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Inca Stonemasonry

Enormous stone blocks were quarried, shaped and fitted so closely that a knife blade cannot be inserted into the joints. How was it done? To provide answers the author cut stones in an Inca quarry

by Jean-Pierre Protzen

It was only in the 100 years or so before the Spanish conquest of 1532 that Inca culture reached its height. During that century Inca society was transformed from a minor agricultural state in central Peru into a mighty empire stretching from Chile to Ecuador. One aspect of the cultural flowering was an ambitious program of new construction initiated by Pachakuti, the ninth Inca (or emperor), in 1438. Pachakuti ordered his stonemasons to rebuild Cuzco, the capital of the emerging empire. The rebuilding did not come to a stop at the death of the ninth Inca. His successors extended the new construction far beyond the boundaries of Cuzco. Throughout Peru temples, palaces, warehouses and waterworks were thrown up, breaking new ground or replacing older structures.

Pachakuti's construction agenda was not only ambitious but also technically innovative. Although most earlier Inca structures were probably built of adobe or mud-bonded stones, the new work was done entirely without mortar. Stone blocks weighing as much as 100,000 kilograms (about 220,000 pounds) were fitted so closely to their neighbors that even now a knife blade cannot be inserted into many of the joints.

For hundreds of years visitors to Peru have been intrigued by the size of the blocks in the Inca stonework and the precision with which each block is inserted among its neighbors. The fact that the Incas had no iron tools makes the stonework even more impressive. In 1979, on my way back to the U.S. from a temporary teaching appointment in Brazil, I visited some of the main Inca sites and marveled at the ingenuity of their construction. When I asked my guides how the Incas shaped the great stones and assembled them into buildings, however, I got answers that were less than satisfying. On returning to the University of California at Berkeley, where I teach architecture, I asked colleagues who are archaeologists about the scholarly literature on Inca stonemasonry. To my surprise I was told there was none.

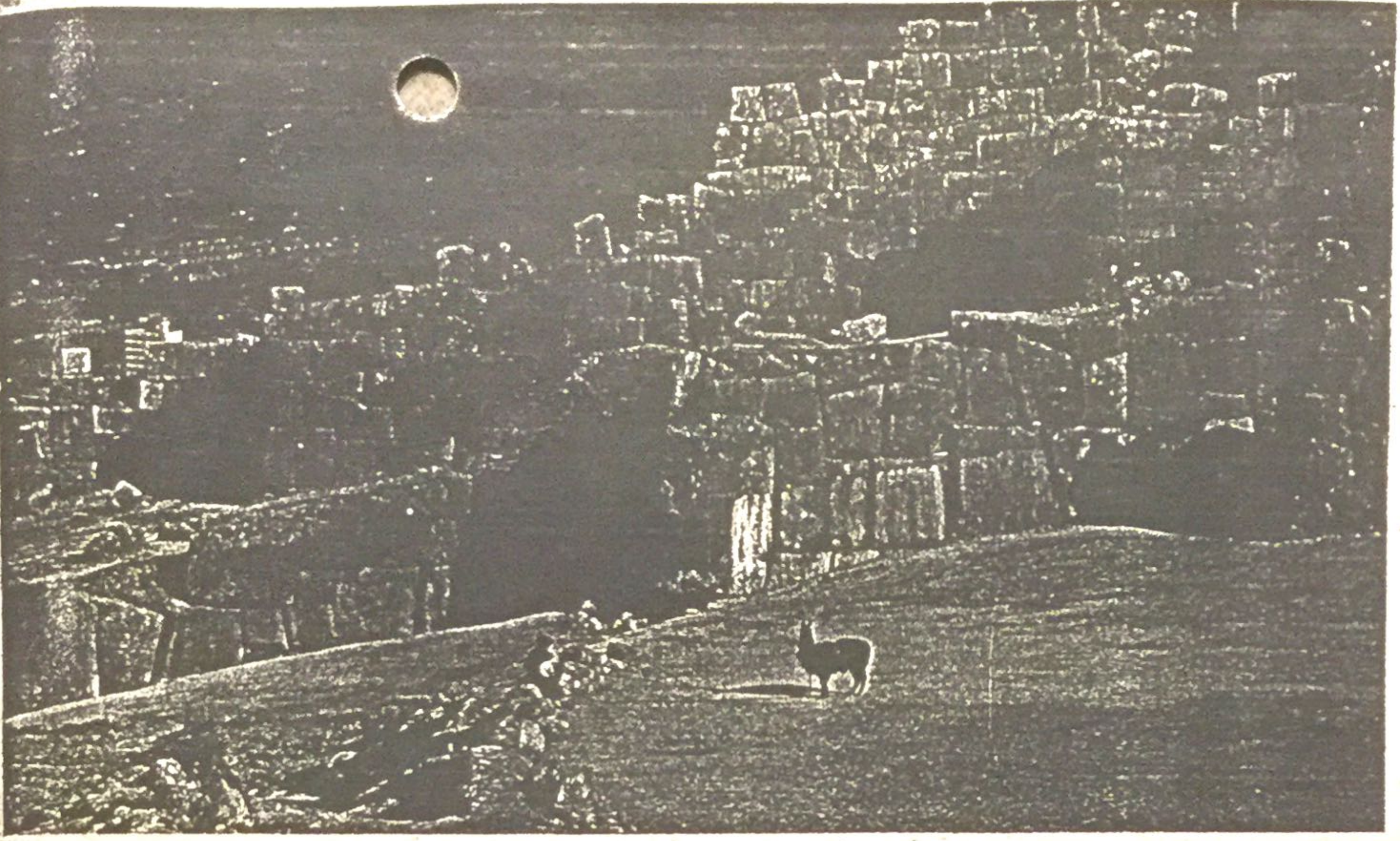
Although I am not an archaeologist, I have a keen professional interest in construction techniques. After turning the matter over I decided to investigate the Inca walls on my own. A sabbatical leave in 1982 provided the opportunity to spend six months in Peru; since then I have returned for about a month each year. My investigation did not stop at the stage of hypotheses. When I had formulated a hypothesis, I put it directly to the test. Using materials available at the Inca sites, I cut, dressed and fitted stones to show that these tasks could have been carried out by the Incas as I propose. Some mysteries remain, particularly in the area of how the big stones were transported and handled at the building site, but by and large my investigation was successful. As a result speculation about how the Incas built their beautiful stone structures can now begin to be replaced by empirical findings.

