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# A Combined Geological and Paleomagnetic Approach towards the Repositioning of Fragments from the Buddha Statues, 2006

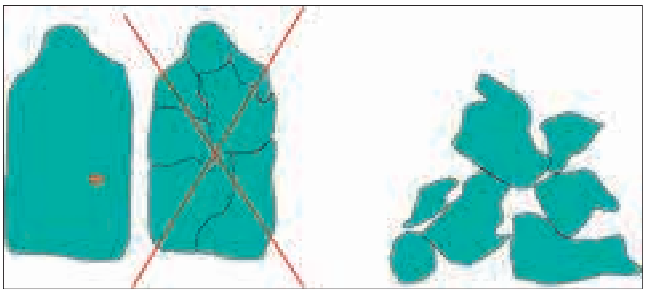
## 1 Introduction

### 1.1 Concept and previous missions in 2003 and 2005

The rationale behind the geological work in the Bamiyan valley presented here is to identify the original position and spatial relationship of the remains of the destroyed, Eastern and Western Buddha. Our approach adopts the fact, that the majority of fragments are characterized by nothing but the, however distinct, geological details of the formerly monument hosting rock (hereafter called sediment). Only a few fragments feature archaeological modifications, such as sculptured surface, which could alternatively be used in any restoration process. In addition, none of the fragments allows for reassembly based on shape or size of the fragments. Crucially, the size of even the largest remains is small compared to any part, e.g. the head, of the former Buddha figures (fig. 1)[1].

The general idea of using geological methodology as to identify the original position of the Buddha fragments is comfortably described by the term 'pattern matching'. Pattern, accordingly, is defined as an array of distinct geological and mineral magnetic information or features which characterize the sediment on a cm-scale. The cliff, i.e., the vertical sedimentary succession of the entire back plane of the Buddha niches, represents such a unique pattern (hereafter referred to as reference pattern). The fragments will contain a distinct part of the entire reference pattern and the minimum size of any fragment to be matched will depend on the minimum amount of recognized pattern features (fig. 2). One vertical line (reference pattern) down the back plane of the niches would be sufficient, if the sedimentary layers were strictly horizontally bedded and have no lateral variation.

There are two mutually beneficial ways to establish the desired patterns. One approach is based on mainly sedimentological information (see 2.2.1) and the other one adds paleo- and rock- magnetic characteristics of the sediment layers (see 2.2.2). Both ways of characterizing



△ Fig. 1. The Buddha fragments cannot be re-positioned in analogy to a broken vase, for example. Potsherd characteristics like shape or ornament need to be replaced by an array of geological and magnetic, sometimes archaeological properties of the Buddha fragments referred as pattern in this report. Small orange rectangle approximates the size of the largest fragments relative to the original height of the standing Buddha figures.

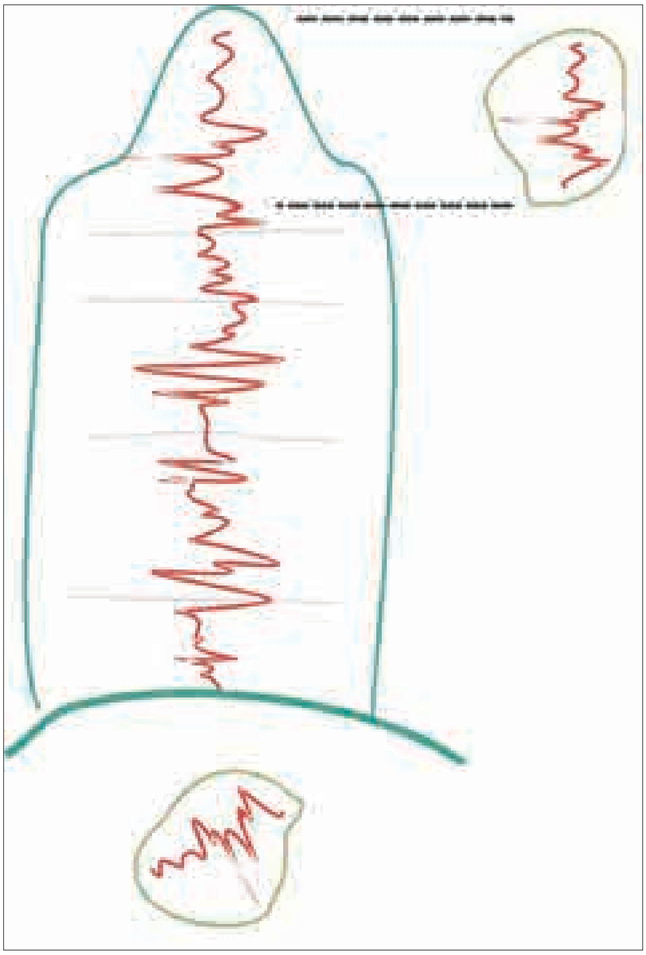


Fig. 2. The fragments originally were part of the sedimentary composing the cliff which hosted the Buddha figures. The term reference pattern used in this report is illustrated by the wiggly red line down the back plane of the Buddha Niche. A displaced fragment contains a distinct part of the reference pattern and is re-positioned vertically by matching the fragment pattern to the reference pattern. Schematic not to scale. ▷

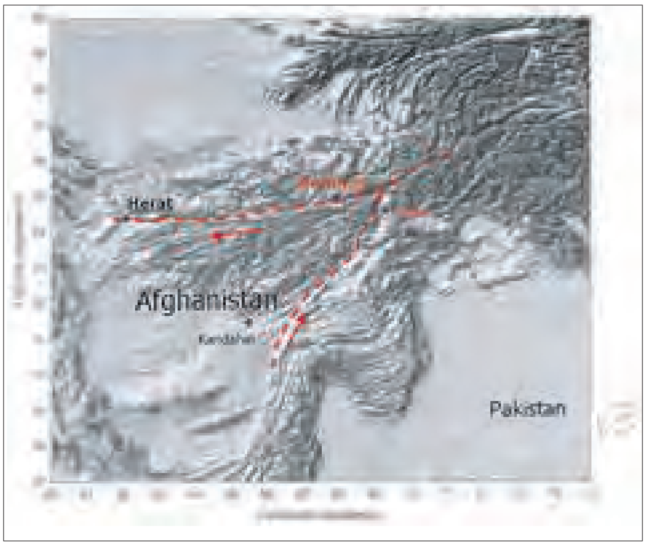
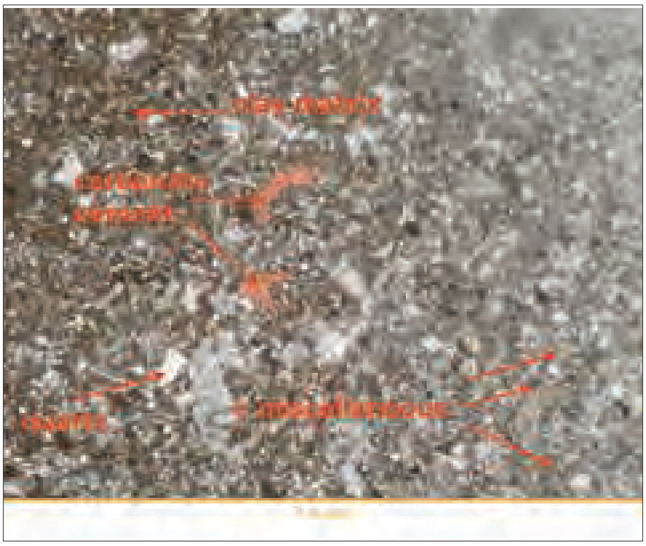



Fig. 3. Tectonic evolution of the Bamiyan Valley along the major east-west trending Herat fault (upper stippled line)

the Buddha material are designed to be (mostly) applicable on-site and, due to practicability, avoid, but not exclude, more sophisticated laboratory methods. Wherever possible, non-geological information such as sculptured surface of the Buddha figures or remains (cement, cavities) from pre-destruction restoration activities (altogether hereafter referred to as archaeological details) will be integrated in the establishment of a characteristic pattern.

