Preliminary investigation on the preservation of Machu Picchu ruins: Discussions from topographical and geological aspects

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Abstract

Machu Picchu is undoubtedly the most famous ruin of the Inca Empire. It is located northwest of Cuzco, the former capital of the Inca Empire, and east-southeast of Lima, the current capital of the Republic of Peru. The ruins are located on a narrow ridge (N15W) between Mt. Machu Picchu (elev. 3060m) on the south and Mt. Huayna Picchu (elev. 2660m) on the north. The site has been investigated by a Japanese mission comprised of experts in archeology, city planning, structural engineering and seismic engineering, seismology, geology and soil engineering. The results of topographical and geological investigations of the site indicate: 1. Construction of the ruins took advantage of topographical conditions and large-scale reconstruction is not feasible. 2. The base rock of the site consists of granite. In situ construction used materials from the local base rock. 3. Colluvial soils exist on the gentle slopes. Their current condition suggests that they were recently formed. 4. As long as there is not a great earthquake or especially heavy rainfall, there is little probability that serious damage will occur from the foundation.

1. Introduction

In 1990, a Japanese survey team composed of JICA experts was sent at the behest of the Republic of Peru to collect information in situ at Machu Picchu, the present capital Lima, and the old capital of Cuzco (or Cusco). The main purposes of this survey were to thoroughly investigate the state of preservation of the ruins and acquire basic data that could be used in conducting comprehensive surveys and formulating far-reaching policies for their continued
preservation. The members of the team included experts from the fields of archaeology, geology, soil engineering, seismology, seismic engineering, and urban planning. In addition, the in situ surveys were conducted with the assistance of the Cuzco office of the Peruvian Culture Ministry (Instituto Nacional de Cultura, Departamental Cuzco : INC-Cuzco), and experts from the Japan-Peru Center for Earthquake Engineering Research and Disaster Mitigation (Centro Peruano-Japones de Investigaciones Sismicas y Mitigacion de Desastres : CISMID). Therefore, the report\(^2\) covered a lot of material.

The present report is concerned with the topographical and geological surveys mentioned in the 1990 report\(^2\) that are directly related to the stability of the foundation of the ruins, as well as evaluations based on these surveys. It concludes with some proposals.

2. Topography and geological conditions

2.1 Topography

The Machu Picchu ruins zone (hereafter referred to as the "ruins zone") is located 75km (straight-line distance) NW of the City of Cuzco at 13° 09' 23" S latitude, 72° 32' 34" W longitude\(^3\). The main stream of the Urubamba River, which flows along the western flank of the Cordillera Oriental in the Andes Mountains, meanders and enters near the ruins zone. The ruins zone itself is bounded on the E, N and W by the valley created by the meandering river. On the NNW there is a large protruding ridge which connects with Mt. Machu Picchu (lit. "old mountain," elev. 3,060m) on the S with Waynapicchu (lit. "young mountain," 2,660m) on the N end, forming the saddle of the ridge that dips roughly toward N15° W.

An open area called Foso Seco is centered in the ruins zone. It forms the boundary between "the built-up area" (Sector Civil) on the north and "the agricultural district" (Sector Agricola) on the south. The agricultural district called Andenes is terraced and surrounded by retaining walls. Please refer to the Figure 4 for details.

The elevation of the ruins zone ranges from 2,400 to 2,550 m in the agricultural district in the S, and from 2,400 to 2,450 m in the built-up area in the N, and rises 450-600 m above the Urubamba River Valley. Slopes on both sides are very steep, with even the relatively level Hiram Bingham Road sloping at an average angle of 35°. Toward the N, the eastern slope of the built-up area averages 40°, the W slope averages 45°, and some slopes in the area are extremely steep 60° or more\(^4\) (Figs. 1 and 2). In addition, there are sheer walls hundreds of meters high in numerous locations, including the SE and SW slopes of Waynapicchu, the W slope (the bridge of Inca, Puente Inca) of Mt. Machu Picchu, the NW side of a ridge that extends to the NE of Mt. Machu Picchu, and both the E and W slopes of Mt. Putukusi (elev. 2,567m), which is on the opposite bank that runs NE from the ruins zone.
Fig. 1 Topographic map of the vicinity of ruins of Machupichu