Much of my research involved analyzing specific Inca walls at Cuzco itself, and at the "fortresses" of Saqsaywaman and Ollantaytambo. Saqsaywaman is near Cuzco and Ollantaytambo is on the Urubamba River about 90 kilometers northeast of the Inca capital. Although many texts refer to Saqsaywaman and Ollantaytambo as forts, recent archaeological investigations suggest they had a religious function rather than a military one. Whatever role they had in Inca society, the two sites are impressive from the point of view of construction techniques. Saqsaywaman is a very large site that includes outworks made up of three separate stone walls, each one more than three meters tall. Ollantaytambo, built on the spur of a mountain, included a religious center, a royal estate and a town planned on a grid.

How were these great stone structures built? To make the question more manageable I divided it into four parts: the quarrying of the stone, the cutting and dressing of individual blocks, the fitting of the blocks and transportation. To investigate the quarrying I visited several Inca quarry sites, of which two—Kachiqhata and Rumiqolqa—were analyzed in detail. Kachiqhata lies about four kilometers across the Urubamba from Ollantaytambo. Its quarries supplied the porphyry (red granite) of which the Sun Temple, the most important structure at Ollantaytambo, is built. Rumiqolqa is 35 kilometers southwest of Cuzco; it supplied much of the andesite (an igneous rock) that Pachakuti's masons used as they rebuilt the imperial capital.

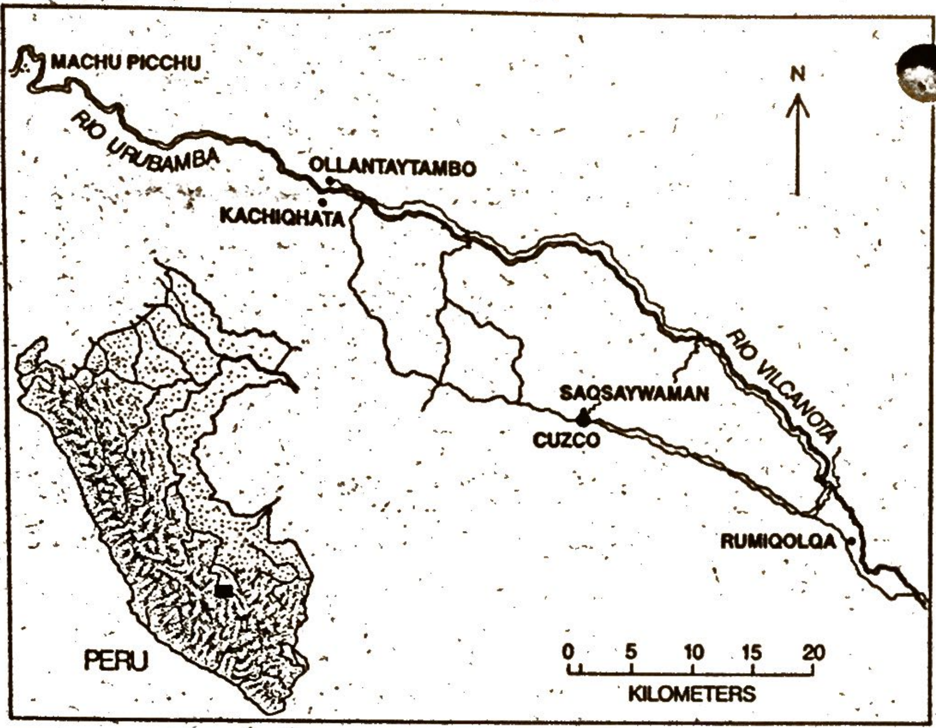
Several bits of circumstantial evidence indicate that quarrying was a matter of great significance to the Incas. Kachiqhata and Rumiqolqa are remote, difficult to reach and far from the construction sites where the stone blocks were assembled. The Incas' motive for exploiting such inconvenient quarries surely must have been that they put a high value on the type of stone found there.