Ultimately, the results obtained will be integrated in a 3D computer model featuring both Buddha niches, which is presently developed in the group around Michael Jansen at the RWTH Aachen. Essentially, this latter step in the analysis of the Buddha remains can provide the essential (technical) basis, before any further preservation activities are considered.

Fig. 4. Example of thin section under the microscope from one of the reddish layers from the Western Buddha niche. Note that any natural cement that would support the stability of the rock fails to do so, because it only appears in nests. Matrix is mostly clay. Length of the long side is 7.3 mm.



A feasibility study of the theoretical approach (K. Krumsiek, M. Urbat, University of Cologne) including the set up of a tentative geological reference profile (see 3.1) was carried out in the frame of the first mission to Bamiyan in October 2003 (M. Urbat). Due to the short time on site and, more crucially, the inadequate accessibility of the vertical, several tens of meters high back plane of the niches work at this stage had to be limited to the measurement of two independent physical properties (magnetic susceptibility and colour variation) in order to approximate the sedimentary succession in the niche of the Western Buddha. These physical logs were supplemented by the visual description of rock fragments as well as some additional palaeo- and rockmagnetic measurements carried out at the Paleomagnetic Laboratory, University of Cologne. This first geological mission yielded promising results and confirmed the practicability of the theoretical approach, which however needed to be modulated with respect to the on-site conditions. Crucially, the final proof of the suggested method could not be given, because the established patterns from the back plane of the niches and the fragments could not be realized at the same scale (lack of resolution).

These initial geological results were considered in close cooperation with the ICOMOS organized experts on natural stone restoration Ulrich Bauer-Bornemann, Edmund Melzl, Hendrik Romstedt and Michael Scherbaum, who participated in the same October 2003 mission to Bamiyan. The more general discussion as well as recommendations on the preservation of the Buddha statues, based on such mutually beneficial, restorational/geological considerations is given in a further report to ICOMOS (Bauer-Bornemann et al., 2003).

The second geological mission in September 2005 succeeded the visit of the Bamiyan site in October 2003. At this time rescue and archaeological documentation of the fragments was underway, bringing more and more, so far covered, fragments to the surface. Moreover, after two winters of exposure the suspected weathering of the fragments needed closer inspection with respect to the validity of the previously envisaged geological approach. Under these premises the main purpose of the September 2005 mission was to proof the suggested method and establish a workable approach to implement the geological methodology into the present overall activities around the fragments from the Western Buddha. In fact, a first successful pattern match, hence the original position, of one of the fragments could be established (see 3.1). Potential and merits of integrating archaeological details were discussed and implemented with the results established by the archaeologist onsite Bert Praxenthaler (see respective ICOMOS report).

### 1.2 The 2006 mission (Eastern Buddha)

The third geological mission in late October 2006 (J. Aubel on-site, M. Urbat) targeted the Eastern Buddha niche and fragments, which had so far, due to the restricted access, been covered to only a minor extent. It was, however, clear from the previous visits to Bamiyan that the geology constituting the eastern niche differs from the western part of the cliff in that layers which might challenge the geological approach appeared more prominent. In the course of the overall activities around the Eastern Buddha all fragments had been cleared from the niche in October 2006 and scaffolding of the back plane of the niche was to be completed prior to the start of the geological investigations (potentially providing a first time unrestricted access to one of the back planes of the niches and, hence, a first time opportunity to establish the required vertical reference patterns essential for the suggested approach). Due to unforeseen time delays in the set up of the scaffold only the lowermost layers of the back plane could be inspected. These results, however, indicate that the geological method established for the Western Buddha is successfully transferable to the Eastern Buddha with only minor modifications (see 3.1.2).

## 2 Explanatory notes

### 2.1 Geological overview

Supposedly in Oligocene/Miocene times (i.e., around 24 million years ago) the Bamiyan Valley developed as an intramountain, west – east oriented, basin along the major Herat-Fault-System, hence, in the course of major tectonic movements in this area (Krumsiek 1980, fig. 3). The basin was subsequently filled with debris originating from the surrounding, elevated parts of the relief – mostly conglomerates of different composition and compaction, sometimes volcanics. Today these deposits constitute the succession of almost horizontally bedded layers the Buddha figures were sculptured in. Lang (1972) suggests at least four different formations during the Miocene, including the so-called Bouddha-Formation, which is laterally replaced by the Qal'ocah Formation of middle Miocene age (around 15 mio. years) in the Bamiyan Valley. The west-east trending, almost vertical wall that hosts the Buddha niches today, developed much later during Pliocene-Pleistocene times (< 2.4 mio. years) as a consequence of fluvio-glacial erosion. Although, in vicinity to, and within the western and eastern Buddha niches the Miocene sedimentary succession is almost horizontally bedded, strata cannot be correlated from one niche to the other, because the sediment layers are offset at a local NE-SW trending fault. Consequently, both the Buddhas were hewn out of different strata, with different lithologic/ static properties, respectively.

*Geology on site*

In a simplified view the sediment of the Bamiyan cliff is composed of horizontally bedded, centimeter to meter thick layers of various conglomerates interbedded with finer grained clay, silt and sand layers or mixtures thereof (also see Zou and Unold, 2002).

Importantly, the conglomerate as well as the interbedded layers are highly variable in composition, grain size, thickness and colour. From a visual inspection of the surrounding blocks the conglomeratic layers in the niche of the western Buddha vary in thickness between several dm and some few meters. The size (diameter) of the usually well rounded components ranges from a few to almost 20 cm within the respective layers. The composition per

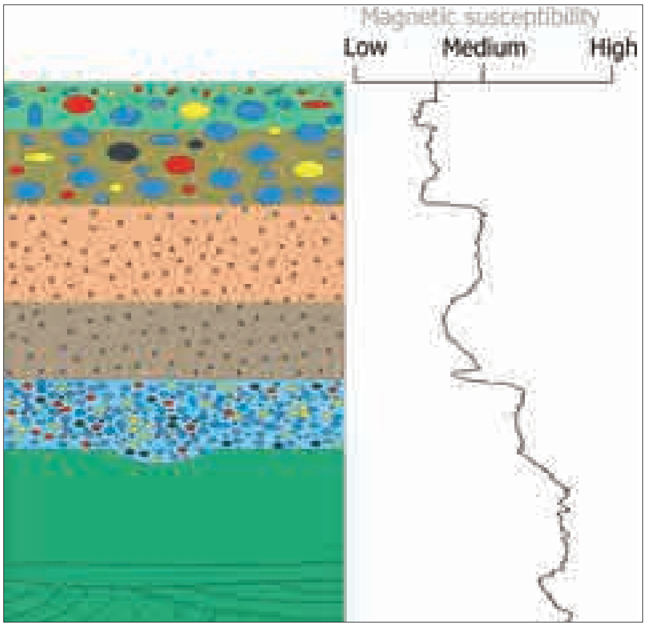



Fig. 5. Schematic drawing illustrating several of the above named sedimentological features – magnetic susceptibility (notional curve) is discussed in the following chapter.

layer is equally highly variable and reflects the Mesozoic and Paleozoic lithology in the vicinity of Bamiyan Valley including volcanic, intrusive and older sedimentary components. Most of the conglomerate layers appear to be relatively loosely packed, with no or only minor (natural) cement to support the stability of the components. Voids in between the pebbles are rather filled with clay or silt, which was likely deposited in the same process as the main components of the conglomerate.

The various conglomeratic layers are interbedded with, equally diverse, silty or sandy layers of reddish or minor yellowish colours. The thickness of these layers may vary between 1–2 cm up to 1–2 meters. These layers are important for several reasons, because first they can be used as marker beds within the reference profile, second they provide the only material that can be sampled for additional paleomagnetic NRM measurements (re-orientation in the horizontal plane), and third these layers reveal that the supposedly horizontal beds do have a rather high lateral variability (figs. 13, 15).

