Machu Picchu: Prehistoric Conservation and Water Handling
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Abstract
Before Columbus sailed for America, the Inca civil engineers built an empire based on roads, agriculture, and water management. Prehistoric civil engineers at Machu Picchu harnessed groundwater with a cleverly designed collection works system, transported it to its point of use in a stone-lined canal, and then distributed it for domestic use via 16 fountains. By transmitting a separation between water supply and drainage runoff, the water quality was insured. Machu Picchu the last city of the Inca, provides an example of New World prehistoric civil engineering genius for environmental, setting, layout, and design has made it a U.N. World Heritage Site and a National Geographic Society World Wonder.

Introduction
Machu Picchu lies about 1,400 kilometers (870 miles) south of the Equator on the eastern slope of the Peruvian Andes at Longitude 72°22' and Latitude 7°20' near the headwaters of the Urubamba River. Machu Picchu is said to lie like a patchwork quilt on a mountain ridge between two prominent mountain peaks: Machu Picchu and Huayna Picchu (Wright 2003).

Native Americans built Machu Picchu before the arrival of the Spanish Conquistadors. It was abandoned after the Inca Empire collapsed, yet Machu Picchu endured under a thick rain-forest until the Twentieth Century. Scientists, engineers, and laypersons alike continue to marvel at the wonders of Machu Picchu, its water management, and its magical ambiance. The mystique of Machu Picchu is in its detail: the hydrology of the water supply, the hydraulics of the canal and fountains, and the blending of men's work with the challenging natural topography and environment with which the civil engineers were faced.

The Ancient Royal Estate
Machu Picchu, the royal estate of the Inca ruler Pachacuti (Rice, 1990), is a breathtaking monument to the ancient engineering skills of the Inca people. Construction of Machu Picchu began in A.D. 1150. It was abandoned in A.D. 1562 and finally abandoned 10 years later. However, it likely ceased normal operation by A.D. 1550 due to the collapse of the Inca Empire.

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Although the Inca did not have a written language, the well-preserved remains of Machu Picchu show that they had an advanced understanding of such principles as canals, fountains, urban planning, hydrology, hydraulics, drainage, and durable construction methods. By studying the Inca's engineering techniques, in conjunction with the natural environment, we are able to supplement existing archaeological theory on the Inca's practice, religion, and the significance of Machu Picchu.

Machu Picchu's technical planning is surely the key to the site's longevity and functionality. The Inca's careful use of hydraulic, drainage, and construction techniques ensures that the site was not reduced to rubble during its many years of abandonment. These techniques, combined with a strong knowledge of hydrology, were made in a grand and operational sense high in the rugged terrain.

Ancient Engineering Care

One of the reasons Machu Picchu endured through the centuries is because the Inca civil engineers used proven water handling technology and a high standard of care in their building process. Much of their work is not visible until excavated. The unseen Machu Picchu exists in its subsurface drainage system and the extensive foundations that underlie the terrace walls and buildings (Wright 1996). Archaeologists who have excavated at Machu Picchu conclude that 60 percent of its building effort went into the site's preparation, drainage, and foundations.

After viewing the steep colluvial slopes of Machu Picchu, the civil engineers quickly realized that the Inca relied upon at least a rudimentary knowledge of slope stability technology. Although analysis of the stability of a colluvial slope is perplexing, the success of slope stability at Machu Picchu demonstrates that the Inca engineers incorporated solutions common to today's engineers.

The canal, fountains, drainage, foundations, and stone walls at Machu Picchu tell us a lot about the workers and civil engineers of ancient Machu Picchu. The civil engineers selected and used a wide variety of wall styles and stonework quality to satisfy particular functions. Walls range from the flimsy—those of the Temple of the Sun and the tight-fitting polygonal stone of the Apartments Wall—to rough field stonework in the agricultural terraces.

Work in Progress

The Machu Picchu we see today was never finished. It was still very much a work in progress when Inca workers packed up their tools in A.D. 1540. While working at Machu Picchu, we didn't realize, at first, how many buildings were still under construction. In fact, what we found was mind boggling and even surprised our colleague, Dr. Alfredo Valencia Zegarra, a veteran local archeologist who grew up with Machu Picchu and who we consider the world's leading experts on the site.

There is abundant evidence that work in progress had been interrupted. For instance, we found a temporary construction ramp near the Sacred Rock. Sloping 30 degrees, this ramp served to lever large stones up onto a high wall. Nearby, a large stone has been left on the wall. It is tilted at a 45-degree angle so that the bottom could be shaped to make it slide snugly onto the stone below.

The huge stones of the Principal Temple were still being shaped when work ceased. And the walls of the Temple of Three Windows still bear the centuries old
store-chipped instructions from the master stonemason to his workers. Further, what one can be seen of the huge raised platform that Hiram Bringham, in 1913, called the Temple of the Jagged Rocks shows that it would have become a striking architectural addition to the site. We also found a haphazard group of partially carved stones from atop Huayna Picchu, we discovered evidence of monumental building. And several hundred yards up the Inca Trail towards Huayna Picchu, we came upon examples of huge stones in the process of being shaped and placed.

