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Claudio Margottini

Instability and geotechnical problems of the Buddha niches and surrounding cliff in Bamiyan Valley, central Afghanistan

Abstract This paper describes the slope-instability processes and geological hazards affecting the historical site of Bamiyan, central Afghanistan, a major world-cultural heritage site. Here, two standing Buddhas carved in rock during the 2nd–4th centuries A.D. were destroyed by the Taliban in March 2001. There are very evident slope instabilities resulting from both explosions and natural processes: rock slides and rock falls had already occurred in the past and most areas are prone to collapse. Under the coordination of UNESCO, field data were collected and laboratory tests were performed to determine mechanisms for potential evolution of the cliff and niches. Areas of greatest instability, based on the field survey and data interpretation for both the small and great Buddha niches and surrounding cliff, were determined. This information helps to identify the most suitable method for restoration, in accord with the high cultural value of this site.

Keywords Buddha statues · Explosion · Rock fall · Consolidation · Afghanistan · Bamiyan

Introduction

In the great valley of Bamiyan, 200 km northwest of Kabul, central Afghanistan (Fig. 1), two huge standing Buddha statues were carved out of in situ sedimentary, at an altitude of 2,500 m. The Emperor Kanishka probably ordered the sculpturing of the smaller Buddha around the 2nd century A.D., while initiation of the great Buddha seems to date from the 3rd to 4th century A.D. (Dupree 2002). Some descendants of Greek artists who went to Afghanistan with Alexander the Great started the sculpturing, which lasted until the 4th century A.D. (Gruen et al. 2002).

The Buddhist art of the Hindu Kush mountain region, of which the Bamiyan Valley is a part, represents the final flowering of Buddhism in Afghanistan. The kingdom of Bamiyan was a Buddhist state, located at a strategic point along a trade route that for centuries linked China and Central Asia with India and the West. Bamiyan served as an important monastic and spiritual centre, as well as a hub of intense commercial activity. The site was of major importance approximately between the 5th and 9th centuries A.D., during a distinctive phase in the history of Buddhist art, a period of intense cultural and religious exchange between the East and the West, and a time of great cultural change

Fig. 1 Geographical settlement of the Bamiyan area

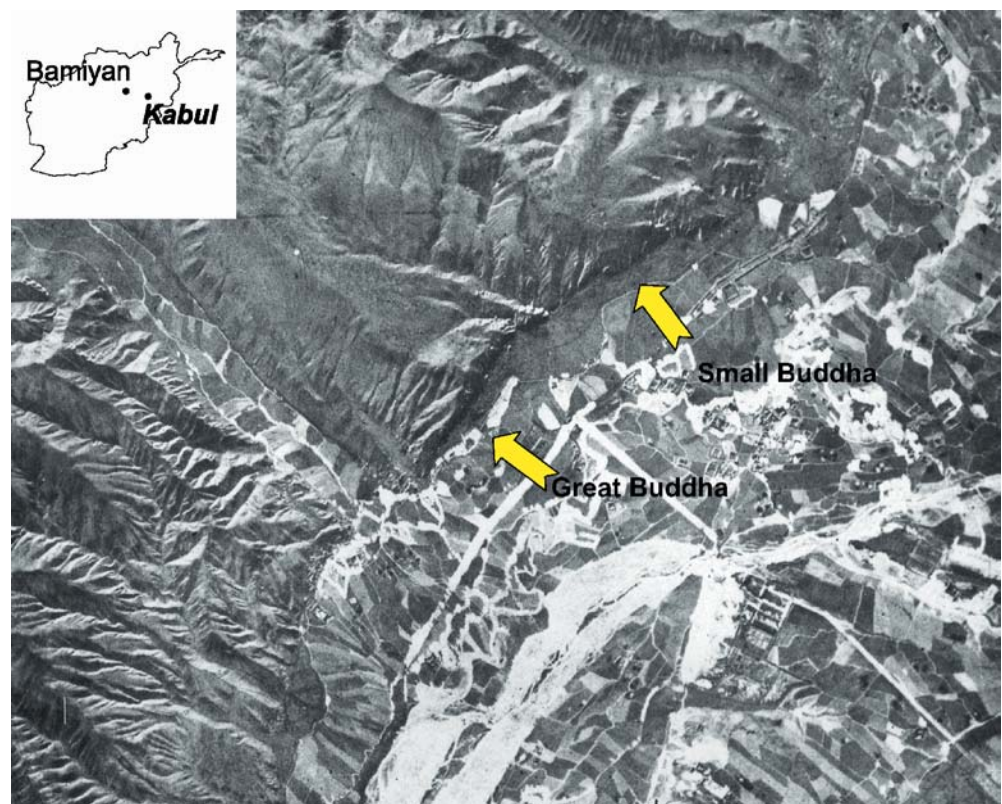




Fig. 2 View of the cliff at Bamiyan, central Afghanistan showing the relationship between the two Buddhas and the caves. The Great Buddha is on the left while small Buddha is on the right

within Buddhism itself. Bamiyan served as a ceremonial and spiritual centre that attracted and accommodated crowds of pilgrims and merchants travelling between Central and South Asia.

During this extended period of Buddhist influence, Bamiyan's two massive Buddha images were carved out of a high stretch of cliff facing the widest part of the valley. The colossal images were the largest Buddhist sculptures in the world. The greater of the two Buddha stood 53 m (175 ft) in height at the western end of the cliff face; the smaller Buddha, at the eastern end of the cliff, was some 35 m (120 ft) tall. The niches containing the statues are, respectively, 58 and 38 m high. Along the cliff face between these monolithic images, hundreds of caves of varying sizes had been cut for use as chapels for both private and communal worship (Fig. 2). Hallways, off of which are further rock-cut chapels and image-niches, surrounded the greater Buddha at the levels of his feet and head. Most of the rock-cut chapels and hallways at Bamiyan are covered with paintings on plastered walls; an incredibly rich, varied, and important body of early Buddhist painting.

The two statues were demolished on March 2001 by the Taliban, using mortars, dynamite, anti-aircraft weapons and rockets. The Buddhists, the world community, UN and UNESCO failed to convince the Taliban to leave such works of cultural heritage, which the Taliban considered to be blasphemous to their God. The fundamentalist Islamic militia, which governed most of Afghanistan from 1996 to December 2001, followed an edict from their spiritual leader, who ordered a campaign of destruction to rid the land of all un-Islamic graven images (Gruen and Remondino 2002).

The result of the Bamiyan demolition was a huge loss of world cultural heritage: the two large statues were destroyed, the niches where the Buddhas were carved are almost to the point of collapse, and many mural paintings have been covered by asphalt.

UNESCO has been involved since 2001, both before and after the destruction of the statues. Presently, one of the most important conservation priorities is to stabilise the two niches before there is further collapse. This paper is the result of two UNESCO missions to the site and laboratory investigations aimed at understanding the ongoing processes affecting the cliff and niches, in order to select the most appropriate stabilization measures in accord with the high cultural value of the site.