Inside the ruins section, erosion has generated micro landforms. This is especially apparent in the N half of the built-up area, where a depressed ground extends along the longitudinal direction of the ridge in the central area. On both sides, there are rows of small peaks that rise 10-30m above the surrounding landscape, forming a double edge-type of topography. The original structures of the ruins were built well utilizing these micro landforms. It does not appear that major modifications (such as cutting and embanking) were made to the landscape.
2.2 Geology and base rock

The Vilcanota region of the ruins zone, as with other regions of the Cordillera Oriental, overlies deformed and metamorphic sedimentary and igneous rocks from the Palaeozoic era, which are intruded by abyssal (plutonic rocks). These deformed and metamorphic processes derived from the Hercynian uplift that occurred at the end of the Palaeozoic era. The region around the ruins is in an immense rock of granitoids that were penetrated during the latter half of the Permian period (230 million- 250 million years b.p.). Near the ruins are areas of intrusive rock that is mainly comprised of medium grain granite, fine-grain Monzonite quartz, and granodiorite (Tables 1), but the interior of the ruins zone is composed of muscovite-bearing biotite granite (Tables 2), whether it be natural stone or building stone. This rock has a medium-grain horocrystalline equigranular texture which is composed mainly of the following minerals, in order of greatest to least abundance: quartz, potash felspar, plagioclase, biotite, and muscovite. Minor mineral components include zircon, apatite, and iron ores. In addition, weak hydrothermal alternation has produced trace secondary minerals such as chlorite, epidote, and sericite. Within the ruins zone, especially in the built-up area, there is an area of huge exposed natural rock comprised of the abovementioned granite, and some structures were built directly on top of the rock, which either envelopes it or is used for parts of walls and retaining walls. The giant rock known as Roca Sagrada is either completely natural, or partially processed. Most of these natural rocks are boulders, but there are also quite a few that appear to be exposed bed lock.
### Table 1 Intrusive rock on the Bingham Trail

<table>
<thead>
<tr>
<th>Primary mineral</th>
<th>Textures</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plagioclase</td>
<td>Medium quantity; Size: 0.08-1.95 mm; Hypautomorphic and automorphic; Columnar and granular; Polysynthetic twin have been observed; Albitic; Affected by saussurization.</td>
<td>Fine grain holocrystalline equigranular texture.</td>
</tr>
<tr>
<td>Potash</td>
<td>Small quantity; Size: 0.05-2.2 mm; Allotriomorphic; Granular; Exhibits bassallite and micro-bassallite textures.</td>
<td></td>
</tr>
<tr>
<td>Quartz</td>
<td>Small quantity; Size: 0.04-3.2 mm; Allotriomorphic; Granular; Exhibits suture-like aggregates and a strong wave-like quenching.</td>
<td></td>
</tr>
<tr>
<td>Biotite</td>
<td>Small quantity; Size: 0.04-0.8 mm; Allotriomorphic; Plate- or flake-like; Light yellow, brown and olive-green.</td>
<td></td>
</tr>
<tr>
<td>Muscovite</td>
<td>Small quantity; Size: 0.015-0.7 mm; Allotriomorphic; Plate- or fiber-like; Colorless.</td>
<td></td>
</tr>
</tbody>
</table>

### Table 2 Boulders at the Inca archaeological site at Machu Picchu

<table>
<thead>
<tr>
<th>Granites composed of muscovite and biotite</th>
<th>Medium grain holocrystalline equigranular texture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Textures</td>
<td></td>
</tr>
<tr>
<td>Plagioclase</td>
<td>Small quantity; Size: 0.05-1.8 mm; Hypautomorphic; Columnar; Carlsbad twin and polysynthetic twin have been observed; Albitic; Replaced with micro-grains of sericite and epidote; and contaminated.</td>
</tr>
<tr>
<td>Potash</td>
<td>Medium quantity; Size: 0.02-5.0 mm; Hypautomorphic and allotriomorphich; Granular; Bassallite and micro-bassallite textures are often observed.</td>
</tr>
<tr>
<td>Quartz</td>
<td>Medium quantity; Size: 0.03-3.0 mm; Allotriomorphic; Irregular granular; Contains pieces of plagioclase, and exhibits a strong wave-like quenching.</td>
</tr>
<tr>
<td>Biotite</td>
<td>Small quantity; Size: 0.015-1.8 mm; Allotriomorphic; Plate-like; Light yellow and brown; Sometimes contains zircon, Replaced by epidote.</td>
</tr>
<tr>
<td>Muscovite</td>
<td>Small quantity; Size: 0.06-0.7 mm; Allotriomorphic; Plate-like And fiber-like; Sometimes bent; Colorless.</td>
</tr>
</tbody>
</table>

