

INCA QUARRYING AND STONECUTTING

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Introduction

Inca builders constructed walls of cut stone without cement and with a precision that often is within fractions of a millimeter. At the same time, they seem to have appreciated the effect of irregularity in patterns of joints and the play of light and shade produced by recessed joints.

How did the Inca stonemasons, who did not have the use of iron tools and did not know the wheel, cut and fit the stones and erect the walls that are the object of so much admiration?

The more prosaic answers to this question presume an immense investment of labor. An explanation still common in Cuzco is that the Incas had an herb the juice of which softened stone so it could be modeled, a motif derived from European folklore. Mystics speak of the application of cosmic energies to resolve the problem. For people interested in construction technology, there must be a better answer. I shall start by separating the operations that had to be performed and by formulating research questions about them.

The first operation that had to be performed was quarrying. What kind of stone did the Inca select; how, and with what devices, was stone extracted from bedrock? The second operation was cutting and dressing. How, and with what tools, were these operations performed, and where? The third operation was fitting and laying. With what technique and devices did the Inca achieve the proverbial fit between stones? Finally, there was a fourth operation involved in Inca building, the handling and transportation of the stones. How, and with what devices, did the Inca transport and lift the building stones?

On the basis of research carried out in the Cuzco area in 1982, I can provide answers to the questions about the first three operations. The research involved analyzing numerous Inca walls in and around Cuzco and visiting several ancient quarry sites. Special attention was paid to two quarries: Kachiqhata, from which the Inca mined the red granite used in part in the construction of Ollantaytambo; and Rumiqolqa, which supplied much of the andesite used in the construction of Cuzco.

Quarrying

Organization of quarry sites

The quarries of Kachiqhata lie across the Urubamba River from Ollantaytambo, about 4 km. southwest of it, and between 700 and 900 m. above the valley floor. They are located in two giant rockfalls just below the cliffs of a granitic outcrop, called Negra Buena, which has penetrated through an environment of metamorphosed sedimentary rocks.

The quarries of Rumiqolqa are 35 km. southeast of Cuzco, past the site of Pikillaqta, on the left bank of the Vilcanota River, just off the Inca highway

leading from Cuzco to Qollasuyu. They are situated in a volcanic outcrop of andesite which, in geological times, has intruded the surrounding sandstone formation.

To the Incas the choice of a particular rock type must have been of utmost importance, or they would not have quarried sites so difficult of access or so far away. The high degree of organization manifested in the layout of these quarry sites, and others I have visited, is a further indication that quarrying was a very important operation to the Incas and not a routine matter.

The quarries of Kachiqhata have probably not changed very much since they were visited by Squier in 1863. His descriptions very closely match what I have observed (Squier, 1877, pp. 505-510). The quarries are reached, as they were in Inca times, by a ramp which leads down from the site of Ollantaytambo to the river and up the mountain on the left bank to the rockfalls. In the whole length of the ramp there are some eighty abandoned blocks. Most of the access road is fairly well preserved and easily traced. The map (fig. 1), constructed from my on-site survey, shows the left bank portion of the road and its ramifications to and within the three quarrying locations: the North, South, and West quarries. The connections between Ñawinpata and the North Quarry and between the North and West quarries have been obliterated by erosion.

The roads have a gentle slope of 8°-12° and are from 4 to 8 m. wide. They are cut into the mountain side and filled in behind retaining walls on the valley side. These walls are from 1 to 3 m. high, with occasional sections of over 10 m. Where the terrain permitted it, the ramps were replaced by slides, the longest of which is at the northern end leading down to the river. It is an awesome drop of some 250 m. down a slope of about 40°, at the bottom of which are 4 abandoned blocks. This slide may not always have been used, as there is clear evidence of a ramp immediately to the east of the slide (fig. 1).

The sketch map of the quarries of Rumiqlolqa (fig. 2), made from an aerial photograph and from inspection on the ground, reveals a similar network of roads or ramps leading to different quarrying areas: the High, East, Central, and South quarries.