The material that the layers consist of can be considered matrix supported sand or silt, with no contact between the sand or silt size components (fig. 4). These are mostly poorly rounded, often even fractured quartz, and less often feldspar, pyrite or volcanic components in varying concentration. The matrix appears to be mostly clay, interspersed with varying amounts of carbonate cement. Unlike the clay matrix, the cement in all of the inspected thin sections only appears in little nests and never persists. The reddish or more yellowish colour of the layers originates from the red clay matrix with various amounts of carbonate (yellow).

Like the conglomerate, the interbedded layers are hence loosely packed clastic components, with no sufficient amount of cement which would result in a higher stability of the material. The above observation also easily explains the strong HCl reaction (carbonate) of all of the samples

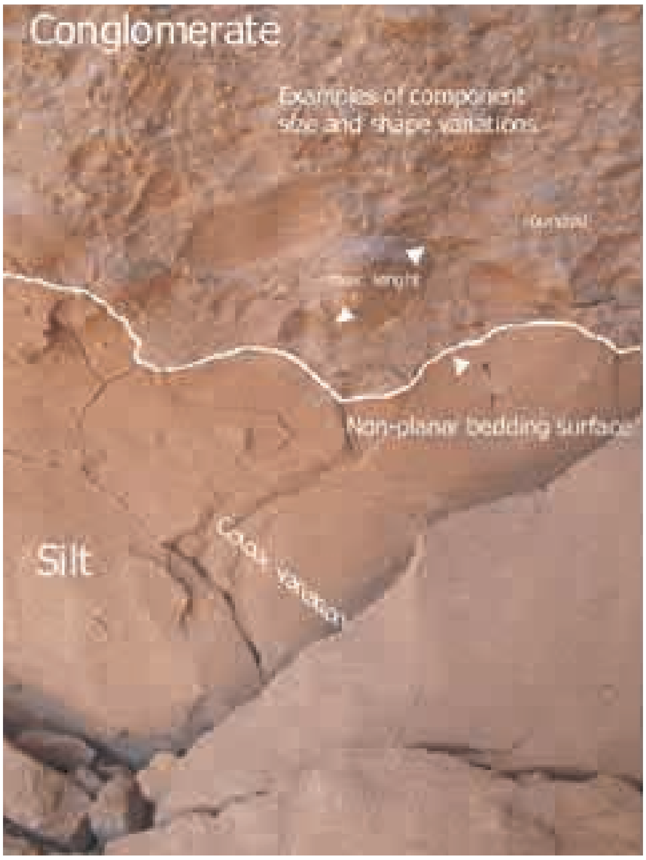



Fig. 6. Illustration of various sedimentological characteristics employed in the pattern matching approach.

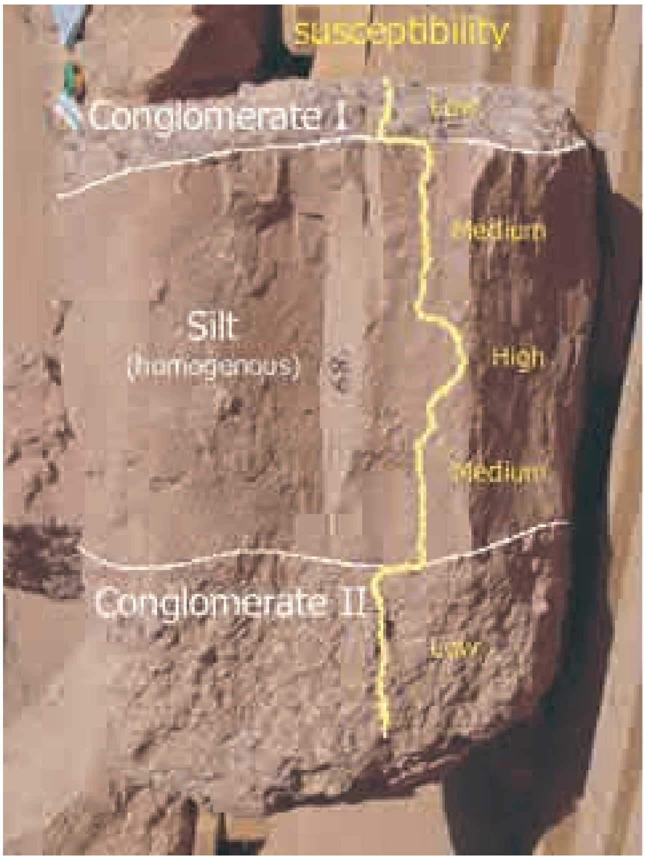



Fig. 7. Schematized magnetic susceptibility variation to illustrate typical variations in between the various lithologies (detrital) and within lithologically homogenous layers (diagenetic). Both features are useful for the pattern matching approach.

investigated on site, as well as the fact that all of the material dissolves in water within seconds (this has been noted previously by Zou and Unold, 2002 – and was confirmed with various samples on site). Salt was not detected in any of our samples (which again confirms the high variability amongst the individual layers), and, hence, cannot account for the low stability of the material as was suggested by Zou and Unold (2002) in this case.

2.2 Methods
2.2.1 Geological criteria

The geological approach to discriminate the required reference pattern is based on a detailed visual description of the varying sedimentological and structural features of the respective layers (figs. 5 and 6). Such are:

- colour variations of the sediment matrix,
- type and composition of rock components of the conglomerate,
- shape of these components (rounded versus non-rounded or etched),
- sorted or unsorted with respect to shape or composition of components,
- grain size changes of non-conglomeratic layers (i.e., clay, silt, sand or mixtures thereof),
- the former terms classify sediment according to grain size,
- mineral composition of non-conglomeratic layers,
- type of natural cement, if present at all,
- sedimentary structures (for example cross bedding, channels),
- bedding (dip, lateral variation),
- secondary alteration, if visible.

2.2.2 Paleomagnetic measurements

The main application of the magnetic methods uses the magnetic susceptibility κ, defined as *κ = M/H, with M = magnetization and H = applied field* of the sediment for the vertical positioning of the fragments with respect to the reference pattern. At its simplest, the magnetic susceptibility, as a measure of the magnetizability of the sediment, is a scalar property and will vary in direct response to the varying sediment composition of each sample. κ reflects a composite of magnetic properties including the diamagnetic, paramagnetic and the various ferromagnetic contributions from the respective minerals, rock fragments or matrix. Note, that the dominating contribution to κ is likely to originate from ferromagnetic minerals, like the iron oxide magnetite, although such account for < 1 vol % of the entire sediment and will have grain sizes of only a few microns (μm). These magnetic minerals can be detrital in origin or secondary, and, hence, uncorrelated to primary sedimentary features. Importantly, both the primary and secondary magnetic signals can be used for the identification of the Buddha remains, if κ of the fragments was not altered since the destruction of the Buddha figures. A possible scenario for the latter could be quicker weathering of the fragments over the past few years due to intensified exposure.

In general, κ will be measured, closely spaced, perpendicular to the bedding plane with a handheld, so-called, kappameter designed for field use. The measurements result in a continuous record of susceptibility values that mirror the distinct properties of the various sedimentary layers of both the back plane of the Buddha niches and the Buddha remains. Accordingly, κ can be viewed as an approximation of the above described sedimentary or secondary diagenetic alteration of the rock. Crucially, it does add important information, which is not easily accessible from a visual geological inspection alone (see results chapter). The respective measurements are quick (< 10 s), non destructive and cost free, however, like the geological documentation require direct contact with the rock surface while taken (crucial in terms of accessibility of the back plane of the niches). Note, that the susceptibility characteristics employed in the pattern matching approach rely on the relative changes of the intensities over a certain thickness of sediment rather than the absolute value of a single measurement (fig. 7).

