Assessment of Current Conditions

Survey

Objectives

As part of the condition assessment of the Hieroglyphic Stairway, a survey of the monument was conducted comprising a stereophotographic survey (under the responsibility of GCI consultant Photarc Surveys Ltd., UK) and a survey of the photographic control points with a total station (under the responsibility of GCI staff).

The goals of the survey were to provide a photographic base for carrying out the condition survey, and to create a photographic record to add to the collection of historic photographs of the monument already existing at Copán for use by a broad range of professionals (conservators, epigraphers, etc.). The control points and the stereo pairs could also potentially be used to create a detailed 3-D computer model of the entire Stairway, as well as to measure changes in stone surface over time if the process is repeated in the future.

Scope

The Hieroglyphic Stairway consists of sixty-three steps framed by balustrades on both sides. It is approximately 10 meters wide by 24 meters high, and rises at an angle of 45°. The survey included all carved surfaces of the Stairway (each of the riser faces and the top surface of each of the two balustrades), as well as all faces of the Seated Figures on the Stairway, the wide Altar at its base, and, on the Plaza in front of the Stairway, separate Stela M and associated zoomorphic Altar C. Additional close-up stereo pairs were also taken of a number of blocks, which were selected as control blocks for the monitoring of condition changes.

Survey Techniques

Laser Scanning versus Stereophotography

A number of different survey techniques were reviewed before the final choice was made. This choice took into consideration the scope of the survey, budget constraints, local resources, staff capacity, archival conditions, and site constraints (for example, the presence of the shelter restricted the use of a hydraulic platform for the photography).

After a reconnaissance visit in March 2000 and further discussions, laser scanning was rejected as a technique because the precision of the survey scanners was not considered high enough for the requirements, and the site time for preparation and data capture would have been significantly longer. There was also the physical problem of getting close enough to the glyphs without operating the heavy equipment on the steps. The construction of a mobile, yet stable platform was not considered viable. The high cost of a laser scanning survey was also an important factor in the final decision.

Close-range stereophotography was selected because of its well-established record of requiring the minimum amount of site time to collect very high resolution 3-D visual information, with the added potential for sub-millimeter precision during any later photogrammetric analysis stage. The stereo images also provided an easily accessible data source for the Instituto Hondureño de Antropología e Historia (IHAH).

Digital versus Analog Photography

Once the decision was made to use stereophotography, an additional choice needed to be made between digital and analog photography. Even though film processing time would be saved if digital imagery were used, it was decided that negatives would be more accessible and be a more appropriate deliverable for IHAH, being consistent with their existing archive. Analog photography archiving would last longer and be better adapted to the local resources, as well as have superior resolution.

Site Survey

The entire site survey was conducted in little over a month, in June 2000, by two teams of two persons conducting in parallel the stereophotography and the survey of the control targets.

Stereophotography

Stereophotography was done with a Rollei 6006 medium-format survey camera with commercial black-and-white film.

In order for the bottom of each riser to be viewed, vertical coverage was restricted to two steps; therefore, approximately twenty camera setups along every second row of stairs were required. It was estimated that 1,300 unique images would be required. Each image was shot twice in order to generate two sets of negatives, one for the IHAH archives in Copán and one for the GCI in Los Angeles **(Fig. 51)**.

All photography was done at the same scale, although for some difficult shots (especially of the Seated Figures), the scale varied slightly. The scale chosen gave a potential digital resolution of 0.2 mm.

Orthogonal (square-on) lighting, rather than oblique illumination, was chosen, to provide blander, flatter images for which—through the lighting capabilities of CAD and a generated surface—shadows could be artificially created to improve depth perception and bring out microrelief. Twin flashguns on either side of the camera were used to provide the orthogonal artificial lighting. A scaffold platform was needed only to obtain coverage of Stela M and its Altar C.

Each day the film was taken to the photo laboratory for processing by the IHAH photographer, and the quality was checked on a daily basis by the Photarc Surveys team.

Photo Control Survey

Small, 10 mm photo control targets were fixed at 40 cm intervals on every other step with the acrylic resin Paraloid B-72, as an intervention layer, to protect the stone surface. This interval was chosen so that each of the images would include enough control points so that stereo pairs could be set up and viewed individually.

The measurement of the 3-D coordinates of these targets would allow for each image to be placed in relationship to every other image. For the survey network, nine temporary stations were established, consisting of short, 4 cm metal rods in concrete or small, 3 mm crosses marked on the rubble core of the sides of the Stairway in order to protect the archaeological fabric. Four other survey stations were established on the grass at the foot of the Stairway, two of which provided visibility to most of the targets. The traverse and target measurements were made with a Leica reflectorless TCR307 total (survey) station. The data were collected on a Hewlett Packard 48 calculator with Tripod Data System's SurveyPro software. The field survey has a potential accuracy on the order of 2–3 mm, because of the short sight distances and the measurements that were taken directly of the control points.

Figure 51 Photarc Surveys Ltd. consultants taking stereophotographs of block 2 using a medium-format camera.

Results and Evaluation of the Survey

Photo Control Survey

For the survey control, the traverse (measurement of each station position in relation to every other station) proved to be extremely accurate, closing to 1 mm in northing and elevation, and 3 mm in easting. A total of 3,059 observations were collected of the 1,558 targets. A total of 80% of the targets were coordinated from pairs of observations, providing a check in horizontal position and elevation; the other 20% were taken from single shots only.

Stereophotography

The photography produced 1,420 unique images (**Table 1**). On-site requests for more detailed coverage of selected control blocks meant that 120 additional images beyond the original estimate were required. After the fieldwork, the negatives were stored in archival sleeves and labeled—one set in English for the GCI, and one in Spanish for IHAH. One set of 8-inch square prints made by hand was also created for the GCI.

Some of the survey and photographic data were used to carry out test analyses. A scanned stereo pair of photographs was opened into the International System Map (ISM) Digital Image Analytical Plotter (DiAP) digital photogrammetric software. The images were then oriented relative to each other, so that their positions were in exactly the same relationship as at the moment of exposure. They were then jointly oriented to the control points to reproduce their exact position in space, in the world coordinate system, at the time of photography. When this procedure is completed, any 3-D tracing of the detail on the computer screen with a 3-D mouse takes place in a true scaled coordinate system.

However, with the ISM automatic image measurement software, it is possible to automatically produce a digital model of the surface (if not the detailed line work) of the stone block (or, in topographic terms, the landscape) by automatic image correlation. This process matches parts of each photograph

Table 1 Photographic survey coverage and control.

Controlled	*Codes*	*Shots*	*Pairs*	*Targets*
Steps	0–63	645	594	641
South balustrade–top surface	S, T	110	108	218
North balustrade–top surface	N, M	110	108	220
South balustrade–south elevation	SE	53	32	76
North and south balustrades–other elevations	NE, L, R	33	22	60
Altar of Stela M	A	68	42	72
Stela M	B	50	33	42
Altar	C	59	40	66
Seated Figure 1	D	45	28	47
Seated Figure 3	E	41	26	42
Seated Figure 4	F	39	24	39
Seated Figure 5	G	31	17	35
Total controlled		*1284*	*1074*	*1558*
Uncontrolled (scale bar only)				
Figure 6		18	9	
Conservator closeups	flash	53	38	Some control*
	daylight	36	25	Some control*
Stones under conacaste tree		10	5	
Stones in lab		19	16	
Total uncontrolled		*136*	*93*	
Grand total		***1420***	***1167***	

**Some control* refers to the fact that these images have incidentally picked up some of the targets but are not fully controlled by targets. The scale bar has been put in the field of view so that the images could be independently scaled if not necessarily related to the overall survey scheme.

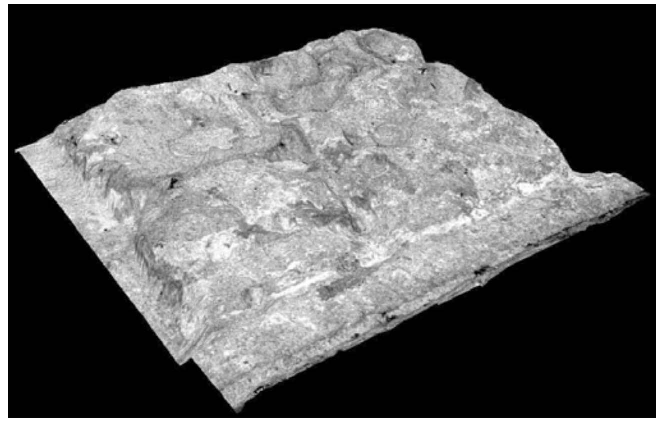


Figure 52 A digital surface model of glyph B, block 20, step 6, with the imagery draped over the surface.

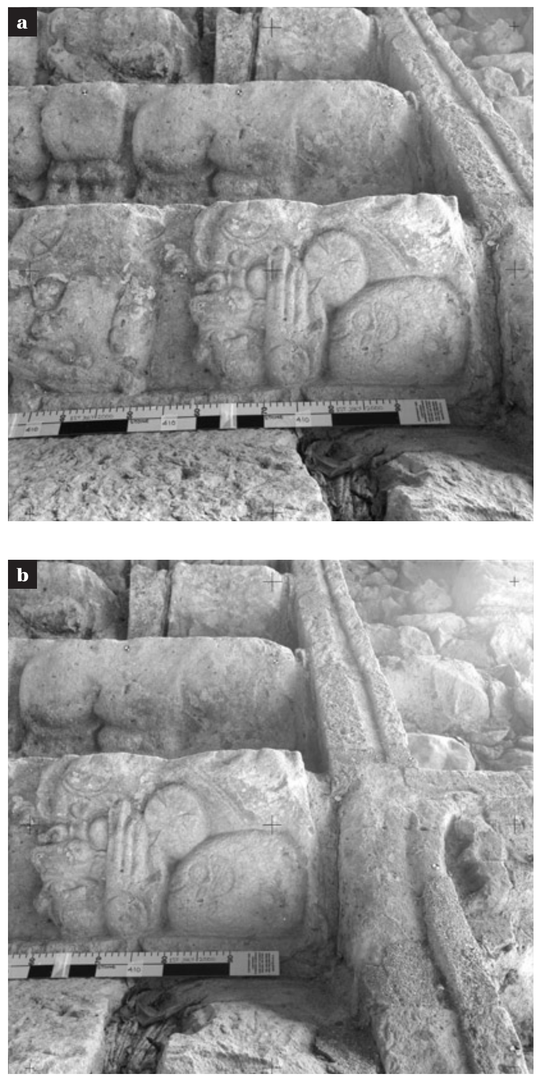
patch by patch to determine similarities. The relative positions of these matched patches is a function of the variation in the surface relief. This 3-D surface or digital surface model can be used to build up a true 3-D model of the subject by draping the imagery over it. The data can also be used to establish a base for future analysis of any erosion of the surface.

A digital surface model of one of the Stairway glyphs automatically generated with a grid interval of 2 mm, and the imagery draped over the surface using ISM DiAP digital photogrammetric software, is shown in **Figure 52**.

Conclusions

The procedure established after the reconnaissance visit appeared to fulfill the documentation requirements, and there were no major site problems encountered for the stereophotography. The daily development of the negatives enabled the photographers to check the previous day's photography thoroughly. This meant that they were always aware of the status of the coverage and could solve problems daily (**Figs. 53a, b**).

The decision to use orthogonal lighting, which produces flatter photographs, has probably not helped the casual (nonstereo) interpretation of the images, but it remains the case that the recessed areas that would otherwise be in



Figures 53a and b Stereophotographs of block 410, step 43. 2000.

shadow are illuminated. Shadows can still be artificially produced, and stereo viewing–aided either digitally or by pocket/mirror stereoscopes–is easily achievable.

The schedule proved to be as estimated, and the rate of about fifty unique, acceptable, and processed images per day should be a good guide for this type of carefully controlled stereo photography in the future.

There are lighter close-range scanners available today that would be viable, but unless multiple scans were taken for each glyph, the resolution would not rival photography. There would also be the problem of the very awkward coverage of the statues–the photographers were sometimes reduced to using a monopod to obtain any coverage. The instantaneous exposure of flash photography removed all problems associated with movement of the sensor.

The control points survey data proved more problematic. Some errors in the data were identified and could be easily corrected, while other data could be improved by a number of mathematical computations, but some data could not be improved. Consequently, not all points could be calculated to the highest precision.

The two main goals of the survey were met: the stereophotography provided a base on which to carry out the detailed condition survey of the surface of the Stairway, and it created a photographic record for the year 2000, for comparison with past and future photographic records.

Condition Survey

Methodology

Objectives

The main objective of the condition survey was to create a base documentation of the Stairway's condition by graphically recording the types, extent, and location of deterioration. The condition survey was to be used both as a diagnostic tool, together with other types of investigations (environmental monitoring, scientific studies, archival research, etc.), and as accurate baseline data for the future monitoring of the Stairway condition, as well as for the planning and recording of future conservation interventions.

Recording Methods

Considering the objectives of the condition recording, it was decided that the final product should be in digital form, not solely in paper form. A digital output allows for more efficient updating and future uses, as well as for ease of reproduction. Paper copies of all drawings will be produced to create a hard copy archive and to ensure some sustainability of the digital output.

The choice of recording process was between traditional manual recording, using scanning to transfer the information digitally, and direct digital recording using computers in the field. The decision had to balance the objectives of the condition recording against the resources available, the constraints of the site, and the requirements of each method.

Direct digital recording was selected to carry out the survey, because it is a faster process for obtaining a digital product. Field time of both recording processes is comparable. However, based on previous experience, post-fieldwork processing time is considerably longer with the traditional method. If one spends a total of 1 hour to obtain a digital drawing directly, one can expect to spend 2.5 hours using the traditional process. The digital method has some important constraints, however–among them the cost of providing a portable computer to each surveyor, the need to have computer-trained surveyors, and the need for a computer-friendly site environment (protection from dust and the weather, availability of electricity on site, etc.).

For the base on which to trace the condition survey, both drawings and photographs were considered. However, the need for a detailed condition survey, and the fact that a number of blocks do not possess enough drawable details to locate conditions precisely, led to the decision to use photographs rather than drawings to create the condition survey base.

Scope of the Condition Survey

Based on the assessment of significance and the history of the Stairway reconstruction, it was decided to survey only the carved surfaces of the Stairway. Consequently, only the front surfaces of the stone blocks of the steps and balustrades were surveyed, while the surfaces of the treads and the uncarved filler blocks were not surveyed at all. Virtually all surfaces of the Stairway sculptures in the round (Seated Figures, etc.) were surveyed, as was the Stairway Altar. The Stela M and zoomorphic Altar C, situated on the Plaza in front of the Stairway, were surveyed as well, to see if the condition of other carved monuments was similar to that of the Stairway.

Glossary of Stone Conditions and Material Characteristics

Before the beginning of the condition recording in 2000, a glossary of terms, based on already published stone glossaries, was developed to describe the main types of deterioration found on the Stairway. These terms were later modified after survey experience indicated that some of the conditions were not found on the Stairway. The final glossary included the following conditions: fissure, flaking, detachment, superficial loss (of stone), mortar loss (between blocks), and microbiological growth (see Appendix D). Surface erosion was not recorded, although many of the blocks are completely eroded and without any remains of original carved surfaces. Also, major loss of stone–namely, significant loss of volume of a block–was not recorded, although some blocks have lost from one-quarter to one-half of their original material.

One material characteristic, the natural geological veins in the stone, was recorded at the same time as the conditions. However, natural mineralogical inclusions in the stone, both large and small, were not mapped. The different

Figure 54 Condition survey done by direct digital recording using a computer in the field.

colors of the stone, ranging from bluish green to light tan or buff, were not mapped, as the color of the stone can change within a single block of stone without any corresponding changes in condition, and accurate readings of color would require cleaning the stones. The stones of the Stairway vary from fine grained to coarser grained, but this characteristic was not mapped either.

Three categories of previous interventions were also recorded: surface fills, surface consolidation, and mortar repointing between blocks. Six types of repointing mortars were visually identified (see the illustrated glossary of conditions in Appendix D).

Before the collection of condition data in the field, the photographic base was prepared. With scanned black-and-white prints of the photogrammetric survey, a 2-D photographic mosaic of the Stairway was created using Adobe Photoshop and AutoCAD software. Separate photographic mosaics were created for each elevation of the Stairway Figures, and for the Altar, Stela M, and Altar C.

Recording

The condition survey was carried out in two separate campaigns, in November–December 2000 and in February–March 2001, by four GCI staff assisted by two local trainees. The project required the equivalent of 86 one-person workdays, for a total fieldwork time of approximately 560 hours. Most of the survey was conducted directly in digital form with laptops in the field (**Fig. 54**). However, as the base photographic mosaic could not be completed prior to the first field campaign, slightly fewer than one-third of the Stairway steps were surveyed traditionally, by tracing the conditions with colored pens on transparent plastic sheets overlaid on the photographic prints. The survey work done traditionally was subsequently digitized to obtain drawings in AutoCAD.

The work of the different surveyors was then combined to create a single CAD drawing for the Stairway, where each condition is contained in its own layer. Separate drawings were also created for each of the Stairway Figures, and for the Altar, Stela M, and Altar C.

Results

The condition survey revealed that the most widespread and main types of deterioration found throughout the Stairway are millimeter-scale flaking and small-scale detachment (**Fig. 55**), often accompanied by thin, short, surface fissures. These types of deterioration occur often, but not always, on the relief parts of the glyphs. In general, the lower halves of the blocks tend to be more deteriorated than the upper parts, a fact that is evidenced

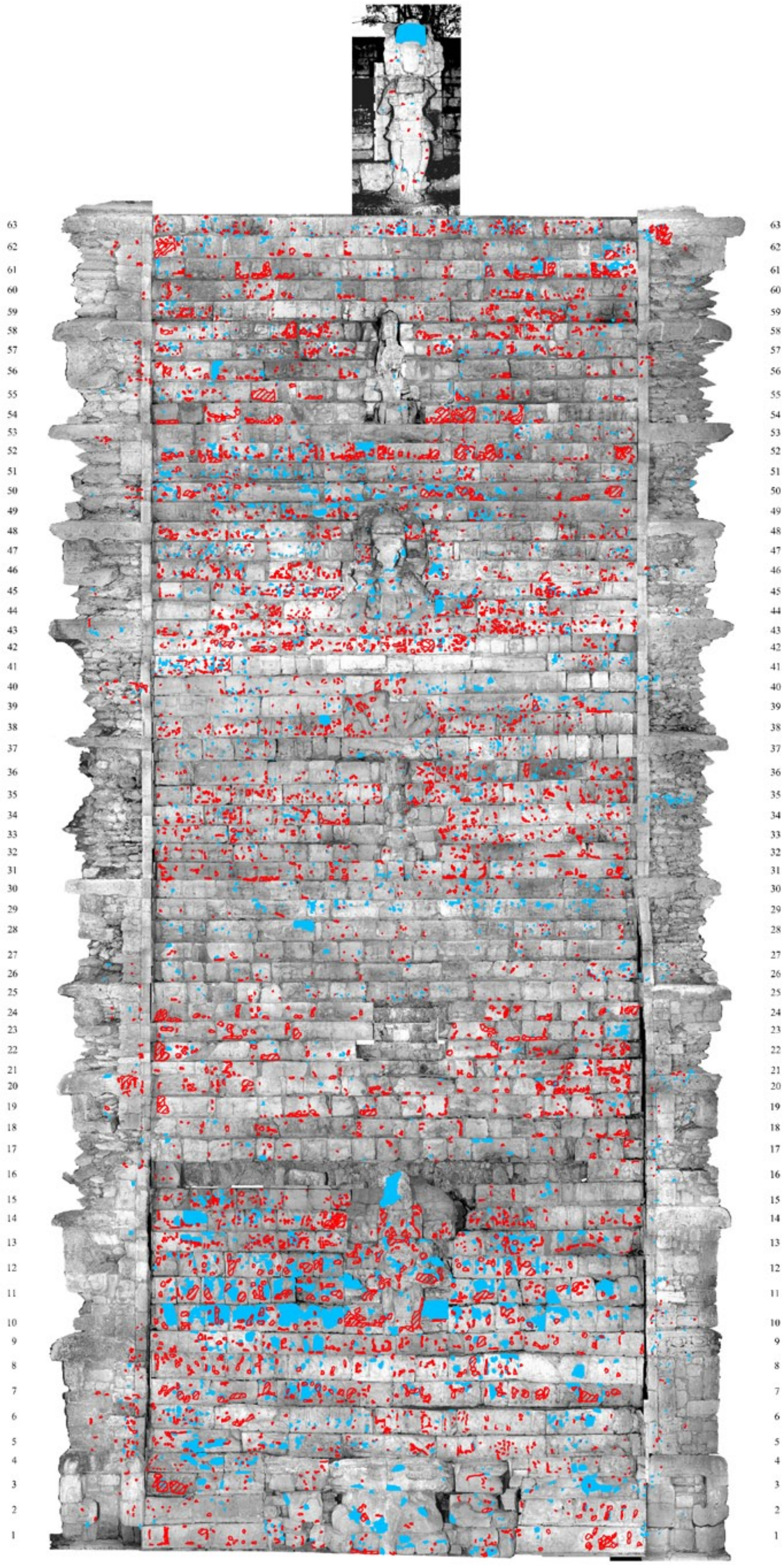


Figure 55 The extent and locations of deterioration by flaking (red) and detachment (blue) on the Hieroglyphic Stairway.