The promised reconstruction of the statues or their conservation in a local museum, is not covered in this paper and will involve the government of Afghanistan, UNESCO and archaeologists and experts in art restoration mainly from the International Council of Monuments and Sites (ICOMOS).

Meteorological and climatic setting

Afghanistan is a dry, mountainous country that experiences extremes of climate and weather. Winters are cold and snowy, and summers hot and dry. The wet season generally runs from winter through early spring (Fig. 3), but the country on the whole is dry, falling within the desert or desert steppe climate-classifications. Very little snow falls in the lowland deserts of the southwest. In the mountains, the snow season extends roughly from October to April, but varies considerably with elevation.

Bamiyan has a mean annual precipitation of 163 mm and mean annual temperature of 7.4°C (Afghan Air Authority Meteorology Department, Climate Section, operating for 8–9 yr in the period 1958–1977, with additional data from October 2001; Operational Climatic Data Summary 2002). Meteorological data are summarised in Fig. 3

Geomorphological setting

The following active processes have occurred in the area:

- Water infiltration from the upper part of the cliff
- Gully erosion in the upper part of the cliff from rainfall and snowmelt
- Progressive opening of cracks in the outer parts of the cliff (Fig. 4)
- Weathering of siltstone strata
- Toppling of large external portions, as well as of isolated blocks
- Occurrence of mud flows in the upper part, probably when the siltstone is saturated (Fig. 4)
- Sliding in a portion of the slope mainly where cracks from the top reach the lower siltstone formation, making it highly fractured and easily affected by weathering (Fig. 4)
- Accumulation of debris at the toe

Geological, mineralogical and geophysical setting

The materials outcropping in the vicinity of both the small and great Buddha are probably derived from erosion of the surround-

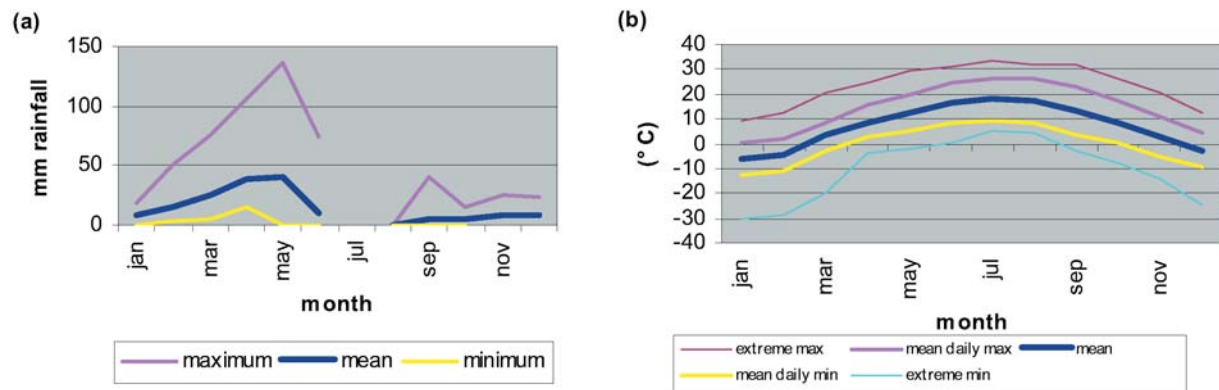


Fig. 3 Summary of the available meteorological data for the site of Bamiyan



Fig. 4 Geomorphological processes in the Bamiyan Valley (from left to right) includes historical sliding near the great Buddha after human activities, progressive opening of a crack in the outer part of the cliff, weathering of siltstone causing mudflows above the Great Buddha

ing mountain peaks and deposition in a flood plain and a small playa lake. Subsequent uplift and river erosion produced the present morphology. The almost vertical cliff where the Buddha statues are carved may also have been partly excavated by humans to create a slope more suitable to host the monastic civilisation. A human influence on the present morphology is likely because such a steep morphology does not occur in other parts of the valley.

The cliff and niches are composed of alternating conglomerate and siltstone (yellow at the bottom and red in the middle of the cliff). In order of relative abundance, the conglomerate is composed of quartz, calcite, mica, feldspars, clay minerals and heavy minerals (from X-ray diffraction). Quartz occurs as individual grains, while calcite is present both as grains and as a carbonate cement. The matrix is mainly of clay minerals.

In microscope thin sections, the conglomerate (Fig. 5) is composed of monomineral grains and lithic fragments moderately sorted and cemented by carbonates. The monomineral grains comprise poorly rounded monocrystalline quartz, and moderately well-rounded polycrystalline aggregates of quartz. Less frequently observed are polycrystalline aggregates of car-

bonates, moderately rounded and rare, slightly rounded monocrystals or aggregates of feldspar. Dimensions of monocrystals may vary from tens of microns to about 1.5 mm; the dimension of aggregates can reach 3 mm.

Lithic fragments range from 1 to up to 15 mm. Most lithic fragments can be grouped in three main families:

- Fragments of rocks with small grains (sandstone?) composed mainly of quartz, calcite and clay minerals
- Moderately rounded fragments of claystone-siltstone; this family seems to be similar to the siltstone formation surveyed on the cliff
- Fragments of probable volcanic or volcanoclastic origin with highly altered clay minerals, oxides and/or hydroxides and, rarely, epidote

Some fragments have slightly altered feldspar phenocrysts and feric minerals altered to oxides and hydroxides in a microcrystalline matrix. Rounded quartz crystals rarely can be detected; more often they are fragments of altered matrix.

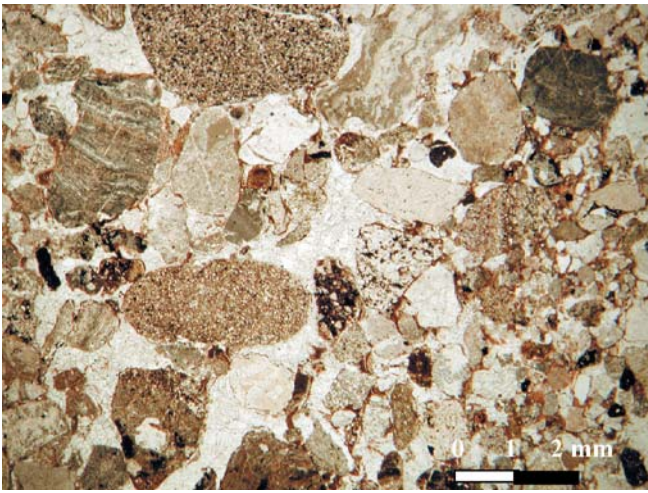


Fig. 5 Thin section view of conglomerate, strengthened by white carbonate cement

The recorded field uniaxial compression strength of about 24–35 MPa is mainly dependent on the carbonate cement, which developed secondarily during diagenesis. Siltstone outcrops on the lower part of the cliff (yellow siltstone) and in some strata in the middle and upper part of the cliff. It is composed of, in order of abundance, quartz, calcite, mica, clay minerals and heavy minerals (determined by X-ray diffraction); quartz is about 70%, calcite 20%, and all the other minerals about 10% of the rock. Using the methodology of Brown (1972), the clay minerals are illite, chlorite, and smectite. X-ray diffraction of the yellow (Fig. 6) and red siltstones revealed no mineralogical differences.