### Characteristics
Granite containing much potash and quartz; Alternated weakly by chlorite, epidote and sericite.
2.3 Geological structure

According to the geological survey map of Kalafatovich (1961)\(^3\) of the area around the ruins, there are many faults running parallel to a roughly NE-dipping vertical slope from the ridge connecting Mts. Machu Picchu and Waynapicchu to the eastern slope. Some of these faults traverse the ruins zone and connect with the western slope face. An open area called Foso Seco, which forms the boundary between the built-up area and the agricultural district, is believed to have been built along a spalling fault zone. In the present survey, exposed faults were observed on the sheer face of the road that winds its way up Mt. Waynapicchu. The faults dip at an angle of about 60\(^\circ\), and a roughly 30cm fault gouge (clay-like substance) was discovered. However, the gouge and both sides of the mother rock were securely consolidated, and no new zones of spalling were found. In addition, near a fault that apparently crossed the Bingham Road, granitoid phases lay on both sides of a fault and was continuously being transformed, so at the very least we can say that at that location, there does not exist a fault that has caused large displacement. However, judging from the orientation of the sheer cliffs that are seen around the ruins, it appears that this region is dominated by a vertical joint system in the NE, and it is quite apparent that part of this system is spalling. In Foso Seco as well, linear and both side dips are quickly changing, so there is a high likelihood that there is a spalling zone below.

![Fig.3 Projection of the joint surfaces of granites at Machu Picchu. Upper hemispher, Schmidt-net projection.](image)

On the other hand, there are very few joints in huge rocks that resemble outcrops in the ruins zone that dip toward the NE like the previously mentioned joints, and we can see from Figure 3 that NE- or SW-dipping joint faces dominate in the NW where these joints are crossed at right or obtuse angles. The main NE-oriented joints have large pockmarks and are spalling, so this might explain why they were not seen in outcrops. The granite in the ruins zone appears to have been gradually aggregating due to the weathering and erosion that have been progressing along the face of the joints. Weathering and erosion are still occurring, especially in the joints of the base section of the aggregate, which is becoming noticeably less stable as erosion progresses.
2.4 Sediments on the surface

As noted earlier, the topography around the ruins is extremely steep, so there is almost no topsoil, and there are many granitoids that are directly exposed to the atmosphere. These granitoids are fresh, and deep weathering (which is commonly seen in the granitic zones in Japan) is almost non-existent. On the other hand, there are weathered residual soils of from a few dozen centimeters to 2 meters thick on the surfaces of the ridges and nearby gentle slopes. These contain yellow-brownish mixed sands (Masado). The slope face of the relatively gentle-sloping Bingham Road offers the opportunity to observe a profile of layered sediments. The base rock of this area is covered with a colluvial soil layer that is 1-3 meters thick. The sediments consist of various sizes of rock masses and weathered residual soils (Masado) that have filled in the gaps. Red soils that are characteristic of warm regions are not evident here, and together with the severe erosion suggests that the age when the surface deposits formed was extremely recent.

3 Slope failure

3.1 Failure near the Bingham Road and hotel

In this zone there are still natural slopes covered with some sediments. Here and there on the Bingham Road there are areas of rubble that are from a few meters to about 10 meters wide. These were probably caused by water flowing out of excavations that were made when the road was built. In addition, on the slope above the visitor center there is a small-scale failure. Since there is a danger that the slope above the adjacent shop will also fail, appropriate measures should be taken.

In 1980, when an addition to the hotel was being constructed, soil that was removed from the work site was used to fill in the road shoulders, but it fell onto a slope of the Bingham Road, which in turn caused natural sediment deposits to fail in a wide area. Soto et al. (1980) estimated that 2,000 m$^3$ was displaced in this way. This has been the largest example of slope failure in the ruins zone.