In both Kachiqhata and Rumiqlolqa, the Incas complemented the access roads with additional works of infrastructure. At Kachiqhata, there are great retaining walls to protect the quarries from rock falls and possibly to stop big blocks hurled down from higher locations. Traces of water canals leading to the quarries and to nearby ruins are clearly visible. At both sites, Kachiqhata and Rumiqlolqa, one finds what, in the local lore, are called the supervisors' or administrators' residences (Soqamarka, Bandoajana?), and the quarters for the quarrymen (Muyupata and Ñawinpata, Waskawaskan?). No excavations have been made at either of these sites, so there is no evidence available that would support or undermine the alleged use of these ruins.

In an article on stonemasonry, the Peruvian architect Emilio Harth-terré has described and mapped what he called the quarrymen's quarters of Kachiqhata (Harth-terré, 1965, pp. 162-168). I have not been able to locate these houses. The ruins that come closest to resembling Harth-terré's description are those of Soqamarka, but the Soqamarka ruins do not quite match Harth-terré's plans and sections. The general layout and the orientation of the complex deviate significantly from Harth-terré's sketches (figs. 3, 4).

What Harth-terré failed to mention about Kachiqhata, but did not escape Squier, are the many burial towers, or *chullpas*, that dot the sites of Muyupata (fig. 5) and the North Quarry. These structures are either circular or square, between 1.5 and 2 m. in diameter or on a side, and about that high as well. What special significance is to be attributed to the presence of these structures remains to be established. There are no *chullpas* at any of the other quarries I have visited.

A feature that appears to be unique to the quarries of Kachiqhata is the existence of stone cutting and temporary storage yards that are distinct from the extraction areas. I have found at least three such yards; one is in the West Quarry near survey point 14, and another in the South Quarry near survey point 54. The third, near Muyupata, is strategically located just below the point where the access ramps to the North and South quarries merge. This last is the largest of the three yards. It is built on a terrace on the valley side of the main access ramp and connected to it by a short inclined plane (fig. 5). Numerous large and small blocks of red granite are still deposited here. Is this the place where the blocks coming from the quarries were checked for suitability and further dressed or cut up according to some schedule?

Rock qualities

In both quarries, the different quarrying areas correspond to specific rock types or rock qualities.

The North and South quarries of Kachiqhata are the ones that provided the coarse-grained red granite which was used in the great structures of what is called the religious sector of Ollantaytambo. Most of the abandoned blocks along the access roads are of that type, with a few exceptions. These exceptions are of a grayish and much finer-grained granite, the principal source of which is the West Quarry.

At Rumiqolqa, the High Quarry provides a distinctly flowbanded andesite, which lends itself to the extraction of thin slabs. Most of the sidewalks in Cuzco today are paved with tiles from this quarry. In the East Quarry the rock is columnar, and in the Central quarries it is boulderlike, with an occasional flowbanded outcrop. The flowbanded and the boulderlike rock are also found in the South quarries.

Extraction

At Kachiqhata, the Incas did not practice quarrying in the proper sense. The stone is neither cut off a rock face nor is it detached from bedrock by undercutting. The Inca quarrymen simply went through a giant rockfall carefully selecting blocks that met their specifications. As far as I can ascertain, once an appropriate block had been located, it was dressed only minimally before it was sent on its way to the construction site. The fine work and the adjustments for the final fitting appear to have been made later at the construction site. Often work was started on a block before the ramp to it had been finished. Evidence of this is particularly obvious at the end of the highest ramp in the South Quarry (survey point 115 in fig. 1), where two blocks, one $4.5 \times 2.5 \times 1.7$ m., the other $6.5 \times 2.7 \times 2.1$ m., raised on working platforms not yet connected to the ramp, are in a state of partial dressing. The cutting marks on these and other blocks are intriguing. They are very similar to those found on the unfinished obelisk at Aswan, and the technique involved must not have been very different from the