In microscope thin-section, the siltstone is an aggregate of clay minerals cut by small irregular carbonate veins. The clay minerals

seem to be associated with iron hydroxides and/or sulphates. Within the aggregate are poorly rounded quartz grains with dimensions ranging from 0.01 to 1 mm, as well as moderately rounded fragments of cryptocrystalline carbonate rock with dimensions less than 2 mm.

No cement has been identified in thin section, and the lack of cement is confirmed by the total loss of mechanical cohesion when the sample is wet. The red siltstone flocculates in water, indicating the presence of soluble salts from the dry environment. The siltstone appears to be a desiccated mud, with an apparent cohesion depending, at least in part, on dryness.

X-ray diffraction does not identify soluble salts (gypsum, halite, etc.) in either the conglomerate or yellow siltstone. This contrasts with the flocculation of red siltstone, which indicates that the depositional environment varied over time.

The depositional environments and diagenetic conditions affect the present-day behaviours of the material; the conglomerate has a permanent cohesion, while the siltstone easily loses cohesion when saturated (Fig. 7). The mechanism for the siltstone's behaviour is probably a slaking process (Franklin and Chandra 1972) and has been investigated by scanning-electron microscopy, as well as by determining physical and mechanical properties in soil and rock-mechanical laboratory tests.

Seismic p-wave velocities V_p were measured in the laboratory for both conglomerate and siltstone (Fig. 8). The conglomerate has values of 2.2–2.5 km/s, and a Poisson's ratio of 0.30–0.40 (for samples perpendicular and transverse to depositional flow direction); a V_p of 1.5–1.7 km/s and a Poisson's ratio of 0.10–0.20 have been measured in the flow direction. The siltstone has a V_p of 1.7–2.0 km/s, and a Poisson's ratio of 0.15–0.20 with no anisotropy.

Stefan Krumm, Geologisches Institut Erlangen, Schloßgarten 5, D-91054 Erlangen

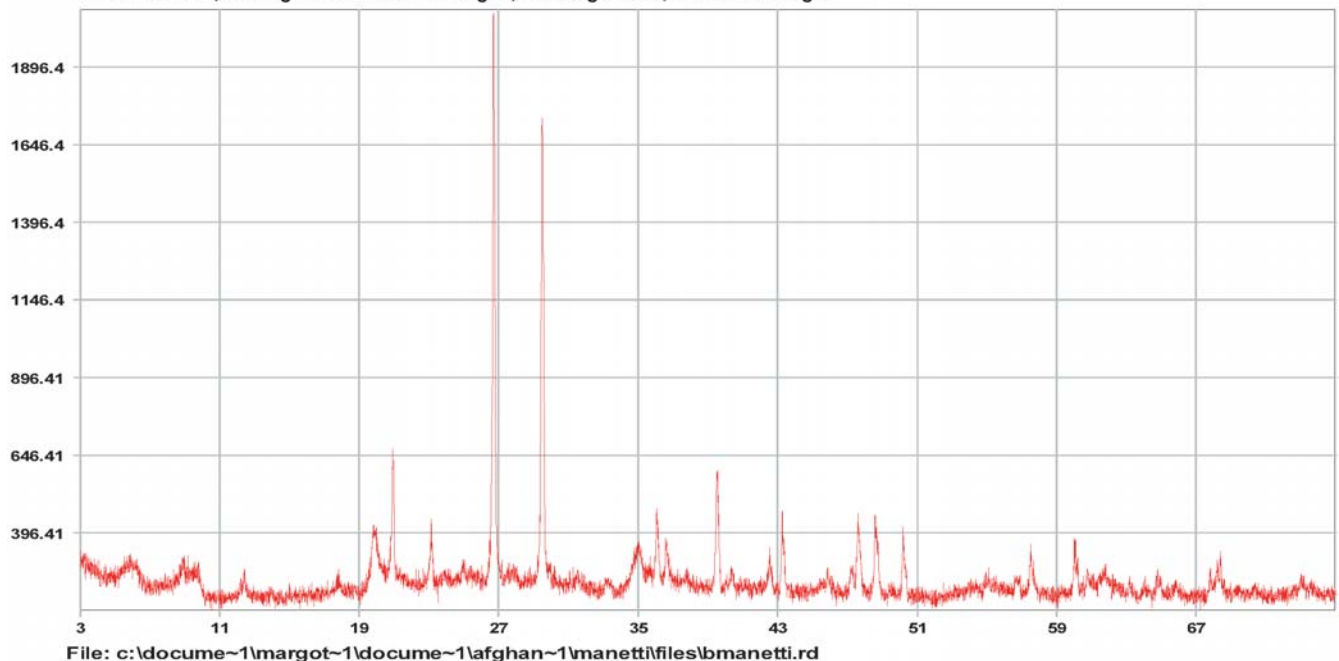


Fig. 6 X-ray diffractometer pattern obtained for a composite sample from the yellow siltstone



Fig. 7 Stability of conglomerate (*left*) and degradation of siltstone (*right*) after only a few minutes of immersion in water

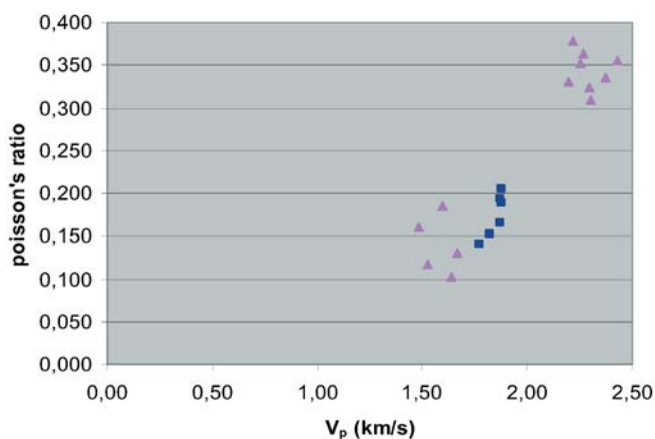


Fig. 8 Seismic p-wave velocities V_p and Poisson's ratios in conglomerate (*red triangles*) and siltstone (*blue squares*). The lower values for the conglomerate are parallel to the sedimentary flux direction

The lowest seismic velocities in the conglomerate are in the direction parallel to sedimentary flux (and stratification). This implies that, in this direction, seismic waves exhibit lower values because they are mainly crossing the more porous matrix of cemented silt; when seismic waves are crossing the samples perpendicular and transverse to sedimentary flux and stratification, the velocity is higher, probably as consequence of intersecting more solid rock in the grains. The values parallel to the sedimentary flux and stratification of the conglomerate, where matrix is predominant, are much closer to the values measured in the siltstone, indirectly confirming a similar origin and composition.

