1. **Machu Picchu, Peru, Inka (Inca) c. 1450–1540**

**MACHU PICCHU AND LIVING AT HEIGHTS**

What remains of the Inca legacy is limited, as the conquistadors plundered what they could of Inca treasures and in so doing, dismantled the many structures painstakingly built by Inca craftsmen to house the precious metals. Remarkably, a last bastion of the Inca empire remained unknown to the Spanish conquerors and was not found until explorer Hiram Bingham discovered it in 1911. He had found Machu Picchu, a citadel atop a mountainous jungle along the Urubamba River in Peru. Grand steps and terraces with fountains, lodgings, and shrines flank the jungle-clad pinnacle peaks surrounding the site. It was a place of worship to the sun god, the greatest deity in the Inca pantheon. The survival of Machu Picchu over hundreds of years, on a mountaintop subject to erosion and mudslides, is a testament to Inca engineering.

Perhaps most unique about Inca civilization was its thriving existence at altitude. The Incas ruled the Andean Cordillera, second in height and harshness to the Himalayas. Daily life was spent at altitudes up to 15,000 feet and ritual life extended up to 22,057 feet to Llullaillaco in Chile, the highest Inca sacrificial site known today. Mountain roads and sacrificial platforms were built, which means a great amount of time was spent hauling loads of soil, rocks, and grass up to these inhospitable heights. Even with our advanced mountaineering clothing and equipment of today, it is hard for us to acclimatize and cope with the cold and dehydration experienced at the high altitudes frequented by the Inca. This ability of the sandal-clad Inca to thrive at extremely high elevations continues to perplex scientists today.

A Marvel of Inca Engineering The ancient Inca wonder of Machu Picchu, perched 8,000 feet above sea level on a ridge in the Peruvian Andes, was a royal estate for the legendary warrior Pachacuti, who was largely responsible for building the Inca Empire in the 15th century. Like other massive stone constructions of this formidable emperor, it was built with eternity in mind. But how did Inca builders ensure that Machu Picchu would survive in its precarious mountaintop setting? Ken Wright, a civil engineer who has been studying the site since the mid-1990s, explains in this interview. While impressive today, Machu Picchu would have been an even greater site to behold in the late 1400s, with gleaming white granite walls topped by golden-colored thatched roofs.

**A ROYAL CHALLENGE NOVA: What was your first impression of Machu Picchu?**

Ken Wright: When I arrived in 1994, my first visit ever, I was blown away by the view of Machu Picchu itself and also by the surrounding territory. The first question in my mind was, why would they ever take on a site this difficult? Engineering wise, it would seem almost impossible to handle. The first day, I was not looking at engineering evidence, I was being awed by the site, just like every other tourist. The second or third day, I began looking at the Inca spring and the canal, a canal that led for 2,500 feet to Fountain Number One and all the way down to Number 16. I saw not just a watercarriage system but a well-engineered system. A lot of thought had gone into it. That was when I first realized that this was an engineering marvel. Why would the Inca build on such a difficult site? The more I became familiar with the site and looked at the mountains and the rivers surrounding it, I realized why. The Huayna Picchu mountain on the north, Machu Picchu mountain on the south, Mount Yanantin, the triangular peak Putucusi—all of these are holy peaks. We know they are because when we're with the Quechua Indians, the people who are the descendants of the Inca, they pray to [these mountains], so the site is a natural. It couldn't have been better as a royal estate for Emperor Pachacuti.

**How did they know that the mountain spring would provide adequate fresh water?**

What the Inca likely did, upon arriving at the site and before deciding that they were going to build there and before cutting down all the trees, they would have studied the spring and made some measurements, so they'd have an idea of how much it would flow and how much it would vary during the year. We know they did that because the evidence tells us that the canal was just the right size for the spring yield, and the fountains are just the right size for the canal. How long they spent studying the site, we don't know. But it couldn't have been a long, long time because all of Machu Picchu was built in roughly 90 years [A.D. 1450 to 1540]. They couldn't have spent a decade studying the water supply. I would think a year or two. If you had been an Inca planner, overseeing the building of the estate, what would have been your greatest challenge? The biggest problem would be landslides, unstable earth, and for that reason I would have my civil engineers focus on being good stewards of the soil. Stabilize the slopes with the appropriate terraces, and plenty of them. The other thing I would do is spend a lot of time and effort on foundations and site preparation, because I knew I was building for the ages. And the Inca engineers did spend about 50 percent, maybe 60 percent of their overall effort underground—doing foundations, site preparation—to make sure that Machu Picchu would last forever.