Check out the evidence on your next trip to Machu Picchu. Imagine the busy stonemasons and civil engineers in A.D. 1540 working to bring this exquisite royal estate to completion. Just look for the clues.

The Inca royal estate of Machu Picchu is clearly the most famous archaeological site in the Western Hemisphere. That it has endured for centuries is due to the skill of the nameless engineers who built it five centuries ago (Kendall 1975).

The well-preserved remains of Machu Picchu show that the Incas had an advanced understanding of urban planning, hydrology, hydraulics, drainage and impressive construction methods. By studying their engineering techniques, we are able to broaden our archaeological knowledge of their building techniques and shed light on the significance of this world famous site.

**Construction Methods**

The precision achieved by Inca engineers is legendary. But until recently, what was known of their construction methods fills only a few pages in the ASCE Press publication Machu Picchu: A Civil Engineering Marvel (Wright and Zegarra 2000). Because of the paucity of data, we returned to the archaeological site on several different occasions during 2001. On those occasions, we set about to inventory, document and analyze what construction remained uncompleted. We used this information to provide advice to an artist as to what Machu Picchu looked like in A.D. 1530 for the National Geographic Society’s beautiful map supplement. This appeared in the May 2002 issue of the National Geographic magazine.

Scientists still argue about the methods the Incas used to move the huge stones into place and match them with others to form perfect joints. Engineers still disagree on what type of timber structures supported the thick, heavy thatched roofs of the buildings, while others marvel at the sophisticated drainage and flood control system that can handle nearly 2,000,000 liters (79 inches) of precipitation that falls on Machu Picchu annually. The Inca engineers who met all these challenges had no written language, wheels, iron or steel (Von Hagen and Morris 1998). Even today, the mystery remains—how the Incas accomplished so much with so few visible means.

**Construction Ramps**

Signs of the considerable construction taking place at The Unfinished Temple (a.k.a. Temple of the Jagged Rocks) are everywhere. One of the most visible indications of this activity can be seen from the construction ramps alongside the unfinished terrace walls on the west and northwest sides. Years ago, Dr. Valencia took us to this ramp when we were studying types of Inca wall construction. The largest construction...
The largest ramp has a slope of approximately 60 percent (39 degrees from horizontal). Along with the construction ramps, there are also several examples of temporary worker platforms along the west wall of the Unfinished Temple and on the northwest wall.

**Rocks Availing Placement**

We found a number of rocks that had been in the process of being transported and placed. Examples include the large stone in the middle of the Sacred Plaza near the Temple of the Three Windows. We removed from the position, shape, and size of the rocks that this rock was being moved into place to serve as a central support for a roof beam for the Unfinished Temple. Another example is a large stone in the main section. The smaller stones beneath the large stones were used like rollers to reduce friction when moving the stones.

Other examples of rocks availing placement can be found along the west wall of the Unfinished Temple. A good illustration of a rock about to be placed is seen at the north end of the west wall. A tool was used for this placement and was to lower the rock, tilted at 60 degrees into position to the left of the cornerstone. Once in place, hammer stones were used to smooth the rock faces.

**Terrace Walls**

Two examples of megalithic stone terraces on the east and west walls of the Unfinished Temple. The construction ramp again served to build up stones and provide a platform to sit them in place. Another unfinished terrace wall is seen along the west side of the Sacred Plaza. It may have been a fourth temple was planned for this location; the small circular wall is oriented to emulate the Cuzco Inca. The rocks nearby have been cleared and are ready for placing in the wall.

At the Unfinished Temple, on the top tier, many cut stones around. These stones provide insight into Inca practice, construction methods, and the exact measurements that characterize Inca stonework. Before placing the stones in their final position, the builders first conducted a dry run, fitting the stones into place on the ground. Once measured a proper fit, the stones were placed in the wall.

In addition to the unfinished walls is found in the Urban Sector, there is unfinished terraces construction and repair work in the Agricultural Sector.

**Roofs**

After conferring with Vince Leo, an expert on Inca design and construction, Ruth Wright Dr. Valencia and Alfredo Marmonty examined every building for roof structures and analyzed construction techniques. At the Principal Temple, we found roof gables that were under construction and others at the Temple of the Three Windows. The niches at the Principal Temple were being enlarged to support larger beams at the time of abandonment.
Tough Hewn Stones

Stones in the process of being finished are seen around the Unfinished Temple, the Temple of Three Windows, the Principal Temple, the Sacristy and the Temple of the Moon. Work marks or unpolished-stone rock faces indicate that the work was ongoing. A wall of the Temple of Three Windows is likewise unfinished. Under the watchful eye of Dr. Vallecrosia, we carefully documented the abundance of evidence. Motifs on the outer side of the wall showed how the rock was being cut back. A line chipped in the stone marked what would eventually be the finished surface. Many inferior walls in the Principal Temple were left unfinished. Many large stones were already in place but would further work before they could be the smooth, meticulously fitted surface for which the Incas are known. Once you know what to look for, work marks on the stone showed, and all over (especially the Sacristy), rough, unfinished stone was needed to maneuver and position the stones have yet to be smoothed away.