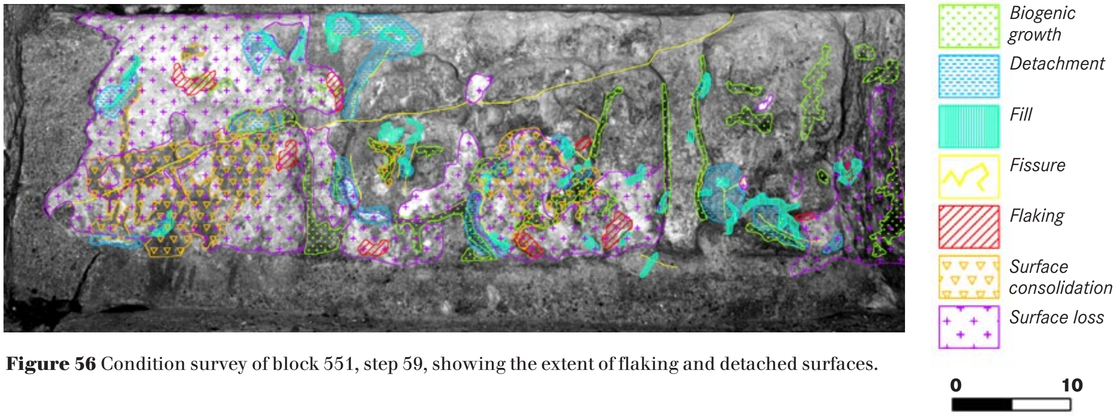


Figure 56 Condition survey of block 551, step 59, showing the extent of flaking and detached surfaces.

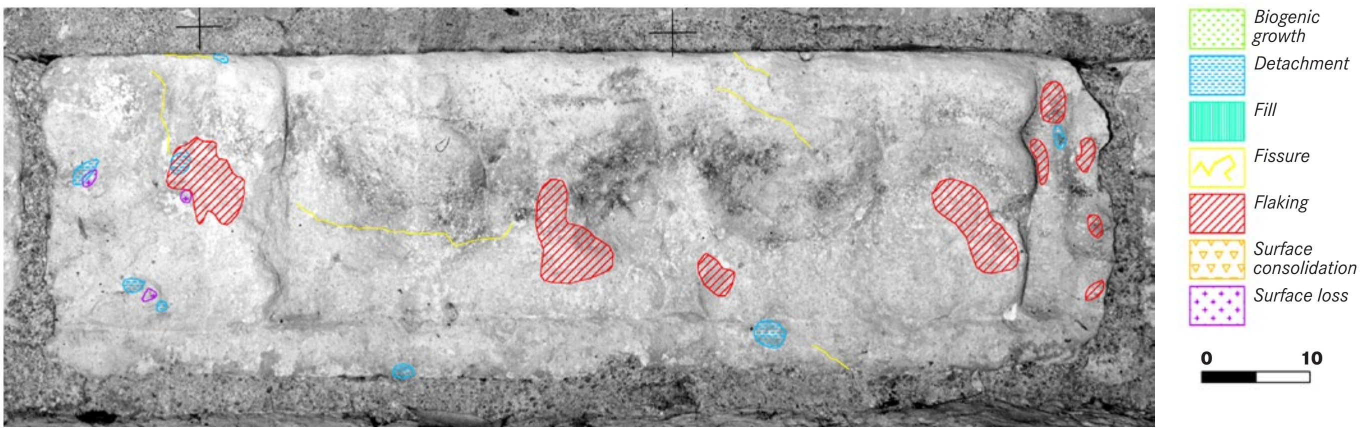


Figure 57 Condition survey of block 197, step 23, showing an overall lack of deterioration.

by superficial microflaking in the lower part, while intact but detached surfaces are often found in the top halves of the blocks (**Fig. 56**). Disaggregation of the stone, a condition that is not widespread, was not mapped separately from flaking. However, it actually constitutes a type of deterioration that would require a different conservation treatment in the future. There was no discernible relationship between geological veins and any condition. Areas of surface whiteness corresponded to areas of surface disaggregation, or to areas behind fallen flakes. There do not appear to be any areas of surface whiteness due to the presence of salt efflorescence.

Structural deterioration is found only on blocks from the bottom fifteen steps, which have always been in situ. Particularly, in steps 9 to 15, large-scale structural detachment, with evidence of deep cracks parallel to the faces of the blocks, can be found. Most of the structural loss observed on the Stairway can be found on blocks from this area, some of which have lost up to half of their width.

A significant number of blocks also present an eroded but stable surface, but erosion was not a condition that was surveyed (**Fig. 57**).

Remains of microbiological growth are found on practically all stone blocks. The deeper recesses created by the glyph carving tend to contain the remains of moss, whereas the blocks' upper parts tend to exhibit horizontal bands of algal growth. Only very few lichens are present today on the Stairway.

Two main types of previous interventions on the block surfaces were recorded: surface consolidation and fills. Most of the blocks presenting superficial flaking have been consolidated with a dilute solution of either Paraloid B-72 or Mowilith 30 (for details, see "History of Interventions"). The applications, which were likely carried out with a brush, have been poorly executed, as evidenced by many drip marks and by a notable darkening of many block surfaces. However, it appears that the applications have had no negative impact on the conservation of the stone. Fills are actually mostly edging repairs of stone flakes, executed with a mix of stone powder and either Paraloid B-72 or Mowilith 30. They have been carried out with variable levels of skill and are often very visible. Fills have undeniably supported flakes and kept them in place. However, because most detached areas have been edged without the void behind them being filled (or they have been re-adhered with only a Paraloid solution), they remain unstable and vulnerable to loss, especially if subjected to physical impact.

Six different pointing mortars were identified on the Stairway: four common types and two that are more rarely found. The four most frequent repair mortars correspond closely to the Stairway sequence of reconstruction (1937–40), while the two others are found only in a few places and correspond to more recent interventions during the last three decades. The mortars range from a hard 1:2 cement:sand mortar, to a soft lime and soil mix, and they have been applied with various levels of skill. No particular stone deterioration, however, seems to be associated with the presence of even the hardest mortars. They are in various states of deterioration, and a number of joints are completely open–a condition that was recorded as mortar loss. This condition does not have implications for the structural stability of the Stairway, as the blocks were replaced on a support stairway during reconstruction, and therefore they no longer perform structurally. Loss of mortar does, however, allow and promote animal activity–in particular, the burrowing of large rodents between Stairway blocks. There are also many vertical cracks between the pointing mortar and the stone throughout the Stairway, but these were not surveyed. These cracks do not seem active, according to a comparison of historic photographs; they could be a result of the settling of the Stairway soon after its reconstruction.

Conclusions

An analysis of the condition survey mapping reveals that the condition of the blocks is, in general, not related to their location on the Stairway but is, instead, block specific. Any given type of condition is generally found throughout the Stairway, and blocks in very good condition can be found adjacent to blocks that are in very poor condition.

This conclusion should not be surprising if one considers that more than three-quarters of the blocks are not in their original locations, and have only been in their current locations for about seventy years. Blocks with structural cracks and the greatest degree of structural loss are found predominantly in the bottom fifteen steps, which have remained in situ. This situation reflects the fact that, because they were always in situ, these steps were more exposed to higher blocks falling on them during the burial process and exposed to tree and plant roots over the centuries. They also have suffered almost fifty more years of weathering as a stairway structure than did the other blocks that were left on the Plaza prior to reconstruction. The section consisting of a dozen steps immediately above the in situ steps is generally heavily eroded, with no visible remains of hieroglyphic carving. But this uniform location-oriented condition is the result of the decision made during the reconstruction of the 1930s to place all the heavily eroded blocks, without any recognizable glyphs, together in one location on the Stairway (see “History of Interventions”).

Overall, throughout the entire Stairway, surface deterioration depends more on the characteristics of the specific blocks than on the location of the blocks within the Stairway, on their color, or on their immediate environment. Therefore, block conditions will vary depending primarily on the geology of each block, including its grain size, its location within the quarry, and its plane of deposition in relation to the orientation of its placement in the masonry structure. Another factor relating to individual block deterioration is its past history, including where it was located between the time of abandonment of the site and the present. As a result, in this case, the condition survey has been found to be of limited utility for diagnosing the causes of deterioration of blocks. It will, however, be useful in planning the future treatment of the Stairway.

For determining whether deterioration is ongoing on the Stairway, as well as determining its possible causes, one can analyze previous documentation performed at different times, if available (as presented in “Comparison of Stairway Photographic Documentation through Time”), and one can begin to monitor conditions by repeatedly carrying out a graphic condition survey over time. The analysis of the most recent photographic documentation showed that active deterioration is generally confined to the surfaces of blocks in the top step of the Stairway (step 63); however, not all of these blocks are undergoing deterioration. The active deterioration of some individual blocks on step 63 could be related to the presence of the mortar platform and cement lip on the top step. The mortar and cement are potential sources of soluble salts. The crystallization-deliquescence cycles of these salts on and under stone surfaces can provoke disaggregation or flaking. To confirm this observation about deterioration being limited primarily to blocks of the top step of the Stairway, it was decided to survey all the control blocks for observable loss of stone surface since 1987, using the photographs taken in that year as the base for the graphic recording.

This survey was repeated five times between April 2002 and August 2004. It was observed that all control blocks had suffered some limited loss since 1987, and that the amount of loss varied greatly from one block to another, with blocks 375–376 exhibiting the greatest amount of loss and most active deterioration from disaggregation and flaking. The surface loss on control blocks is generally located in already deteriorated areas where detachment, flaking, and previous treatments were present in 1987. However, a few control blocks have been observed to exhibit surface loss in previously untreated areas between April 2002 and August 2004. Most of these losses appeared to be due to impact, resulting from people accessing the Stairway to repair or change the tarpaulin shelter; these tasks were performed four times between January and July 2003. In conclusion, active deterioration of block surfaces by disaggregation and flaking is not limited to certain blocks of the top step. There are, in fact, a very few blocks located in other areas of the Stairway that continue to lose surface in this manner, despite the protection of the shelter. Loss of surface due to impact related to human access to the Stairway is, nonetheless, the more significant ongoing cause of surface deterioration of all Stairway blocks.

Analyses of Materials

The scientific analysis of the materials that make up the Hieroglyphic Stairway has been carried out as part of the diagnostic investigation of the deterioration of the monument. Several types of materials were analyzed: large samples of Copán stone and, from the Stairway, small stone flakes, repointing mortar, and surface treatment materials. The results of these analyses contribute to the development of a comprehensive conservation plan for the Hieroglyphic Stairway.

Experimental Procedures

Materials

Four types of samples were analyzed.

1. Four large bulk samples (BF) of the stone that the Hieroglyphic Stairway is built of were collected at the site, in order to characterize the stone and to carry out physicomechanical testing (samples BF1, BF2, BF5, and BF6).
2. Thirteen small stone flakes were sampled from the Hieroglyphic Stairway to investigate decay mechanisms and to test for the presence of salts on stones from the monument.
3. Eleven samples of mortar from different areas of the Stairway were collected. They include mortars from different phases of the 1930s Stairway reconstruction and more limited later repairs. In particular, these mortars were tested to determine the presence of potentially damaging salts.
4. Finally, eleven samples from previous treatments applied to the Stairway stone surfaces in recent decades were taken to confirm the types of adhesives, which had not been documented accurately.

Analytical Methods

Standard methods were used to characterize the samples. **Table 2** summarizes the analyses carried out and the procedures followed. In all tables standard deviations are given in parentheses; no standard deviation indicates that the measurement was done on only one sample.

Based on the measured physicomechanical properties of the stone, the Wärme und Feuchte Instationär (WUFI) program (Künzel 1995) was used to calculate transient heat and moisture transport. This simulation provides a graphic presentation of moisture and temperature depth profiles for an annual cycle, given approximate environmental conditions. The basic input parameters, which are approximated, are bulk density, porosity, specific heat capacity and thermal conductivity, water vapor resistance factor, and liquid transport coefficient for suction and redistribution. In the absence of environmental data from Copán properly formatted for the WUFI program, comparable weather data from New Orleans, Louisiana, which were available through the program, were used instead.

Results

Characterization of Copán Stone

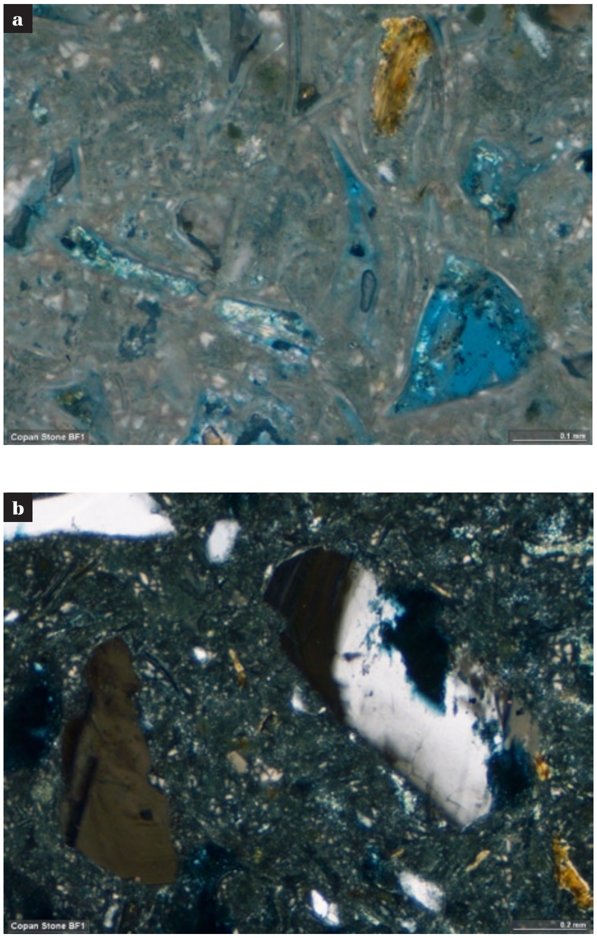
Petrographic and mineralogical description

The archaeological site of Copán is located in an alluvial pocket along the Copán River at about 620 meters above sea level; the surrounding ridges rise to 1,400 meters (Webster 1999). The bedrock of the Copán Valley consists mainly of Tertiary period volcanic deposits of rhyolitic and andesitic ashflow tuffs, biotite tuffs, and some basalt known regionally as the Padre Miguel group (Heiken et al. 1991; Kozuch 1991).

Based on chemical and mineralogical analyses carried out using X-ray diffraction (XRD), X-ray fluorescence (XRF), and optical and scanning electron microscopy, the main stone in the Copán Valley that was used to build the Hieroglyphic Stairway is a green andesite to rhyolite volcaniclastic tuff. This tuff, with a color varying from green to buff, is fourteen million years old and originally contained ash (volcanic glass) and large mineral fragments such as feldspar, quartz, mica, and weathered chlorite. It has undergone substantial alteration since burial, with zeolites, quartz,

Table 2 Analyses and procedures.

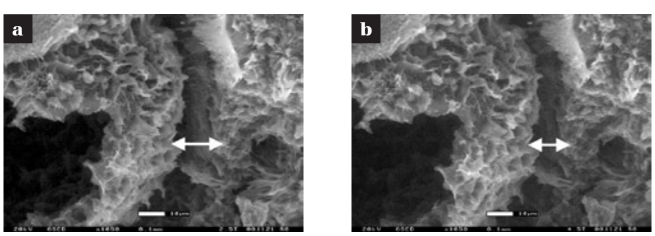
Mineralogical and chemical composition	
X-ray diffraction (XRD)	
X-ray fluorescence (XRF)	
Ion chromatography (IC)	
Fourier transform infrared spectroscopy (FTIR)	
Wet chemical analysis–mortar	BS4551:Part 2:1998
Salt concentration–mortar	NORMAL 13/83
Microanalysis and textural characterization	
Polarized light microscopy (PLM)	
Environmental scanning electron microscopy/energy dispersive spectroscopy (ESEM/EDS)	
Electron microprobe analyzer (EMPA)	
Properties and characteristics related to pore space	
Porosity accessible to water	RILEM I.1
Free porosity and saturation coefficient	RILEM II.1
Bulk and real density	RILEM I.2
Mercury intrusion porosimetry (MIP)	
Moisture transport characteristics	
Water absorption coefficient	ISO 15148
Water vapor permeability and water vapor resistance factor	ISO 12572
Drying kinetics	RILEM II.5
Hygric dilatation	RILEM II.7
Mechanical strength	
Compressive strength–stone	BS EN 1926 (1999)
Others	
Thermal dilatation	RILEM VI.3
Color	
Ultrasonic velocity	



Figures 58a and b Thin section images by polarized light microscopy of bulk Copán stone. Sample BF1 under normal light (a) shows pores in blue, where volcanic glass has dissolved; the sample under cross-polarized light (b) shows a partially dissolved feldspar grain in a zeolite matrix.

Table 3 Mineralogical and chemical composition of the four bulk samples of Copán stone (BF1, BF2, BF5, and BF6).

	BF1	*BF2*	*BF5*	*BF6*
SiO_2 content (%)	70.45 (±0.07)	70.2	71.6	72.3
Fine (< 2 µm) fraction content				
Smectite (swellable clays)	Medium	Medium	High	High
Mordenite (zeolite)	High	Medium	Low	Low
Illite (nonswellable clays)	Medium	Low	Low	Low
Quartz	Trace	Low	Trace	Trace



Figures 59a and b Expansion (a) and contraction (b) of clay in ESEM during wetting-drying cycles (sample BF1).

and sanidine largely replacing the original glass matrix; mineral fragments are dissolved or altered to a lesser degree (**Figs. 58a, b**).

The silica content of the rock determined by XRF is about 71% SiO_2 by weight (average of the four samples). There is significant variation among various samples of Copán stone in the type, amount, and homogeneity of distribution of larger crystals (feldspar, quartz, mica, etc.) and of dark basaltic inclusions. However, the fine-grained matrix, which makes up the bulk of the stone, has a more consistent composition, with microcrystalline mordenite, quartz, and sanidine having largely replaced shards of volcanic glass during devitrification (**Table 3**).

XRD analysis of the fine (< 2 µm) fraction of crushed Copán stone shows that the zeolite mordenite is abundant in all samples. No glass was detected; however, clays are present: illite (nonexpanding clay) and a small amount (2%–6%) of smectite (expanding clay). If significant amounts of swellable clays are present, then the expansion upon exposure to liquid water can be a cause of physical stress and an important factor in the decay process (**Figs. 59a, b**).

Properties and characteristics related to pore spaces

The main properties of the Copán stone related to pore spaces are presented in **Table 4**.

Copán stone has a relatively high porosity. Sample BF6 has a higher total porosity (N_t, measured under vacuum) than BF1, as well as a much higher free porosity (N_{48}, porosity open to water by capillary). This result shows that BF6 has more connected pores that allow water to penetrate easily by capillarity (**Fig. 60**). These properties lead to a greater saturation coefficient (S_{48}) for both stones. The saturation coefficient is related to the susceptibility of the stone to frost, if temperature goes below zero, and to salt damage, if salts are present. When the saturation coefficient is greater than 0.85, the stone is considered susceptible to damage; when it is between 0.75 and 0.8, the stone is moderately resistant, and when it is less than 0.75, the stone is considered frost and salt resistant.

The pore-size distribution obtained by mercury intrusion porosimetry (**Fig. 61**) shows that all samples have more than half of their total pore volume made up of pores smaller than 0.1 µm. These pores are generally considered micropores where capillarity condensation can occur. In contrast to this high microporosity, all samples have a small percentage (1.2%–7.2%) of pores larger than 5 µm, a dimension at which liquid water circulates freely within the pores.

Moisture transport characteristics

The main properties related to moisture transport characteristics of the Copán stone are presented in **Table 5**.

The samples show a wide range of water absorption coefficient values (W-values), ranging from 0.66 kg/m²√h, a very low value, similar to that of a very dense limestone or an altered marble, to 3.24 kg/m²√h, a value typical of porous limestone or sandstone. The wide range of water absorption

Table 4 Properties related to pore space for the four bulk samples of Copán stone (BF1, BF2, BF5, and BF6) (MIP = mercury intrusion porosimetry).

		BF1		*BF2*	*BF5*	*BF6*
Porosity accessible to water	N_t (%)	23.8 (±2.2)		–	–	33.8
Free porosity	N_{48} (%)	19.4 (±3.3)		–	–	31.9
Saturation coefficient	S_{48} (no unit)	0.81 (±0.08)		–	–	0.94
Bulk density	ρ_{bulk} (kg/m^3)	2323.8 (±80.5)		–	–	2473.0
Real density	ρ_{real} (kg/m^3)	1769.1 (±36.2)		–	–	1636.0
Total porosity	MIP (%)	32.15 (±2.98)		20.06	24.92	32.17
Percent of total pore volume	MIP (%)	*BF1-1*	*BF1-2*			
Pore diameter > 5 µm		3.3	2.9	7.2	2.8	1.2
0.1 µm < pore diameter < 5 µm		28.3	43.3	9.0	21.9	33.8
Pore diameter < 0.1 µm		68.4	53.8	83.8	75.3	65.0

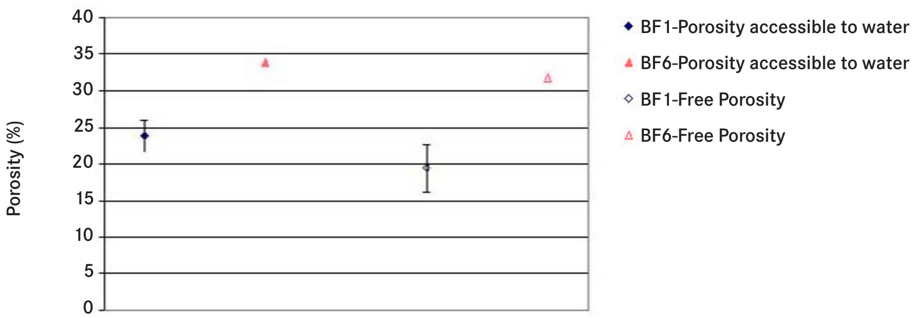


Figure 60 Porosity data for samples BF1 and BF6.