Additional, more sophisticated analyses of the magnetic properties of the rock can be obtained using laboratory methods (Urbat 2003)[2]. The latter measurements cannot be achieved on-site and will require samples to be taken to the laboratory, and, hence, will only be employed in critical sections where on-site criteria do not provide sufficient details. Note, that these laboratory measurements will be required especially for (supposedly few) fragments whose up/down orientation or necessary amount of rotation in the horizontal plane can not be otherwise determined. Under such circumstances the vector properties of the remanent magnetic minerals contained in sediment (having stored the orientation and intensity of the former earth's magnetic field) will be used.

### 2.2.3 Archaeological details

Archaeological details such as parts of the sculptured robe, re-enforcement cavities or mud plaster (see respective archaeological reports, fig. 8) all in first place indicate that a fragment belongs to the front part of the former Buddha figures. Roughly estimated the amount of such fragments is less than 25 % of the total remains. All other fragments originate from the inner body of the figures and do, accordingly, not features anything but geological and magnetic information. Given the relatively small size of even the few largest fragments (which measure about 2 meters across) in relation to the 55 m and 35 m high standing Buddhas an unambiguous assignment of the remains to their original position – for example using high resolution photographs from pre-destruction times – based on archaeological details alone will only exceptionally be possible. Clearly, in combination with the geological and magnetic characteristics of a fragment such archaeological features (fig. 9) are of utmost importance for any successful re-positioning (i.e. the establishment of a characteristic pattern) as the front/back orientation of a fragment is clearly indicated (fig. 8).

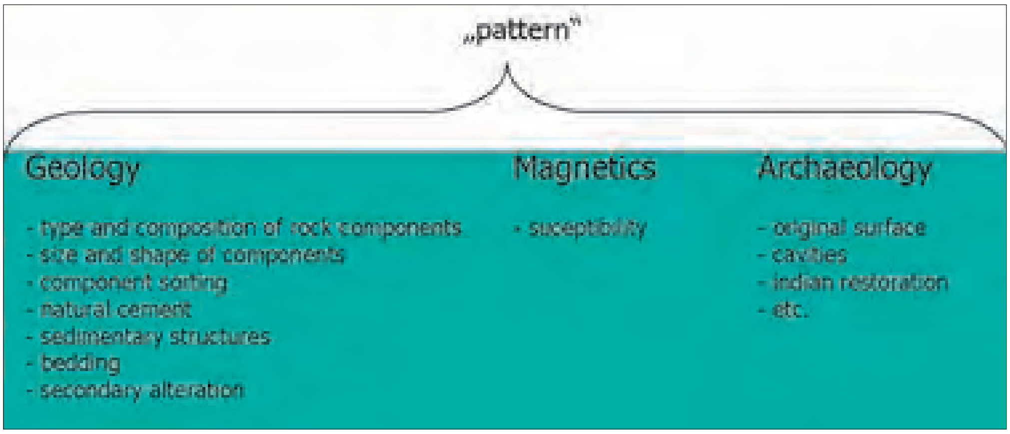



Fig. 9. Summary of criteria applicable on-site constituting a pattern

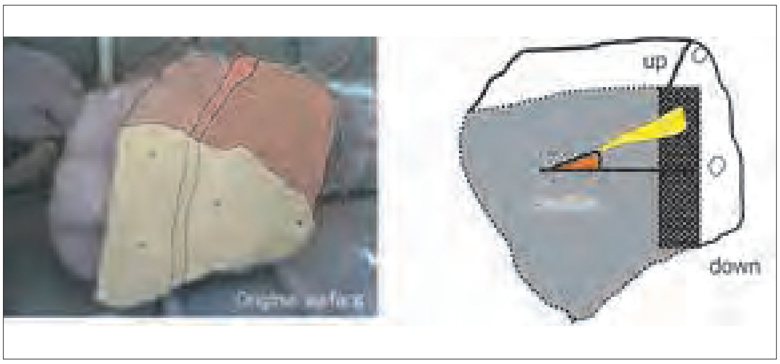



Fig. 8. Left photograph illustrates one of the larger fragments from the Western Buddha featuring original surface (highlighted in yellow, covered with mud plaster typically having a thickness of about 1–2 cm, small dots indicate location and size of re-enforcement cavities). Also shown and highlighted in brown and red colours is the 3-dimensional orientation of the sedimentary layers with respect to the surface. Right hand schematic illustrates how the re-enforcement cavities provide (additional) information on the up/down orientation of a fragment, given that these cavities were forced into the rock under the acute angle with respect to horizontal.

Note that measurements of magnetic susceptibility as well as a thorough geological description of the sediment (fragments, back plane of the niches) are not feasible for parts covered with mud plaster (i.e. original surface). These values, however, are easily obtained from the non-covered sides of the fragments (fig. 8).

### 2.3 Situation on site

Both the geological as well as the magnetic analyses require direct contact with the material to be investigated. Hence, unrestricted access to the back plane of the niches and the respective fragments is the essential prerequisite for the success of the suggested pattern matching approach. Recovery of fragments from the heap of remains at the bottom of the respective niches continued over the past few years (figs. 10–12) and was completed in October 2006 for the Eastern Buddha. The fragments from both niches were placed in storage next to the western and eastern sites and scaffolding of the eastern back plane was begun in late October 2006, providing access to the lowermost 10 meters above ground of the 38 m high wall. The upper part of the wall could, as of yet not be investigated adequately. As for the Western Buddha niche only one 4.5 m long section from the lower part of the 58 m high back plane could be geologically researched using an extension ladder (see 3.1).

The remainder of the wall awaits further inspection by the geologist in order to set up the essential reference profiles once direct access to the wall can be gained.

## 3 Results

### 3.1 Back plane (reference profiles)

#### 3.1.1 Western Buddha niche

One of the most important prerequisites for any successful pattern matching approach will be the establishment of a thorough, high resolution reference pattern from the back walls of the respective niches. A first step towards such a reference profile for the Western Buddha was made during the 2003 mission based on successive measurements of magnetic susceptibility (fig. 13). It must be clearly stated that this recorded susceptibility profile cannot provide anything but a rough frame for the required reference pattern at high resolution, because it lacks the geological details and the spatial resolution of the susceptibility measurements is too low.

During the fieldwork in October 2003 both the 58 m high wall in the back of the Buddha niche would only be accessible with the aid of a professional climber (provided by RODIO, Inc.). Any attempts in the niche of the Eastern Buddha were cancelled in 2003, because engineering work by the Italian firm RODIO to consolidate the intensely fractured side walls of the niche was in full swing, and furthermore, the equally highly fragile wall appeared to be too high a risk (for the climber, but also to further damage the wall) without time consuming preparatory work. We therefore attempted to approximate the reference profile in the niche of the Western Buddha by way of scanning for magnetic susceptibility and colour variations. The lowermost approx. 10 m of the profile could not be accessed, because it was then hidden by the blasted rock fragments.

Magnetic susceptibility was measured using a handheld Kappameter KT-5c (AGICO, Brno, CZ) at a spacing of approximately every 20–30 cm (fig. 13), while the location in the wall was measured at the same time using a Total Station (Topcon GTS) with a local reference system, placed in front of the niche. The measured profile follows a sub-vertical line downwards from the window on top of the former head of the Buddha. Several additional susceptibility profiles at a spacing of about 10 cm were measured perpendicular to bedding of the larger blocks within the niche.

Relative colour variations (fig. 13) down the same reference profile were measured using a spectrophotometer Minolta CM-2002 (MINOLTA, Japan) at approx. every 80–100 cm. Again the position of each respective measurement was determined using the Total Station. A denser sampling rate could not be realized with the relatively fragile spectrophotometer, which proved less user-friendly under rock climbing conditions.