Investigation of siltstone under scanning electron microscope (SEM)

The swelling behaviour of fine-grained sedimentary rocks (claystones, mudstones, shales, etc.) is a complex phenomenon. When in contact with water, these materials can increase considerably in volume, resulting in breakdown and high pressures which sometimes develop. The swelling behaviour is controlled by

numerous factors acting jointly, and thus the main agent is frequently hard to identify. Swelling rocks generally behave in a manner intermediate between a rock and soil, which complicates the sampling and testing required to forecast their geotechnical behaviour. Some weak rocks are much more sensitive to wetting and drying cycles than others, and can almost totally break down after a number of cycles or, as in the siltstone from the Bamiyan cliff, just upon wetting. Identification of this behaviour is crucial in planning work in areas where weak rocks occur (Pejon and Zuquette 2002).

Sample preparation and observation followed the recommendations of Goldstein et al. (1992) and Le Roux (1971). All samples were about 15–20 mm long, 5–10 mm wide and 10 mm high, and were obtained by simple rupture. They were dried by cryosublimation (Le Roux 1971; Shi et al. 1999) before being examined. This procedure is intended to preserve microtexture and original structure and to allow observation of modifications caused by swelling tests. All samples were observed with the electron microscope before and after the swelling tests to analyse textural, structural or mineralogical modifications associated with the swelling. Representative SEM photographs (Fig. 9) show the undisturbed structure and more open structure after wetting and breakdown. When samples were wetted, complete breakdown was rapid, and occurred in a few minutes, despite the low concentration of swelling clay minerals.

Observation of the samples under SEM demonstrated that the compact, laminar structure (O1 in Fig. 9) no longer existed after the breakdown (R1 in Fig. 9). The laminar structure could be the consequence of the orientation of clay minerals completely filling voids in the siltstone and producing a dense material. The wetted and reconstituted material loses the structure typical of undisturbed samples; it clearly shows the granular composition, where some of grains are laminar, and some are probably clay minerals. The number of voids clearly is higher with respect to undisturbed siltstone, and so the original high density is lost after one wetting-and-drying cycle.

Possibly a small amount of swelling clay (such as smectite) in certain positions in the rock texture could promote swelling and breakdown, as observed by Pejon and Zuquette (2002) in French mudrocks with similar granulometric and mineralogical composition to the Bamiyan samples.

Compression of entrapped air may also be a factor in the swelling and breakage of mudrocks (Taylor and Spears 1970). The resistance to slaking is a function of a number of different controlling parameters; among them are permeability and porosity, adsorption, solution or disruption of the bonds, disruptive forces and initial degree of weathering (Crosta 1998).

Physical and mechanical properties of materials

A reconnaissance field survey and some laboratory tests were conducted to provide data to assist geotechnical stability analysis. Laboratory testing provided physical properties (such as Atterberg limits and grain-size distribution) for the siltstone. Point-load tests gave an indication of uniaxial compressive strength for both the conglomerate and siltstone. Field investigations included in situ density for conglomerate and rock classification (RMR and

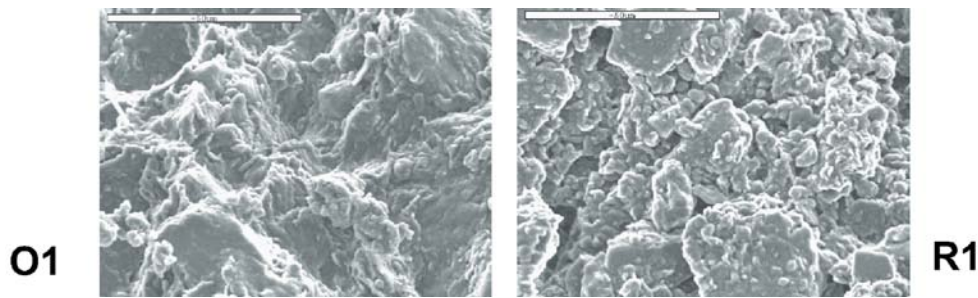
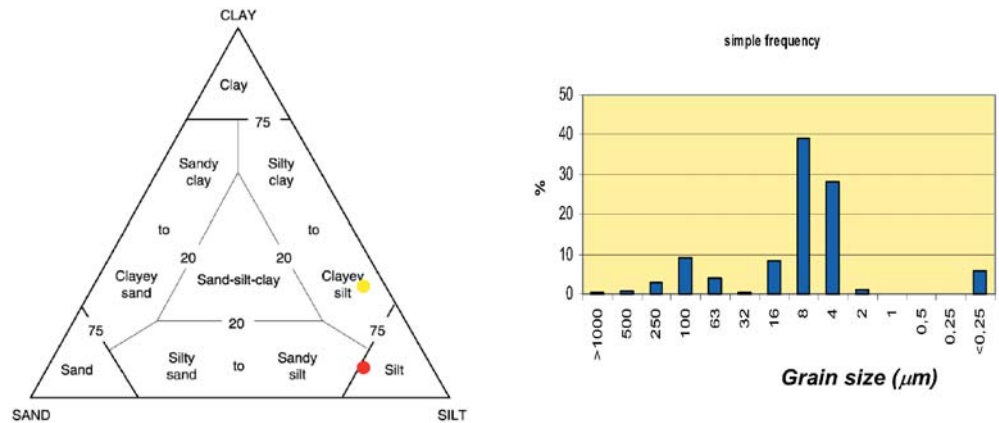


Fig. 9 Scanning-electron microscope microphotographs (1000X) of the siltstone. Sample O1 is undisturbed while R1 is from material first broken down by wetting and then dried to obtain a sample similar to natural conditions

Fig. 10 Shepard (1954) diagram for siltstone grain-size distribution (red dot is from sedigraph and yellow dot is from hydrograph), classifying the material as “silt” (red) and “clayey silt” (yellow). Histogram is from sedigraph



Q system) and uniaxial compressive strength by means of a Schmidt hammer for both the siltstone and conglomerate.

Soil and rock tests on both lithologies were necessary since the two show completely different behaviour when weathered. As already described, the conglomerate has a permanent cohesion due to the carbonate cement, while the siltstone (a desiccated mud) quickly loses cohesion when wet.

It also was important to define the major parameters characterising the two rock types in order to estimate their respective behaviours to possible stabilisation techniques or, conversely, to select stabilisation techniques appropriate to the real behaviour and properties of the in situ materials.

The grain-size distribution of the siltstone is about 7% clay, 76% silt and 17% sand (determined with an electronic sedigraph), depicted as a “silt” on the Shepard (1954) diagram (Fig. 10). The grain-size distribution of another sample of siltstone, but determined by standard hydrometer methods, was 28% clay, 66% silt and 6% sand.

The plasticity characteristics reflect the low clay content; the liquid limit is 39.8% and the plastic limit is 17%. The material is characterised as CL in the Unified Soil Classification System (ASTM 1977), which fits in the category of “inorganic clays of low to medium plasticity, gravely clays, sandy clays, silty clays and lean clays”.

The siltstone has a natural density of 2.28 gm/cm³, and a dry density of 2.23; according to these data it is 85% solid matter, 5% water and 10% air. The porosity (15%) and void index (0.18) are low. These data are from samples taken away from the site, and do not exactly reflect the real conditions. Nevertheless, the high natural density is a matter of fact. The siltstone is almost in a state

of critical natural density (maximum allowed); the volume increases with any remoulding of the material as indicated by the SEM photography.