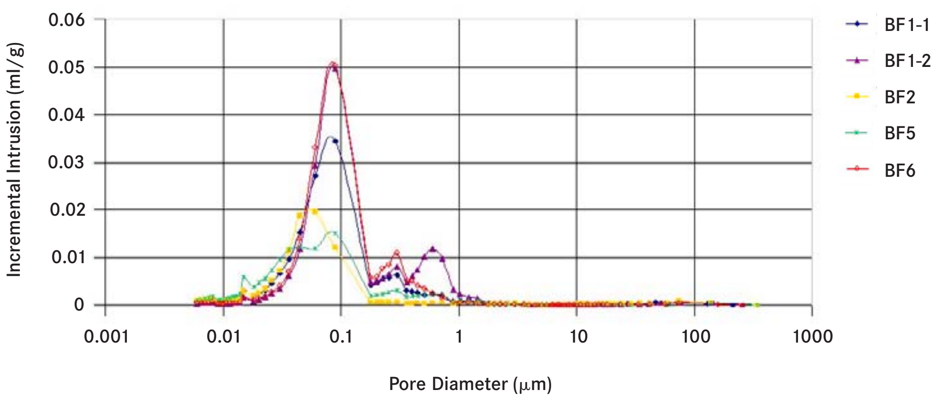


Figure 61 Pore-size distribution by mercury intrusion porosimetry.

Table 5 Properties related to moisture transport characteristics of the four bulk samples of Copán stone (BF1, BF2, BF5, and BF6).

		BF1	*BF2*	*BF5*	*BF6*
Water absorption coefficient	W (kg/[m^2 • √h])	0.66 (±0.03)	2.39 (±0.18)	1.54 (±0.09)	3.24 (±0.26)
Water vapor permeability	δ_p (g/[m • h • Pa])	2.15 (±0.05) • 10^{-5}	–	2.83 (±0.32) • 10^{-5}	2.82 (±0.12) • 10^{-5}
Water vapor resistance factor	µ (dimensionless)	29.1 (±0.8)	–	22.3 (±2.7)	22.2 (±0.9)
Drying kinetics					
Density of vapor flow rate	g (g/[cm^2 • s])	2.4 • 10^{-6}	–	2.4 • 10^{-6}	2.7 • 10^{-6}
Critical time	t_c (h)	10–15	–	19–24	17–22
Hygric dilatation					
Orientation 1	ε (µm/m)	277 (±20)	–	252	268 (±16)
Orientation 2	ε (µm/m)	590 (±76)	–	442 (±42)	

coefficient values shows that the Copán stone exhibits different behavior regarding liquid water transport. Some samples, BF1 in particular, absorb water much more slowly than others. The water uptake coefficient is an important parameter, because it partly controls the location of the water-air interface, which affects the locations where soluble salts accumulate, if they are present, and where stress to the stone from wetting-drying cycles is concentrated.

The results indicate that relative vapor transport rates are low and similar for all samples, varying from 22.2 to 29.1. As a matter of comparison, a μ-value of 40 is average for a limestone, 200 average for a marble. These low μ-values explain in part the slow drying rate of all stone samples (**Fig. 62**).

After almost two weeks, all of the samples still had significant moisture content, and none seemed to have reached equilibrium time (T_{eq}). However, a difference in the drying rate can be seen between the samples. For example, BF1, the sample with the lowest initial maximum moisture content, is the slowest-drying one. The horizon of evaporation withdraws beneath the surface, marking the end of the drying period entirely due to liquid water transport, a point called critical time (T_c), approximately 10–15 hours after the last maximum capillary wetting. BF5 and BF6 reach critical time (T_c) later, at around 20 hours.

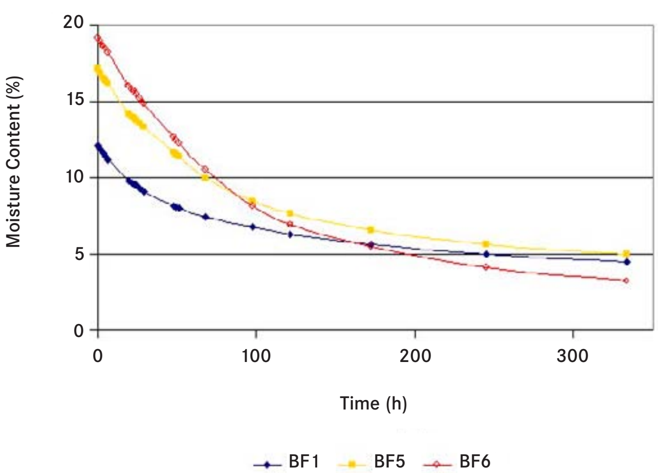


Figure 62 Drying rate of three Copán stone samples.

The hygric dilatation measurements of the Copán stone are within the range expected for this stone type, with significant variation, depending on the sample's orientation. One important factor contributing to hygric dilatation is the amount of swellable clays contained in the material. However, XRD data for these three samples show a medium amount of smectite in BF1, and high amounts in BF5 and BF6, a difference that does not correlate with the hygric dilatation data.

Additional physicomechanical characteristics

Samples of Copán stone generally have fairly high compressive strength, indicating a strong material. In comparison, a compressive strength of 100 N/mm² would be a typical value for a strong, dense limestone, while a value of 50 N/mm² would correspond to the weakest limestone. However, there are significant differences among the samples, with BF6 having about half the strength of BF1, and BF5 being in between the two. Stones with higher compressive strength tend to have lower porosity, a trend that is verified for BF1 and BF6 (**Table 6**).

Thermal dilatation coefficients show a wide range of values, varying from low (BF5, 4.00 μm/m•°C) to high (BF1, 8.25 μm/m•°C). According to environmental monitoring data, unsheltered stone in Copán can be subjected to daily temperature variation of close to 50°C, which translates to thermal dilatation of 200.0 to 412.5 μm/m over the course of a day—the same order of magnitude as for hygric dilatation. However, one must keep in mind that cooling or heating of surfaces is a much slower process than wetting, so at a given point in time, the thermal gradient between the stone surface and its interior is likely to be smaller than the hygric one. Consequently, even if the thermal and hygric dilatations are of the same order of magnitude, the stress to the stone due to temperature variation is likely to be less than the stress induced by water content variation.

Color measurements of freshly cut stones in the laboratory, taken with a colorimeter, show that BF1 is a green stone, whereas BF6 is a buff stone. In the L*a*b* color notation system, hue and chroma are expressed by a* and b*, with a* indicating the color's placement on the red-green axis. The two stones differ essentially in their a* value, with the green stone, BF1, having a negative a* and the buff stone, BF6, having a positive a* (see **Fig. 63**).

The ultrasonic velocity is similar for all samples, with results in a medium range for stone.

Table 6 Other physicomechanical characteristics of the four bulk samples of Copán stone (BF1, BF2, BF5, and BF6).

		BF1	***BF2***	***BF5***	***BF6***
Compressive strength	(N/mm²)	104.1 (±12.8)	–	81.5 (±9.6)	54.1 (±2.9)
Thermal dilatation	α (μm/m•°C)	8.25 (±1.06)	–	4.00 (±2.83)	6.25 (±0.35)
Color	L*a*b*	66.24/-3.14/+10.26	–	–	70.85/+0.55/+9.03
Ultrasonic velocity	v_L (km/s)	2.6 (±0.1)	–	2.6 (±0.3)	–

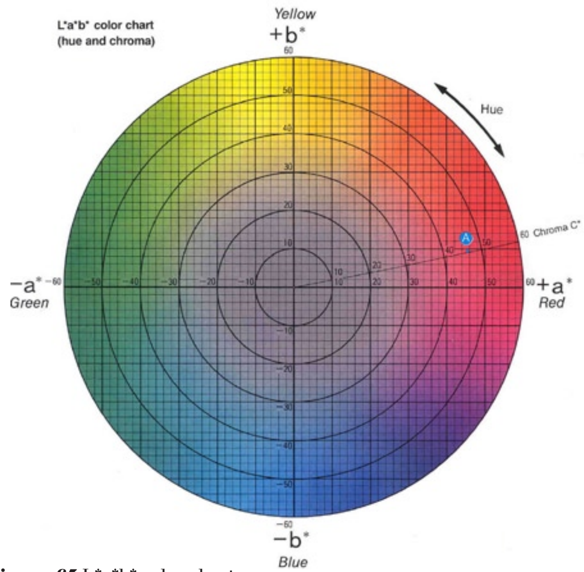
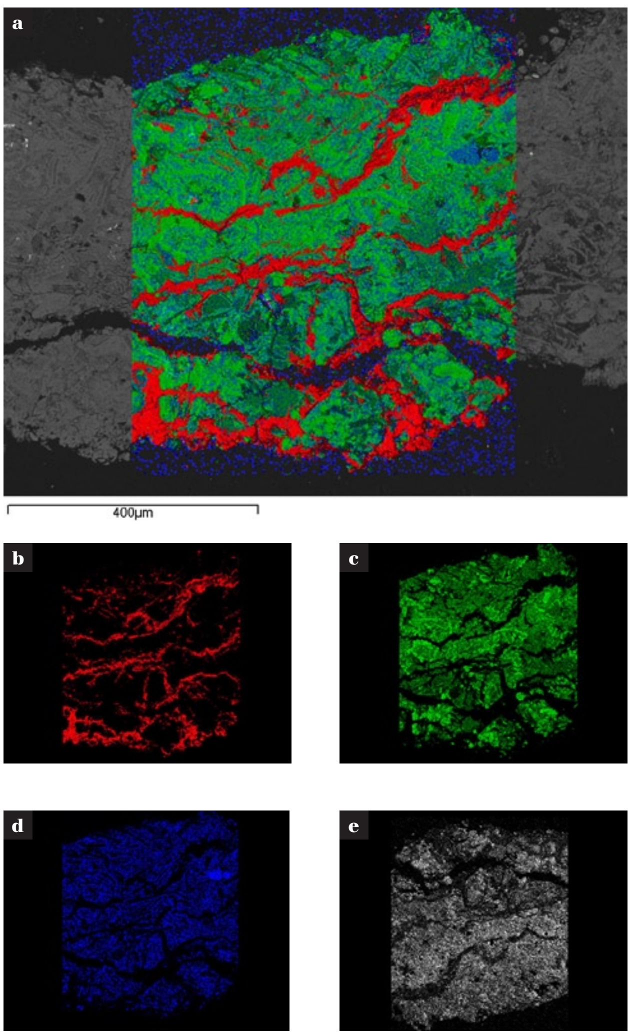


Figure 63 L*a*b* color chart.



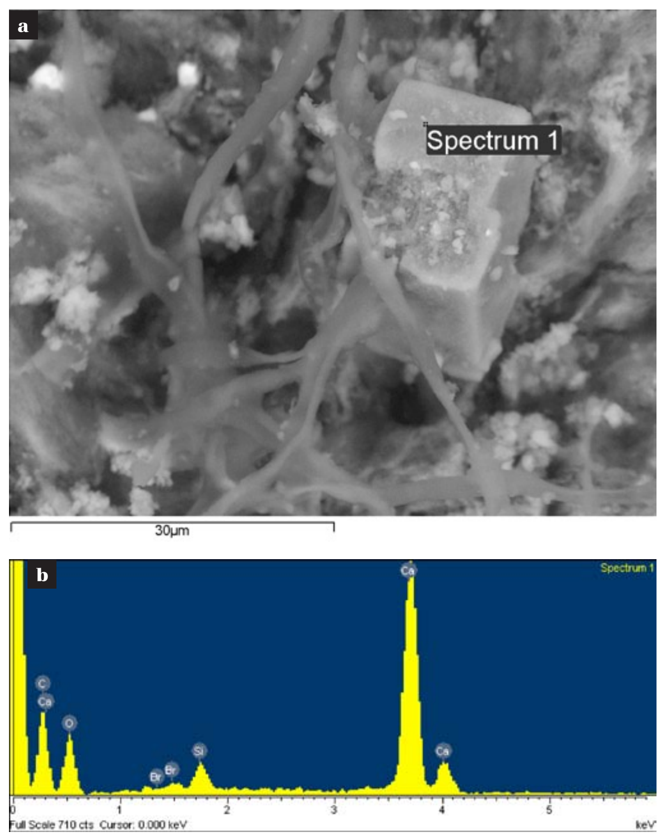
Figures 64a–e ESEM/EDS images of Copán stone flake C1 in BSE mode, with X-ray overlayers of four elements showing distribution of calcite in fractures (false color–red) (a), calcium X-ray overlayer (b), silicon X-ray overlayer (c), aluminum X-ray overlayer (d), and oxygen X-ray overlayer (e). Scale bar is 400 µm.

Characterization of Flakes of Copán Stone from the Hieroglyphic Stairway

Microanalysis and textural characterization

On the Hieroglyphic Stairway, whitish efflorescences have often been observed behind detaching flakes of surface stone. An examination by polarized light microscopy of cross sections of six typical stone flakes shows surface-parallel cracks filled partly with white crystals. Under UV light, the filling material is more fluorescent than the stone, suggesting incorporation of organic material (Druffel 1997). The analysis by environmental scanning electron microscopy/energy dispersive spectroscopy (ESEM/EDS) reveals a precipitation of calcite along those cracks (**Figs. 64a–e**). The same analysis shows that the inner surface of the flakes, which is the plane of detachment, is depleted in silicon and oxygen, suggesting a selective dissolution of these components in the course of weathering.

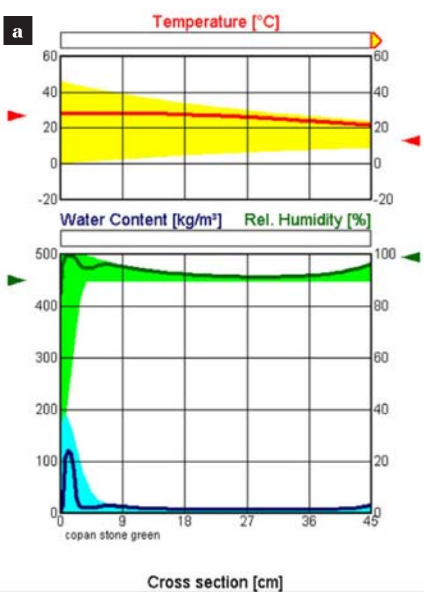
Additionally, the cracks in the flakes are often filled with organic material, including remnant fungal hyphae (**Figs. 65a, b**), which can sometimes be associated with calcite formation (Chen, Blume, and Beyer 2000).

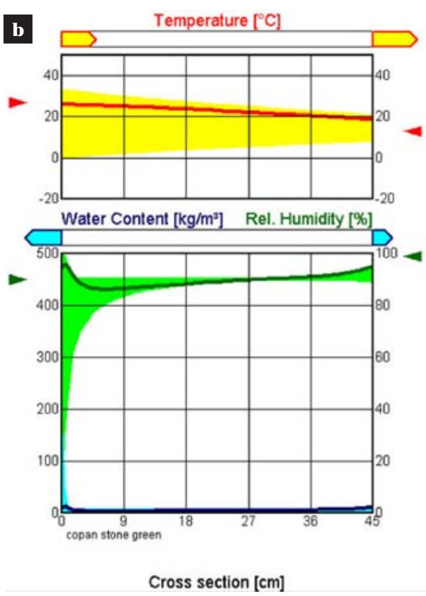


Figures 65a and b ESEM/EDS image of Copán stone flake C5, showing calcite crystals and fungi on flake surface (a); EDS X-ray “spectrum 1,” showing calcium and oxygen peaks identifying the crystals as calcite (b).

Table 7 Ion chromatography results for water-soluble anions and cations from seven samples of stone flakes from the Stairway.

		Anions (mg/g)					*Cations (mg/g)*			
Samples	*Location (step/block)*	*Cl^-*	*NO_3^-*	*PO_4^{3-}*	*SO_4^{2-}*	*$C_2O_4^{2-}$*	*Na^+*	*K^+*	*Mg^{2+}*	*Ca^{2+}*
EE-06	12/172-173	0.06	0.54	0.00	1.11	Low	0.90	0.20	0.10	4.00
EE-07	12/Seated Fig. 1	0.04	0.10	0.00	0.38	Moderate	0.60	0.30	0.10	4.70
EE-14	50/462	0.05	0.06	0.00	0.10	Low	0.30	0.60	0.10	3.80
EE-19	63/595	0.22	0.37	0.16	17.19	Trace	1.80	0.70	0.20	7.00
EE-20	63/589	0.27	1.35	0.00	19.43	Trace	1.40	0.70	0.20	12.40
EE-21	11/71	0.04	0.30	0.00	0.23	Moderate	0.00	0.10	0.10	4.00
EE-24	Seated Fig. 1	0.06	0.07	0.11	0.34	Moderate	1.30	0.20	0.10	3.30





Figures 66a and b WUFI calculation for depth profiles of temperature, water content, and relative humidity. The lines do not represent the average but represent the final state at the end of the annual cycle. The colored areas illustrate the range of values covered in a typical year for unsheltered stone (a) and sheltered stone (b).

Salt content

The soluble salt content of seven Copán stone flakes from the Stairway was measured using ion chromatography (see **Table 7**).

Results show generally low and moderate concentrations of salts, with the exception of sulfates, on the two samples, EE-19 (block 595) and EE-20 (block 589), from step 63, which, in correlation to very high amounts of calcium, can be attributed to the presence of calcium sulfate or gypsum. All samples show a very high amount of calcium. This can be attributed, as seen above, to the presence of calcite, which is generally observed behind flakes on the Hieroglyphic Stairway.

WUFI Model

The physicomechanical properties measured for the stone and weather data from New Orleans, Louisiana, were used to generate graphic representations of the stone moisture and temperature depth profiles over a year, with the WUFI program (Künzel 1995). **Figures 66a and 66b** give the results of simulations run with sample BF1 parameters under two different situations. The upper figure (Fig. 66a) simulates an unsheltered situation, the lower figure (Fig. 66b), a sheltered situation, such as at the Stairway.

The upper graphs represent the calculated stone temperature depth profiles; the lower graphs represent the calculated stone water content profiles (in blue) and stone relative humidity profiles (in green). The lines do not represent the average but represent the final state at the end of the annual cycle. The colored areas illustrate the range of values covered in a typical year.

The WUFI model calculates that, as could be expected, the unsheltered stone (i.e., without the shelter) has a significantly higher maximum surface temperature, reaching a value above 45°C, than the sheltered stone, whose temperature does not exceed 35°C.

The lower diagrams show the interaction of the stone with water. Without the shelter, the stone would contain a significant amount of water, with up to 200 kg/m³ of water at the surface, which corresponds to the maximum water content of the stone under atmospheric pressure, with a maximum depth of penetration of the wet zone of 5 mm. The extension of the wet zone corresponds to the typical thickness of flakes found on the

Stairway, which are the result of past weathering. For the sheltered stone, drying can take place even when water vapor is transported from behind the blocks. WUFI calculations illustrate the beneficial influence of the shelter in preventing episodic wetting-drying cycles.

Characterization of Previous Conservation Treatment Materials from the Stairway

Both oral and written sources refer to the use, in the past decades, of both the acrylic resin Paraloid B-72 and the polyvinyl acetate resin Mowilith 30 as products used in the treatment of stone surfaces on the Hieroglyphic Stairway. Eleven samples of previous treatment materials were characterized to confirm their nature, using Fourier transform infrared spectroscopy. Analysis revealed that both Paraloid B-72 and Mowilith 30 were used mixed with stone powder for edging repairs, and that Paraloid B-72 was also used as a surface consolidant. They also confirmed the fact that these two products can be correctly distinguished in the field by their behavior after acetone impregnation: Paraloid B-72 softens with acetone and can be removed progressively, whereas Mowilith 30 remains brittle and compact and is harder to remove after repeated applications of acetone.

Characterization of Repointing Mortars from the Stairway

Archival research indicates that all repointing mortars on the Stairway are very likely to be modern, dating from the period of reconstruction in the late 1930s onward. Nine samples from different areas of the Stairway were collected for analysis.

Chemical composition and textural characterization

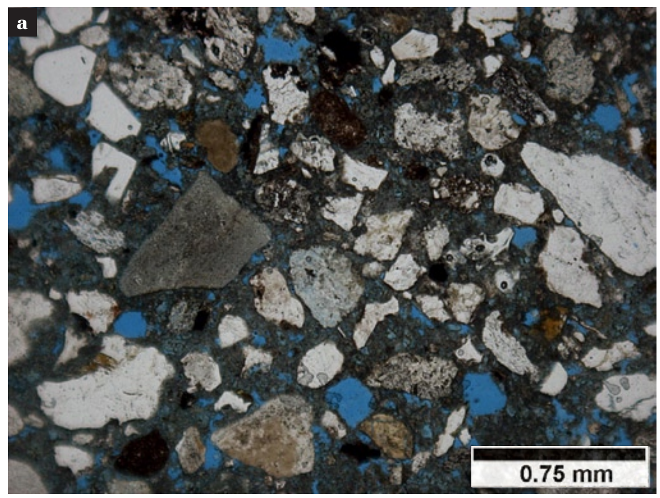
Three samples were analyzed for mix constituents, binder-aggregate ratio, aggregate grading, and soluble salts. In addition, water absorption was determined for two samples, and a petrographic examination was done for the third one. Results are summarized in **Table 8**.