one used by the Egyptians, who used balls of dolerite to pound away at the work piece until it had the desired shape (figs. 6, 7; Engelbach, 1923). In 1959, Outwater reported that "Very few tools are in evidence at the site [Kachiqhata]. There were some hammer-stones of diorite but very few picks or wedges" (Outwater, 1959, p. 28). And indeed, tools are rare at this site. It was not until a subsequent visit to Kachiqhata in 1983 that I did discover three hammer-stones, one of quartzite, one of chert, and one unidentified to date, at the storage yard near Muyupata. Since I shall argue below that there is only very scant evidence that the Incas split rocks with the aid of wedges, I am rather skeptical about Outwater's claim that he found picks and wedges.

As mentioned before, the rock at the West Quarry is of a grayish and fine-grained granite. Very few large blocks abandoned on either the ramps or the construction site are of that material. Nevertheless, local lore maintains today, as it did in Squier's time, that this is in fact the real quarry of Ollantaytambo. Two millstones, one almost finished, the other roughly hewn, would indicate that the quarry was worked in colonial times. But other aspects, in particular the construction of the ramps, associate this quarry with the other two. The one surprising feature at the West Quarry are the many long thin blocks in various stages of production lying just off the main ramp. Some of these are almost 7 m. long, and have a cross section of only 40 x 40 cm. How these "needles" have been extracted remains something of a puzzle. From the way some "needles" are strewn about, it is evident that long blocks with large cross sections have been split repeatedly into blocks with ever smaller cross sections, but how? There are no identifiable tool marks on the work pieces, no traces of wedge holes, nor any signs of channeling. The only thing I can assert with confidence is that these "needles" have not been pounded as the big blocks have in the North or South quarries.

What were these "needles" used for? I have been told by local informants, as was Squier before me, that these "needles" served in the construction of the bridge over the Urubamba River. This explanation is doubtful, as the respective spans from either bank to the still existing pier in the river are about 20 m. and 30 m. wide. Curiously enough, there are no abandoned "needles" on the ramps leading from the quarries to the construction site. The only blocks at Ollantaytambo that fit that description at all are the lintels over the doorways in the walls of Manyaraki at the entrance to the "fortress."

At Rumiqlqa, in contrast to Kachiqhata, one encounters at all sites quarrying in the proper sense, the rock is broken off a face or extracted from pits. Much of the area is still worked today, so that much of the evidence of ancient exploitation has now been obliterated. I did succeed in finding one well preserved quarry pit in an inaccessible area of the central quarries. It shows hardly any evidence of modern quarrying activity, although modern quarrymen are closing in fast. I named this pit the Llama Pit from two petroglyphs of llamas that I found on a rock face in the pit. The pit is about 100 m. long, 60 m. wide, and between 15 and 20 m. deep (figs. 8, 9). The outstanding feature of the Llama Pit is the 250 or so cut stones, finished and ready to be shipped, lying around 4 major extraction areas (fig. 10).

Under an overburden of very porous, loose, and small-sized material, the Llama Pit yields three distinct rock qualities. First, there is a stratum of still porous and loose, but larger rocks, a material that seems to correspond to the one used in the small-scale, regular bond masonry in Cuzco. Directly below this, comes a layer of somewhat larger rocks of a light gray or brown color, which is

considerably denser and not really loose, but very fractured. The bottom stratum features the best stone, dense, in large pieces, and of a beautiful sparkling dark gray color. The various strata are most likely the result of the speed of cooling of the andesite mass during its extrusion, the more porous the rock, the faster the cooling.

The quarrying of this stone does not pose any major problems. Even the densest quality is still fractured enough so that it can easily be broken out of the face of the rock. To break it out, the Inca quarrymen may have used pry bars of bronze, of the kind exhibited in the museums in Cuzco and Lima, or they may have simply used wooden sticks, as I have observed contemporary quarrymen do.