The uniaxial compressive strength from field Schmidt-hammer testing highlights the general satisfactory strength of the materials, at least in the dry season (Fig. 11). In the area of both the smaller and larger Buddha, the average values of about 30 MPa for conglomerate and about 34 MPa for siltstone show the materials to be of moderate strength (ISRM 1981). The siltstone generally is stronger than the conglomerate when dry. The situation is completely reversed when the rock is wet, but siltstone appears to make up only 20–30% of the cliff.

The in situ strength testing has been confirmed for both siltstone and conglomerate with some point load tests on samples taken outside of Afghanistan (Fig. 12). They show the general higher uniaxial compressive strength of dry siltstone, with respect to conglomerate. In general terms, the uniaxial compressive strength of siltstone (11.0 MPa) is about 30% of that exhibited in in situ tests, while the strength of the conglomerate in point load (5.6 MPa) is about 20% of the in situ Schmidt hammer tests. This difference is not surprising given the limitations of both methods in the indirect definition of uniaxial compressive strength, and the different confining condition of in situ samples and the cubes tested in the laboratory. The field survey gives useful information about the distribution of mechanical parameters along the entire area of investigation.

Geotechnical classifications of materials (Barton Q-system, Beniawsky RMR, Geological Strength Index GSI) were made on site. The results show mainly a different behaviour between intact and blasted materials. The fractured siltstone generally performs

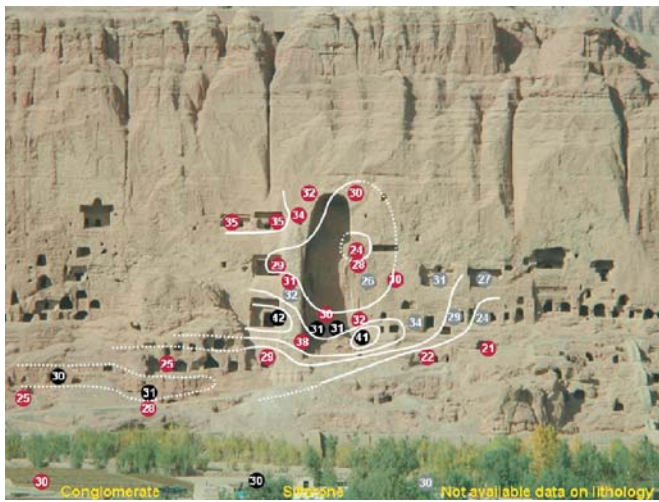


Fig. 11 Uniaxial compressive strength from Schmidt-hammer field survey

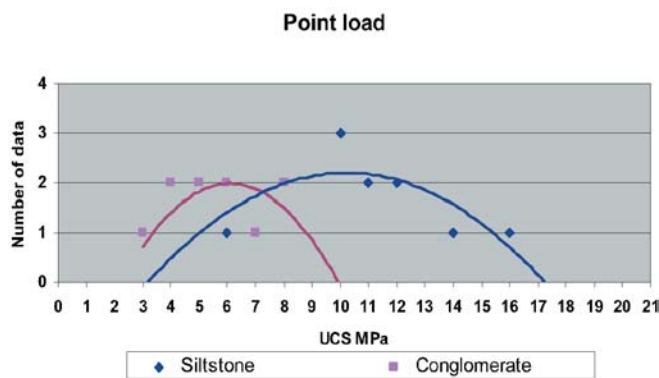
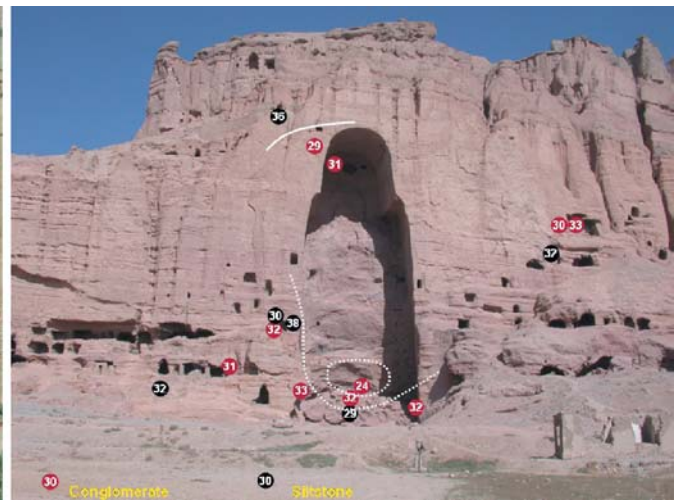


Fig. 12 Uniaxial compressive tests from point load in both conglomerate and siltstone

Table 1 Rock mechanic classification in terms of RMR (basic value) and Q-system estimation

	Conglomerate		Siltstone					
	Undisturbed	Blasted	Undisturbed	Blasted				
Buddha	RMR	Q	RMR	Q	RMR	Q	RMR	Q
Small	74	95	66	13.3	64	21.25	57	8.3
Great	69	90	64	16	69	22.5		

The in situ density of the conglomerate at Bamiyan is $17.65 \pm 0.03 \text{ kN/m}^3$ (at 1 SD). This is lower than that of the siltstone (22.35 kN/m^3) in laboratory tests

poorly, due to the presence of discontinuities spaced at about 0.3–1 m. Table 1 reports the obtained values for RMR (basic value, Beniauskis 1989) and Q-system (Barton et al. 1974).

Shear-strength parameters for both lithologies are considered to exhibit Hoek and Brown (1980) behaviour. Based of this standard assumption, c' and ϕ have been determined by simulating the behaviour of a sample in a triaxial test by means of an explicit difference finite code, FLAC (ITASCA Consulting Group 2000). The results from the small Buddha site are a friction angle of 32° and cohesion of 1.42 MPa for the siltstone, and a friction angle of 52° and cohesion of 1.13 MPa for the conglomerate. A field permeability test was conducted at the site

according to AGI (1977) standards in order to acquire information on hydrogeological characteristics of the rocks. The test on conglomerate not far from the small Buddha, gave a value of permeability $K=2 \times 10^{-4} \text{ m s}$.

Geomechanical character of the discontinuities

Discontinuities play a major role in rock stability and have been investigated in terms of roughness and friction angle. Joint roughness coefficients (JRC) obtained from about 30 field tests give a mean value of about 2 for the siltstone and about 15 for the conglomerate. The first and second order asperities (wavelength less than 50 cm and higher) were also investigated from the roughness profile in order to assess the contribution of asperities to the total friction angle ($\phi' = \phi_{\text{basic}} + i_{1\text{st}-2\text{nd}}$).

The shear-strength parameters of the fractures (ϕ') were estimated by means of tilt-meter tests (Barton et al. 1985) with an average of about ten measurements for any sample. The results for the site of the small Buddha are $42 \pm 6^\circ$ and $38 \pm 4^\circ$ (at 1 SD) for conglomerate and $32 \pm 4^\circ$ for siltstone.