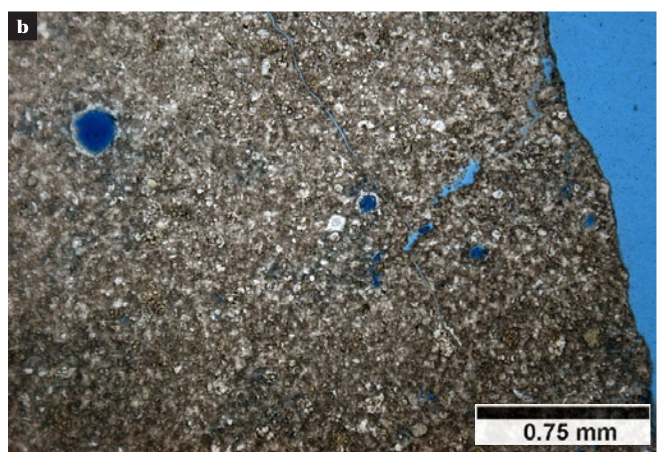
The binder of all samples was determined to be portland cement in proportion varying from 1:6 (S1) to 1:3 (S2). Sample S1, in addition to having the lowest amount of portland cement, contains a sand with substantially finer material, passing 75 µm, whereas S2 and S3 could be described as having reasonably well graded sands. Apart from particle size, generally similar sand was found in the three samples. As expected, sample S2, with more binder, has a lower water absorption rate than S3. The petrographic examination of sample S1 shows poor mixing and compaction; therefore, its porosity would be expected to be greater than that of samples S2 and S3 (Sandberg Consulting Engineers 2000). Qualitative testing revealed a small amount of nitrates in sample S2. The acid-soluble sulfate contents determined during the general analysis indicated normal sulfate levels.

Texture analysis of thin sections of six additional samples of repointing mortar from the Stairway confirmed the previous results. These later samples show a large range of texture and aggregate grading, as **Figures 67a and 67b** illustrate.

Table 8 Data on chemical composition for three samples (S1, S2, and S3) of repointing mortars from the Hieroglyphic Stairway.

	S1	*S2*	*S3*
Mix constituents	Portland cement: sand		
Mix proportions (by volume)	1:6	1:3	1:4
Water absorption (% per weight)	–	7.1	9.8
Soluble salts			
Chloride	None	None	None
Nitrate	None	Small amount	None





Figures 67a and b Thin sections of two different samples of Stairway repointing mortars. In sample M2 (a), cement mortar has angular to sub-rounded particles, moderately sorted. There are mostly floating grains, with a few long contacts, high content of binder, and no orientation of the grains. Pore volume is mostly interstitial, with a few air voids. A few cracks are evident. In sample M4 (b), the dense cement mortar has fine, sub-angular to sub-rounded grains, well sorted. There are mostly floating grains, with high binder content, and some interstitial pores, with few rounded pores and fine cracks.

Table 9 Ion chromatography results for water-soluble anions and cations from eight samples of repointing mortar from the Stairway (N.A. = not analyzed).

		Anions (mg/g)					*Cations (mg/g)*				
Samples	*Location (step/block)*	*F^-*	*Cl^-*	*NO_3^-*	*PO_4^{3-}*	*SO_4^{2-}*	*Na^+*	*NH_4^+*	*K^+*	*Mg^{2+}*	*Ca^{2+}*
M1	13/93–94	0.01	0.08	0.68	0	0.62	0.07	0	0.13	0.06	0.46
M2	Fig. 3, steps 34–35	0.03	0.37	0.23	0	0.67	0.40	0.04	0.41	0.01	0.33
M3	53/501–south balustrade	0.01	0.03	0.13	0	0.40	0.08	0.01	0.19	0	0.39
M4	57–58–north balustrade	0.03	0.13	0.15	0	0.52	0.19	0	0.10	0	0.37
M5	63/589–north balustrade	0.06	1.36	6.66	0	3.55	0.14	0	0.45	0	4.84
M6	63/599–south balustrade	0	0.30	3.73	0	0.58	0.11	0.02	0.21	0	1.48
EE-02	4/11	N.A.	0.08	1.96	0.10	0.27	0.10	N.A.	0.30	0.10	4.80
EE-03	25/216	N.A.	0.54	5.63	0	1.91	0.10	N.A.	0.10	0	14.40

Salt content

Soluble salt content of eight mortar samples from the Stairway was measured using ion chromatography (see **Table 9**).

Results show that the mortar samples contain mostly low to medium salt content, with the exception of samples M5, M6, EE-02, and EE-03.

These four samples show very high concentrations of nitrates (6.66 mg/g and 3.73 mg/g respectively) and calcium (4.84 mg/g and 1.48 mg/g). In addition, samples M5 and, to a lesser extent, EE-03 show a high concentration of sulfates (3.55 mg/g) and chlorates (1.36 mg/g). It should be noted that the two stone flake samples from step 63 did not show a high concentration of chlorates or nitrates, but both exhibited a very high concentration of sulfates.

Conclusions

Copán Stone

Scientific analysis has shown that the Copán stone is andesite to rhyolite volcanistic tuff containing ash (volcanic glass) and larger mineral fragments, as well as a small amount of swellable clays (2%–6%). It exhibits relatively high total porosity, along with high microporosity.

Its moisture transport characteristics cover a wide range of values; in particular, the highest water absorption coefficient value is almost five times greater than the value of the sample that absorbs water most slowly. All samples of Copán stone are slow drying, so that moisture is kept inside for a long time. However, the sample that takes up water most slowly also gives off water most slowly.

All samples of Copán stone show a fairly high compressive strength—but here again, variations among samples are significant, and some samples have twice the compressive strength of others. Similar variations can be seen in terms of thermal dilatation as well.

The emerging picture is that of a stone that, despite fairly homogeneous bulk composition, shows important variation in the type, amount, and homogeneity of distribution of larger mineral crystals and a wide range of values for a number of physical properties and mechanical behaviors.

Possible Causes of Deterioration and Hypotheses for Deterioration Mechanisms

Water

One important characteristic of stone flakes from the Stairway revealed in thin section is the presence of parallel surface cracks partially filled with precipitated calcite. The origin of the parallel cracks—which, with time, create flaking, the most common deterioration phenomenon on the Stairway—could not be clarified completely. They could be the result of successive wetting-drying cycles, associated with hygric dilatation of the outermost stone surface during rain events, while the inner section of the stone stays dry. These cycles can create shear stress in the stone. In fact, the thickness of the flakes corresponds quite well to the depth of the maximum moisture content for Copán stone on average over time, as calculated by the WUFI computer program for one of the stone samples. The selective dissolution of more soluble amorphous silica in the horizon of maximum moisture content, manifested by the silicon depletion, has also been observed on the thin sections, and it can be linked to the deterioration phenomenon of flaking.

In addition, the presence of water generates cyclic shear stress because of physical expansion and contraction from clays and/or organic material contained in the stone, in response to wetting-drying cycles. These cycles appear to have led to microcrack development and contribute to the surface flaking of the stone.

The presence of the tarpaulin over the Stairway since 1985 has practically eliminated liquid water on the stone surfaces. Prevailing water vapor transport is through the stone from the interior to the exterior, as expected under the shelter; this process is not expected to have a negative impact on stone decay. Current environmental monitoring shows relatively dry conditions in the sheltered area on the Stairway, in contrast to the situation before the shelter was installed, when rain would regularly wet the stone surfaces.

Salts

Most of the materials on the Stairway are currently contaminated with relatively low salt concentrations, which in most places are unlikely to be a cause of deterioration. High concentrations of salts have been found only in selected areas on the Stairway, in particular in step 63, in both stone flakes and mortar samples; salt is not, however, currently a problem for the Stairway as a whole. High concentrations of sulfates have been found in both types of samples, while only nitrates have been found in mortar samples. Those concentrations are probably due to the adjacent mortar-based platform and cement lip. Nitrate is often associated with organic material, especially bird droppings, and is present at lower levels on the rest of the Stairway, as would be expected in an area with abundant organic material and a high rate of decay of organic material.

Cement mortars

Mortar analysis confirmed the fact known from archival research that the repointing mortars on the Stairway are modern and cement-based, of various strengths and workmanship. Prior to the installation of the tarpaulin, the cement mortar joints could have been a potential source of damage, not so much because of their elevated mechanical strength, since the Copán stone has a comparatively high compressive strength, but because of the mortar's density and low water transport capability. The differences in water transport behavior between the stone and the mortar would force evaporating moisture to take pathways preferentially through the adjacent stone surfaces instead of through the mortar joints, increasing the possibility of water-induced damage (salt crystallization, hygric dilatation, etc.). However, no evidence of stone deterioration in areas adjacent to mortar joints has been observed, and often, due to poor workmanship, cracks are present at the stone-mortar interface.

Previous repair materials

The Paraloid B-72 and Mowilith 30 used in previous edgings and surface treatments may have had a detrimental effect by reducing water transfer rates locally where applied; however, this hypothesis is not supported by any data.

Chemical transformation of minerals

Many previous scientific reports mention that the chemical transformation of the minerals making up the stone is the leading deterioration mechanism of the Copán stone. However, from the geological literature, we now know that most silicate mineral transformations, such as the alteration of feldspars to clay, take place too slowly for this to be an important deterioration factor of the Stairway stone since excavation.

Environmental Monitoring

In September 2000, meetings were convened to discuss conservation efforts taking place at the Hieroglyphic Stairway in Copán, and participants included staff members of the Getty Conservation Institute (GCI), the Instituto Hondureño de Antropología e Historia (IHAH), and a number of external consultants (Getty Conservation Institute 2000b). One of the conclusions arising from this meeting was the identification of environmental monitoring as a necessary complement to the GCI's condition survey and stone analysis already under way, with an emphasis placed on the need for investigations on issues such as moisture infiltration and drainage at the Stairway, and the collection of site data on wind speed, wind direction, and rainfall intensity.

Initially erected only during the rainy seasons of 1985–86 and made permanent in 1987, a tarpaulin shelter has been used to provide environmental protection, particularly from rainfall, for the Hieroglyphic Stairway (Larios V. 1985c, 3). Although the presence of a shelter is thought to have been beneficial with regard to the overall condition of the Stairway, the resulting microclimate beneath the shelter, as well as the surface and subsurface environment of the Stairway itself, had yet to be examined. Furthermore, environmental monitoring was needed to augment the sparse availability of general climatic information for the site.

In response to these gaps in knowledge, the GCI established two environmental monitoring stations at Copán in March 2001, one located at the top of the Hieroglyphic Stairway (Escalinata Station) and the other in the East Court (Jaguar Station) (**Fig. 68**).

Environmental Monitoring Stations

The environmental monitoring station at the Hieroglyphic Stairway was designed to record climatic conditions and the Stairway's surface and subsurface conditions, in order to better understand their interaction. General climatic parameters—air temperature, relative humidity (RH), rainfall, solar radiation, wind speed and direction—were measured at the south end of the plateau at the top of Structure 26 (the Stairway sits on its west face). Despite the Escalinata Station's 35-meter elevation above the floor of the Great Plaza, climatic data collected there remain influenced by the presence of vegetation to the north and by nearby structures to the southeast and southwest, which provide partial protection from the natural environment (**Fig. 69**).

A web of sensors placed throughout the sheltered Stairway allowed for the characterization of its surface and subsurface environment. Environmental parameters measured directly on the Hieroglyphic Stairway included surface temperature, subsurface temperature, RH, illumination, and perimeter time of wetness.

Located at the eastern edge of the East Court, or Jaguar Plaza, the Jaguar environmental monitoring station also provided climatic information for the site. Although the parameters measured at both stations were similar, climatic data collected at Jaguar Station presented a more general characterization of environmental conditions for the site because of its more unobstructed surroundings, compared with the location of the Escalinata Station (**Fig. 70**). Thus, general climatic conditions at Copán will primarily be based on data from Jaguar Station.

At both stations, data were collected in 15-minute intervals and downloaded daily via UHF radio transmissions to a base station located at the Centro Regional de Investigaciones

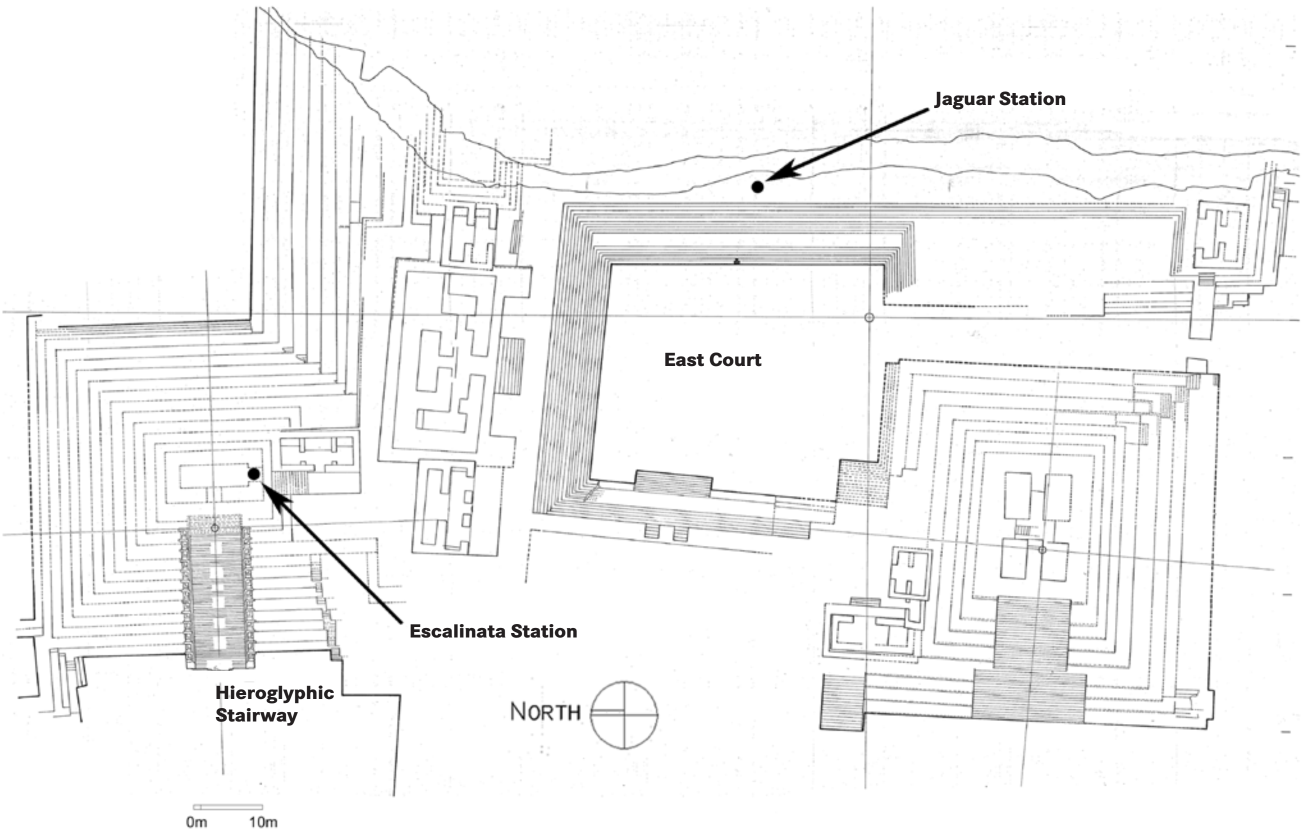


Figure 68 Locations of the Escalinata and Jaguar environmental monitoring stations in Copán. In addition to the climatic data collected at both sites, sensor arrays specific to each station were used to examine the Hieroglyphic Stairway and the East Court, or Jaguar Plaza.

Figure 69 View of the Escalinata environmental monitoring station from the south.

Figure 70 View of the Jaguar environmental monitoring station from the northwest. While the presence of surrounding vegetation at Escalinata Station can impact its climatic dataset, the relatively unobstructed environment of Jaguar Station allows its dataset to provide a more general characterization of the site climate.

Arqueológicas (CRIA) of IHAH. Weekly datasets were e-mailed by an IHAH staff member to the GCI for data processing and analysis. The analysis presented in this environmental summary encompasses the study period from March 2001 to August 2004 for Escalinata Station, and from March 2001 to January 2005 for Jaguar Station. Appendix E lists an inventory of the equipment utilized at both sites and at the base station.

General Climate

Situated near the border with Guatemala and El Salvador, the Maya site of Copán (latitude: 14°51'30"N, longitude: 89°09'W) is located in an alluvial pocket along the Copán River in western Honduras. Although Copán lies within a tropical region, its climate is tempered by its elevation—the valley floor sits about 600 meters above sea level (Webster 1999). Because there is no active weather station within a reasonable distance from the site, monitoring of the general climate of Copán became a necessary component of the environmental monitoring study. Though there is a greater focus on the Jaguar dataset, climatic data for both stations are presented in tabular form in this text (**Tables 10, 11**); figures for several individual parameters are also shown in Appendix E.

Rainfall

The climate at the site of Copán can be roughly divided into a wet season (May to October) and a dry season (November to April). Wet season rainfall at Jaguar Station accounted for 90% of the cumulative total (2,936 mm) during the study period (Appendix E, Fig. E.1)—the heaviest 15-minute (19.4 mm on June 13, 2001) and 24-hour (71.6 mm on October 23–24, 2001) periods of rainfall were also recorded during the wet season. The mean annual rainfall recorded at Copán during this study (1,013 mm) is similar to that of Tegucigalpa (918 mm; 14°05'N, 87°20'W), the Honduran capital, at an elevation of 1,007 meters above sea level, but much less than that recorded at the coastal city of Tela (2,786 mm; 15°72'N, 87°40'W) (Vose et al. 1992).

Although trends were similar between the two stations, the cumulative rainfall total at Escalinata Station (1,962 mm) was approximately 20% less than was recorded at Jaguar Station. This reduction in rainfall may be due to the protection afforded by the surrounding tree canopy near the top of Structure 26.

Air Temperature and Solar Radiation

Seasonal trends were also evident for air temperature (AT) and solar radiation (SR) at the site of Copán. In both cases, the wet season mean values (AT: 24.2°C, SR: 213.6 watts/m²) exceeded

Table 10 Seasonal climatic statistics for air temperature (AT), relative humidity (RH), dew point temperature (DPT), humidity ratio (W), solar radiation (SR), 15-minute vector averaged wind speed (WS), and 5-second vector averaged wind gust speed (WG–Jaguar only) at the Jaguar and Escalinata environmental monitoring stations. The data were collected from March 2001 to January 2005 for Jaguar Station and from March 2001 to August 2004 for Escalinata Station. The wet and dry seasons extend from May to October and from November to April, respectively (std dev = standard deviation; RSD = relative standard deviation; N = number of observations).

Jaguar Station														
	AT (°C)		***RH (%)***		***DPT (°C)***		***W (g/kg)***		***SR (watts/m²)***		***WS (m/s)***		***WG (m/s)***	
	Wet	*Dry*	*Wet*	*Dry*	*Wet*	*Dry*	*Wet*	*Dry*	*Wet*	*Dry*	*Wet*	*Dry*	*Wet*	*Dry*
Mean	24.14	22.07	79.49	75.82	19.70	16.76	15.89	13.32	216.35	178.09	1.25	1.51	1.74	2.12
Max.	38.34	38.06	100.00	100.00	23.49	23.04	20.18	19.51	1224.00	1162.00	8.31	8.11	11.73	13.19
Min.	16.70	9.82	18.46	13.81	8.11	1.92	7.32	4.72	0.00	0.00	0.45	0.45	0.45	0.45
Std dev	3.75	4.68	18.33	19.73	1.24	2.34	1.24	1.88	305.38	277.82	1.10	1.31	1.68	1.96
RSD (%)	15.55	21.20	23.06	26.03	6.29	13.93	7.80	14.11	141.15	156.00	87.99	86.74	96.48	92.19
N	38,623	35,591	38,623	35,505	38,623	35,505	38,623	35,505	38,623	35,591	38,623	35,591	25,029	23,043
Escalinata Station														
	AT (°C)		***RH (%)***		***DPT (°C)***		***W (g/kg)***		***SR (watts/m²)***		***WS (m/s)***			
	Wet	*Dry*	*Wet*	*Dry*	*Wet*	*Dry*	*Wet*	*Dry*	*Wet*	*Dry*	*Wet*	*Dry*		
Mean	24.20	22.09	78.42	75.23	19.49	16.66	15.68	13.13	185.42	179.38	0.90	1.07		
Max.	39.16	38.82	100.00	100.00	23.78	22.90	20.46	19.34	1150.00	1133.00	5.51	5.12		
Min.	14.42	9.85	18.24	13.23	8.19	1.64	7.37	3.79	0.00	0.00	0.45	0.45		
Std dev	3.85	4.71	18.61	19.54	1.26	2.27	1.26	1.87	272.58	282.97	0.66	0.81		
RSD (%)	15.89	21.31	23.73	25.97	6.48	13.62	8.04	14.24	147.01	157.75	73.93	75.44		
N	55,409	49,148	55,409	49,148	55,409	49,057	55,409	49,148	55,409	49,148	55,409	49,148		

Table 11 Seasonal climatic statistics for the daily variation of air temperature (AT), relative humidity (RH), dew point temperature (DPT), and humidity ratio (W) at the Jaguar and Escalinata environmental monitoring stations. The data were collected from March 2001 to January 2005 for Jaguar Station and from March 2001 to August 2004 for Escalinata Station. The wet and dry seasons extend from May to October and from November to April, respectively (std dev = standard deviation; RSD = relative standard deviation; N = number of observations).