**A STABLE FOUNDATION How did you get a sense of all the underground foundation work they did?**

We had an excavation done in the Plaza, a very important part of Machu Picchu that separates the eastern urban sector from the western urban sector. It went down probably nine feet. In that nine feet, we found about three feet of topsoil, rich topsoil. Under that was a sandy, gravelly-type soil, and then we came across an underground, subsurface drainage system made out of waste rock from all of the stones that they'd been cutting for years and years and years. This rock turned out to be white because it was white granite originally, before turning color with age. So while we look at Machu Picchu today and see gray buildings, when it was built, it was white granite. At any rate, the white granite told us a lot about their engineering ingenuity and their desire to provide good drainage for Machu Picchu, because without good drainage, there would be no Machu Picchu existing today. Wright's excavation revealed a vast underground drainage system with layers of topsoil, sandy gravel, and granite waste rock

**There was a surprise for you at the bottom of the excavation, right?**

Yes. At the very bottom of the excavation was a golden bracelet—the only gold found at Machu Picchu—and we are very pleased to have that. It's in the Cusco Regional History Museum today.

**Why was good drainage essential?**

How much rain does the area get? About 76 inches per year, and it mostly falls during the wettest seven months or so. That's a lot of water, roughly two and a half times as much as the city of Chicago gets. What role do the many terraces play in this system? The terraces, the 700 or so terraces, have a high permeability, so the water goes down underground to be carried safely away. Terraces at Machu Picchu are fundamental to its longevity. Without terraces, the mountain would have slid terribly, so we see them primarily as the means for soil stabilization and support of buildings or trails. But they also provide agricultural area. Roughly 700 terraces carved into the mountain and fortified by granite walls help keep Machu Picchu stable.

**In the urban areas, where the residents lived, did the Inca use anything like our modern sewer drains?**

Yes. In the urban areas, you would find lots of thatched roofs. A thatched roof has a lot of run-off. It's almost like a parking lot, so they had to deal with the run-off, and that was handled by a well-planned urban drainage system. Overall, we've found some 130 drainage holes that were planned during the initial construction of the walls, not put in as afterthoughts. The Inca were better urban drainage engineers than we are at the present time, because they planned ahead. My reaction was one of admiration, one of awe, because these people did not have a written language, they did not have iron or steel, they did not use the wheel, and yet they were developing drainage systems that were good. And we know they were good because Machu Picchu has lasted for some 500 years. How does the stability of land at Machu Picchu compare with that on surrounding peaks? You can look around at surrounding mountainsides and see landslides that have happened in the past 10 years or so. But at Machu Picchu, it's been quite stable. Now, that doesn't mean that the Inca were perfect. When we look carefully, we find some buildings have settled, like the Principal Temple, and we find clues that the Inca had a landslide that they were in the process of curing. So there are a few places where the magic aura of the Inca did not mean that they were perfect. Another Inca marvel: On the morning of the summer solstice, light pours into a window of the Temple of the Sun to illuminate a sacred rock.

**Did the quality of the Inca stonework also play a role in Machu Picchu's longevity?**

Certainly. The Inca buildings have endured because of the good foundations, the slope, the interconnected stones, the tight joints. They built for the ages. The stonework is beautiful, too. It is. Hiram Bingham [the American explorer who found the site in 1911] called the Sun Temple's Inca wall the most beautiful in South America because of its exceptional design, the way the stone is shaped and carved. It's a masterpiece, and it's beautiful, and it has withstood earthquakes now for 500 years. But from my standpoint as a civil engineer, my greatest admiration is for the water system and the fountains, because they are so out of this world.