Furthermore, the internal organization of the quarries shows that careful attention was paid to the process of obtaining building stone. Both Rumiqolqa and Kachiqhata have networks of access roads leading to the points where the building stones were retrieved. The quarries of Kachiqhata are reached by a road leading down from Ollantaytambo, across the Urubamba and up the far bank of the river to a series of large rockfalls, where rocks split off naturally from the face and accumulate in great piles. Where it reaches the rockfalls the access road divides into several branches extend-



SAQSAYWAMAN, near Cuzco, is the site of some of the most impressive Inca stonework. The photograph shows part of an outwork system that includes three walls, each one more than three meters high. The largest stones in these walls weigh about 100,000 kilograms. Although Saqsaywaman is often referred to as a fort, recent archaeological work suggests that it was probably a religious center.

REMARKABLE FIT of the Inca building stones is shown in a photograph of a wall from Ollantaytambo. The material of the blocks is a type of stone called meta-arkose. The protrusions were used in handling the stones at the construction site; they were often left on the blocks after the wall was finished. The blocks are covered with small scars made by the hammers that were employed to shape the stone. The scars are finer at the edges than in the center of the face, which suggests different hammers were applied to the two areas.



SOME INCA SITES are concentrated in the highlands of south central Peru near Cuzco. Cuzco was the capital of the Inca empire, and the technique of fitting stone blocks without mortar reached a new height there in the 15th century. The stone for many of the structures at Cuzco came from quarries at Rumiqolqa. At Ollantaytambo is an impressive Inca ruin that, like Saqsaywaman, is often referred to as a fort but was probably a religious center. Quarries at nearby Kachiqhata provided the stone for Ollantaytambo. Machu Picchu, one of the most famous and beautifully situated of all Inca ruins, sits among mountain peaks. Urubamba and Vilcanota are two names given to one river in different parts of its course.

ing to the quarry sites. The road can readily be traced because it is reasonably well preserved and is lined with about 80 abandoned Inca blocks.

On uphill grades, on the flat and on mild downhill grades the access network consisted of ramps that were probably originally covered with gravel. On steep downhill grades the ramps are replaced by slides down which the blocks were allowed to plunge freely. The longest of the slides at Kachiqhata is an awesome 40-degree slope with a 250-meter vertical drop; at the bottom are four abandoned blocks. The quarries of Rumiqolqa have been worked extensively since the conquest and are not as well preserved as the ones at Kachiqhata. Even at Rumiqolqa, however, a network of roads leading to the quarry sites can be traced. At both quarries the Incas supplemented the access roads with other structures such as retaining walls, water canals and living quarters.

Although the two quarry sites are similar in plan, the Inca quarrymen used methods at Kachiqhata that were slightly different from those employed at Rumiqolqa. At Kachiqhata the Incas did not undertake quarrying in the technical sense, which implies that the stone is cut from a rock face or detached from the bedrock by undercutting. Instead the quarrymen simply combed the giant rockfalls and selected the blocks of coarse-grained red granite that met their specifications. My observations suggest that when a block had been selected at Kachiqhata, it was only minimally worked before being transported to Ollantaytambo. The later stages of dressing the stone and the adjustments for fitting appear to have been carried out at the construction site.

At Kachiqhata the rough work on a block was often begun before the ramp leading to the block had been completed. That this was so is particularly clear at the end of the highest ramp in the south quarry at Kachiqhata. Near the end of the ramp two huge blocks, one 4.5 by 2.5 by 1.7 meters, the other 6.5 by 2.7 by 2.1 meters, are raised on stone working platforms. Although the blocks are partially dressed, the access ramp does not extend to the platforms on which they stand.

Intriguingly, the cutting marks on those blocks and on others in the Inca quarries are very similar to marks found on the pyramidion of the unfinished obelisk from Aswan in Egypt. (The pyramidion is the small triangular form at the top of an obelisk.) Both the pyramidion from Aswan and the stones at Kachiqhata have cuplike depressions on their surface. It is known that the Egyptians shaped their stones by pounding away at the workpiece with balls of dolerite (an igneous rock). It seems reasonable to think the Incas did the same.