3.2 Failure in ruins on the periphery of the ruins zone (Points A, B, C and D in Fig. 4)

While the slopes surrounding the ruins zone are supported by a terraced retaining wall, there are several locations here that have become arc-shaped (Points A, B and C in Fig. 4). These areas are believed to be the remnants of failure areas that were in existence before the structures were built. As of this writing, no abnormalities have been found in the retaining walls. However, on the natural slope in the SW part of the residential area ruins on the southern end of the agricultural district, there is some surface disruption that apparently

Fig.4 Collapsed locations inside and outside the built-up area
occurred relatively recently (Point D in Fig. 4).

3.3 Failure inside the ruins zone (Points 1, 2, 3, 4 and 5 in Fig. 4)

In the following description, stone structures are divided into two categories: 1) those that rise up from the ground surface, and 2) those that are attached to the ground. While there are some differences between residences, gates, peripheral walls, etc., that comprise the former, they are collectively called "stone walls" here. Although the latter category is divided into "retaining walls for terraced fields" and "retaining walls in built-up areas," they are all (with the exceptions of stairways and canals) referred to as "retaining walls".

(1) Point 1 The eastern slope of the northern end of the agricultural district which borders Foso Seco is about 5-20m wide, and the 12 levels of terraced fields (Andenes) below that show signs of either failure or deformation. This is the largest example of failure within the ruins zone. The upper section of the retaining wall that makes up the Andenes shows some collapsed areas about 2-5 m wide, and the retaining wall on the Foso Seco side is leaning forward by about 1 meter, with a maximum of 1.4 meters. In the lower section there are few areas of collapse, with the bottom three retaining walls being completely intact, and it appears that the flexured retaining walls are leaning forward like the aforementioned Foso Seco retaining wall. In conjunction with this, the surface of the terraced fields, which had originally been level, has either subsided (upper section) or settled (lower section) up to a maximum of 80cm.

(2) Point 2 A small of amount of retaining wall deformation (maximum 1.2 m of rock masonry) has been found in an area that stretches from farther above the top of steps that are used as a visitor's trail. From the above information, it appears that the series of failures and deformations in Points and were caused by hollowing from piping of groundwater in soil that was below where the Andenes had been built. However, the Andenes on the Foso Seco side have held their relative position and have not exhibited any failure, so the cause of the forward leaning is not known, but it could be due to very slow slope failure in this section. Failure and deformation here are said to have existed for a long time, from at least the time of the discovery of the ruins. At the present time, there is no phenomenon (such as percolation from the retaining wall, moistening of the soil, etc.) that suggests the existence of groundwater flow, and the area is believed to be completely stable.

(3) Point 3 A part of the Andenes retaining wall roughly 2 meters wide exhibited a slight bit of failure in the lower NE part of the agricultural district, but it appears to be old.

(4) Point 4 A roughly 8 m section of the peripheral wall of the residential district in the lower SE side of the built-up area exhibited failure that included those sediments. From its external appearance, it seems to be of recent origin.
There is a pile of rocks of varying sizes that have fallen on a slope immediately above a collapsed retaining wall, but this rockfall dates from before the time of the former failure.

(5) Point In the lower section of the EN part of the cemetery zone (Cementerio), there is a retaining wall that holds in an extremely steep slope, and minor failure of 2-3 meters in width has occurred. This failure part corresponds to a protruding part of old failure part of Point C in Fig. 4, and is originally an unstable slope.

3.4 Ground stability in the ruins zone

At the time the ruins were discovered by Bingham in 1911, many if not most of them were in a terrible state of disrepair. We can observe this state today in the unrestored residential district bordering on Foso Seco in the SE end of the built-up area. However, as far as the present survey could ascertain, there were only a few places where damage was apparent in the upper part of the rock wall rising up from the ground surface, and points to in the retaining wall and foundations of some buildings. These sites were previously mentioned as small-scale damage sites.