At the quarry at Machu Picchu you can see another dramatic example of work in progress. An unfinished stone staircase lies near the Rock of the Serpents. This stairs clearly fits into some overall design, but its final destination is unknown.

Uncompleted Canal

You will find a terrace just below the Inca Canal, as it crosses the Agricultural Sector. Here, there was to be a secondary canal. On this traverse, we encountered numerous stones, with a small imperceptible cross section cut into them. After examining the stones, we concluded that the lower streamcross cut the ends of the stones and left them to be connected by the workers. Some partially finished, were left when the workers abandoned the site. The secondary canal was meant to be smaller and narrower than the main canal, but it was never finished. Based on the location of these stones—too low to deliver water to Fountain 1—and given the small size of the canal, we deduced it was intended to feed water from the main canal, perhaps to supply another series of fountains. No one will ever know for sure.

Landslide

Landslides damaged the Agricultural Sector; Wright has estimated that 80 percent of this problem was corrected before construction ceased left Machu Picchu. Our colleague, geologist Eric Buka, carefully studied the prehistoric ground shift and mapped them with a scientist's devotion to detail.

One quarter landslide, from map to sea, covered 140 m, with a vertical drop of 66 m. This landslide damaged many terrace walls, displacing several by 1 to 2 meters. The full-length ancient staircase is intact, however, showing that it was either constructed at a later date or was completely repaired. The landslides left a stable position of steep slope without terracing, a relocated canal, a drainage channel to intercept runoff water, and ten partially completed terraces. By A.D. 1540, Inca engineers managed to stabilize the slope, but the terraces were still being repaired when the site was abandoned.
In a Nutshell

To build walls Inca engineers made use of ramps formed by stone walls filled with earth. Workers stood on platforms of stacked stone to shape and place the stones. As there is no evidence otherwise, we concluded that the Inca did not use ladders at Machu Picchu. This is why no ladders are shown in the National Geographic May 2002 map supplement. Larger stones were moved around using smaller stones underneath to reduce friction. It's our opinion that the engineers at Machu Picchu commonly employed the levering techniques described by Vincent Lee (Lee 1999).

The Inca carefully fit the megalithic terrace walls to provide structural stability and prevent a fire appearance. Though excavations, we determined that, unlike the visible front side of the terrace walls, the backside had not been smoothed but left in a rough state. Terrace walls tilt back at a 3- to 6-degree slant.

We found five Inca roof types: gable, hip, conical, shed and the waynnna (i.e., the elegant unbalanced gable form one finds on three-sided buildings) as seen in National Geographic. The Inca cut niches in the stones to support the beams. We came across several niches that had been in the process of being enlarged, presumably to accommodate a larger and stronger beam than called for in the original design. Throughout, we found evidence of thoughtful design and crafting.

It seemed a common practice for Inca workers to put stones in place before finally shaping the rock. Often they oriented stones upward to allow final shaping of the bottom of the stone face. Smoothing and polishing the stones was accomplished with hammerstones of various sizes, ranging from 20- to 25-centimeter (cm) (8- to 10-inch) river cobbles down to 6-cm (2.5-inch) diameter cobbles. It is clear that the Inca set the very large stones in place first, then shaped them to predetermined building lines. Evidence for this can be found on the Temple of Three Windows and the Principal Temple. Stairways, on the other hand, seem often to have been roughly hewn at the quarry and then moved to their final destination. And in some cases the Inca appear to have placed the lower rocks of a building temporarily in position to check the size and alignment. They were then moved away, shaped and returned for final placement.

Dozens of stones strung out in a row indicate what was to have been a canal. Here, you can see a good example of the division of labor between worker and master mason: once the shape and position of the channel was established, the cutting and shaping of the individual channel stones was left to the workers.

Summary and Conclusions

Our investigations convinced us that Machu Picchu was still very much a work in progress up until A.D. 1540, when the Inca Empire collapsed. There is no doubt that the Spanish conquest interrupted the work at Machu Picchu. Had the civil engineers finished their work, Machu Picchu would be even more attractive. Visitors would find an imposing temple, rising over the large central plaza just south of the Sacred Rock.

To achieve the vaunted precision and monumental design, Inca engineers relied heavily on building techniques seen in earlier civilizations throughout their far-flung empire. The willingness of the Inca to adopt technology from other cultures is a valuable lesson for modern engineers. The similarities in construction between...
The Inca selected the most beautiful terrace sites for the placement of their huacas and ceremonial centers. These huacas were not only valued for their aesthetic qualities but also for their strategic locations that provided access to water sources and other natural resources. The Inca's understanding of the landscape, coupled with their sophisticated engineering skills, resulted in the creation of huaca complexes that were both functional and symbolic.

References