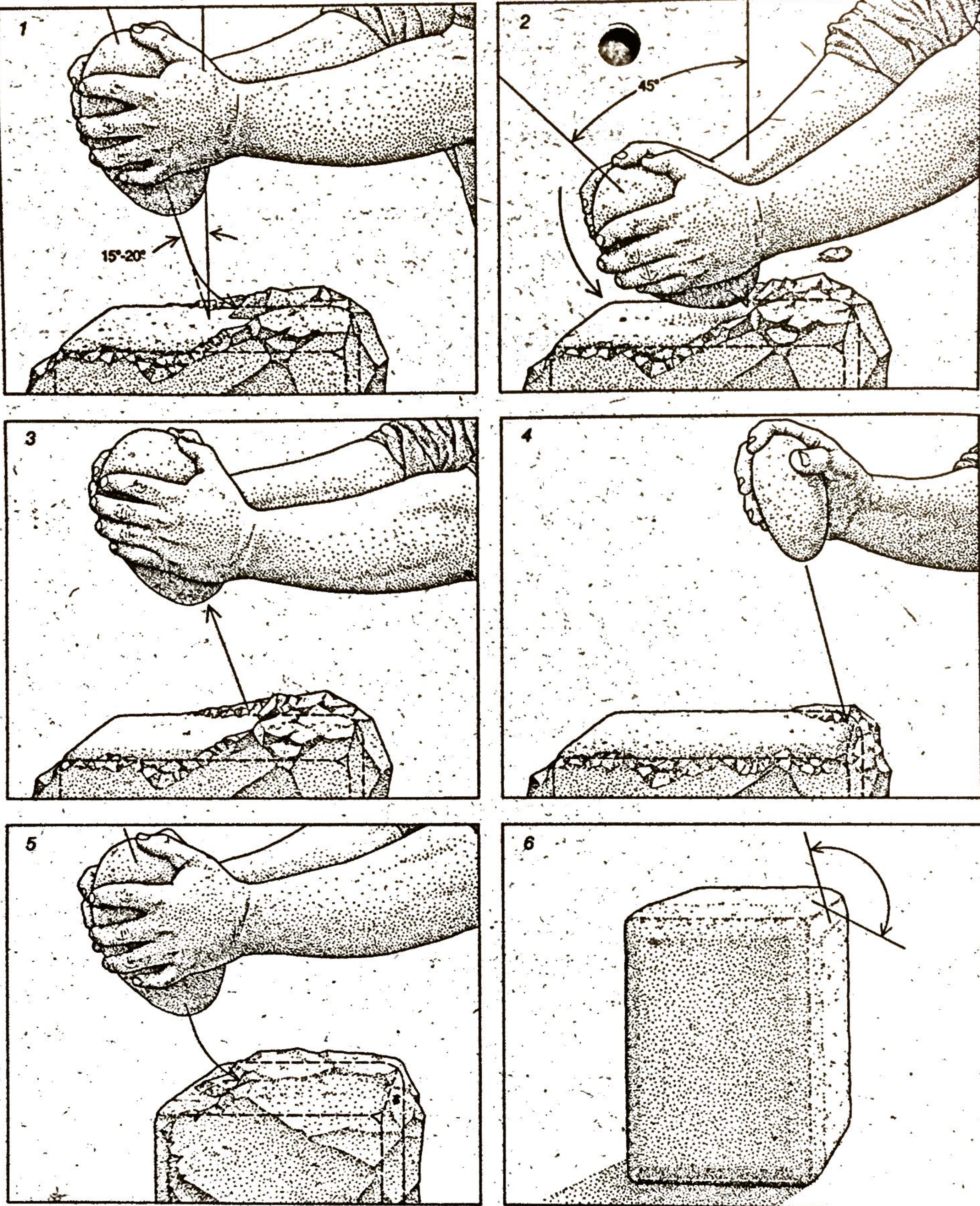
After a careful search of the ground in the quarry at Kachiqhata I found some rounded stones of quartzite, a metamorphosed sandstone that does not occur naturally among the stones of the quarry but is present along the banks of the nearby Urubamba. An examination of the quartzite stones revealed pit marks on the smaller end of the stones, which indicates they were employed for pounding. I conclude that the Inca quarrymen at Kachiqhata picked up rounded river cobbles on the banks of the Urubamba and used them as hammers for imparting a rough shape to the blocks before the process of dressing was completed at Ollantaytambo.

At Kachiqhata, then, stones were selected from the rockfalls rather than quarried in the technical sense and were only roughly dressed before being transported. At Rumiqolqa, on the other hand, there was true quarrying: the rock was broken off the face. Because Rumiqolqa has been worked since the conquest and is still being worked today, much of the evidence of the Inca exploitation of the rock has been obliterated. I did, however, succeed in finding one well-preserved Inca quarry pit in an area of Rumiqolqa that is hard to reach and therefore has not been worked in modern times. I named it the Llama Pit for the two petroglyphs of llamas carved on one of the rock faces.

The Llama Pit turned out to be a rich source of information about how the Incas quarried and dressed their building stones. Quarrying the andesite at Rumiqolqa does not pose major technical problems. Even the densest rock is fractured enough in its natural state to be broken out of the face quite easily. The quarrymen may have pried the stones they wanted from the rock face with pry bars like those that have been found at other Inca sites. The pry bars, which are made of bronze, are about a meter long; they have pointed ends and a rectangular cross section four or five centimeters on a side. The stone at Rumiqolqa is so fractured, however, that bronze pry bars would not have been necessary. I have seen quarrymen break the stones out of the face with sticks, and the Incas may have done the same.

Understanding how the Incas quarried their stones is a fairly straight-

LLAMA PIT is a well-preserved quarry site at Rumiqolqa. The Inca quarrymen probably pried stones from the rock face (*left*) with bronze pry bars or wood sticks. The building blocks were then shaped and dressed before being taken from the quarry. Scattered about the Llama Pit are 250 abandoned blocks in various stages of dressing. By examining these abandoned stones the author was able to reconstruct Inca stonecutting methods. The finished stones were carried away from the Llama Pit on ramps paved with gravel.