Considering that these ruins exist on extremely steep slopes, it appears that potential damage resulting from naturally occurring rockfalls, ground disturbance, etc., was held in check by the retaining walls, which protected the built-up areas. Closer examination shows fissures, out-of-place rocks, expansion, shearing of rocks, etc., in some locations, but this is not of recent occurrence; at the very least, damage does not appear to be progressing at a noticeable rate. Therefore, as long as there is not a major earthquake or especially heavy rainfall, there is probably little probability that damage will occur from the foundation in areas other than those just mentioned. However, at the time of discovery, the retaining wall on the E slope of Intihuatana was in a state of major disrepair, and was restored to its current condition in several stages up to the 1960s. Although there appears to be slight disrepair in other locations, due to the lack of old records, we can only make educated guesses from the current state of rock structure.

3.5 Points of caution (Points 6, 7, 8 and 9 in Fig. 4)

The following points should be given special attention because they might cause some instability in the foundation (note: upper structures of buildings (walls) are not discussed here).

(1) Point Pockmarking is occurring in a section of the retaining wall that protects the E slope of Solitary Hill in Intihuatana. From the summit to the lower right, there are pockmarks several cm wide that intermittently occur over a space of about 10 meters from top to bottom, and there is also a slight looseness in a nearby retaining wall. As reported earlier, the retaining wall
underwent major restoration work up until about 1960, but we cannot tell when after that the pocks started developing because there are no old photos available for comparison. Although it is unclear at the present time whether the cause of the abnormality can be traced to the base rock (probably outcrops of granitoids), there are at any rate no abnormalities in granitoid outcrops immediately beneath the pockmarked retaining walls, nor in the retaining wall on the W side of Intihuatana. Therefore, it appears that piled stones of the retaining wall had merely “peeled off” from the base rock, and there is no abnormality. At any rate, there is a chance that this pile will collapse if left alone, so it is necessary to discover the cause and take appropriate action as soon as possible.

(2) Point ⑦ The huge natural rock (Roca Sagrada) located in the SE of the built-up area and considered to be an outcrop from the summit is being cut down on the lower E side by joints. Therefore, its center of gravity is rising, making it very unstable.

(3) Point ⑧ On the E side of the stone mortar district (Sector de Los Morteros), there is a building on top of a huge natural rock on the boundary with the Andenes. The lower section is an attic-like space that has been created by immense joint faces, making it very unstable. In the boulder stone that is believed to be supporting some of the load, there are some fissures that have apparently developed recently, and there is a possibility that they could reduce the bearing strength.

(4) Point ⑨ On the S side of the Templo del Condor, natural stone joints have formed a cavern. Some of these joints have been made loose by groundwater, so that part of the natural rock is in an unstable condition. It should be noted that some fissures have been found in the natural rock of this temple, but they appear to be old fissures and the rock itself is believed to be stable. If left alone, the natural rocks in , and , even if they did not fall over, might lean over so far that they would affect nearby structures. Therefore, detailed surveys must be made and appropriate measures taken. ⑧ The same suggestion is also described in reference ⑦ without concrete points.

4. Summary of and proposals for survey activities

The coordination activities and proposals that follow are based on a consensus reached by the experts from the six fields who participated in the 1990 survey. However, since the majority of these are closely related with the results of the topographical and geological surveys described in the previous section, there will be somewhat more focus on the topographical and geological aspects.
4.1 Summary of survey activities

The area surrounding the Machu Picchu ruins is a region of rugged young mountains. The ruins are bounded on three sides by the meandering Urubamba River and are in the col of a hilly section having a relief of 500 meters. The surrounding slopes range from 30-50°, with very steep slopes exceeding 60° in some places. The foundation of the ruins zone is composed of granites overlain by an extremely thin depositional soil layer, with huge outcrops and boulders scattered about.

Despite their location on very steep slopes, most of the terraced field (Andenes) that come into direct contact with the ground surface, as well as the major portion of the retaining walls in the built-up areas, remain in more or less the same state they were in when they were built, and there are only a very few, limited areas that have been damaged or deformed. At the same time, most of the structures were discovered in a dilapidated condition, but there are few places where the damage extends down to the foundations of the structures.

The following is a list and description of the very small number of places that are having problems with preservation:

(1) The vicinity of the Temple of the Sun (Templo del Sol) and the Royal Tomb (Tumba Real)
Due to poor drainage, the foundation is becoming very damp. Although it is in only a small section, some of the masonry appears to be coming out of place. If this condition is left as is, there is a chance that damage could soon occur in the surrounding ruins.