Squier wrote about Rumiqolqa:

Of the manner in which the stones were separated from the natural rock there are here, as in other places, abundant illustrations. Excavations were made, where possible, under the masses of rock, so as to leave some portions of them impending. A groove was then cut in the upper surface on the line of desired fracture, in which oblong holes were worked to a considerable depth, precisely in the manner now practiced. The presumption is strong that wedges of dry wood were driven into these holes, and water turned into the groove. (Squier, 1877, p. 419)

Neither at Rumiqolqa nor at Kachiqhata did I encounter evidence conclusive enough to confirm the use of this technique by the Inca quarrymen. I found the only positive indications of such usage on a single block of red granite on the ramp up to the site of Ollantaytambo. A short channel, 145 cm. long, 4 cm. wide, and 2 cm. deep, traverses the top face of this block. In the channel are 3 holes, from 10 to 13 cm. long, 4 cm. wide, 6 cm. deep, and from 32 to 34 cm. apart. Ten more such holes are to be found in the block, three of which are curiously staggered across the top face. The irregular shape of the holes, their rounded edges and bottoms, the sinuous tracing of the channel, and the pit marks in it strongly suggest that channel and holes were pounded out rather than cut with a chisel (fig. 11). This example is in sharp contrast to the one split rock in the quarries at Machu Picchu, which features clean cut wedge holes, regular in shape and size, but no channel. There can be little doubt that these holes were cut with a metal chisel (fig. 12). I am led to believe that the rock at Machu Picchu has been split in more recent times. The lack of traces of channeling and of the use of wedges does not, of course, rule out the application of this technique by the Inca quarrymen to mining stone or to breaking up large blocks. However, contrary to most accounts in the literature, it does suggest that the technique was not in common use.

Cutting and Dressing

At Rumiqolqa, in contrast to Kachiqhata, the stones generally had been finished, or nearly finished, on five sides in the quarry. Once broken out of the quarry face, how were these stones hewn and dressed? Among the many blocks in the Llama Pit, one can observe blocks in all stages of production, from raw, to roughly cut, to partially hewn, to finely dressed, so that one can easily imagine what the process may have been.

Tools

I have found enough tools at this site to be quite certain about the techniques involved in that process. These tools were simple river cobbles, used as hammer stones, loosely strewn about the chippings of andesite or halfway buried in them (fig. 13). The map (fig. 15) indicates the location of each of the 68 lithic implements found in the Llama Pit.

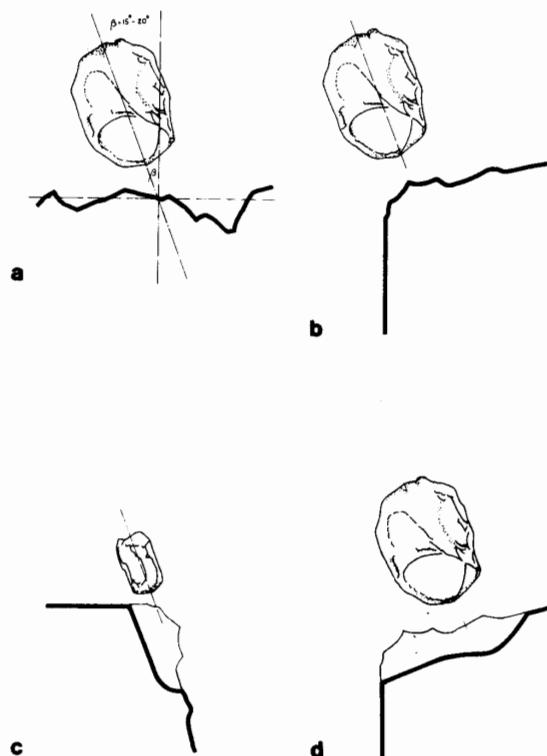
These hammers were easily identified as they are foreign to the site because of both their shape and their petrological characteristics. Most hammers are of quartzo-feldspathic sandstones, which have metamorphosed to various degrees, a few are of pure quartzite, others of granite, and some of olivine basalt. The weights range from a couple of hundred grams to hammers of 8 kg., with two groups in between, in the 2-3 kg. and the 4-5 kg. ranges. All types of hammer stones have a hardness of at least 5.5 on Mohs' scale. This is comparable to the hardness of the andesite on which the hammers were used. The hammers are tougher than andesite, which, due to differential cooling during its formation, is easily shattered by impact. The provenance of the hammer stones is most likely the nearby Vilcanota River. Large quantities of river cobbles can also be found on the northwest side of the quarries, away from the river, all the way up to the High Quarry. It appears as if the upthrust of volcanic rock cut off the Huatanay River from joining the Vilcanota at Rumiqolqa, and dislodged its old bed. Outwater is clearly wrong when he argues that "I found two hammer-stones of quartzite which must have been brought to the site from considerable distance, as there is no evidence of such material near the site" (Outwater, 1959, p. 28).