The tests were performed on rough materials, so the results include a contribution from asperities. This is more true for the conglomerate, where JRC is about 15, and is less significant for the siltstone with a JRC of about 2. In fact, the results of the tilt-meter test for siltstone are almost identical to that from simulation of triaxial tests using the Hoek and Brown (1980) approach. The resulting ϕ' for the conglomerate is smaller than that obtained in triaxial simulation, possibly demonstrating the importance of asperities in the total behaviour of the conglomerate with respect to a tilt-meter test that is using a small sample of material (~20 cm cubes).

For the Great Buddha, the properties of discontinuities are not too different from those for the site of the small one. The average joint roughness coefficient (JRC) from eight sites is 16 for the conglomerate and 4 for the siltstone.

Tilt-meter tests (Barton et al. 1985) aimed at identifying the strength parameters of discontinuities ($\phi' = \phi_{\text{basic}} + i_{1\text{st}-2\text{nd}}$) were conducted at the site of the Great Buddha on both conglomerate and siltstone; in the siltstone the different behaviour of the material with and without asperities also was investigated ($\phi' = \phi_{\text{basic}} + i_{1\text{st}-2\text{nd}}$) with asperities and after smoothing with carbo-

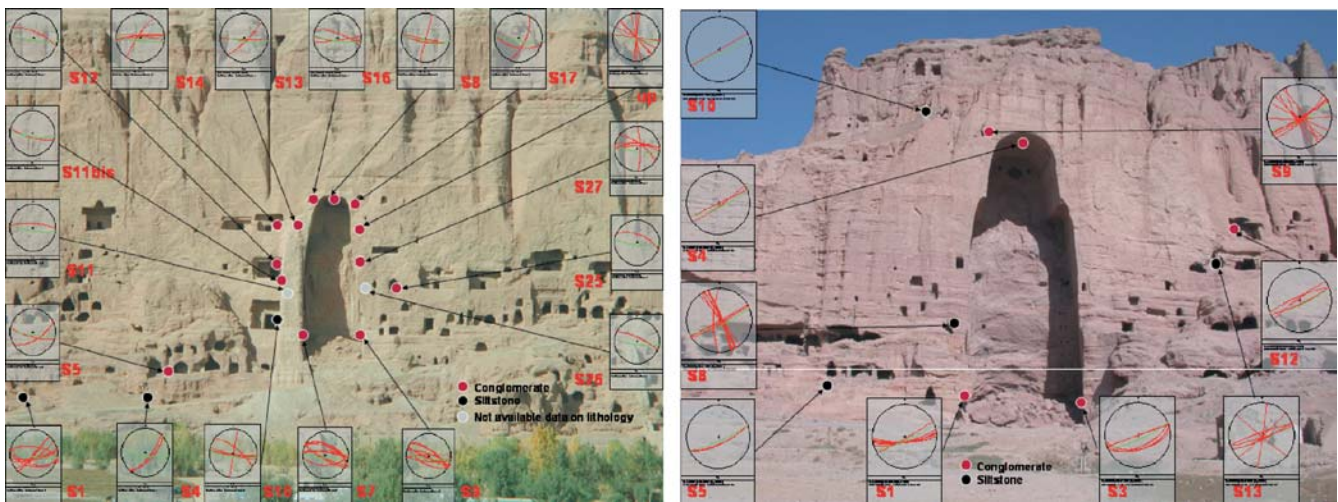


Fig. 13 Discontinuity trends shown by stereonet plots for both small and Great Buddha sites

rundum stone ($\phi^{\circ}=\phi$ basic). The conglomerate ranged from 38° to 41° . The siltstone had a value of 28° for the smoothed sample, and 38° for natural conditions.

Structural analysis of discontinuities

Discontinuities play a major role in rock slope stability. At Bamiyan there is a natural distribution of discontinuities, probably as consequence of unloading during the excavation of the valley by the river. More recently, explosions have produced some new fractures, but mainly enlarged pre-existing ones.

Distributions of discontinuities at the small Buddha and great Buddha sites are reported in Fig. 13. These data show a major pattern in the autochthonous materials, and some orthogonal discontinuities. The lower siltstone formation, especially that belonging to an old sliding phenomenon to the left of the small Buddha niche (small Buddha), shows two major sets and a random pattern. Only in the upper part, on the right side of the small Buddha niche, is there evidence of discontinuities generated by explosions.

In the Great Buddha, a major pattern of two sets is only evident in the cave at the top of the niche. It suggests a potential long-term instability in that area.

Kinematic analysis

Possible collapse mechanisms have been investigated by comparing slope morphology and discontinuity patterns (wedge failure, planar sliding, etc.). The coincidence of slope face and major discontinuities patterns can be seen in Fig. 14. This does not satisfy the conditions for planar sliding or wedge failure (Turner and Schuster 1998). Note that some discontinuities plotted in the figure represent the same fracture detected in different vertical levels in the field survey (see Fig. 13 for measurement sites).

Seismological setting

Afghanistan can be divided into four seismic zones of differing likelihood in regards to shaking damage (Amateur Seismic Centre 2003): main, medium, minor and safe (nonseismic) zones. According to the Global Seismic Hazard Assessment Programme (Zang et al. 2002), the northeastern parts of Afghanistan have the highest risk of hazard in the country. This includes the provinces

of Badakshan, Takhar, Konduz, Balkli, Jowzjan, Samangan, Sar-e-Pol, Baghlan, Parvan, Kabul, Kapisa, Konar, Laghnan, Nangarhar and Lowgar. Maximum peak ground-acceleration (PGA) ranges from 0.24 to more than 0.48 g in the easternmost regions.

The site of Bamiyan is on the edge of this highest-hazard area. Without direct information on historical earthquakes affecting the site, an estimate of maximum expected ground shaking can be derived from Zang et al. (2002) and related maps. A rock-site peak ground acceleration (PGA m/s^2) with a 10% chance of exceedance in 50 yr, ranges between 1.6–2.4 m/s^2 . Historical data and earthquake lists for Afghanistan are reported in Ambraseys and Bilham (2003). Nevertheless, even without direct historical information, it is easy to say that the two Buddhas have survived about 1,600 yr of seismic shaking without major effects.