Despite the still restricted access to the back wall of the niches, the first real test of the pattern matching approach could be established during the September 2005 mission. One of the larger, as of yet not recovered fragments from the Western Buddha niche (fig. 14) was suspected to originate from the lower part of the back plane based on geological criteria (see previous paragraph). The 4.5 m long section from the back plane (in 2003 still hidden by fragments) was investigated using an extension ladder. The lithological succession is summarized in figure 14. Importantly, a several cm-thick red clay layer with unique primary bedding structures (dewatering streaks), which had been noted in the fragment as well, could be used as a marker bed (i.e., a tie point). Susceptibility profiles were measured for the back wall section and the targeted fragment. Both the susceptibility profiles were measured at high resolution, i.e., at about every 5–10 cm, and, hence, for the first time on the same scale of resolution. Confirmed by the position of the marker bed both the susceptibility profiles from the back wall and the fragment yield a perfect match (fig. 14), and, hence, validate the suspected original vertical position of the fragment. Minor deviations of the two susceptibility profiles reflect the slight lateral variability of the sedimentary layers.

#### 3.1.2 Eastern Buddha niche

Before the 2006 mission the Eastern Buddha had been given less attention due to the situation on site. During the 2006 geological mission several short profiles from the lowermost part of the back plane could be geologically and magnetically investigated by Jens Aubel. In summary, while the sedimentary layers in this lower part of the wall are sufficiently distinct (fig. 15) to promote the success of the pattern matching approach in analogy to the results from the Western Buddha, the apparently more prominent coarse conglomerates in the upper part of the cliff (observation from the distance) will possibly require special attention.

Susceptibility measurements were taken at the highest possible resolution (i.e. at about every 5 cm) with the handheld KT-5c Kappameter from the sections indicated in figures m and ff, as well as from several fragments, which could be assessed (see 3.2.2). Magnetic susceptibilities are on the same order as was noted for the Western Buddha sedimentary succession and displays an equally distinct variation with the lithology (figs. 16, 17). Hence, these results are more than promising for the suggested pattern matching method to be used for the Eastern Buddha as well.

3.2 Fragments[3]
3.2.1 Western Buddha

The main purpose of investigating the fragments, in 2005 accessible in greater number and detail than was previously possible, was to establish whether they are in fact geologically distinct to a degree, that the idea of pattern matching is further supported. A second important goal was to check on any possible alteration (weathering) of the remains which might challenge the geological approach. In addition, the recovered fragments provided a good opportunity to look into useful combinations of geological criteria and archaeological details from the original (carved) Buddha figure surface.

The results can be summarized as follows:
As was previously suspected (Urbat 2003) a selection of 22 fragments confirms, that all of the sedimentary layers are geologically distinct amongst the individual fragments. Hence, the most important prerequisite for the pattern matching approach is satisfied. The following summary is based on fragments GBF 001, 002, 004, 006, 007, 047–049 and 052–0653 plus several observations from not yet registered fragments from the western and eastern Buddha niches:

- In all fragments the layering (bedding plane) was clearly visible, and, hence, allowed for the recognition of the sedimentary horizontal plane (basic re-orientation of the fragment).
- Since all of the investigated fragments had remains of the original surface, which in a first approximation indicates a vertical plane, the horizontal indicated by the layering could easily be confirmed. Note, that any acute angle between the bedding plane and the original surface may hint towards an original position of the fragment with a nonvertical carved surface (e.g. shoulder areas).
- All layers, which can be generally classified under a common term (e.g. conglomerate, silt, sand etc.) yield individual geological features allowing for a clear distinction among one another. Individual characteristics include colour, composition of components or mineral grains, size and shape, layer thickness and succession, type and amount of natural cement, HCl reaction and magnetic susceptibility (fig. 5).
- Magnetic susceptibility displays three typical ranges of values: low ($0.2 – 0.5 \cdot 10^{-3}$ SI), medium ($0.6 – 1.0 \cdot 10^{-3}$ SI) and high ($1.1 – 2.3 \cdot 10^{-3}$ SI). Lowest values are typically associated with the conglomerates. Importantly, visually homogenous non-conglomeratic layers typically display characteristic susceptibility variations in the medium and high ranges, even within the same layer (fig. 7).
- Several fragments have tectonic fractures on a small scale (hence unrelated to the detonation of the Buddha statues) or typical bedding structures (e.g. non-planar bedding surfaces) which will than be correlative with the respective tectonic or sedimentary features on the back wall of the niches as well (figs. 13, 14).
- Fragment GBF_049 (180 x 150 x 150 cm), which contains both conglomeratic and silty layers could be positively identified as one of the fragments which had been investigated during the first geological mission in 2003 (termed fragment 1531 at the time, fig. 18). Being one of the fragments on top of the heap of remains in 2003, hence only partly covered, three faces of the fragment experienced maximum exposures over the past two years. Importantly, no critical alteration or weathering of the material could be observed in 2005. This refers to the susceptibility measurements which were reproducible in 2005 as well as to any visible signs of material alteration (for example colour), apart from some minor mechanical damage due to the recovery of the fragment.

3.2.2 Eastern Buddha

Results from the Western Buddha fragments can be adopted for the eastern fragments. Absolute values are on average slightly lower as compared to the Western Buddha fragments due to an increased (less magnetic carbonate content), yet vary distinctly enough to identify a significant pattern to be used in the re-positioning approach (fig. 19).

## 4 Conclusions and recommendations

The geological details of the Buddha fragments combined with results from magnetic susceptibility measurements yield sufficient information to successfully solve the puzzle – at least for the larger sized remains of the Buddha statues (1 m across and up), even if only methods are used which can be easily applied directly on-site. The application of laboratory methods would allow for a re-positioning of even smaller fragments as has been described in Urbat (2003). Considering the rather small size of even the larger fragments (m-scale) as compared to the original height of the entire Buddha figures, it is suggested that the described pattern matching approach based on geological and magnetic criteria will be essential for any significant re-positioning of the remains, even if they do contain original Buddha surface (archaeological details). Importantly, any combination of archaeological details (for example, orientation of reinforcement cavities, fig. 8) with the suggested approach will significantly enhance the results. Further results of the 2003, 2005 and 2006 geological missions can be summarized as follows:

- A combination of geological and magnetic criteria satisfies the needs of the pattern matching approach. Geological, magnetic and archaeological criteria need to be combined as neither of them will provide sufficient detail in all cases.

△ Fig. 10a, ▽ Fig. 10b. Temporary storage of geologically investigated Western Buddha fragments in September 2005 (10a), situation at the foot of the Western Buddha niche at the same time.

▽ Fig. 11a, b. Temporary storage of Eastern Buddha fragments in October 2006 (larger sized fragments above, smaller sized fragments measuring less than 1 meter across below). Unfortunately, the tight storage of the fragments substantially restricts the required access for the geological analyses.

△ Fig. 12a, ▽ Fig. 12b. Eastern Buddha niche in October 2006 (above), maximum height of the scaffold attained by the end of the geological mission in November 2006 (below, upper level is about 10 meters above ground)

- Minor weathering of the fragments does not challenge the approach.
- A thorough geological description of both the fragments and the back plane of the niches by a trained geologist is essential for the success of the method.
- The respective reference profiles from the back walls still need to be established and therefore direct and unrestricted access to the walls is required. This can only be achieved with a scaffolding or a crane.
- Lateral variability of horizontal layers is high and requires more than one reference line per niche.
- Resolution and details of the preliminary frame for the pattern matching approach established by Urbat (2003, western niche) is not sufficient for a successful application of the suggested method and needs to be refined.
- It is not feasible to restore dust or, for example, loose sand.
- The fragments need to be cleaned from dust or rubble to improve the geological and magnetic recording – this will be best achieved using a vacuum cleaner or blower.
- Unrestricted access to each respective fragment is mandatory for a successful geological and magnetic analysis. The present storage of the recovered fragments does not match this requirement. The fragments will have to be pulled out for analysis.
- It is strongly recommended to implement a common reference system with respect to any position in the Buddha niches. Fixed reference points to be used by all involved parties need to be established.