(2) Retaining wall on the E side of Intihuatana
A continuous fissure was found that extends about 10 m from top to bottom. If left unchecked, the fissure could expand, potentially causing part of the retaining wall to partial collapse.

(3) Part of the outcrop or huge boulders seen in the Prison Sector (Sector Carceles) and its environments
Fissures, etc., are expanding in the rock that supports this zone, possibly resulting in a weakening of the bearing strength.

4.2 Proposals

When viewed in terms of the conditions that we have just described, the foundations of the ruins are relatively stable, and they do not appear to be in any danger of collapse. However, given that these ruins are very moist and are located on steep slopes, they might not be completely safe against the effects of a major disaster such as an earthquake (refer to (3)) or unusually heavy rain event (refer to (2)) sometime in the future. To maintain these world-class treasures for future generations, an intensive effort must be made to formulate and implement long-term preservation policies.
As the first step toward this goal, and as a means for obtaining an accurate understanding of the natural environment of the ruins and the condition of their foundations, we would like to propose the following fundamental activities:

(1) Creation of large-scale topographic maps
Because of its location on steep slopes, there is no doubt that the local undulating topography would have a tremendous effect on estimating the input seismic force and for calculating slope stability, seismic response spectra, etc.
However, while there are 1:5,000 topographic maps available for the area around Machu Picchu, there are only planar diagrams of the ruins zone itself. Detailed topographic maps with a scale of at least 1:500 and contour lines based on increments of 0.5-1.0 meter should be created to provide basic materials for earthquake, landslide and drainage policies.

(2) Weather observations
The purposes of weather observations in this region are to 1) use long-term observational data to estimate rarer catastrophic weather events such as deluges, abnormally strong winds, etc., and 2) use daily observations to formulate appropriate measures, such as issuance of fire warnings due to abnormal drying and high winds, closure of the ruins due to heavy rains, high winds, etc., and evacuation of tourists. Because these observations would be made in an especially precipitous area, data from different environments cannot be used in place of local data, so it is vital that observations be made in the ruins zone itself.

(3) Seismic measurements
While there has been no reported earthquake-induced damage in the vicinity of the ruins, this may be due to the sparseness of the population and lack of historical records. The Cuzco area 75 km to the SE of the site has witnessed several damaging quakes over the centuries, including ones in 1650, 1707 and 1986. In addition, the Cuzco area touches the Cuzco Fault Zone, a group of active normal faults that extend toward the WNW. The ruins lie to the north of the 50 km-long Zurite Fault, which comes within 35 km of the ruins. In addition, the ruins are in a unique place in that is it mostly steep slopes, making it difficult to estimate seismic intensities from measurements taken in flat areas. To obtain useful data on the seismic activity in the surrounding area as well as the seismic intensity that occurs in the ruins zone, we propose the establishment of a network of seismic monitoring points.

(4) Fundamental surveys for diagnosing the state of ruins and their foundations
In the reinforcement and restoration of cultural treasures having special and valuable architectural styles, locational conditions, etc., such as what are found at Machu Picchu, we must first have a satisfactory understanding of the civil engineering and architectural techniques in use at the time of construction. Therefore, we propose detailed surveys of the ground and foundations of
important structures and typical points throughout the zone, as well as of the state of walls, including at places that have been restored, that can provide for the creation of a civil engineering, architectural and archaeological diagnostic record.

(5) Detailed mechanical surveys and evaluations of individual points requiring immediate action
Specialists in soil engineering and stone structures are conducting detailed surveys and will make proposals for measures needed to preserve the following problem points requiring immediate action:
1) Continuous fissures found in the eastern retaining wall (stone wall) at Intihuatana, and
2) Instability of outcrops or rock clusters found at two or three points at or near the Prison Group.

5. Concluding remarks

After the 1990 survey, the author (Fujisawa) conducted a series of observations in 1995, 1998 and 2000 on the state of slope failure and stability. While there are visible signs of some of the work that has been done to prevent dampness in the vicinity of the Temple of the Sun and the Mausoleum, repair the gaps in the retaining wall on the steep east side of Intihuana, install weather monitoring equipment, etc., as per the suggestions of the Japanese survey team, nearly all of the area remains as it was during the 1990 survey.

Acknowledgments

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accompanied us on our in situ survey of Machu Picchu and provided their assistance, advice, and technical skills.

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