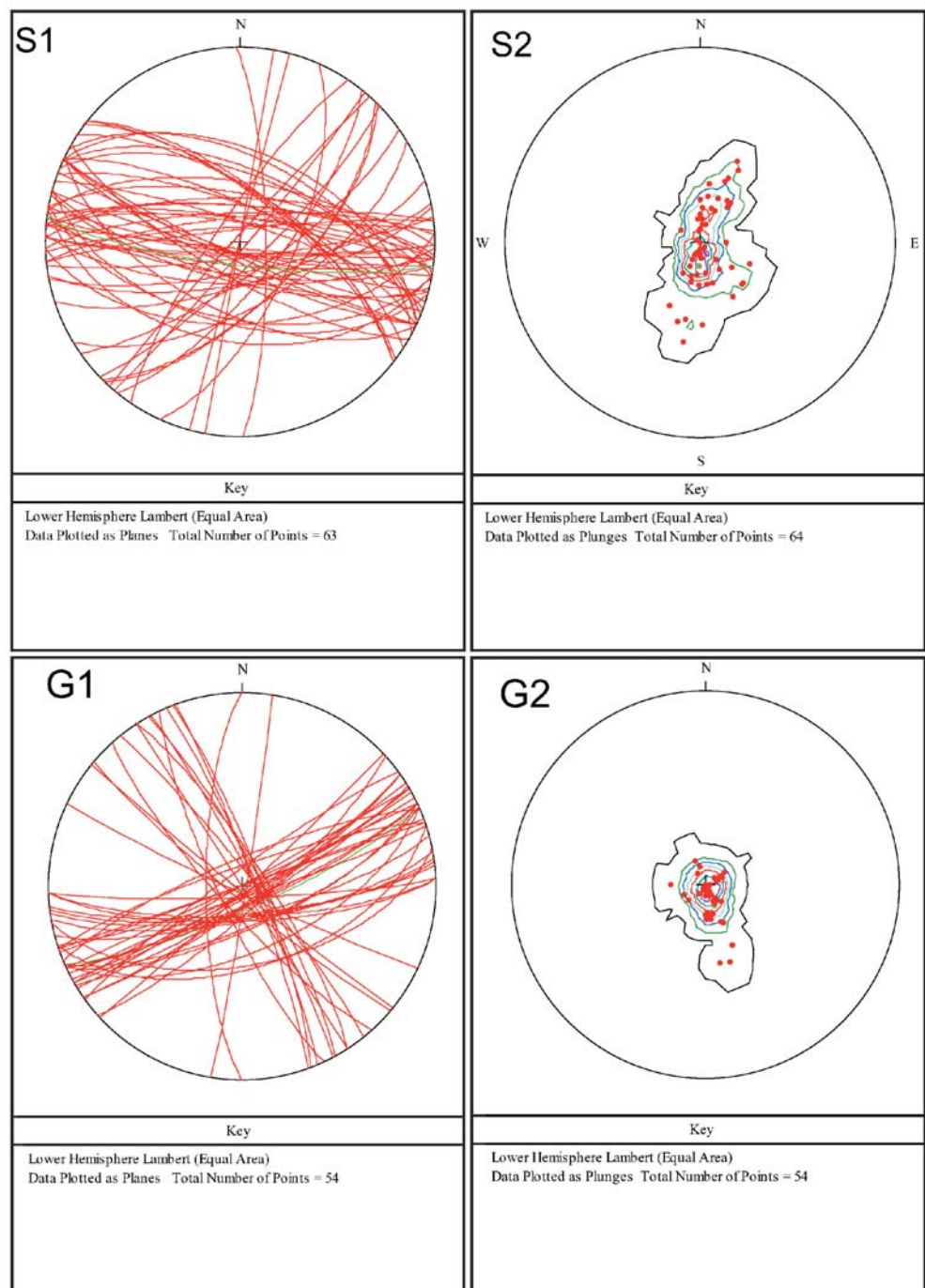
Identification of most critical areas

The explosions of March 2001, in addition to demolishing the statues, reduced the stability of the shallower parts of the niches. In the small Buddha niche, besides the collapse of the statue, three minor rock falls occurred from the top of the niche. Blasting also degraded the strength of the rear of the highest right part of the niche, where a stairway is located inside the cliff and the wall between the stairs and the niche is quite thin (about 30–50 cm). This part presently has the most critical instability (A3 in Fig. 15, right). As a consequence of an existing buttress, the left side did not suffer as much damage, although in the upper part a rock fall occurred and some instabilities are now evident.

In the Great Buddha, the major blast effects were the collapse of the statue and the consequent instability of the rear of the niche. A small rock fall occurred from the top of the niche (left side). Probably, the greater thickness of wall between the stairway going up into the cliff and the niche (about 1 m) inhibited propagation of the effects of blasting, and resulted in less severe damage. A large crack, about 20–30 cm wide, is present in the corridor at the back of the head of the statue. Fig. 15 shows the most critical areas found in the field inspection and/or identified by analysing the different geological aspects investigated in this paper.

Various different types of stabilising measures have been considered, especially because of the need to do the work in an area of high cultural value but with little current available

Fig. 14 Stereonet plots for kinematic analysis at the small and Great Buddha sites. *Green lines* represent the slope face. The contour increments every 10%



technological support. It must be emphasized that any restoration project in the field of slope stabilisation must be based on reliable data including, for example, 3D topography, detailed rock-mechanics information from bore holes, meteorological data, etc., which are presently only partially available. For this reason, the following proposed work is only a feasibility study to be considered in a second and more detailed operational phase. More detailed investigations have been performed, however, on the small areas where restorative intervention is extremely urgent (A3 of small Buddha, in Fig. 15).

In general, the niche and the cliff need holistic stabilisation work and not episodic and local intervention. Nevertheless, it must be recognised that one cannot propose a specific stabilisation

plan at the moment because any intervention has to be specified for the local conditions. At the present stage, it is convenient to set up a general master plan to be locally adapted according to further, more specific investigations and data. The master plan includes mainly nails, anchors and grouting, which will have a low environmental impact on the site. The working area and general density of intervention is shown on Fig. 16.

Summary and conclusion

The investigations performed in the Buddha niches and surrounding cliff in the Bamiyan valley (northern Afghanistan) highlight the following:

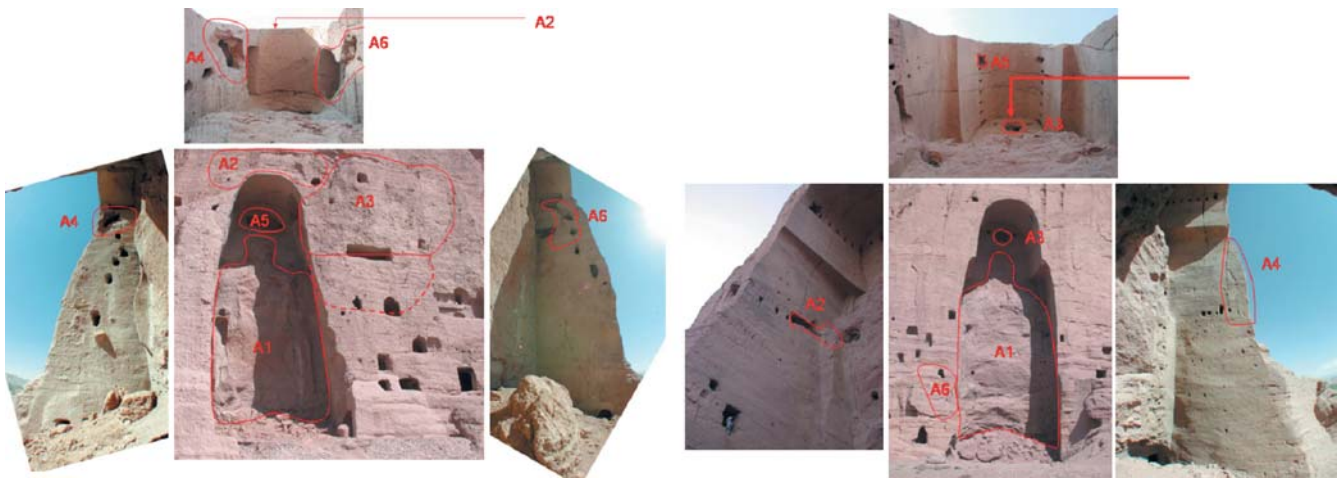


Fig. 15 Areas of greatest instability based on the field survey and data interpretation, for small (*left*) and great (*right*) Buddha niches. The A3 block in the small Buddha (*left*) has the most acute instability. The *arrow* points to a serious problem inside the niche