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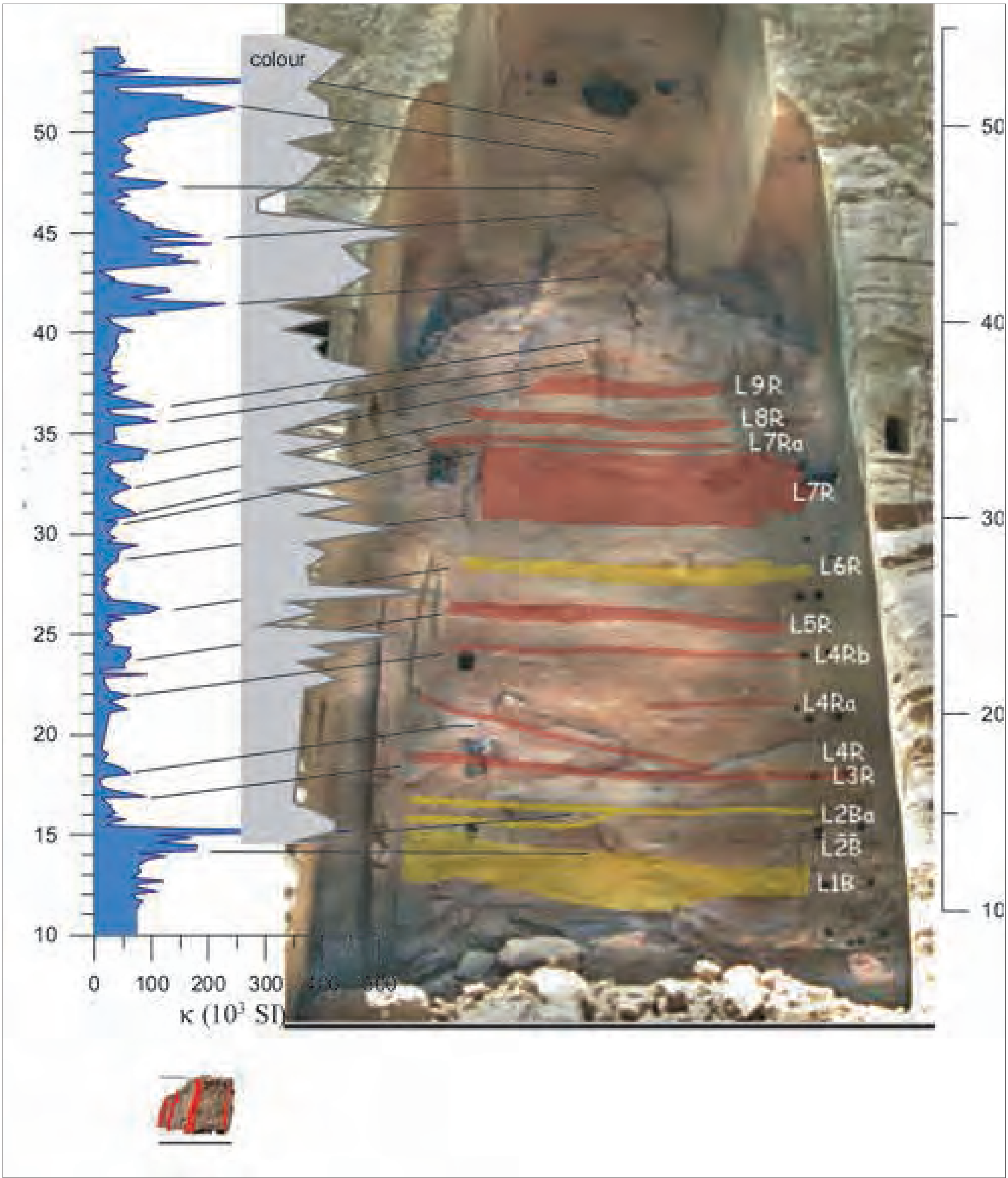
### *Notes*

1 The term figure rather than statue is used here, because the Buddhas were not completed as freestanding sculptures and rather remained semi-detached to the geological strata (cliff) they were hewn out.

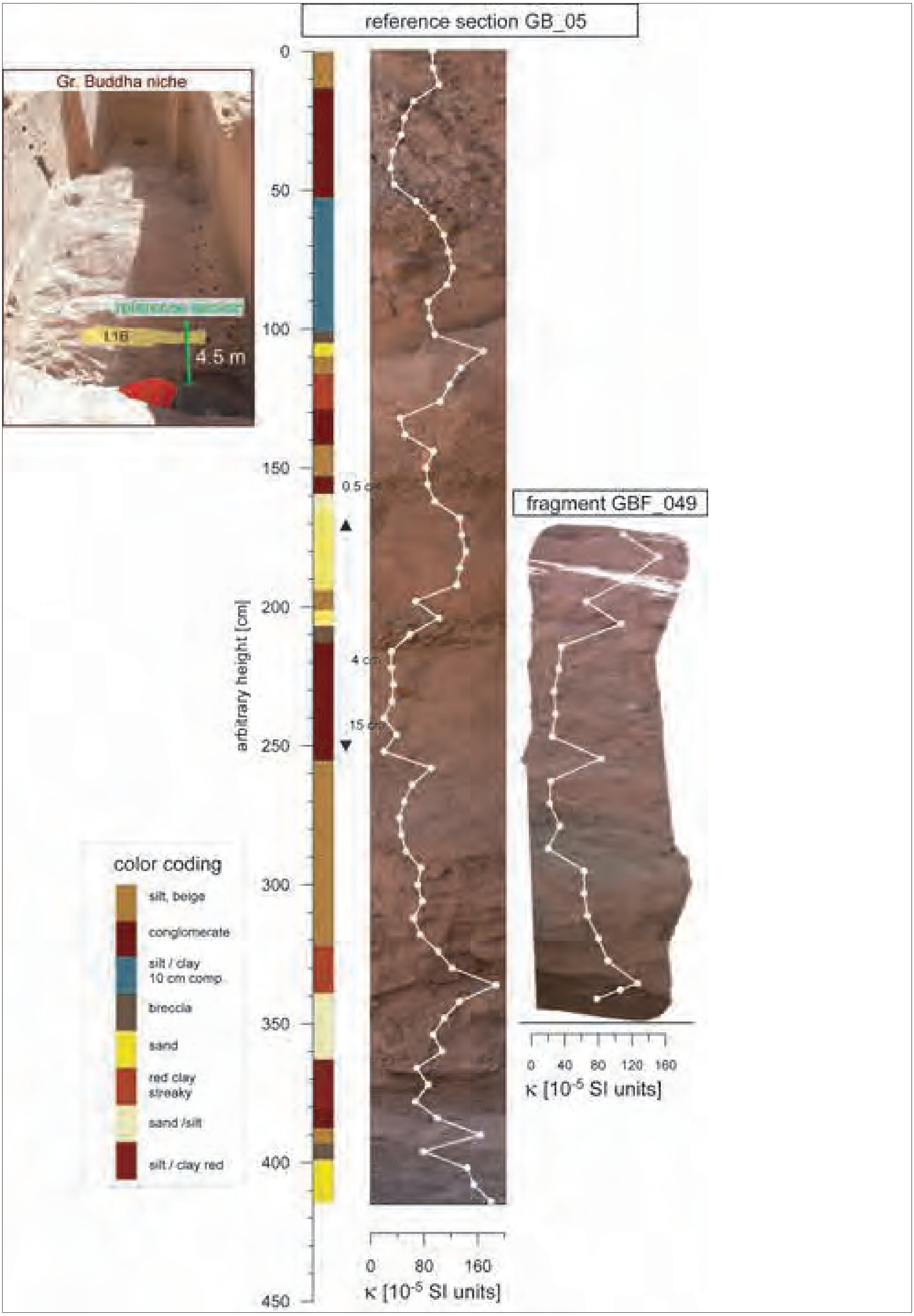
2 The paleo- and rockmagnetic measurements in the laboratory confirm two important aspects with respect to a possible reconstruction of the original context of the rock fragments. First, a combined interpretation of the laboratory induced magnetizations IRM (flat acquisition curves and values of the remanent coercivity Bcr $> 100$mT) and ARM as well as the high-temperature susceptibility measurements confirms the high variability of the respective sedimentary layers with respect to their composition, i.e., the prerequisite for a meaningful positioning of rock fragment with respect to the reference profile. The dominant carrier of the remanent magnetization is a high coercivity phase (presumably hematite-like, $Fe_2O_3$), however, with differing grain size distribution and possibly varying relative concentration and oxidation state. Second, this hematite-phase carries a stable NRM direction, which is the prerequisite for a meaningful reorientation of a rock fragment in the horizontal plane. The hematite-phase (which has a maximum grain-size of only a few µm) resides in the clay matrix of the interbedded layers and likely in the matrix in between the conglomerate components, hence, could be used in the conglomerate layers as well. The reddish colour of the entire sediment succession likely originates from the hematite contribution.