Jaguar Station								
	AT (°C)		***RH (%)***		***DPT (°C)***		***W (g/kg)***	
	Wet	*Dry*	*Wet*	*Dry*	*Wet*	*Dry*	*Wet*	*Dry*
Mean	10.52	11.10	48.98	48.99	3.52	4.40	3.94	4.41
Max.	16.89	21.82	72.64	82.28	13.50	12.90	8.12	12.97
Min.	2.73	2.53	17.06	17.27	1.23	0.82	0.08	0.08
Std dev	2.26	4.48	8.21	15.38	1.31	2.25	1.24	2.65
RSD (%)	21.49	40.39	16.77	31.40	37.24	51.08	31.48	60.02
N	406	381	406	381	406	381	406	381
Escalinata Station								
	AT (°C)		***RH (%)***		***DPT (°C)***		***W (g/kg)***	
	Wet	*Dry*	*Wet*	*Dry*	*Wet*	*Dry*	*Wet*	*Dry*
Mean	11.04	11.35	49.94	49.41	3.51	4.29	3.24	3.30
Max.	17.19	23.24	73.42	82.22	13.25	15.28	9.31	8.59
Min.	2.67	2.49	15.97	16.73	1.38	0.89	1.31	0.89
Std dev	2.20	4.44	7.60	14.87	1.23	2.23	0.96	1.50
RSD (%)	19.91	39.13	15.21	30.09	34.97	51.95	29.61	45.51
N	575	487	575	487	575	487	575	487

those of the dry season (AT: 22.0°C, SR: 170.3 w/m²) (Table 10). This pattern can be attributed to changing lengths of daylight during the summer and winter months. Despite this seasonal trend, it should be noted that daily solar radiation can vary widely, based on the amount of cloud coverage. Seasonal mean air temperatures recorded at Copán during this study were between those observed at the cities of Tegucigalpa (wet: 22.2°C, dry: 20.7°C) and Tela (wet: 27.5°C, dry: 25.0°C) (Vose et al. 1992).

During the study period, the maximum and minimum recorded air temperature values were 38.3°C (wet season) and 9.8°C (dry season), respectively (Table 10). Although the mean daily variation in air temperature (approximately 11°C) remained similar throughout the year, the range of daily temperature variation during the wet season (2.3°C standard deviation) was slightly narrower than that of the dry season (4.5°C standard deviation) (Table 11).

Relative Humidity, Dew Point Temperature, and Humidity Ratio

Data for RH, dew point temperature (DPT), and humidity ratio (W) also revealed marked seasonal variations. (Dew point temperature and humidity ratio were calculated from air temperature and RH data.) Mean wet season values of RH (79.5%), dew point temperature (19.7°C), and humidity ratio (15.9 g of water/kg of dry air) were elevated above those of the dry season (RH: 75.8%; DPT: 16.8°C; W: 13.3 g/kg) (Table 10). These differences are due to the dependence of these parameters upon water, as each will typically exhibit higher values during periods of increased atmospheric moisture.

For each of these variables, maximum values (RH: 100%; DPT: 23.5°C; W: 20.2 g/kg) were recorded during the wet season (RH maximum occurred during both seasons), while minimum values (RH: 13.8%; DPT: 1.9°C; W: 4.7 g/kg) occurred during the dry season (Table 10). Mean daily variations of RH (approximately 49%), dew point temperature (approximately 4°C), and humidity ratio (approximately 4 g/kg) also did not show drastic seasonal changes, though the range of daily variation values (standard deviation) for these variables increased during the dry season (Table 11).

Wind Speed and Direction

Prevailing and gusty winds at the site of Copán largely originated from between the north-northeast and east-northeast directions throughout the year (Appendix E, Figs. E.2a, b). Although this wind direction remained consistent during rain events, the infiltration of wind-driven rain beneath the shelter of the Hieroglyphic Stairway may be more strongly influenced by the localized wind field resulting from the presence of surrounding structures and vegetation.

The maximum recorded 15-minute vector-averaged wind speed was 8.3 m/s, while the maximum gust wind (5-second vector average) was 13.1 m/s (Table 10). Mean dry season wind speed (1.51 m/s) was also elevated over that of the wet season (1.25 m/s), and daily maximum wind speeds generally occurred between noon and 6:00 p.m. year-round. Although displaying similar wind direction, wind speeds recorded at Escalinata Station were roughly 30% less than those observed at Jaguar Station—surrounding vegetation near the top of Structure 26 may be acting as a natural windbreak.

The wind field immediately surrounding the Hieroglyphic Stairway is highly affected by the presence of nearby vegetation and structures, as well as by its west-facing position on the Structure 26 pyramid. This relative positioning presumably creates a highly variable and complex wind field that is much different from that measured at Jaguar Station or Escalinata Station (at the top of Structure 26). During the study period, the protective shelter has been damaged on at least one occasion (17 March 2003), possibly as the result of localized gust winds. Tearing of the shelter fabric occurred on the north-facing edge of the tarp approximately two-thirds of the way up from the Great Plaza floor; tearing extended 2 to 3 meters perpendicular to the edge. Detailed study of the wind field surrounding the Stairway would likely yield useful information for the design of a new shelter.

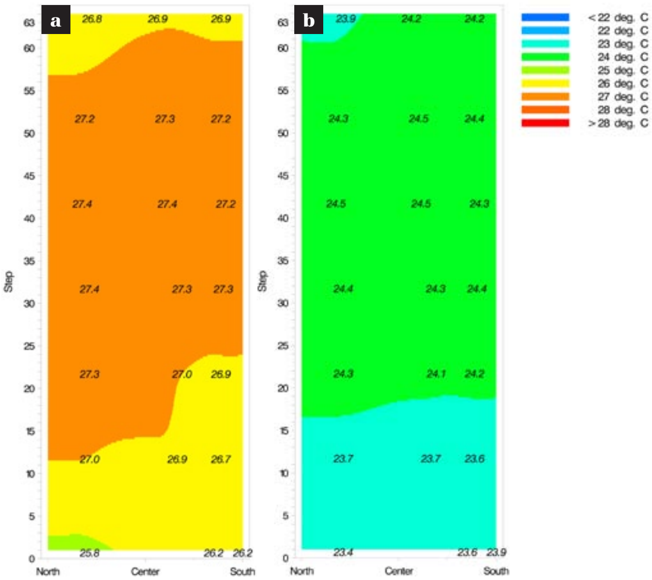
Hieroglyphic Stairway

The environmental parameters measured at the Hieroglyphic Stairway included surface temperature, subsurface temperature and RH, illumination, and perimeter time of wetness. Multiple sensors for each variable were positioned throughout the Stairway (Appendix E, Figs. E.3a–c, E.4) to achieve maximum coverage and allow for the creation of contour maps. Selected contour figures are presented within this text; additional figures are shown in Appendix E.

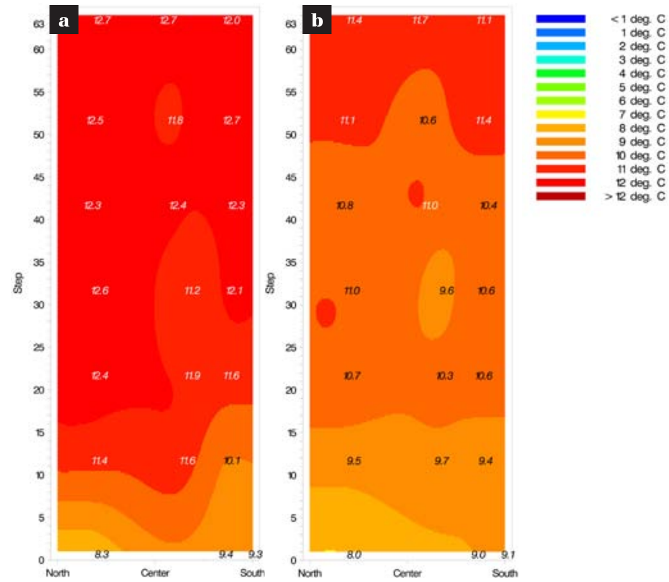
Surface Temperature

Reflecting trends in air temperature, surface temperatures on the Hieroglyphic Stairway exhibited seasonal differences. Mean wet season surface temperatures on the Stairway ranged from 25.8°C to 27.4°C, exceeding the range of dry season values (23.4°C to 24.5°C) (**Figs. 71a, b**). Surface temperatures were also elevated above ambient air temperatures during both the day and the night hours, preventing condensation from forming at the surface-air interface and limiting surface microbial activity.

Excluding days on which the shelter was removed for maintenance or replacement, maximum Stairway surface temperatures ranged from 38.9°C to 43.6°C during the wet season, and 34.5°C to 47.5°C during the dry season. However, surface temperature values above 40°C accounted for less than 0.2% of the sheltered Stairway data collected during the study period, and they may be the result of short-term exposure to direct sunlight from its penetration through eyelets and loose seams in the tarp. The mean daily variation of surface temperature ranged from approximately 8°C to 12°C throughout the year (**Figs. 72a, b**), but daily variation values during the dry season displayed a wider range than those of the wet season. The maximum daily variation recorded for a sheltered surface temperature sensor during the study period was 25.5°C (south side of step 12).



Figures 71a and b Contour maps displaying the mean surface temperature (°C) on the Hieroglyphic Stairway during the wet season, May to October (a), and the dry season, November to April (b). Values indicate the mean seasonal level for specific sensors on the Stairway. The data were collected from March 2001 to August 2004 (known dates of shelter removal are excluded).



Figures 72a and b Contour maps displaying the mean daily variation of surface temperature (°C) on the Hieroglyphic Stairway during the wet season, May to October (a), and the dry season, November to April (b). Values indicate the mean seasonal level for specific sensors on the Stairway. The data were collected from March 2001 to August 2004 (known dates of shelter removal are excluded).

The spatial patterns of mean surface temperature and its daily variation remained similar during both seasons–upper sections of the Stairway exhibited mean values that were elevated above those at the base (Figs. 71a, b, 72a, b). This phenomenon is a result of the natural rise of heated air beneath the shelter and the shorter distances between the tarp and the stone as one moves up the Stairway. A preliminary study of air temperature in 2000 beneath the shelter indicated that elevated values were indeed observed in the upper sections of the Stairway, because of the daytime radiation of heat absorbed by the tarpaulin (Maekawa 2000), and concerns were raised regarding possible differential heating of the Stairway surface. However, the difference between the high and low mean surface temperatures across the Stairway remained relatively minimal during the wet (approximately 1.6°C) and dry (approximately 1.0°C) seasons.

During the study period, the protective shelter was removed on at least four occasions (17 March, 10 April, 10 July, and 16 July 2003) for tarpaulin repair or replacement, thus exposing the Hieroglyphic Stairway to direct sunlight. Data collected during these unsheltered periods revealed stone surface temperatures and daily variations as high as 67°C and 47°C, respectively (both values were recorded on 16 July). Although surface temperatures increased during all periods of exposure, marked increases in surface temperature relative to the days preceding and following shelter removal were only observed on days with high levels of total solar radiation–i.e., on clear and sunny days. These elevated values indicate that the presence of the shelter effectively limits this daytime solar heat gain and reduces nighttime radiation heat loss, which is of particular importance in preventing condensation during the early morning hours.

Subsurface Temperature, Relative Humidity, and Humidity Ratio

Placed in the mortar joints between stone blocks, sensors were used to measure temperature and RH at depths of 30 cm (approximately March 2001 to January 2002) and 12 cm (approximately January 2002 to August 2004) below the mortar surface. Although the sensors were not placed directly within the stone, these mortar measurements give some indication of the subsurface conditions in the adjacent stone.

Subsurface temperatures of the sheltered Stairway displayed seasonal variation. Mirroring seasonal temperature changes, mean wet season internal temperatures (30 cm: 25.5°C to 26.5°C; 12 cm: 26.3°C to 27.4°C) exceeded those of the dry season (30 cm: 22.1°C to 23.3°C; 12 cm: 23.4°C to 24.4°C). Maximum sheltered subsurface temperatures recorded during the study were 33.9°C (north side of step 63) and 37.4°C (south side of step 4) at depths of 30 cm and 12 cm, respectively (Appendix E, Figs. E.5a, b, E.6a, b).

While mean surface temperatures were roughly similar to those recorded 12 cm below the surface, mean values at the deeper, 30 cm location were slightly less than both, and they remained closer to the more stable temperature of subterranean soil. However, on the several occasions on which the shelter was removed during the study and the skies were sunny and clear (16 March and 17 July 2003), mean subsurface temperatures at a depth of 12 cm were reduced below mean surface temperatures by roughly 4.5°C.

Compared with the average daily variation of surface temperature, the mean daily variation of sheltered subsurface temperature sensors at both depths displayed much lower values. At 12 cm depth, the mean daily variation in temperature ranged from approximately 1.3°C to 5.0°C during both seasons. Seasonal variations were more apparent for the average daily variation of temperature at 30 cm depth, ranging from 0.1°C to 1.6°C during the wet season, and from 0.3°C to 4.4°C during the dry season (Appendix E, Figs. E.7a, b, E.8a, b).

Data for subsurface RH were influenced by the significant amount of moisture present in the soil and rubble that form the pyramid structure beneath the Stairway. Elevated above ambient RH levels, year-round mean internal RH ranged from 93% to 100% at 30 cm depth, and from 85% to 99% at 12 cm depth—minimum recorded values of subsurface RH were 91% and 68% at 30 cm and 12 cm, respectively (Appendix E, Figs. E.9a, b, E.10a, b). Although these internal spaces maintain a high-RH environment, the absence of light prevents any significant microbial activity at depth. The mean daily variation of subsurface RH at 12 cm below the mortar surface (1.5% to 9.3%) exceeded that observed at 30 cm depth (0.0% to 2.1%), but both were much lower than the daily variation for ambient RH (Appendix E, Figs. E.11a, b, E.12a, b).

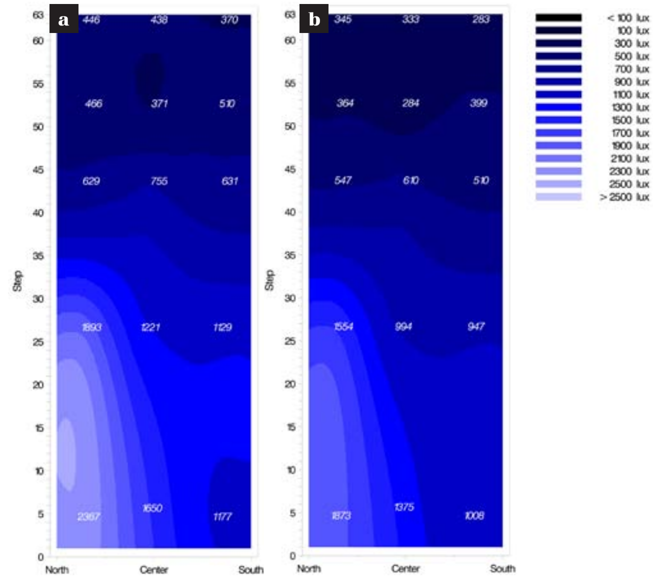
Although the mortar harbors saturated or near-saturated air between the depths of 30 cm and 12 cm, the transfer of moisture from the mortar pore spaces to the surface is limited to the vapor phase. This is consistent with the observed lack of liquid water and the presence of sandy fill (limiting capillary rise) during the drilling of holes in the mortar joints for placement of subsurface sensors. The present shelter configuration—a tarpaulin elevated above the Stairway with the top, bottom, and sides open to the air—maintains high air-exchange rates that allow for the dissipation of surface moisture. Limiting this air-exchange rate may subject the stone surface to humid or even wet conditions, which would likely promote microbial growth.

Based on data for subsurface temperature and RH, the subsurface humidity ratio was also calculated at depths of 30 cm and 12 cm below the mortar surface; these measurements provide a better gauge of moisture content than is given by RH. Although displaying seasonal differences, mean subsurface humidity ratio values were roughly the same at both depths: the mean internal humidity ratio ranged from 21.4 g/kg to 24.3 g/kg during the wet season, and from 17.6 g/kg to 20.3 g/kg during the dry season (Appendix E, Figs. E.13a, b, E.14a, b).

Indicating elevated water content, the mean values of subsurface humidity ratio far exceeded mean ambient values. This moisture gradient between the internal and ambient humidity ratios indicates the year-round transfer of water vapor from the base of the stone to the ambient air. In addition, the mean daily variation of subsurface humidity ratio (0.2 g/kg to 3.6 g/kg) was typically less than that of ambient air (Appendix E, Figs. E.15a, b, E.16a, b).

Illumination

Viewing of the Hieroglyphic Stairway surface during the day is difficult because of the large spatial variations in Stairway illumination, as well as the increasing distances between the stone and the observer. Because of the minimal distance between the stone and the tarpaulin, the upper third of the Stairway displayed midday illumination values below 750 lux (both seasons), and mean values at the top step were as low as 280 lux (south side of step 63, dry season) (**Figs. 73a, b**). In contrast, midday illumination for the lower two-thirds of the Stairway, where the stone-tarpaulin distance was much greater, exceeded 1,120 lux and 940 lux during the wet and dry seasons, respectively. Furthermore, due to the wide contrast between the dimly lit upper Stairway and the bright sky (approximately 3,000 lux), which is brought into view through the opening at the top of the shelter, the upper reaches of the Stairway become very difficult to see when viewed from its base. Minimizing this contrast in illumination should improve the visual presentation.

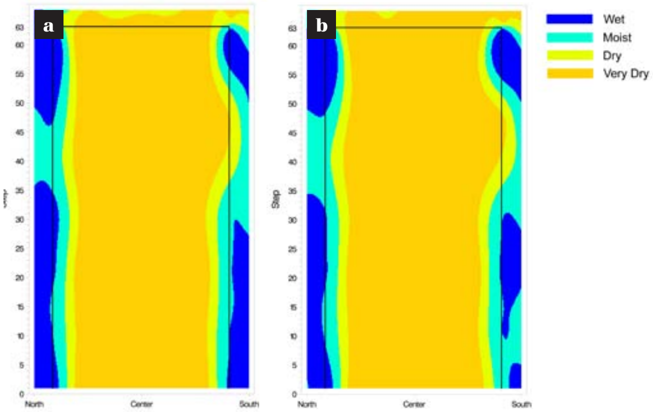


Figures 73a and b Contour maps displaying mean illumination (lux) at noon on the Hieroglyphic Stairway during the wet season, May to October (a), and the dry season, November to April (b). Values indicate the mean seasonal level for specific sensors on the Stairway. The data were collected from March 2001 to August 2004 (known dates of shelter removal are excluded).

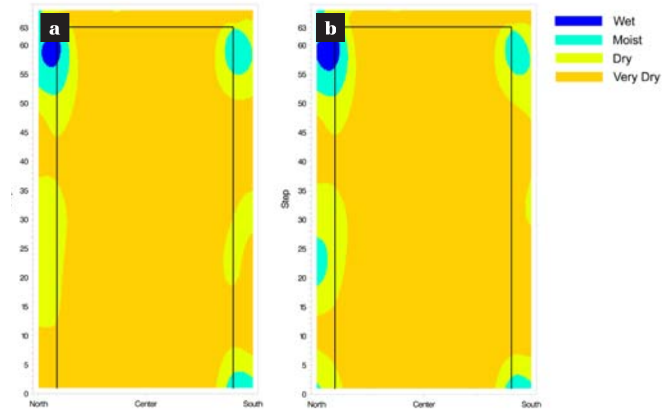
Although it constitutes a lesser factor regarding viewing of the Stairway, a consistent year-round spatial pattern of Stairway illumination was observed because of the orientation of Structure 26, adjacent structures, and the tarpaulin shelter. Due to the relatively unobstructed north side of the Stairway—the south side is blocked by an adjacent structure—and the wider tarp-stone distances near its base, maximum mean illumination values (1,500 to 2,350 lux) were typically observed on the north sides of steps 5, 6, and 27 (Figs. 73a, b).

Perimeter Time of Wetness

Placed at equal intervals (at the edge and 1 meter away) to the north and south of the Stairway balustrade and behind the top step, time of wetness sensors were used to examine the presence of water around the perimeter of the Stairway (Appendix E, Fig. E.4). Time of wetness resistance measurements were divided into four categories: wet (0–10 kΩ), moist (10–100 kΩ), dry (100–1,000 kΩ), and very dry (1,000+ kΩ). Since the protective shelter prevented rain from falling directly



Figures 74a and b Contour maps displaying the discrete wet season perimeter time of wetness events at noon on September 24, 2001 (a), and September 10, 2002 (b). The resistance output of the sensors was categorized as follows: wet (0–10 kΩ), moist (10–100 kΩ), dry (100–1000 kΩ), and very dry (1000+ kΩ). Because of the protective shelter, the Hieroglyphic Stairway was assumed to be dry. The black borders within the figures delineate the top step of the Hieroglyphic Stairway and the north and south edges of the Stairway balustrade.