AUTHOR'S EXPERIMENT reveals how the Inca stonemasons might have dressed the building blocks. The author chose a block of andesite (an igneous rock) from the Llama Pit. After giving it a rough rectangular shape he took up a four-kilogram (8.8-pound) hammer and began pounding at one of the six faces (*1*). The hammer was held loosely between the hands and allowed to fall at an angle of between 15 and 20 degrees from the vertical. Just before striking the stone the hammer was given a twist with the wrists so that the angle of impact was about 45 degrees (*2*). After each strike the hammer rebounded about 25 centimeters (*3*). When the first face was finished, the block was left in the same position and a smaller hammer was employed to draft the edges of the next face to be dressed (*4*). The small hammer, which weighed 560 grams (1.2 pounds), was held tightly to deliver grazing blows directed away from the edge. Then the block was turned so that the large hammer could be used on the second face (*5*). The author's experimental technique resulted in a block with corners that are slightly convex, much like the corners observed on the Inca stone blocks (*6*).

forward matter. Understanding how the stones were cut and dressed poses greater technical difficulty. Here again the Llama Pit was helpful. The most striking feature of the Llama Pit is the 250 Inca blocks scattered about the site. In contrast to the stones from Kachiqhata, stones from Rumiqolqa were generally finished, or nearly finished, on five of their six surfaces while they were still in the quarry. One can find among the 250 blocks at the Llama Pit examples of all the stages of production, from raw stone to finely dressed blocks. By examining these stages I have been able to reconstruct the process by which the blocks were manufactured.

One of my first tasks was to identify the tools used in dressing the stones of the Llama Pit. Scattered among the chippings of andesite in the quarry pits I found stones foreign to the site in both shape and material. My search turned up enough of the foreign stones for me to be quite sure they had served as hammers for shaping the building blocks. As at Kachiqhata, most of these foreign stones are river cobbles. They appear to have come from the banks of the Vilcanota River, which flows close to the quarry. A few of the hammers are pure quartzite, others are granite and some are olivine basalt. (Basalt is an igneous rock and olivine is a mineral found in the basalt.)

The hammers and the andesite of the building stones have roughly the same hardness. One standard measure of hardness is called the Mohs scale. On the Mohs scale talc, the softest mineral, has a rating of 1 and diamond, the hardest, a rating of 10. The hammerstones I found at the Llama Pit have a rating of about 5.5, roughly the same as the hardness of the andesite in the building blocks. The hammerstones, however, are tougher than the blocks. Differential cooling during the formation of the andesite led to the accumulation of stresses in the rock. When the andesite is hit, the stresses are released and lead to a fragmentation of the rock. As a result the river cobbles make good hammers for shaping and dressing the building stones.

The Inca masons apparently employed hammers of different sizes for the various phases of the shaping process. In my search of the quarry sites I found three groups of hammers. The first group included hammers weighing from eight to 10 kilograms, the second those weighing from two to five kilograms and the third those weighing less than a kilogram. I believe each group had a specific function. The largest hammers could have served for the rough work of breaking up and squaring off the blocks after they had been broken out of the quarry face. Most of the unfinished blocks show distinctive flaking scars similar to the scars on flaked stone tools, but much larger. The flaking scars are probably the result of pounding with the large squaring-off hammers. The medium hammers may have served for dressing the faces of the blocks and the small hammers for drafting the edges.

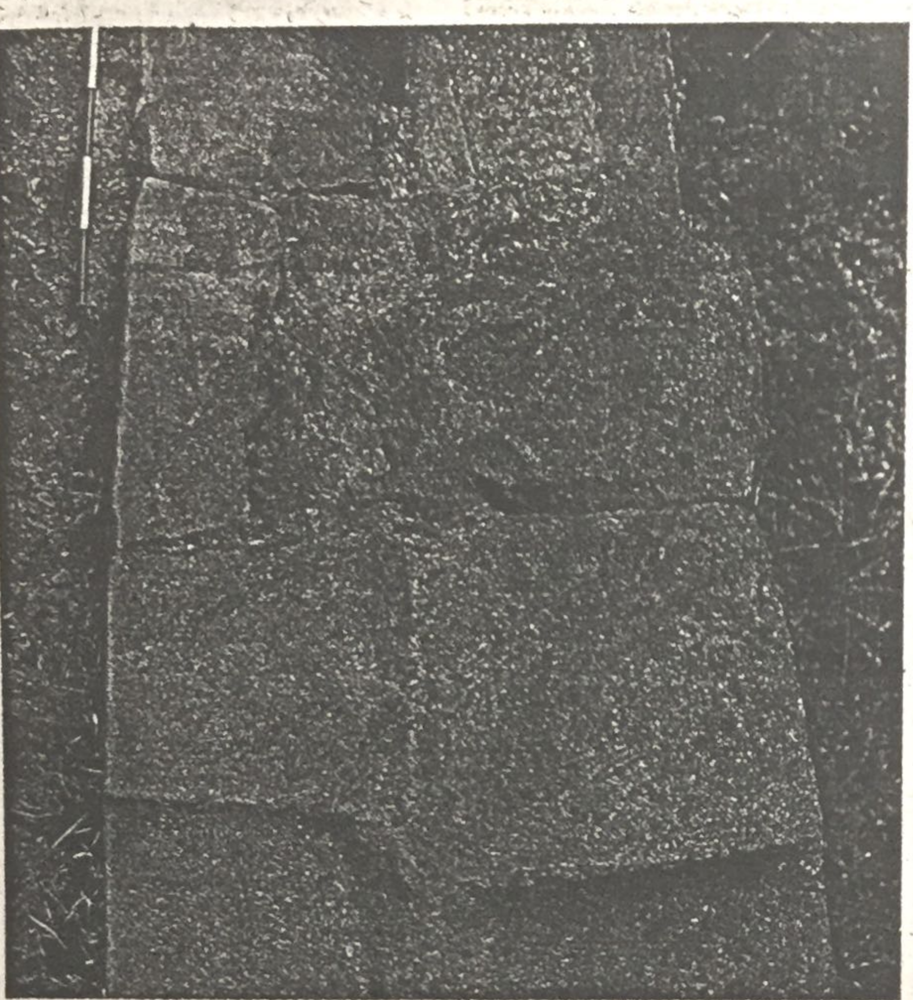
To find out whether the Inca masons could have employed the three groups of hammers in this way, I proceeded from observation to experiment. The raw material of my experiment was a rough block of andesite measuring about 25 by 25 by 30 centimeters. With a hammer that weighed about four kilograms I knocked off the largest protrusions to create a roughly rectangular block. Six blows were enough to do so. The next objective was to smooth one of the six faces of the rectangular block. For this purpose I chose a different four-kilogram hammer and began to pound. One might think wielding a four-kilogram hammer for an extended period would be very tiring. The work is made easier, however, by gravity. Holding the hammer lightly, one can allow it to fall onto the surface of the block while still guiding it in both hands. If the hammer is dropped onto andesite, it will rebound 15 to 25 centimeters; it can then be allowed to fall again. The process can be repeated for a long period, and the effort required is small.