3 For any denotation of the fragments in this report the consecutive numbering introduced by the ICOMOS experts (B. Praxenthaler, E. Melzl) is adopted. GBF stands for Great Buddha fragment in conjunction with a 3-digit number starting from 001, which indicates the successive recovery of individual fragments from the niche irrespective of other fragment characteristics. In 2005, only those fragments with remains of the original surface have been included in the documentation. The fragments are temporarily stored under canopy next to the Buddha niche (fig. 10).




△ Fig. 13. Western Buddha niche. Initial 2003 geologic reference profile with suggested numbering system based on reddish (LxR) and light brownish (LxB) silt/sand layers interbedded with the conglomerates. Also shown is magnetic susceptibility κ and suggested correlation to the respective layers (thin black lines). Highest susceptibilities correlate with concrete remains on the wall which originate from a former Indian consolidation work in the 1970s. Shown in grey is the colour variation measured with the photospectrometer. Size of a 2 m size rock fragment is shown for comparison.

Fig. 14 ▷
First successful pattern match based on geological and susceptibility details of a fragment from the Great Buddha. The fragment originates from the lower part of the back wall just below Layer L1B (Urbat 2003). Inset (western Buddha niche, upper right indicates the location of the 4.5 m long profile investigated on the back wall of the niche as well as position and approximate size of the matched fragment in September 2005. Note that absolute susceptibility values as well as the shape of the two curves match nicely.


reference section GB_05
Gr. Buddha niche
L18
4.5 m
0
50
100
150
200
250
300
350
400
450
arbitrary height [cm]
0.5 cm
4 cm
15 cm
0
80
160
κ [10-5 SI units]
fragment GBF_049
0
40
80
120
160
κ [10-5 SI units]
color coding
silt, beige
conglomerate
silt / clay
10 cm comp.
breccia
sand
red clay
streaky
sand /silt
silt / clay red

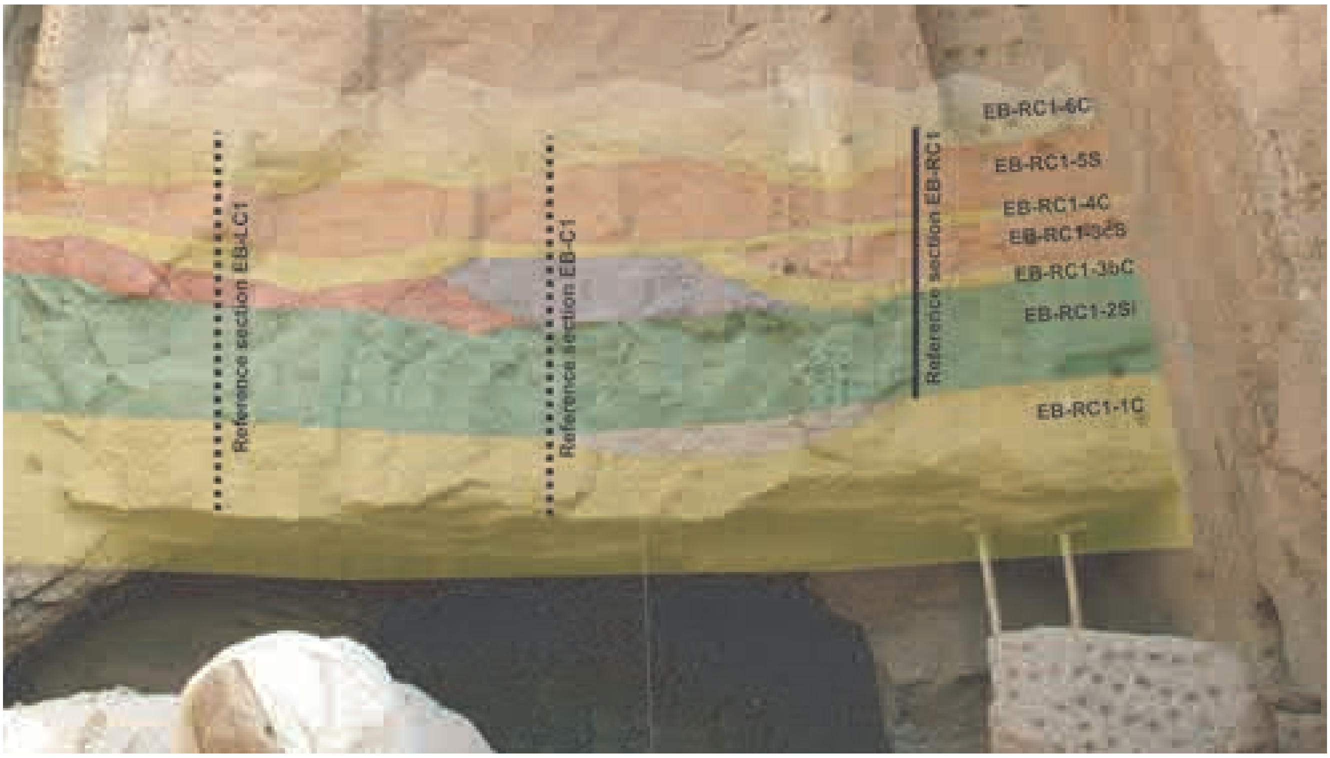
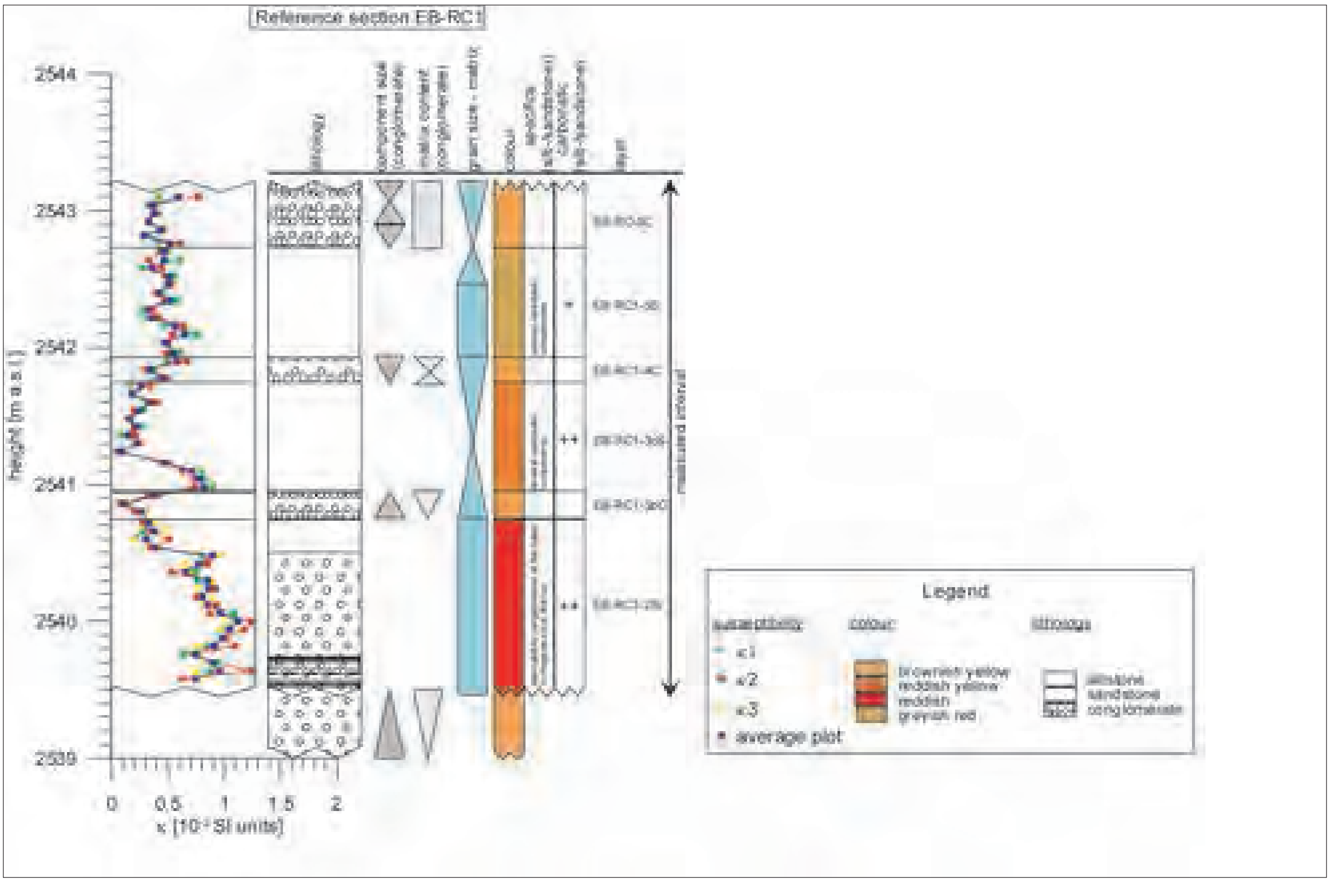