Figures 75a and b Contour maps displaying the discrete dry season perimeter time of wetness events at noon on March 17, 2001 (a), and April 1, 2002 (b). The resistance output of the sensors was categorized as follows: wet (0–10 kΩ), moist (10–100 kΩ), dry (100–1000 kΩ), and very dry (1000+ kΩ). Because of the protective shelter, the Hieroglyphic Stairway was assumed to be dry. The black borders within the figures delineate the top step of the Hieroglyphic Stairway and the north and south edges of the Stairway balustrade.

onto the Stairway and the balustrade, the Stairway itself was assumed to be dry at all times for purposes of this exercise.

During the rainy season, the lower two-thirds of the Stairway perimeter remained wet (**Figs. 74a, b**). One factor may be the variability in distance between the Stairway and the tarpaulin from top to bottom. The larger distances between the tarp and stone in the lower sections of the Stairway can allow for wind-driven rain to reach the base of the balustrade and the Stairway itself. The presence of water on the Stairway has occasionally been observed–likely the result of wind-blown rain passing under the shelter.

A more important factor in perimeter wetness is the surface drainage surrounding the Stairway. The wetness displayed on the north side of the Stairway in Figures 74a and 74b is the result of a consolidated rubble slope between the Plaza floor and the Stairway's midpoint that channels water toward the balustrade rather than away from it. A similar, but less drastic, scenario involves the terraces on the south side of the Stairway, extending from the Stairway base to roughly step 45 (above is consolidated rubble). This geometry provides for less-than-ideal drainage conditions, and accumulations of water have been observed on the terraces during periods of heavy rainfall. Although wetness sensors were not installed at its base, flooding at the bottom of the Stairway has also been observed during periods of heavy rain. These drainage problems should be corrected to allow for the swift drainage of rainwater away from the balustrade and the Stairway base, minimizing the potential for erosion, microbial growth, and salt migration.

Although the Stairway perimeter remained dry in the absence of rainfall, the area between steps 54 and 62 on the north side of the balustrade, and to a lesser extent on the south side, exhibited apparent wetness (low electrical resistance) throughout the year (**Figs. 75a, b**). Since rainfall is largely excluded from these areas by the shelter and because it can be disregarded as a factor during the dry season, these patches of low resistance may hint at the localized presence of salt.

Past restoration efforts utilized portland cement in the upper sections of the Stairway (Larios V. 1985c, 3), and the presence of sulfate and nitrate salts has been confirmed by material analyses of mortar samples (see "Analyses of Materials"). Moreover, the location of mortar samples harboring elevated concentrations of nitrate salts correlates well with the areas of low resistance shown near the top of the Stairway in Figures 75a and 75b. It is possible that salt-related damage can occur if intrusions of water in this area are allowed to deliquesce and transport salts. Future shelters should be able to provide at least the same level of protection as does the current shelter for this vulnerable location.

Conclusions

This study characterized the general climate at the site of Copán, as well as the surface and subsurface environments of the Hieroglyphic Stairway over a period of more than three years. The following sections provide a brief summary of the major environmental findings.

Wind and Rainfall

General wind direction at the site originated from the north-northeast and east-northeast directions, and the maximum gust wind (5-second vector average) recorded during the study was 13.1 m/s. However, the positioning of the Stairway likely results in a highly variable and complex wind field, limiting the applicability of this wind dataset to future shelter design.

Rainfall at the site of Copán was, as expected, largely limited to the wet season, from May to October. The most intense levels of recorded rainfall were 19.4 mm in a 15-minute period and 71.6 mm in a 24-hour period. Although the length of study was limited, these high values may guide maximum site drainage requirements.

Stone Surface

The presence of the shelter above the Hieroglyphic Stairway has effected a reduction in both thermal cycling and heat gain/loss at the stone surface. Compared to maximum surface temperatures reached when the shelter was removed and the Stairway exposed to direct sunlight, maximum sheltered surface temperatures were much lower. Surface temperature also continually remained higher than that of ambient air, as the tarp effectively limited daytime solar heat gain and nighttime radiation heat loss. This condition is particularly important in preventing condensation during the morning hours and in limiting surface microbial activity.

Mortar Subsurface

Sheltered subsurface temperatures displayed values at 12 cm depth similar to those of the surface, while temperatures at 30 cm depth remained slightly lower. However, when the Stairway was exposed to direct sunlight during periods of tarp removal, a temperature gradient between the surface and 12 cm depth was evident.

Although mean subsurface RH at 30 cm depth slightly exceeded that at 12 cm depth, mean internal humidity ratio remained roughly equivalent at both subsurface locations. Subsurface humidity ratio, however, greatly exceeded that of ambient air, indicating a continuous outward transfer of water vapor from the stone. Despite elevated RH conditions at depth, subsurface microbial growth is deterred by the lack of light.

Illumination

Due to its narrowing tarp-stone distances, illumination of the top third of the Hieroglyphic Stairway was reduced in comparison to that of its lower sections. Because the bright sky was visible through the opening at the top of the tarp, the shadowed upper reaches of the Stairway remained very difficult to see in the context of the wide contrast in illumination. Minimizing this contrast would greatly improve the visual presentation of the Stairway.

Perimeter Wetness

Perimeter wetness alongside the balustrades of the Hieroglyphic Stairway was evident during rain events, particularly for the lower two-thirds of the structure. The major factors for this issue are the channeling of water toward the north balustrade and water accumulation on the terraces next to the south balustrade. Surface drainage should be corrected to minimize potential erosion, microbial activity, and salt migration.

Patches of low electrical resistance were also observed year-round near the top of the north and south balustrades. This may be due to the presence of salt, as these areas correlate well with the location of mortar samples shown to be elevated in nitrate salt concentration. Water intrusions into these specific regions should be limited to prevent possible salt-related damage.

Biological Analysis

The role of lichens, algae, mosses, higher plants, and other biological populations in the deterioration of monuments in tropical countries is abundantly stressed in the conservation literature. However, publications on the biological colonization of monuments in Mesoamerica are actually limited to only a few contributions (Hale 1979a; Guiamet, Gómez de Saravia, and Videla 1998; Maldonado et al. 1998; Videla, Guiamet, and Gómez de Saravia 2000; Videla and Sáiz-Jiménez 2002).[1]

The Copán archaeological site is situated in a tropical region with a climate tempered by its elevation at about 600 meters above sea level. In the lower parts of the Copán Valley, a typical mixed seasonal semideciduous forest remains, with many large trees (more than 30 meters in height) forming a well-stratified structure. In this forest, dominant species are *Ficus* sp., *Simarouba glauca, Trichilia cuneata, Ceiba pentandra* (the sacred tree of the Maya), *Hura crepitans, Prockia crucis, Guazuma ulmifolia,* and *Acacia* sp. (**Fig. 76**). In the past, many natural plant communities were destroyed or modified to give space to agriculture and forestry. After the collapse of the Mayan culture and the abandonment of the territory, these forests returned to colonize the city, hiding and burying the evidence of Mayan activity.

The Hieroglyphic Stairway, along with a number of other structures in the Copán Acropolis, was excavated between 1892 and 1900 by the Peabody Museum. The removal of the earth and the dense tree cover surrounding the monument created new environmental conditions very favorable to the growth of new biological populations that are much more aggressive toward the stone than those present when the Stairway was buried. The increased lighting, the air circulation, and the rainfall have, for the most part, favored a high colonization of saxicolous (rock-growing) lichens.

In the 1970s lichenologist Mason Hale of the Smithsonian Institution in Washington, D.C., analyzed the biological colonization and gave a detailed list of the species present, including cyanobacteria and algae (*Oscillatoria* sp., *Trentepohlia* sp.), mosses (*Calymperes richardii, Frullania riojaneiriensis, Lejeunea flava, Mastigolejeunea auriculata, Neohyophila sprengelii, Papillaria nigrescens, Rhacomitrium tomentosum, Stereophyllum cultelliforme*), and especially lichens (*Caloplaca* sp., *Candelaria concolor, Candelariella* sp., *Candelina* sp., *Chiodecton antillarum, Coccocarpia cronia, Dirinaria confluens, D. picta, Heterodermia casarettiana, H. leucomelaena, Lecanora* sp., *Lepraria* sp., *Leptogium* sp., *Leptotrema* sp., *Parmelina dissecta, Parmotrema crinitum, P. dilatatum, P. endosulphureum, P. mordenii, P. sancti-angelii, P. sulphuratum, P. tinctorum, Physcia sorediosa, Pyxine* sp., *Sticta weigelii, Usnea rubiginea, Xanthoparmelia congensis*). The most common lichen species were *Physcia sorediosa,*

Figure 76 The archaeological site of Copán below the dense tree cover, seen from the north.

Parmotrema mordenii (in shaded places), and *Dirinaria confluens* (in sunny areas).

Because of the remarkable biological colonization and the severe damage inflicted by lichen growth, Hale stressed the need to use biocides for their control. Different biocide treatments were applied from the mid- to late 1970s under his supervision. Monuments, including the Stairway, were initially sprayed with a dilute solution of Clorox (5.25% in water up to 300 cc/m^2) and Borax (5% in water up to 500 cc/m^2), and the treatment was repeated after six months and again after one year.

In 1985, a few years after the biocide treatments, a shelter was installed over the Stairway. While it was in place at first only during the rainy season, the shelter became permanent two years later.

Material and Methods

Forty samples were taken from the site and from the surrounding areas for the purpose of analyzing biodeterioration (**Fig. 77**). Sampling was usually carried out where macroscopic biodeterioration phenomena were appreciable; in some cases patinas of uncertain origin were also collected in order to establish their chemical or biological nature. When possible, already detached small stone flakes were collected, for the investigation of possible in-depth biodeterioration by means of polished sections. Otherwise, to reduce destructive sampling, powder was collected by gently scraping the stone surfaces.

Most samples were collected from locations in the Stairway that were determined after several factors were considered. A wide distribution of locations from the bottom to the top of the Stairway was desired, as was a selection of stones of different colors and conditions. Four additional monuments (Altar 41, Stela H, the Ballcourt, and a stela near the entrance) were sampled to obtain wider data from areas of the site where biodeterioration phenomena are still occurring (**Figs. 78a, b**). Samples from the old Mayan quarry were also collected as representatives of common biodeterioration processes occurring in a natural environment on the same stone that was used to construct the site monuments (**Fig. 78c**). Finally, a sample was collected from an altar in the site sculpture museum, in order to analyze the residual vitality of biological communities in a confined space, sheltered from the rain but otherwise open to the environment.

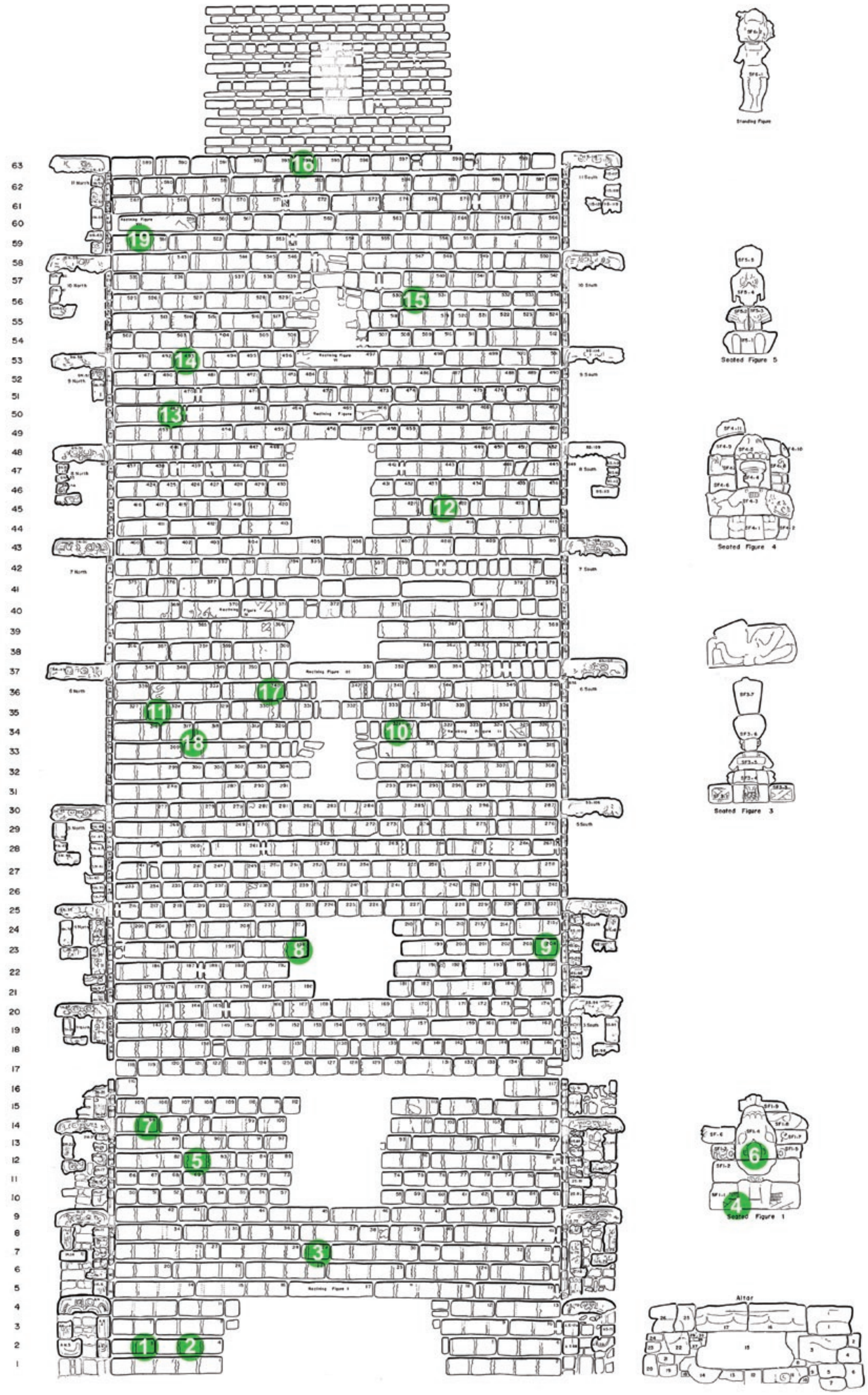
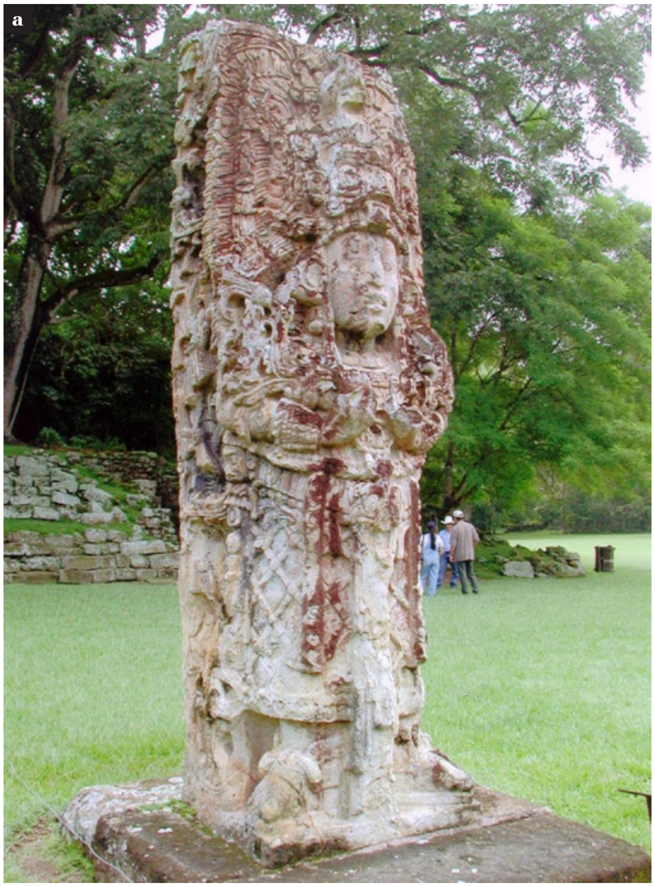


Figure 77 Locations of the biological samples taken from the Hieroglyphic Stairway, given as step number/glyph letter: 1 = 2/B; 2 = 2/D; 3 = 7/J; 4 = Seated Figure 1 (bottom); 5 = 12/D; 6 = Seated Figure 1 (mouth); 7 = 14/B; 8 = 23/J; 9 = 23/Q; 10 = 34/H; 11 = 35/B; 12 = 45/M; 13 = 50/D; 14 = 53/C; 15 = 56/J; 16 = 63/H; 17 = 36/F; 18 = 33/D (tread); 19 = 59/B (tread).



All the samples were microscopically observed at different magnifications and with different techniques. Polished cross sections obtained from the inclusion of stone samples in a polyester resin were observed under the reflecting microscope, to investigate the relationship between microorganisms and stone, including the character and depth of penetration, and the thickness of colonization and its distribution.

Staining methods were used in order to highlight some specific features otherwise not easily appreciable under the optical microscope (Whitlach and Johnson 1974):

- Lactophenol cotton blue, to highlight fungal structures;
- Periodic acid Schiff (PAS), to highlight total carbohydrates of insoluble polysaccharides (this technique especially colors the cell wall, but starch also reacts very strongly);
- Methylene blue, to highlight the nuclear materials.

Scanning electron microscopy (SEM) of some selected specimens (coated with gold under vacuum) was also carried out, in order to better understand some microscopic features and evaluate the relationships of the species with the substrates.

Determination of the algal species was performed through direct observation by optical microscopy; taxonomic identification was drawn from a number of monographs (Desikachari 1959; Bourrelly 1966; Bourrelly 1970) and from updated reviews on some groups of cyanobacteria (Komárek and Anagnostidis 1986; Anagnostidis and Komárek 1988). For

Figures 78a–c The present condition of sampled Stela H (a), of a sampled stela near the entrance (b), and of a sampled area of the quarry (c).

Table 12 Surface biological growths observed on the Stairway samples and on the site (r = rare; + = sporadic; ++ = common).

Sample	***1a–b***	***2***	***3a***	***3b***	***4a***	***4b***	***5a***	***5b***	***6***	***7***	***8***	***9***	***10***	***11***	***12***	***13***	***14***	***15***	***16***	***17***	***18***	***19***
Navicula sp.										+												
Nitzschia sp.										r			r									
Gloeocapsa rupestris			+					+		+	+	+	+	++	+	++			r			+
Gloeocapsa kuetzingiana			+											+	r							
Stigonema hormoides															+							
Apatococcus lobatus			+	r																	r	
Moss protonemata			r										r									
Hyphae and conidia										+				+	r		+			+	+	
Bacteria						r		++					++							++		
Fragments of plants				+			+					++	+		r							

Table 13 Comparison among the Stairway samples of superficial biological growth and deep colonization (1 = low growth; 2 = presence of growth; 3 = high growth; – = no data).

Sample	***1a–b***	***2***	***3a***	***3b***	***4a***	***4b***	***5a***	***5b***	***6***	***7***	***8***	***9***	***10***	***11***	***12***	***13***	***14***	***15***	***16***	***17***	***18***	***19***
Superficial biological growths	1	1	2	2	1	1	2	2	1	2	2	2	3	3	3	3	2	1	1	2	2	2
Deep biological colonization	1	–	2	2	2	2	2	2	–	–	–	2/3	3	–	3	3	1/2	–	1/2	2	2	2

lichens, the keys of Nash and colleagues (Nash et al. 2002; Nash et al. 2004) were used.

Counts of the different taxonomic groups in each sample were made by calculating the covering values of each single species with respect to the whole biological mass present in the slide, and expressing them according to the Braun-Blanquet scale of values, using the following conversion: 1 = rare; 3 = +/sporadic; 5 = ++/common; 9 = +++/abundant (the method used by Rizzi Longo, Poldini, and Goia 1980).

For the ecological analysis, the results of the biological samples collected on the Stairway and on the site have been organized, using the quantitative data, and placed in a numerical matrix with two variables (species/sample). The matrix (26 rows • 40 columns) has been analyzed with the software package SYN-TAX 5.1 (Podani 1997) and with similarity algorithms, as well as with average linkage or complete linkage that executes statistical elaboration through the methods of classification and ordination.

Results

Biological Colonization of the Hieroglyphic Stairway

Tropical climates show high values of biodiversity and biomass, and an increase of ecological successions, from the pioneer stages to the mature ones; consequently, the biodeterioration processes in these climates are equally diverse.

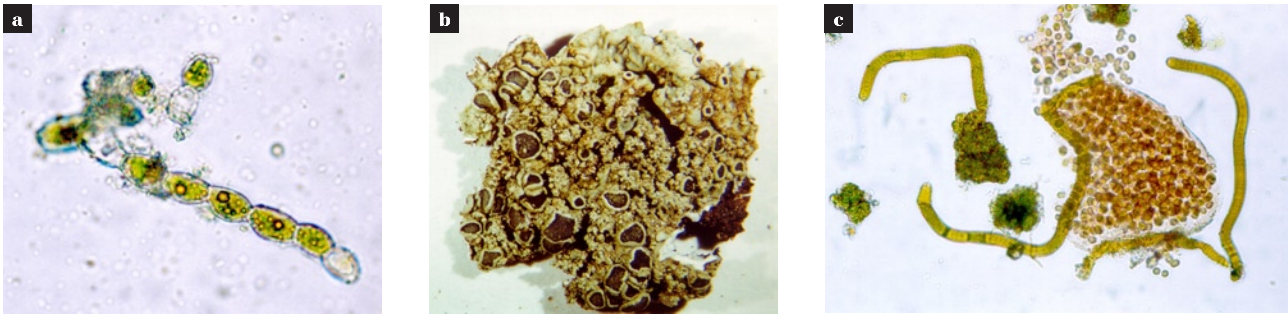
Analytical characterization, however, shows a low level of biological colonization on the stone surfaces of the Stairway (see **Table 12**). The microscopic analyses indicate only the relatively high presence of cyanobacteria, such as *Gloeocapsa kuetzingiana*, *G. rupestris*, and *Stigonema hormoides*, and few green algae (*Apatococcus lobatus*), fungal spores, and moss fragments. The identified species are typical of pioneer stages, but they can promote evolution to more complex stages (Golubic, Friedmann, and Schneider 1981; Anagnostidis, Economou-Amilli, and Roussomoustakaki 1983; Caneva and Salvadori 1988; Hoffmann 1989; Warscheid and Braams 2000).