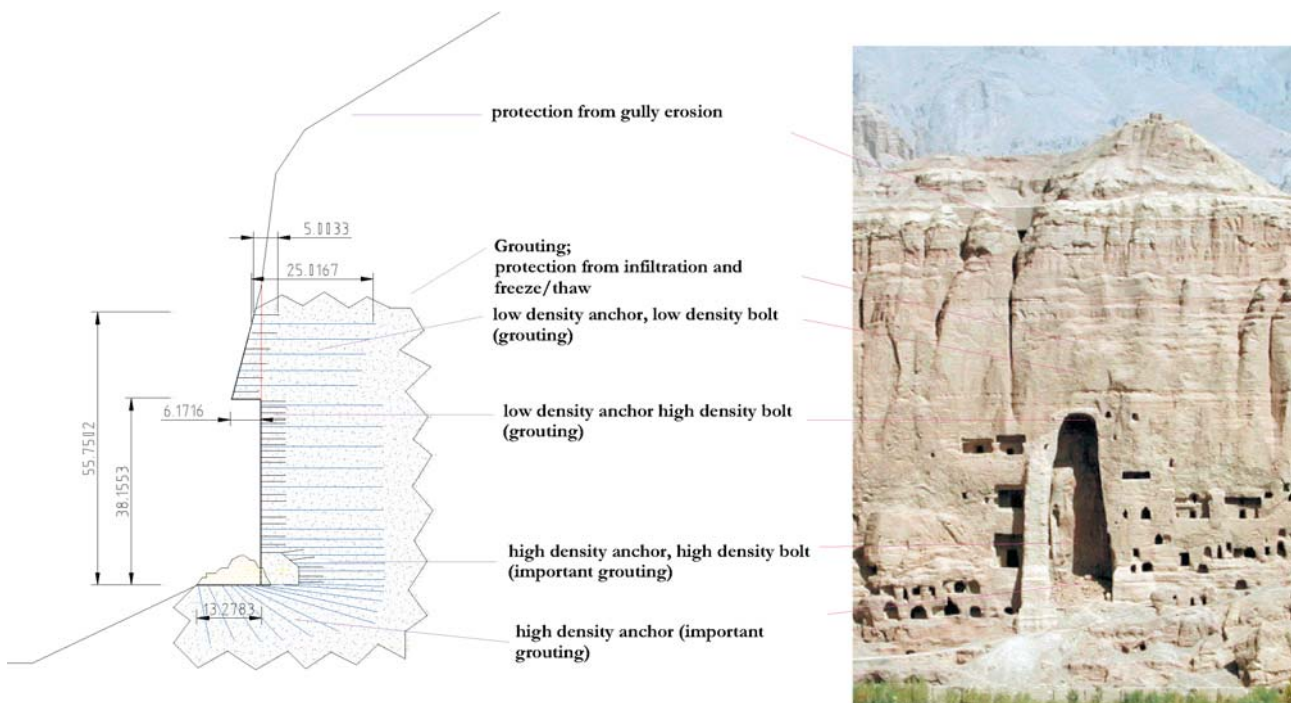


Fig. 16 The working area for the small Buddha site showing the most feasible types of restoration works

- The area is located in mountainous central Afghanistan in a dry part of the world that experiences extremes of climate and weather. Winters are cold and snowy, and summers hot and dry. Mean annual precipitation in Bamiyan is about 163 mm and mean annual temperature is 7.4°C.
- The rocks outcropping in the area are mainly conglomerate, with some strata of siltstone that slake when wet. The lower part is predominantly siltstone with two main sets of discontinuities spaced every 20–40 cm. The central part of the cliff is mainly conglomerate, well-cemented and with a limited number of vertical discontinuities mainly paralleling the profile of the slope.

Major geomorphological processes include water infiltration, gully erosion, progressive opening of discontinuities in the outer parts of the cliff, weathering and slaking of siltstone levels, toppling of large external portions as well isolated blocks along the cliff face, occurrence of mud flows probably when the siltstone is saturated, sliding of a large portion of the slope and accumulation of debris at the toe.

The explosion of March 2001, as well as demolishing the statues, reduced the stability of the slope, mainly in the outer parts of the niches. In the small Buddha niche, besides the collapse of statue, there were three minor rock falls from the top of the niche. The blasting also degraded the upper-right part of the niche where a stairway is located inside the cliff and the wall

between the stairs and the niche is quite thin (about 30–50 cm). This part is presently the most critically unstable site. The left side, as a consequence of an existing buttress, suffered less damage. A rock fall occurred and some instabilities are now evident only in the upper part.

Major effects in the Great Buddha niche were the collapse of the statue and the consequent instability of the rear of the niche. A small rock fall occurred from left side of the top of the niche. Probably, the strength of the greater thickness of wall between the stairway going up into the cliff and the niche (about 1 m), reduced the effects of blasting and resulted in less severe damage.

A feasibility project (master plan) for stabilising the niches and cliff was prepared. This includes mainly nails, anchors and grouting, which have low environmental impact on the site. Nevertheless, to define an operational stabilisation project, there is need for further data which is presently missing such as topographical setting, terrestrial photogrammetry, detailed stratigraphy, a monitoring network, 3D static analysis, rock-mechanics site tests and others. The following recommendation is believed to be relevant for the detailed restoration work:

- Establish a crack monitoring system before any intervention is started
- Install temporary support before starting with other structural intervention, especially in the small Buddha
- Avoid any water contact with the siltstone
- Avoid any drilling vibration in the most acute locations
- Avoid scaffolding before consolidation of the upper part; climbers will likely be the most suitable solution
- Grout with cement with a low water release
- Restrict drilling of nails/anchors and related bulbs to the conglomerate strata
- Use consolidation techniques that minimise the impact on the environment
- Stabilise the rear of the niches, where the remains of the statues still stand, in cooperation with experts in archaeology and art conservation

Finally, it must be emphasized that, in this fragile environment, any reinforcement must be designed according to the real local conditions and stability model of every single block; a unique standard intervention for the whole site is strongly not recommended.

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C. Margottini (✉)

ENEA CR Casaccia,
Via Anguillarese 301, S. Maria di Galeria, 00060 Rome, Italy
e-mail: margottini@casaccia.enea.it
Tel.: +39-06-30484688
Fax: +36-06-30484029