Cutting stone in this fashion is essentially a matter of crushing the rock. If the hammer is directed at an angle of between 15 and 20 degrees from the normal (perpendicular) to the surface, however, tiny flakes chip off and the cutting is much accelerated. I found that the efficiency of the strike could be increased even more by giving the hammer a twist with the wrists just before it drops onto the surface of the block. Twisting the wrists increases the angle of impact to between 40 and 45 degrees from the normal [*see illustration on opposite page*]. The mechanism by which the increase in angle augments the efficacy of cutting is readily explained. When the hammer is directed vertically, the entire force of the strike is converted into compression, which crushes the rock. On the other hand, if the strike deviates from the vertical, it gives rise to a shear in addition to the compression. The shear increases with the angle of the strike, and it is the shear that tears off the tiny flakes of stone and thereby accelerates the cutting.

After one of the block's six faces has been smoothed, the mason must change his technique. If the block were simply turned over and the same hammer used to cut the new face, large flakes would undoubtedly be torn from the edge of the new face by the blows of the large hammer. To avoid that result the mason must take up a smaller hammer and use it for drafting the edges of the new face before its inner part is smoothed. For this work I used a hammer weighing about 560 grams. The method is quite different from that of cutting the face. Rather than striking the surface of the block more or less vertically, the hammer grazes the edge. Gravity has little part in the work done on the edge of the block. The hammer of 560 grams is too small to be dropped and then allowed to rebound. It must be held tightly, with the force of the blow coming solely from the mason's arm.

Once the edges have been drafted the block can be turned over. The small hammer is put aside, and the mason takes the heavier hammer again to dress the new face. On my experimental block I dressed two faces after the first one while trying out several more hammers that had a weight of between 3.5 and four kilograms. When I finished, I had a block that was mostly dressed. The entire process, from squaring the block to drafting five edges and finishing three sides, took no more than 90 minutes. My experiment shows that stones can be mined, cut and dressed using simple tools in a way that takes little time or effort. The next question is whether these are the methods the Incas actually employed.

The physical evidence that the Incas used techniques similar to mine is abundant. On the stones of all Inca walls, regardless of the type of rock, one finds scars resembling the scars left by my pounding on the experimental block. If the block is of limestone, there is a whitish discoloration in or around the scar. The white spots undoubtedly indicate a partial metamorphosis of the limestone resulting from the heat generated by the impact of the hammerstone. On every stone I examined the pit scars are smaller toward the edge of the stone than in the center, which suggests that the hammers used to work the edge were smaller than those used on the center of the face. Additional evidence comes from the contemporary commentator Garcilaso de la Vega, known as "the Inca." De la Vega, the son of a conquistador and an Inca princess, wrote in 1609 that the Incas "had no other tools to work the stones than some black stones...



DISMANTLED INCA WALL at Ollantaytambo yields clues about how the Incas fitted stones. Each concave depression marks the place where a stone has been removed. The depressions were pounded out to precisely match the convex bottom surface of the upper stone.

DRAG MARKS on the bottom of a building block from Ollantaytambo suggest that some stones were pulled to the construction site over the gravel surface of the Inca roads. The marks can be analyzed to find the direction in which the block was dragged. For example, the circular depression (*left center*) is sharply defined on its left side and fuzzy on its right side. As the block was pulled along, gravel slipped into the depression under the front edge, which remained sharp. When the gravel reached the back of the depression, it was compressed between the roadbed and the rear edge of the recessed area, which became polished and fuzzy. Such reasoning suggests that the block shown in the photograph was dragged toward the left.

with which they dress the stone by pounding rather than cutting."

Perhaps the most intriguing questions of all concern not quarrying or dressing but the way the great stones were fitted to each other so precisely. Masonry joints are of two main types: bedding joints and lateral joints. The bedding joints are the seams through which most of the weight of a block is transmitted to the course, or row of stones, below. The lateral joints are seams between stones in the same course; little or no weight is transmitted through them. Here I shall be concerned mostly with the bedding joints.