Fig. 15. Eastern Buddha niche - lower part of the back plane including entrance to the central chamber. Solid black line indicates the position of the 4.2 m long reference section EB-RC1. Overlaid colours highlight the sub-horizontally bedded succession of conglomeratic and silty layers (with suggested numbering EB-RC1-1C through EB-RC1-6C) and indicate their notable lateral variation and deviations from horizontal, which calls for at least two more reference lines (indicated by stippled lines).

Fig. 16. Summary plot of geological and magnetic results from reference section EB-RC1, Eastern Buddha niche. Both the geological details as well as the susceptibility logs vary distinctly on a cm-scale down section. Susceptibility (κ1 through κ3) measurements were taken repeatedly within a lateral displacement range of about 1m, while keeping the vertical position (m.a.s.l.) of the respective measurements. The reproducibility of the measurements clearly satisfies the needs of the pattern matching approach.



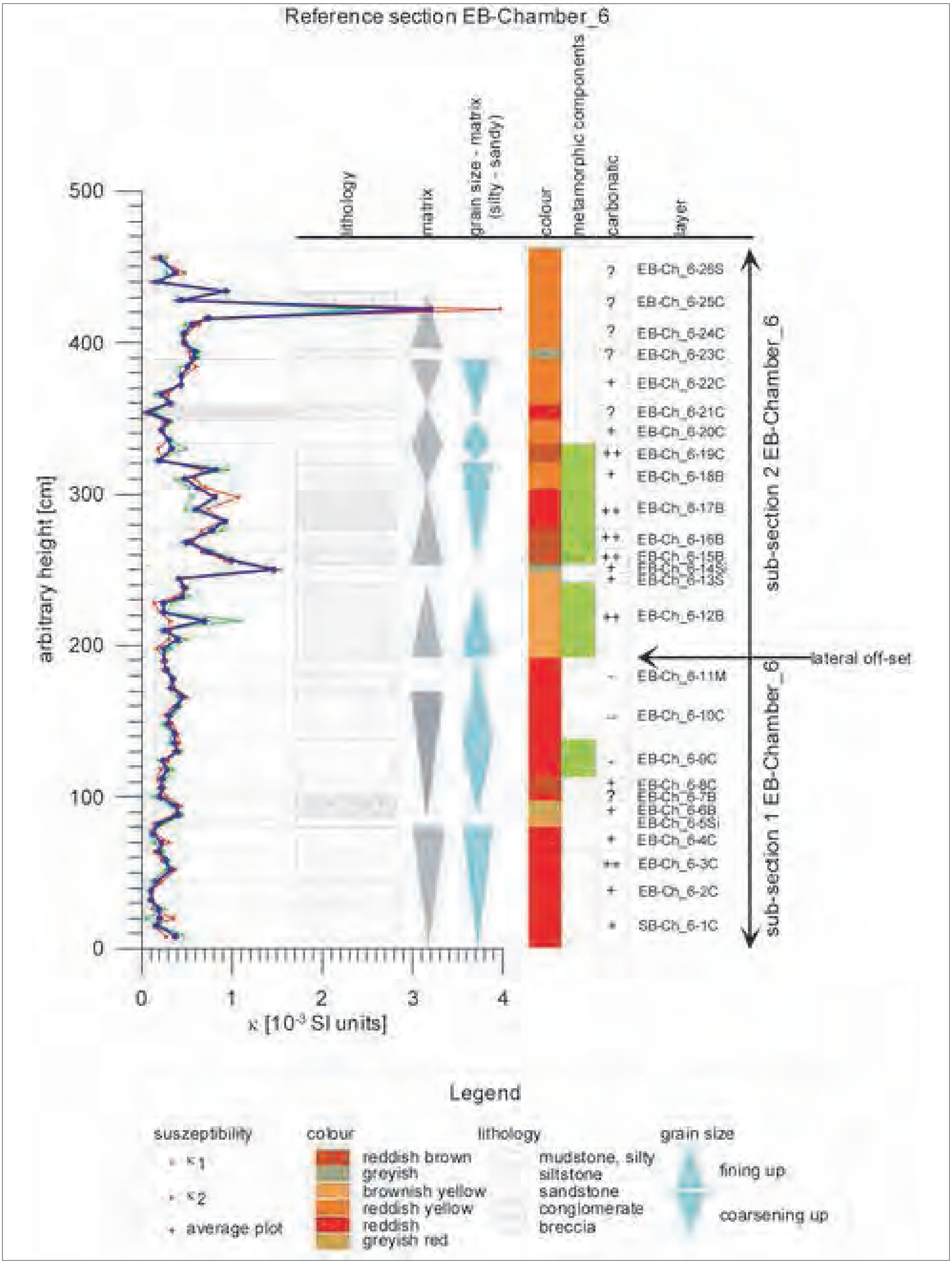



Fig. 17. Summary plot of geological and magnetic results from reference section EB-Camber Eastern Buddha niche. Both the geological details as well as the susceptibility logs vary distinctly cm-scale down section. Susceptibility (κ1 through κ2) measurements were taken repeatedly within lateral displacement range of about 1m, while keeping the vertical position (m.a.s.l.) of the respective measurements. The reproducibility of the measurements again clearly satisfies the needs of the pattern matching approach. Highest susceptibility peaks correspond with cements remaining from pre-destruction consolidation works.

Figs. 18a, b. Fragment GBF_049 under canopy in 2005 and in the niche in 2003 (right side). In the left-hand picture parts of the original Buddha surface including the typical reinforcement cavities are clearly visible.

Fig. 19. Susceptibility measurements taken from three selected Eastern Buddha fragments