**SACRED WATERS How did the Inca plan the layout of the estate, particularly given that they had no written language?**

Machu Picchu is a planned estate. It certainly was not built haphazardly. But we know that the Inca had no writing, so they may have drawn plans up with clay models. We don't know that, but we do know that it was planned because the evidence is there. Everything is orderly; it fits. The Inca spring, in many ways, controlled the layout of Machu Picchu. The location of the spring was fixed, and the Inca engineers figured out the slope of the canal and set it at an average of about three percent, and the length was fixed at about 2,500 feet. These things were determined by nature and by hydraulics. The canal and fountain system, designed to provide a steady flow of fresh water, shows remarkable planning and foresight.

**So did that help determine, for instance, where the Emperor's residence was sited?**

Yes. Obviously, the Emperor should have first use of the water, the cleanest water [from Fountain One]. So that's where they built the residence, and they also built the Temple of the Sun there, and Wayrona [a three-sided building], and Fountain Number Three, which is a sacred fountain. How do we know that water had a sacred nature for the Inca? They went to special care to provide the sight and sound of flowing water, or falling water. And that included the sight and sound of water from the Urubamba River 1,600 feet below. The roar at Fountain Number Three and the Wayrona was loud, and delightful. Also, just outside the walls of Machu Picchu is an overhanging rock, a very important rock. This overhanging rock catches the sound from the Urubamba River 1,600 feet down and amplifies it, so when you're in this little area, the roar is good. So we could tell from the evidence of the layout that water certainly had a sacred aspect in their religion.

**Do you see a reverence for nature in other ways at the site?**

Yes. Walking through the main gate, the only formal gate into Machu Picchu, you find that the doorway frames perfectly the wonderful peak of Huayna Picchu. The ancient windows have special views, either of the Urubamba River below or of a mountain peak, and then when we look at the terraces near the guardhouse, we realize that these terraces weren't built just for utilitarian soil stewardship purposes. The beautiful curves are a masterpiece of environmental and aesthetic design. The breathtaking view looking down toward the residential complex.

**KEEPING CLEAN How much water could the canal and fountain system handle?**

All of the fountains, all the way down to 16, were established to handle about 25 gallons per minute maximum. In the event that run-off water came into the canal during heavy rainfall, the Inca engineers provided two safety valves, one in the middle of the agricultural zone—it would discharge out onto the agricultural slope and just infiltrate into the ground—and another at the main drain. So what we saw was a balanced system all the way from the spring to the main drain. And do we know that the water was kept clean? What do we know about Inca hygiene? Well, Inca hygiene, we know little about it except the evidence that they left in the field. And we were amazed that the water supply canal was built in such a way that it would be pretty well isolated from drainage holes and from potential pollution. So it was laid out in such a way as to provide for maintaining pure water.

**What about sewage?**

Well, all we can say is that these people were agriculturally oriented. The power of the Inca Empire lay in its ability to produce food, food surpluses. But the [Emperor's] residence, which is nearby Fountain Number One, has a room in the back that's considered to be the bathroom area. The only house sanitary drain that we've found coming out of any building in Machu Picchu came out of that room, and it didn't go to any place where it could possibly contaminate. So we concluded that these people somehow had a sense of hygiene and pure water, long before Westerners did, for instance, in the city of London. Another thing that impressed you, I imagine. We've been doing this for roughly 15 years now, and every time we visit Machu Picchu and study some aspect of it, we are more amazed than before. The whole system of Machu Picchu is a marvel—not just the water system or the most beautiful wall—but how everything fits together, ranging from the foundations, which would be geo-technical engineering, to site layout, which would be city planning, to trails that deliver people from one location to another without interfering with someone's privacy, to the huge plaza which provided the space for celebrations. When you look at Machu Picchu as a whole, complete with the temples and the solar observatories, you realize that it is a site that's well designed, well balanced, and somewhat of an engineering marvel.