface.

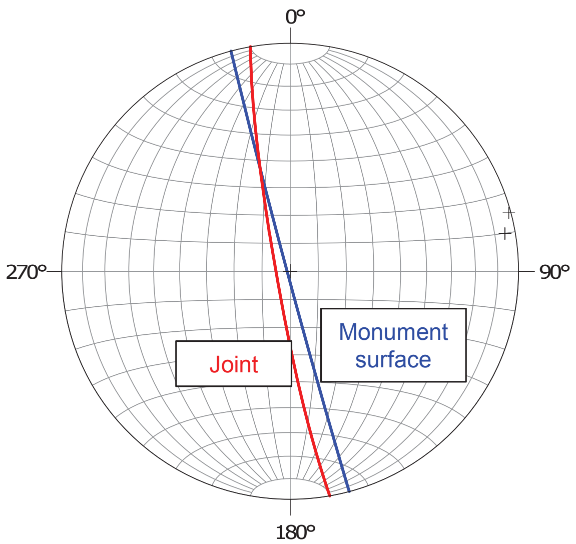

Abb. 17: Monument Nr. 808. Darstellung der Raumlagen von Bauwerksoberfläche (255/89) und potentieller Gleitfläche (Kluft, 260/85) im Schmidt´schen Netz. Potentieller Versagensmechanismus: ebenes Gleiten.

Fig. 17: Monument No. 808. Illustration of the orientation of monument surface (255/89) and potential sliding plane (joint, 260/85) in the Schmidt net. Potential failure process: plane failure.

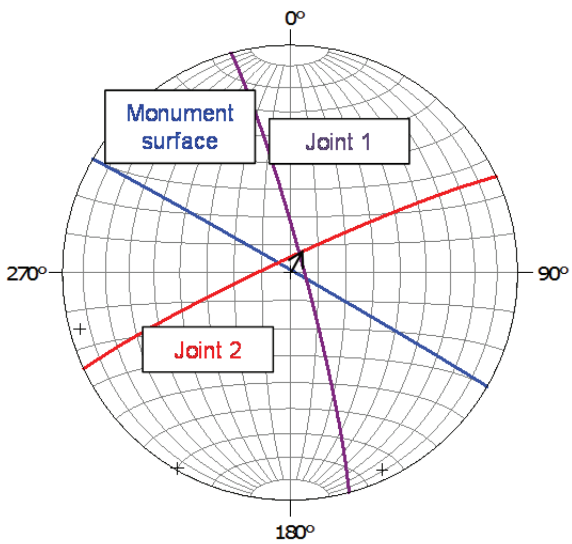

Abb. 19: Monument Nr. 69. Darstellung der Raumlagen von Bauwerksoberfläche (30/89) und potentieller Gleitflächen (Klüfte, 75/85 und 335/85) im Schmidt´schen Netz. Potentieller Versagensmechanismus: räumliches Gleiten.

Fig. 19: Minument No. 69. Illustration of the orientation of monument surface (30/89) and potential sliding planes (joints, 75/85 and 335/85) in the Schmidt net. Potential failure process: wedge failure.

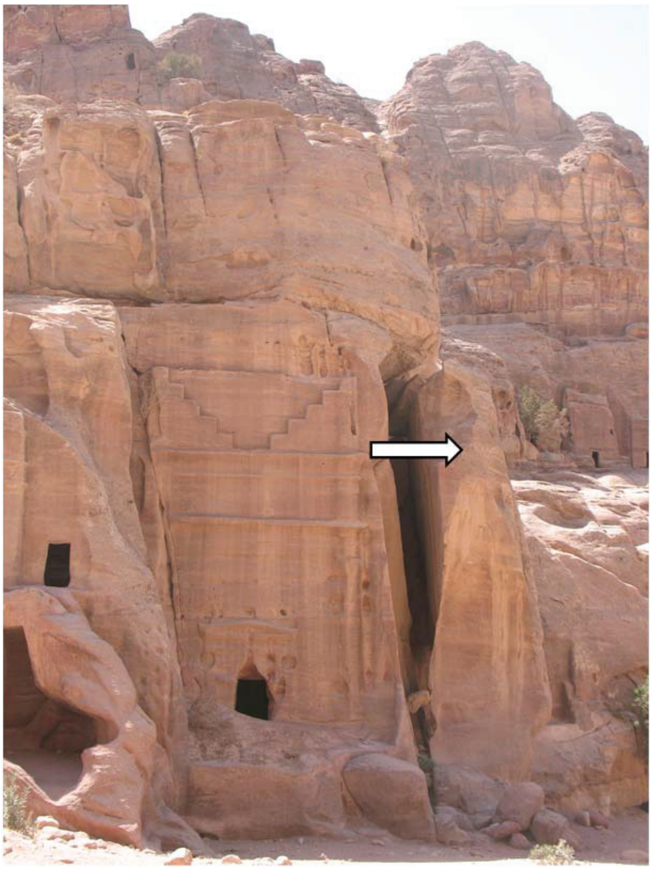

Abb. 20: Kippen eines Felsblockes am Rand von Monument Nr. 138.

Fig. 20: Toppling of a block of rock at the side of Monument No. 138.

Following the proposed inventory of the monuments, further more detailed studies required for precise risk prognosis, especially on condition of the discontinuities (e.g. persistence, surface trace length, aperture, degree of separation, surface roughness, infillings, alteration / weathering), could focus then on those monuments identified to be under potential threat.

As a very innovative technology, the use of a wireless sensor network with motion / vibration sensors could be taken into consideration, ideally in conjunction with an early warning system, taking into account that the Petra region is considered to be still tectonically active. At present, a wireless sensor network is already applied in Petra for continuous high-resolution environmental monitoring in the framework of the DFG research project 'petraSalt – Investigation of salt weathering on stone monuments by use of a modern wireless sensor network exemplified for the rock-cut monuments in Petra / Jordan' (HEINRICHS & AZZAM 2012).

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