After examining many Inca walls I concluded that when the walls were built, the bedding joints of each new course were cut into the top of the course already laid below. The stones generally had faces that were slightly convex, and the depressions that were cut to accommodate the upper stones are therefore concave. Wherever a wall has been dismantled one can clearly see the concave depressions in the remaining courses, making it appear that the removed stones have left precise impressions of their bottom surfaces [*see top illustration at left*]. These concave depressions refute a hypothesis often advanced in relation to Inca masonry: that neighboring stones were ground against each other to achieve the perfect fit. It is clear that grinding two surfaces against each other cannot yield perfectly matching concave-convex joints such as the ones I observed. How, then, was the wonderful fit achieved?

As in dressing the stone, I tried the fitting myself to learn how it was done. The experiment entailed the block of andesite from the dressing experiment and a larger block into which the bedding joint was to be cut. I started by putting the smaller block on the larger one and tracing its outline. I removed the smaller block and, using the outline as a guide, pounded out a depression that matched the overall shape of the bottom of the smaller stone. The pounding produced much dust, which had to be whisked away. The dust is annoying because it dampens the hammer blows, but it is also quite useful. When the upper block is put in place again, it leaves an impression of its lower surface in the dust. Where the fit is tight the dust is compressed and where the fit is loose it is not. After the stone is removed again one pounds away at the places where the fit is tight, which are indicated by the compressed areas. By repeating the process one can achieve as close a fit as one wants.

The same technique can be applied to form the lateral joints. The block to be added to the course is against the blocks already in place, and concave depressions are cut out of the blocks in place. The lateral joints differ from the bedding joints in that the close fit observed from the front of the wall is sometimes only a few centimeters deep and the interior of the joint is filled with rubble. In many instances, however, the lateral joints are fitted with the same care as the bedding joints over the entire plane of joining.

It appears that the Inca technique of fitting the stone blocks together was based largely on trial and error. It is a laborious method, particularly if one considers the size of some of the huge stones at Saqsaywaman or Ollantaytambo. What should be kept in mind, however, is that time and labor power were probably of little concern to the Incas, who did not have a European notion of time and had plenty of tribute labor from conquered peoples at their disposal. Furthermore, my experiments show that with a little practice one develops a keen eye for matching surfaces, so that the time needed for constructing a joint is greatly reduced. In favor of my method it should be emphasized that it works and that it does not postulate any tools other than those for which there is evidence. Moreover, it has the support of at least two 16th-century writers. One of them, Jose de Acosta, a Jesuit priest who traveled with the Spanish conquerors and is considered a highly reliable observer, wrote in 1589: "All this was done with much manpower and much suffering in the work, for to fit one stone to the other, until they were adjusted, it was necessary to try the fit many times."

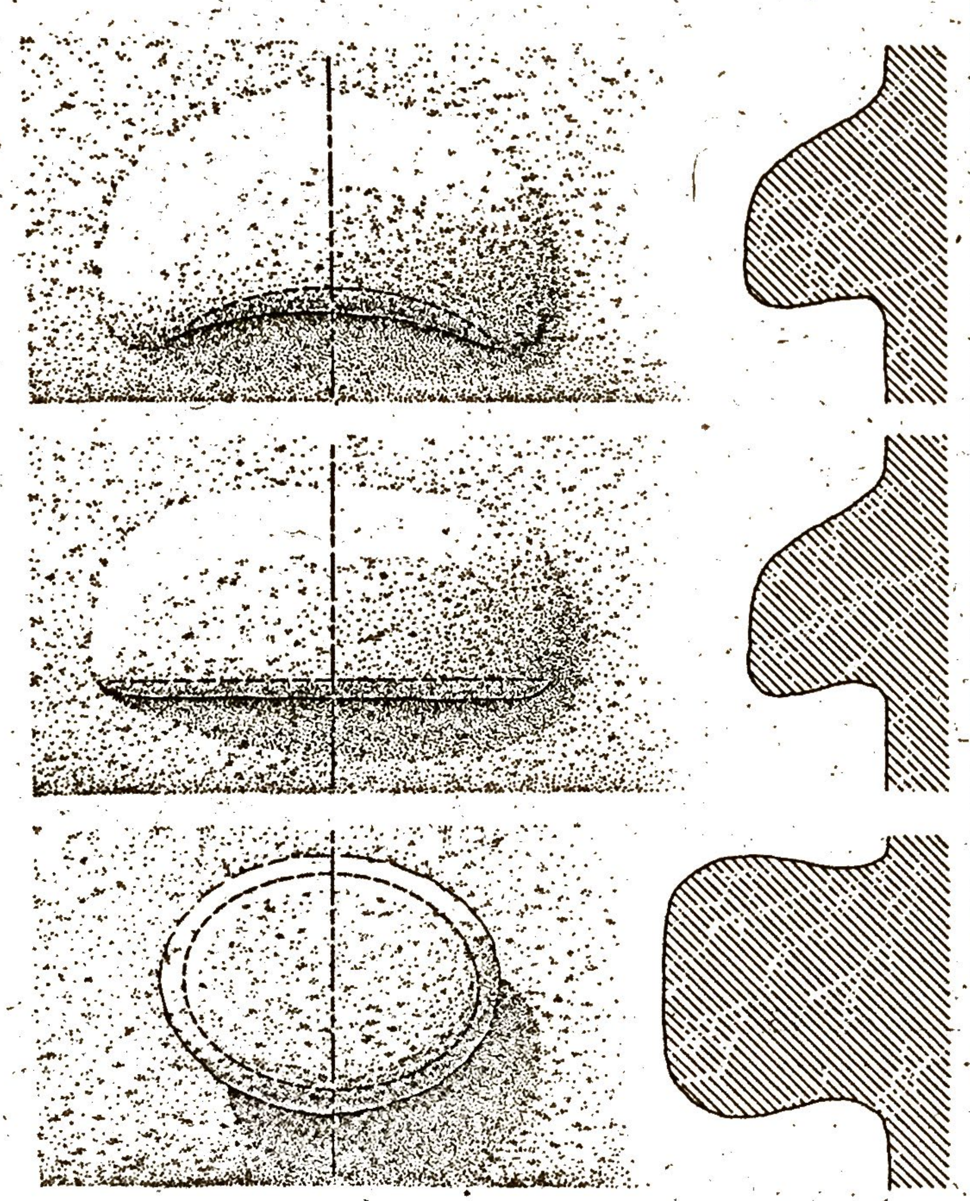
I think my experiments provide a reasonable account of how the Inca masons quarried their stones, shaped them and fitted them together. How the stones were transported to the building site and how they were handled at the site, however, are questions that have not yet yielded completely to investigation.