In contrast to this relatively low level of superficial colonization, the deep biological growth appears substantial and sometimes looks very heavy. It was attributed mainly to the residuals of previous growths (**Table 13**). Various kinds of structures were observed in depth:

- *Moss protonemata*, brown filaments of large size (0.05 mm), with oblique walls between cells, not stained by lactophenol cotton blue.
- *Fungal filaments*, very evident on SEM microphotographs and also sometimes with the PAS coloration. They sometimes give rise to a dense mycelium penetrating into the stone.
- *Extrapolymeric substances*, sometimes forming filamentous structures of variable diameters, differing in shape and in aggregation morphology.

Throughout the Stairway, biological colonization shows some differences both qualitatively and quantitatively, and some parts of the Stairway appear more damaged than others. The superficial and inner biological colonization could contribute heavily to the weathering processes of stone, and particularly to its flaking through different physical and chemical processes. Moreover, some algae growing in the fissures (chasmoendolithic groups) could accelerate flake detachment.

However, as previously stressed, it is not easy to distinguish between primary and secondary effects. In fact, when the stone is weathered by any kind of agent, the biological populations can generally more easily colonize the substrate, contributing to an increased weathering rate. In this case, they can be considered secondary deterioration agents, even if biological species, especially in these climatic



Figures 79a–c Microscopic view of (a) algal sample *Trentepohlia monilia* (x500), (b) lichen sample *Dirinaria picta*, and (c) cynobacteria sample *Gloeocapsa rupestris* and *Scytonema javanicum* (x280) from Copán.

conditions, sometimes can be more damaging than the physicochemical factors.

Biological Colonization on Other Monuments and Ecological Relationships

On the various monuments of the site, different patinas of cyanobacteria (e.g. *Gloeocapsa rupestris, G. kuetzingiana*, and especially *Stigonema hormoides* and *Scytonema javanicum*), green algae (*Trentepohlia aurea*), foliose and crustose lichens (e.g., *Parmelia incurva, Parmotrema crinitum, Candelaria concolor, Dirinaria picta, Buellia* sp.) (**Figs. 79a–c**), and cushions of mosses were widely distributed, especially in areas not protected from rainfall.

The biological colonization in the quarry appeared very high, and many different populations (especially green algae, such as *Trentepohlia aurea* and *Coccomyxa confluens,* and lichens such as *Buellia* sp. and *Porinia chlorotica*) were observed in various ecological gradients. Differences in lighting conditions and, in particular, the percolation of water from the top over the sampling area, which enriched the stone with water and salts, can explain the gradients. The deepest biological colonization (excluding chasmoendolithic algae) was observed on a quarry sample. Imprecisely identified black fungi, which start their growth on the residuals of a white, crustose lichen, developed inside the stone up to a depth of 3 mm (**Fig. 80a**). A wide polysaccharidic production was also observed (**Fig. 80b**).

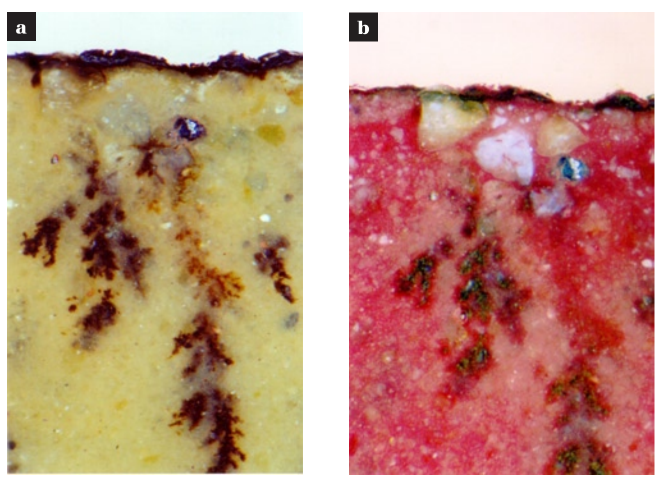
On the museum sample, only a slight presence of pioneer cyanobacteria (*Gloeocapsa rupestris*) was observed; however, the cross section of the PAS-stained sample shows a heavy past biological activity (intense red, surrounding a crystal that is not attacked). Prior to its installation in the museum, it is very likely that the monument was strongly attacked by lichens and other biological populations, which were almost certainly killed by a biocide treatment. The present conditions, drier than in the past, do not permit new lichen colonization, which explains why only cyanobacteria were observed.

Comparison of all the observations shows that the Stairway samples are more similar to one another than to any other samples. They show some similarities with the museum's sample and with some samples of Stela H that could be explained by a similar light biological cover on all of these samples and by the common presence of the same species of algae and cyanobacteria. The Stairway samples are not too dissimilar to the Ballcourt sample, despite a significant difference in biological cover. This finding could be explained by the fact that the difference is mainly quantitative. The most significant differences, both quantitative and qualitative, are between the Stairway samples and the quarry samples. There is also a significant difference between the Stairway samples and those from the stela near the site entrance, which show microflora typical of dark and humid places.

Changes in Biocolonization of the Hieroglyphic Stairway over Time

Previous photographic and scientific documentation shows a past high level of biological colonization of the Stairway, as well as of the other monuments of the site, with, in particular, a high coverage of lichens and mosses. This type of colonization was due to wet and sunny conditions–the exposure of the monument to direct rainfall and sunlight.

Changes from the past situation to the present one are both quantitative and qualitative. Today the biological colonization of the Stairway and other sheltered monuments (Stela H, for example) has been sharply reduced to a few algae and cynobacteria. The quantitative decrease is due to past biocide applications and to the shelter installation over the Stairway and other site monuments, which created darker and drier condi-



Figures 80a and b Cross section (a) and cross section stained with PAS (b) (x114), showing the deep fungal penetration in the quarry samples.

tions. The qualitative change is likely a result of the higher tolerance of isolated cyanobacteria to water deficiency, as compared with lichens.

A comparison between the floristic list of Hale and the present situation shows that in protected monuments, algae and cyanobacteria populations generally appear dominant now, while lichens and mosses were much more abundant in the past. The number of algal species also appears to have increased (Hale's list for algae was probably incomplete and, because of nomenclature and taxonomic revision, *Oscillatoria* is now named *Scytonema*), while generally the lichen diversity appears to have decreased, even if the present lichen list cannot be considered complete, owing to the limited number of sampled areas.

Monuments treated with biocides in the past and left exposed have been recolonized differently, depending on their environment. In the Ballcourt, which has been treated with biocides but is still exposed and without tree cover, a very high number of cyanobacteria and algae, forming a continuous black patina, was observed (**Fig. 81**). In this case, the new biological colonization seems to be more fully correlated with the higher solar radiation, and with consequent warming and desiccation, than to an absolute reduction of water input. In contrast, Altar 41, and especially its front side, which was cleaned in 1985 (**Fig. 82**), today shows rapid recolonization by lichens (**Fig. 83**). This finding can be explained by environmental conditions very favorable to lichen growth: partial shade without protection from rainfall—a situation with some similarities to that of the Stairway in the past.

A summary of the relationships among the ecological conditions, the microflora, and the visual appearance of the biological colony at the archaeological site of Copán, as well as the expected rate of biodeterioration, is given in **Table 14**. The ecological conditions—as defined by the two main factors, water and light, impacting the various analyzed Copán monuments—are shown in **Figure 84**, along with the visual aspects of the different biological colonies.

Conclusions

The ecological analysis and the hypothesis suggested to explain the changes in biological colonization that occurred in the

Figure 81 The present condition of the Ballcourt, showing a black patina on the horizontal surfaces and its absence on vertical surfaces.

Figure 82 Altar 41 in 1985, after the biocide treatment for lichen removal.

Figure 83 Condition of Altar 41 in 2000, revealing rapid recolonization of lichens (*Candelaria concolor, Parmotrema tinctorum, Dirinaria picta*).

Table 14 Ecological relationships and biodeterioration at the Copán archaeological site.

Ecological conditions	*Microflora*	*Phenomenology of biodeterioration*	*Weathering rate*
Very dark and humid	Fungi and bacteria dominant	Black or brown patinas	Variable
Dark and humid	Green algae dominant (e.g., *Pseudococcomyxa* sp., *Stichococcus bacillaris*, *Monoraphidium pusillum*, *Trentepohlia umbrina*), mosses and liverworts (*Jugermannia atrovirens*)	Green patinas	Not negligible, but slow growth
Semishadowing and humid	Mixed populations: Green algae (*Trentepohlia aurea*, *Coccomyxa confluens*, *Stichococcus bacillaris*, *Pseudococcomyxa* sp.), some cyanobacteria (*Phormidium* sp.), mosses and sciophilous lichens (e.g., *Porinia clorotica*, *Physcia sorediosa*, *Parmotrema mordenii*)	Reddish and brownish patinas	Not negligible, but slow growth
Average lighting and semihumid	Lichens dominant (*Candelaria concolor*, *Parmotrema tinctorum*, *Dirinaria picta*, *D. confluens*), but presence of algae and cyanobacteria	Whitish to brown crusts	Highest biological damage
Good lighting, water variable, from xeric to humid	Cyanobacteria dominant (e.g., *Scytonema javanicum*, *Stigonema hormoides*, *Gloeocapsa rupestris*), and some lichen	Black, gray patinas	Usually low biodeterioration
High lighting and dry	Very poor biological growth	Stone more or less free; original stone color	Low biodeterioration

Hieroglyphic Stairway as a result of different past interventions are useful to evaluate possible future conservative actions. Considering the present level of biological colonization and the fact that it occurs less frequently at the stone surface than at inner depths, the use of a biocide does not seem to be an appropriate means of treatment. The previous biocide treatments, even if effective and satisfactory, left in-depth fungal hyphae, probably belonging to lichens previously growing on the surfaces. Even if some future recolonization phenomena from heterotrophic organisms cannot be excluded, any new biocide treatment would probably not be completely effective, because of the difficulty of eliminating microorganisms inside the material. Additionally, these treatments risk being ineffective over the long term, as well as being too aggressive, considering the condition of the stone.

For an effective reduction of biological growth, the best system is to modify the environmental conditions toward levels not favorable to the growth of the existing organisms. In many cases, this would not completely stop the development of the organisms, but it would induce changes in the community toward less aggressive stages. In practical terms, the reduction of water content of the stone seems to be the most efficient indirect control method. Therefore, the design of the shelter and its efficiency in shedding rainwater are of primary importance. However, the impact of sheltering on ventilation and on the reduction of light should be carefully considered, as it has a great influence on photosynthetic organisms. Darker conditions tend to increase humidity, and they do not stop biological growth, as many fungi and bacteria can develop without direct sunlight.

The removal of the Stairway to the site sculpture museum would be costly and cause the irrevocable loss of the monument's original context. It would also not provide significantly better environmental conditions. In the museum, air circulates freely and exchanges with the outdoors, so that the museum is only slightly less humid and less dark than the Stairway under the current conditions. The museum environment does not permit new lichen colonization; however, any lichens, especially cyanobacteria, which have not been completely destroyed, can still survive. Only with a further reduction in ventilation and humidity will these growths completely disappear.

Another significant conservation problem related to these archaeological buildings comes from the presence of nearby trees, whose strong roots penetrate in depth and damage the substructures. The presence of the peculiar forest and grasslands in the plazas also influences the microclimate of the site. They create a higher environmental humidity, because of

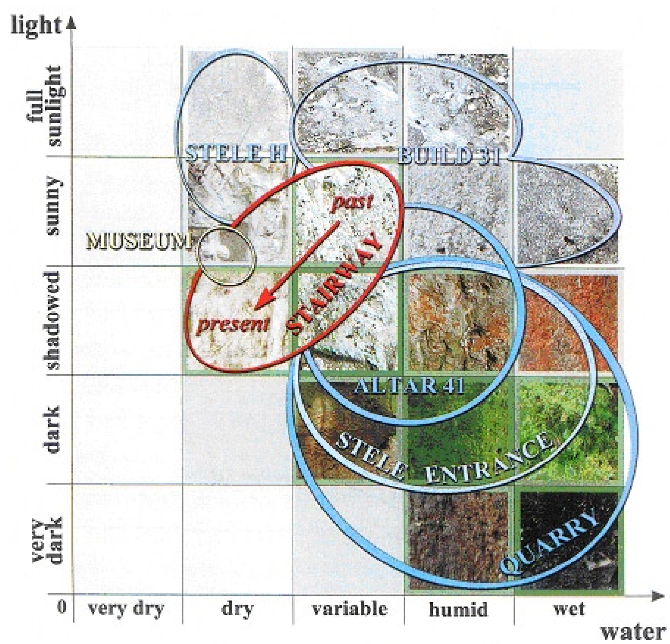


Figure 84 Ecological locations of the analyzed monuments in the Copán archaeological site, as well as the main biological weathering patterns (note also the changes of biodeterioration phenomena in the Hieroglyphic Stairway).

Figure 85 Entrance to the tunnel on the north side of Structure 26.

Figure 86 The north end of block 375, step 41, next to the balustrade, seen in April 2002 with a photograph of the same location taken in 1987. The same space between the balustrade and the stair can be seen in both photographs.

shadowing, and reduce heating of the stone surfaces during the day—and, therefore, reduce evaporation and cooling during the night. The tree cover also partially protects the monuments from heavy rainfall. The relationships between higher vegetation and monuments in the archaeological site are therefore important to consider. A botanical plan should be developed, in order to increase the positive effects of the trees while diminishing the negative ones.

Structural Assessment

This section summarizes two reports produced by consulting engineers after missions to Copán, one from 1999, at the beginning of the project (Wenzel 1999), and one from 2002 (Gemperline and Rutenbeck 2002). The summary focuses on the issues surrounding the Hieroglyphic Stairway and Structure 26, while the reports themselves are broader in scope and include considerations of tunnel stability, drainage, and the impact of trees on other areas of the Copán Main Group.

Both consultant missions were conducted to assess the structural stability of the Hieroglyphic Stairway and Structure 26, on which it is located. The first mission aimed to give a preliminary assessment of the structural stability of the monument and to identify the potential needs for further study. The second one aimed to analyze the cracks observed earlier on the Stairway, review the overall structural stability of Structure 26 and its tunnels (**Fig. 85**), assess the impact of tree growth on the archaeological fabric, and evaluate site drainage effectiveness.

Assessments were carried out through above-ground visual observations, inspection of underground tunnels, and interviews of local staff in charge of tunnels and Stairway maintenance. Additionally, selected plans, sections, and elevations of the Copán Acropolis were provided by archaeologists to assist the engineers, and historic photographs of the Stairway provided helpful time-related information.

Structural Stability of the Stairway

No major deformations or displacements in the Hieroglyphic Stairway have been identified; however, some evidence of movement is clearly visible. There are two cracks located between the steps and the north and south balustrade respectively, running upward from about the middle of the Stairway. There is also vertical cracking between stone blocks just south of the center line in the upper half of the Stairway. Comparison of selected areas with 1987 photographs shows that the movements that created these vertical cracks have not taken place recently, and that no recent changes in crack width are visible (**Fig. 86**). These cracks are likely the result of settlement following the 1930s Stairway reconstruction. They also may have occurred during past seismic events.

Downward deflection in the upper part of the south balustrade was also observed, along with some related cracks, which are suspected to be associated with the more recent reconstruction of the terraces on the west facade of Structure 26, south of the Stairway (**Fig. 87**). Finally, the crack through one of the large horizontal south balustrade stones has been created by an unfortunate attempt at jack-lifting the stone during stabilization work undertaken in 1987 (**Fig. 88**).

None of the observed cracking and settling represents a threat to the stability of the Stairway, as none of it appears to have taken place recently. Furthermore, due to the stable structural geometry of the Hieroglyphic Stairway, there is no threat of the entire monument collapsing from any progressive movements. Additionally, the lack of movement in the Stairway indicates that the pyramidal structure supporting it is not currently moving. This finding is confirmed by the lack of cracks in both the reconstructed terraces south of the Stairway and the consolidated rubble north of it. However, as with all unreinforced masonry structures in Honduras, there is always the threat of instant collapse in case of a large seismic event.

As a consequence of the assessment of the Stairway stability, no instrumental monitoring of structural movement was considered necessary. However, it was recommended that visual inspections be continued and that prompt action be initiated when failures are observed.

Structural Stability of the Tunnels

Numerous tunnels under the Copán Acropolis have been created throughout the years for the purpose of archaeological investigation. Some tunnels have been later backfilled, but most of them have been left open to maintain access to buried structures (**Fig. 89**).

Underlying the final phase of Structure 26, which includes the Hieroglyphic Stairway, there is a successive series of monumental constructions that archaeologists have accessed through a network of tunnels (**Fig. 90**). No specific problems—in particular, tensile stress fractures indicating concentrations of load forces—were identified in the tunnels located in the area close to the Stairway. One shallow tunnel section, which had been excavated directly beneath the Stairway about halfway up the Structure has subsequently been filled with cobbles, sand, clayey earth and some cement. Another tunnel located farther from the Stairway was left unfilled, but it is at such a distance that it does not represent an immediate threat to stability. However, water infiltration and seismic activity represent threats to the stability of any tunnel, and a collapse could lead to major disruption to Structure 26, as well as to damage of the Stairway.

Potential Damage from Trees

Trees provide shade for visitors and influence the microclimatic environment of the structures in ways that may be beneficial to the conservation of the stone. However, the presence of trees is also a significant source of damage to the monuments. The growth of their roots directly lifts and disrupts the masonry structures (**Fig. 91**), and they provide preferential channels for the infiltration of water into the structures. In case of high

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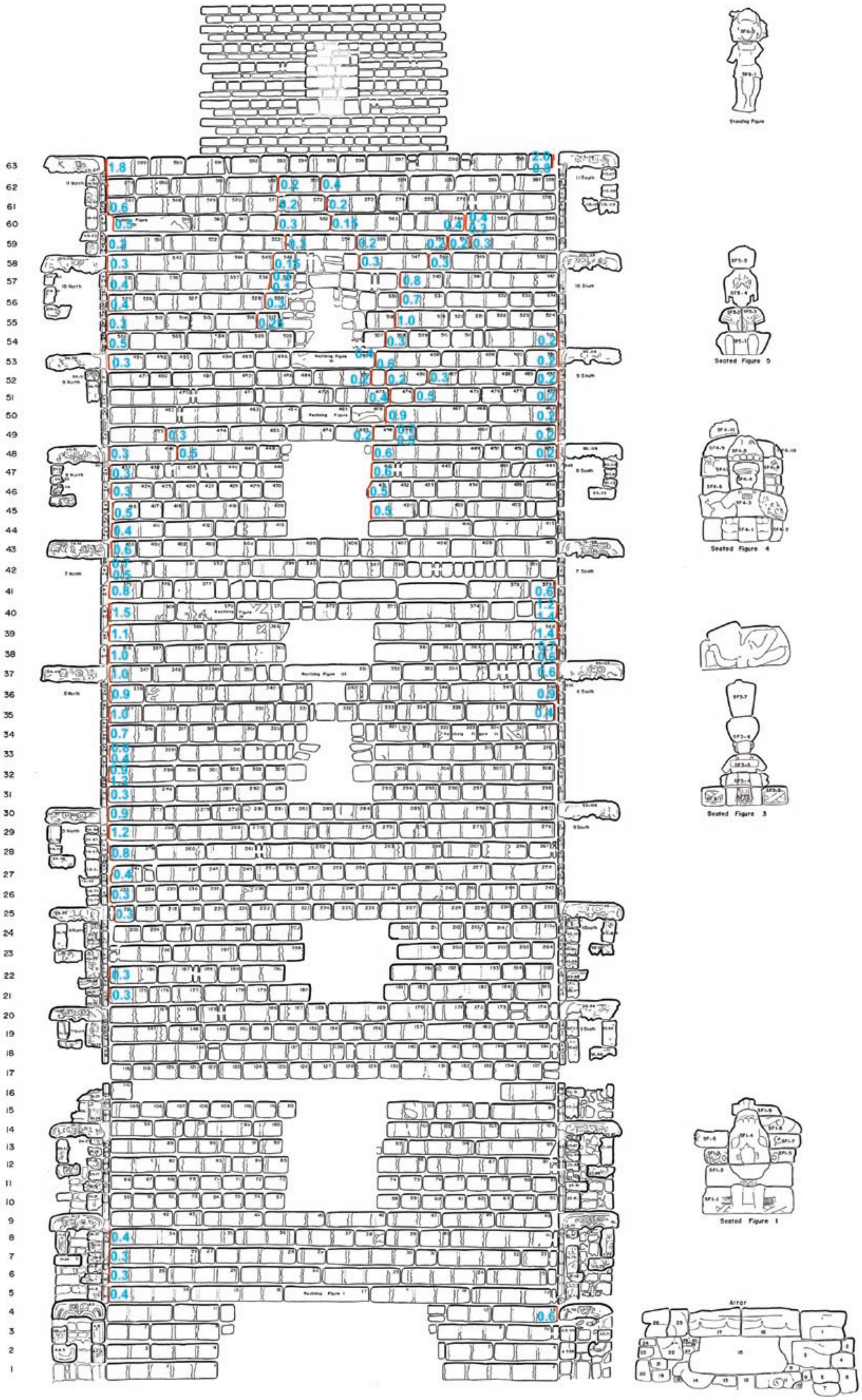

Figure 87 Map of the main cracks on the Hieroglyphic Stairway, with their widths in centimeters.

Figure 88 A crack in a large horizontal stone (6S-107) of the south balustrade, near step 37.

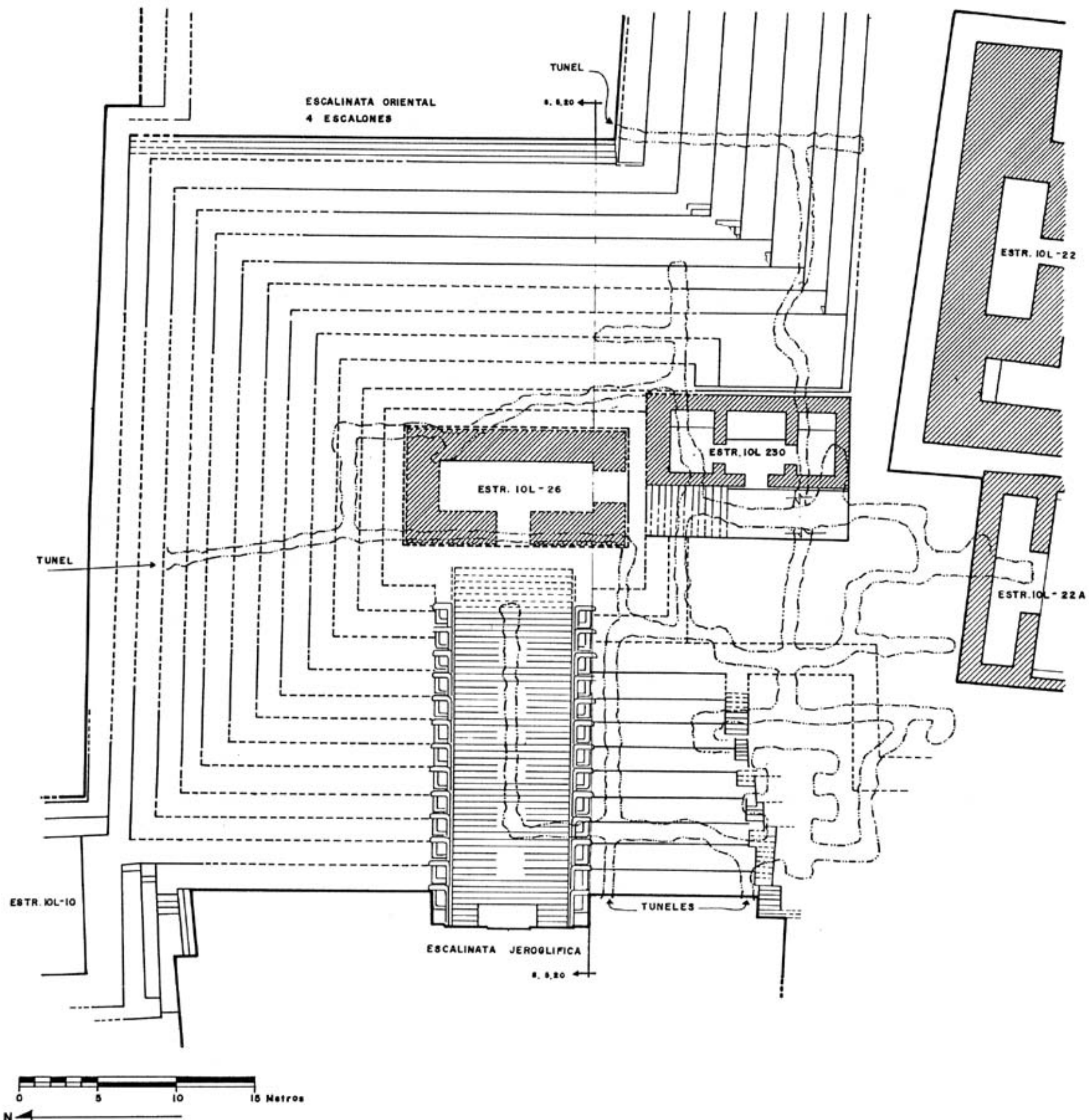

Figure 89 Plan of the tunnel system underneath Structure 26.

Figure 90 View of a tunnel in the Margarita Tomb, showing work in progress.

winds, trees can be blown over, and roots, cubic meters of soil, and building remains can be pulled from the ground. Finally, as they become diseased or die, they leave behind open water channels and weakened structures.

No tree of any size is growing on the west elevation of Structure 26, where the Hieroglyphic Stairway is located, but medium and small trees are growing on the north and east faces (**Fig. 92**). Special consideration should be given to preventing damage from trees on Structure 26, which, as it provides structural support for the Stairway, should be maintained carefully. In particular, the west face should be kept free of trees, but beyond this, consideration should also be given to removing all trees on Structure 26.

The relationship between trees and the conservation of the structures in the Copán archaeological park is a complex issue, and thought should be given to establishing a comprehensive tree management program.

Drainage Issues

The Court of the Hieroglyphic Stairway is part of a wider area that includes the Great Plaza, the Middle Plaza, and the Ballcourt. There is no modern drainage system in the 250 by 100 meter area, but the ground is slightly sloping to the southwest corner of the Stairway Court, where an ancient rectangular drainage opening has been located (**Fig. 93**). Rough estimates suggest that this opening may be adequate to drain the Hieroglyphic Stairway Court during a normal heavy storm event but inadequate to remove rainwater from the entire area. The drainage of the main plazas is critical to the stability of tunnels within structures, at and below Plaza level (**Fig. 94**).

During heavy rain, the water collected by the Hieroglyphic Stairway shelter flows down and accumulates on the Plaza at the bottom end of the tarpaulin, as does rainwater falling on the west face of Structure 26. The water pooling on the Plaza is generally prevented from reaching the first step of the Stairway by one course of stones, but in the case of heavy rain, the stones are not sufficient, and the barrier should, therefore, be enlarged.

The current slope of the consolidated rubble north of the Stairway channels some rainwater back to the north balustrade. Mortar and small stones should be added to one area to prevent this from happening.

Figure 91 View of the stone steps of Structure 9, showing deformation from tree roots.

Figure 92 A small tree growing on the north end of the east face of Structure 26; it could easily be removed before it grows to a damaging size.

Figure 93 An ancient drain outlet in the southwest corner of the Court of the Hieroglyphic Stairway.

Conclusion

Cracking and settling currently visible on the Stairway have occurred in the past, possibly after the 1930s reconstruction, and no recent movement of the Stairway, or of Structure 26 on which it is located, has taken place. Additionally, the structural geometry of the pyramid and the Stairway is very stable, so the monument is under no immediate structural risk. However, regular inspection should be carried out, a photographic and graphic record should be maintained, and remedial action should be taken promptly if changes occur.

To protect the Stairway, the growth of trees on Structure 26 should be controlled–and perhaps prevented entirely. Inadequate drainage around the Stairway is also a major source of concern, as it can lead to flooding and the collapse of nearby tunnels. This issue should be addressed as part of a comprehensive water collection and drainage plan for the site plazas.

Principal Findings

When the Hieroglyphic Stairway was excavated in the late 1890s, the condition of the blocks varied greatly, ranging from those heavily eroded and devoid of any carved surfaces to those with still sharply carved surface details. The range of conditions at present is therefore due in large part to what happened to each block over the centuries after the abandonment of the monument. For example, some blocks remained more exposed, while others became quickly covered with soil and debris during the Stairway's gradual collapse. Since their excavation, the stone blocks have been exposed to the tropical environment of Copán, and they have been without the lime coating that originally covered and protected them in the Maya period. Historic photographs have clearly shown that over the past one hundred years, some of the stone blocks have deteriorated considerably, while others have undergone a negligible change in appearance. Those that have deteriorated have done so in the past, and, with the exception of a few selected blocks, surfaces are currently in stable condition. Some recent loss of stone flakes has been observed in different areas of the Stairway, but most losses are located in previously treated areas where previous treatments are failing, or they can be attributed to mechanical impact from people walking on the Stairway.

Intrinsic Qualities of the Stone

The detailed condition survey showed that the deterioration is very much block specific rather than being related to the location of the blocks within the reconstructed Stairway. This finding is not surprising, given that more than three-quarters of the stones have been in their current locations for only the past seventy years. The fact that well-preserved blocks are located next to blocks with delaminated and flaked surfaces shows that under the same environmental conditions, certain blocks are more susceptible to damage than are others. Therefore, the condition of the blocks is related to the characteristics and durability of each specific block of stone. The way

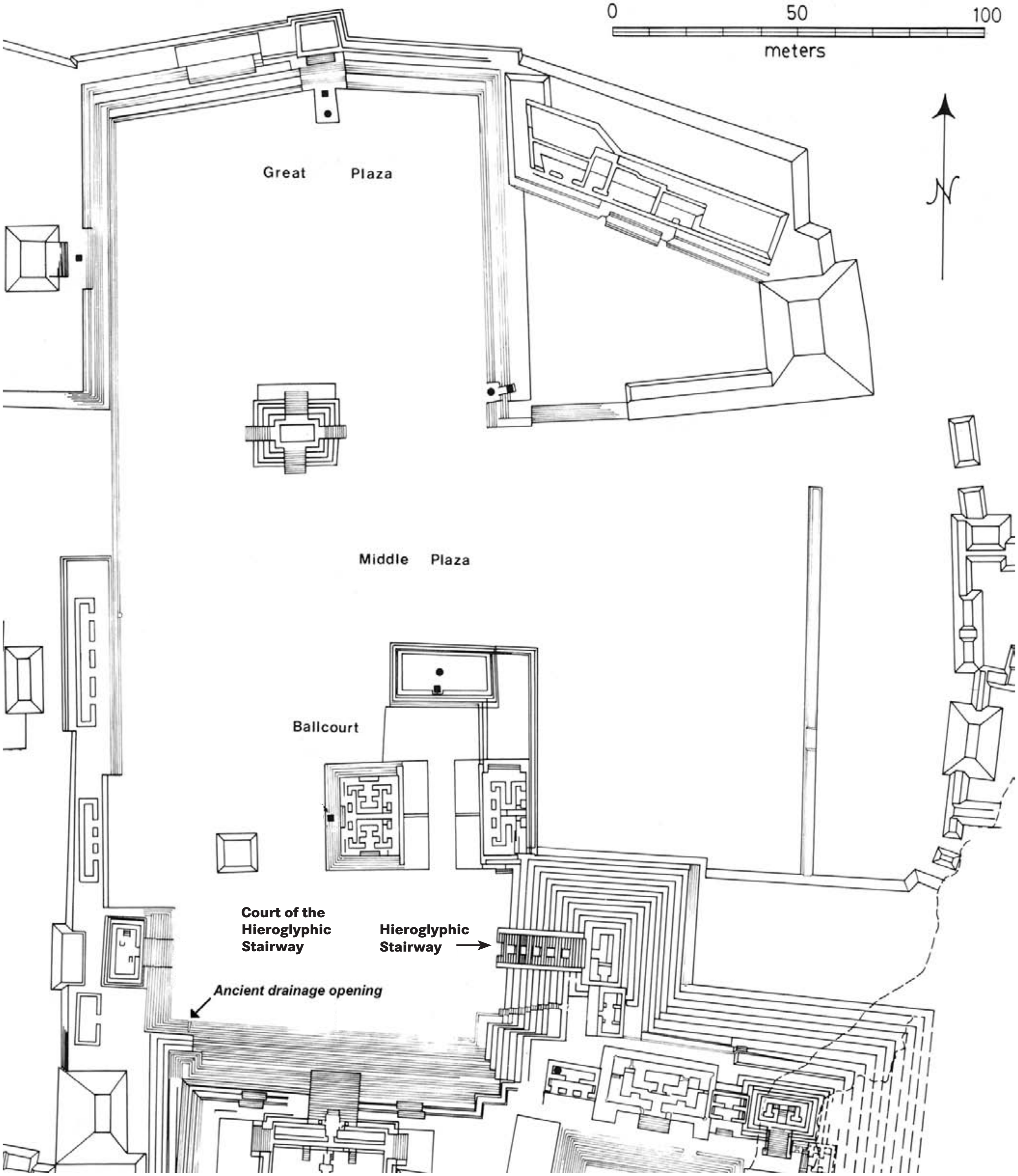

Figure 94 Map of the Great Plaza and the Court of the Hieroglyphic Stairway, showing the location of the ancient drain (see Fig. 93).

each block is placed on the Stairway in relation to the original orientation and bedding of the stone in the quarry also plays a role in its condition. Physicomechanical studies have shown that the Copán tuff is a stone with a significant variability at a macroscale. Its physical and mechanical properties—including compressive strength, grain sizes, pore size distributions, water storage properties, and transport properties—cover a broad range of values, and therefore, blocks quarried from different areas respond differently to the aggressive tropical environment of rapid temperature and moisture changes.

Environmental Exposure

The tropical environment of Copán is particularly harsh to stone, and throughout the site, ongoing delaminating and flaking surfaces are visible on exposed stones of different monuments. The combination of rapid wetting-drying cycles and extreme surface temperature variations, which occur particularly in the summer rainy season, is the major cause of stone deterioration at Copán. These environmental conditions are also particularly favorable to biological activity. Lichens and mosses and, to a lesser extent, algae and cyanobacteria heavily colonize all exposed stones, exploiting microcracks and areas of weakness and contributing to the overall deterioration process.

The dominant form of deterioration of the Stairway stone surfaces is millimeter-scale flaking, accompanied by cracks parallel to the surface. The analyses have shown that the depth at which the stone surface begins to flake—a few millimeters—corresponds closely to the depth of maximum moisture content for Copán stone averaged over a year. One hypothesis for the deterioration mechanism is that the formation of these flakes is due to wetting-drying cycles associated with hygric dilatation of the surface of the stone and dissolution of the more soluble amorphous silica. The shear stresses, which are expected to develop during rain events in the outermost surface of the stone, would, over time, lead to the development of microcracks and be responsible for the formation of the flakes.

Approximately three-quarters of all Stairway blocks display some evidence of this form of deterioration. The differences in degree of deterioration may be due to differences in the water transport behavior and swellable clay content from one block to another. Water uptake and penetration coefficients control the location of the water-air interface during the wetting-drying phases and therefore determine the location of dilatation stress, as well as the dissolution and the accumulation of salts, if they are present. Different Copán stones have different water transport characteristics; thus, some stones are more susceptible to flaking, while others are more susceptible to uniform recession through intergranular disintegration.

Environmental monitoring data have shown that the conditions for subsurface salt crystallization exist throughout the Stairway; yet analyses have shown that highly soluble salts are found only in some stones of the top step. Salt dissolution/crystallization is therefore currently not an important deterioration factor, except for these few blocks that are observed to be actively decaying. This decay could be attributed to the presence of soluble salts originating from cement mortars applied immediately above or behind the top step within the past twenty years.

Studies have shown that behind flaking surfaces of the Stairway, there are the remains of past biological growth, such as fungal hyphae, which could shrink and swell with changes in surface humidity and exacerbate the flaking mechanism of the stone; this process is not, however, currently occurring because of the shelter.

Previous Interventions

For the Hieroglyphic Stairway, past human interventions have also played a particularly important role in the deterioration of the stone. According to archival research, many Stairway blocks were molded with paper in the 1890s. It is likely that, in subsequent years, selected blocks were molded again with synthetic materials, without this having been documented in any way. These successive moldings may have caused damage to certain blocks; however, the absence of documentation does not permit us to draw conclusions.

The reconstruction of the Stairway almost seventy years ago, which was, at the time, carried out to ensure its long-term preservation, has subjected the blocks to a more exposed, aggressive environment than when they were originally set on stones in the Plaza. The reconstruction has probably been one of the actions most damaging to the monument that has ever been undertaken. Very likely, the stones were cleaned mechanically before they were placed back on the pyramid and then left exposed on its west side for over forty years. During these years, the stones were subjected to the mechanical action of cascading rainwater, which passed over the surfaces with far greater volume and speed than it had before, to the pooling of rainwater on the Stairway treads, to more direct exposure to the sun, and to more abundant microbiological growth, including lichens, fungi, and algae. A collateral effect of the reconstruction was that visitors were then able to walk on the Stairway, undoubtedly causing significant mechanical damage and the loss of fragile surfaces. These negative effects of the reconstruction can be seen through a comparison of historic photographs that show greater deterioration of surfaces between the 1940s and 1987 than occurred before or after this period.

While the cement-based mortars used to reset the blocks during the reconstruction of the 1930s no longer contain soluble salts, the mortars could have been a source of salts and a cause of deterioration in the past. However, even the hardest mortars on the Stairway have not caused visible mechanical damage to the adjacent stones. This fact may be partly attributed to poor initial workmanship, such that shrinkage cracks formed at some stone-mortar interfaces, but it could also be attributed to the comparatively high compressive strength of the Copán stone. While the 1930s reconstruction mortars do not seem to have been a source of deterioration, the cement platform that was added at the top of the Stairway in the past twenty years may be a source of soluble salts, and thus it may have a role in some of the active deterioration observed on the top step.

Another intervention, the 1978–79 biocide treatments, caused negative effects for the conservation of stone surfaces. These treatments with Clorox and Borax may have had some direct transient leaching effects on the stone, but these are probably minor compared to the long-term exposure of the stone to the tropical environment. The killing and subsequent detachment of biological organisms left the fragile surfaces more exposed to physical erosion. In addition, the possible mechanical removal of the lichens, which had penetrated inside the stone, may have also provoked further damage to the surfaces. However, neither historic photographs nor archival documentation can confirm these potentially negative effects of the biocide treatments. Obviously, an important positive effect of the treatment was loss of the lichens, which permitted viewing of the surfaces of the stones again.

The consolidation and edging repair treatments of the past twenty-five years, which used primarily the acrylic resin Paraloid B-72 and, to a lesser extent, the polyvinyl acetate resin Mowilith 30, have not provoked further deterioration of the stone surfaces, and these areas have been shown to be re-treatable. However, the resins have had an increasingly negative aesthetic impact, because they have darkened considerably over time. This process makes the blocks look very dirty and makes many of the glyphs more difficult to read. However, fills carried out with Paraloid B-72 or Mowilith 30 and stone powder have had the effect of supporting and keeping flakes in place, some of which would otherwise have fallen off years ago.

The 1985 construction of a shelter over the Stairway has been, after the reconstruction, the second most important intervention since the excavation of the Stairway. Although shelters can sometimes provoke damage that they were intended to prevent, environmental data have shown that the Stairway shelter has created a much more stable environment for stone, and thus it has been the single most important intervention for the conservation of the Stairway (see "Environmental Monitoring"). The shelter has eliminated the Stairway's exposure to almost all liquid water and direct sunlight, significantly reducing rapid wetting-drying cycles as well as the amplitudes of thermal cycling. The protective tarpaulin limits daytime solar heat gain and nighttime radiation heat loss; consequently, the surface temperature of the stone remains continually higher than that of ambient air, so that condensation during morning hours is prevented. The drastic diminution of the water available from direct rainfall and condensation has also greatly limited biological activity. This stable environment is the primary cause of the generally stable stone conditions observed through photographic comparisons of the past fifteen years. One unknown damage factor is the immediate effect that the erection of the shelter had on the stones when they began to dry. This short period of drastic change in the stones' environment may have had a temporary negative impact on their condition.

And finally, the restriction of public access to the Stairway, put in place in the mid-1970s, has contributed to the conservation of the stone by greatly limiting mechanical impact and physical abrasion of the fragile block surfaces.

Summary

The successful integration of archival information, condition survey, laboratory analysis, and environmental data has shown that even though significant stone deterioration has taken place since the Hieroglyphic Stairway was excavated, the monument is currently, for the most part, in stable condition. Hygric dilatation is considered to have been the primary cause of surface deterioration in the past. Another damage factor is thermal expansion/contraction; however, the expected temperature gradient between the inside and the outside of the stone would produce less dilatation stress than hygric dilatation. Mechanical actions resulting from biological growth, rainwater erosion, and walking on the Stairway have also played an important, yet secondary, role in the deterioration of the Stairway's surfaces. Previous interventions have also contributed to deterioration—primary among them being the reconstruction of the Stairway, which has exposed the stone to a more aggressive environment.

The present stable condition of the Stairway stone can be attributed primarily to the shelter that has been in place since the mid-1980s. It keeps the surfaces dry, significantly reduces the daily environmental variations the Stairway is subjected to, and limits biological growth on the stone. Stability can be maintained by ensuring that the current environmental conditions produced by the shelter continue (with some limited, localized modifications), as well as by continuing to limit direct access to the Stairway.

Note

1. The subject of this section, biological analysis, is discussed as well in a 2005 journal publication (Giulia Caneva, Ornella Salvadori, S. Ricci, and S. Cechin, Ecological analysis and biodeterioration processes over time at the Hieroglyphic Stairway in the Copán (Honduras) archeological site, *Plant Biosystems* [Società Botanica Italiana] 139, no. 3 [Nov. 2005]: 295–310). The principal author of that article, Giulia Caneva, is also the author of this section of the present volume.