In the handling of the stones a variety of protuberances carved on the face of the block undoubtedly had a significant role. The protuberances come in several sizes and shapes [*see illustration on next page*]. Generally they are found on the lower part of a block that has been set in place. The projections may have served as points to which ropes could be attached or to which the force of a lever could be applied. The projections were apparently cut only at the building site and served specifically for the purpose of handling stones there. Since none of the blocks abandoned along the transport routes have protuberances, it would seem that the projections did not have a role in bringing the blocks to the building site.

How were the blocks transported? Some preliminary evidence comes from blocks strewn about at Ollantaytambo. On these blocks one can observe a peculiar polish marked by more or less parallel longitudinal striations. Both the polish and the striations seem to be the result of dragging the blocks from the quarries to the construction site. The direction in which the block was dragged can readily be determined from the marks. If the surface is inspected closely, one finds irregularly shaped areas that have not been polished because they are slightly recessed. These regions generally have a sharp boundary on one side and a fuzzy, gradual boundary on the other. When the stone was being dragged, the sharp edge was at the front and the diffuse edge was at the rear. Gravel from the roadbed would have accumulated at the back of the depression and been ground between the block and the road, yielding the smoothed area at the trailing edge.

Other evidence from the blocks helps to fill out our picture of the transport process a bit. The polish is found only on the broadest of the block's faces, suggesting that the stones were dragged in their stablest position. The blocks in the quarry show no polish and the extent of the polished surface increases with distance from the quarry. The presence of the polish tends to refute the suggestion that the Incas moved the larger stones on rollers or skids. The presence of drag marks does not exclude the possibility that rollers or skids were employed on the uphill parts of the ramps, but no material evidence of such implements has been found.

If the blocks were dragged along the access ramps, the Incas must have devoted considerable labor power to the task, particularly for the largest stones. The force required to drag any block depends on the coefficient of friction between the stone and the material of the ramp, the slope of the ramp and the weight of the block. I determined the coefficient of friction experimentally and measured the slope of the ramp at Ollantaytambo as being about 10 degrees. The largest block at Ollantaytambo weighs about 140,000 kilograms. I have calculated that it would take a force of some 120,400 kilograms to pull such a block up the ramp. If a man can pull consistently with a force of 50 kilograms (which may be an overestimate), it would have taken some 2,400 men to get the block to the top of the ramp. That figure is consistent (at least in order of magnitude) with the account of the 16th-century writer Cieza de Leon, who observed that of the 20,000 men assigned to the construction of Saqsaywaman, 6,000 were delegated to the transport detail.



PROTUBERANCES on Inca stone blocks take various forms that probably had specific functions. One type (*top*) is well suited for the application of levers. Another type (*bottom*) may have been used for tying ropes. A third type (*middle*) could have served both functions.

The foregoing account seems reasonable, yet it raises significant questions that I have not been able to answer so far. The Inca ramps were only from six to eight meters wide, and I have not been able to propose plausible solutions for two problems posed by this narrowness. One is how 2,000 men or more could have been harnessed to the block so that each was contributing to the pull. The other is how the crowd of workers was arranged on the cramped road. These are only two of the unsolved problems concerning the transport of the blocks. Among the others are the techniques for tying the ropes to the blocks and the methods for maneuvering the huge stones.

Moreover, the stones from Rumiqolqa were probably not dragged at all. Unlike the blocks from Kachiqhata, those from Rumiqolqa were finely dressed before they left the quarry. No drag marks are found on them, and it seems unreasonable to think that a finely dressed face would be dragged on a stone ramp. How then were the dressed blocks transported? This question and many others remain to be answered before the final account of Inca stonemasonry can be written. Yet by experiment and observation some of the fundamental questions about the quarrying, dressing and fitting of the stones have now received answers.