Once blocks were broken from the quarry face, the largest of the hammers were used to break them up and square them off by flaking. The fact that the technique used for shaping was one of flaking is clear when one looks at the scars on actual blocks (fig. 14). The scars are similar to ones on flaked stone tools, but much larger. Dressing was done using medium weight hammers to cut the surfaces and smaller ones, of 200-600 gr. to draft and finish the edges.

Experiments

To test the above assertions, I have proceeded from observation to experiment. Starting with a raw block of andesite, about 25 x 25 x 30 cm. (fig. 16), I first knocked off the largest protrusions using a hammer of metamorphosed sandstone of about 4 kg. to form a rough paralleliped. Six blows were enough to complete this step. The next objective was to cut a face. Using another hammer of the same material and weight, I then started pounding at a face of the block, holding the hammer in my hands (fig. 18). Cutting stone in this fashion is essentially a process of crushing the rock. However, if one directs the hammer at an angle of

Diagram 1



between 15° and 25° off the normal to the surface to be worked, tiny flakes will chip off and the cutting is accelerated considerably (Diagram 1a). The efficiency of each strike is further enhanced by increasing the angle of impact to about $40-45^\circ$ just before the hammer hits the surface. This is accomplished with a twist of the wrists at the last moment. The mechanics of this process are easily explained. When the hammer is directed vertically at the surface, the whole force of the strike is converted into compression, crushes the rock (or at worst may even split it). As soon as the direction of the strike deviates from the vertical, the force of the strike is decomposed into a compression and a shear component. The larger the angle of impact, the larger the shear component becomes. It is the shear component of the force that tears off the small flakes.

One would think that wielding a 4 kg. hammer for an extended time period would be very tiring work. Taking advantage of gravity and the hammer's own mass, however, one can simply drop it on the surface to be worked, while following with both hands. On the anesite, the hammer bounces back 15-25 cm. and can be caught again in the hands. The stonemason then directs the hammer at the next spot he wants to hit drops it again, catches it again, and so forth. If he feels like working faster, he may at every catch impart a new impulse to the hammer. Even in this case, the effort involved in drop pounding is quite small. The work from the rough block to the stage with one face dressed took only twenty minutes.

When one face of a block has been cut, the block cannot simply be turned over to cut the next face (Diagram 1b). The big hammer would most likely chip off large flakes near the edges. To avoid this danger, the edge must be drafted first with a small hammer and with grazing strikes away from the edge (Diagram 1c). Only once the edge is drafted can one return to the technique of dressing a face (Diagram 1d).

To draft the edges of the experimental block I used a hammer of about 560 gr. (fig. 17). With hammers of that size, gravity cannot be put to use and the nature of the strike does not have the advantage of the rebound. The hammer needs to be held tightly while pounding, and the force of the blow is the force with which the mason drives the hammer. To avoid pain, and possible later injury, the hammer has to be held so that the palm of the hand is parallel to the direction of the strike, as one would grasp a stick. Attempts to hold the hammer as one would hold a tennis ball, i.e., with the palm of the hand perpendicular to the direction of strike, proved to transmit the shock of percussion directly to the bones of the wrist and the lower arm.

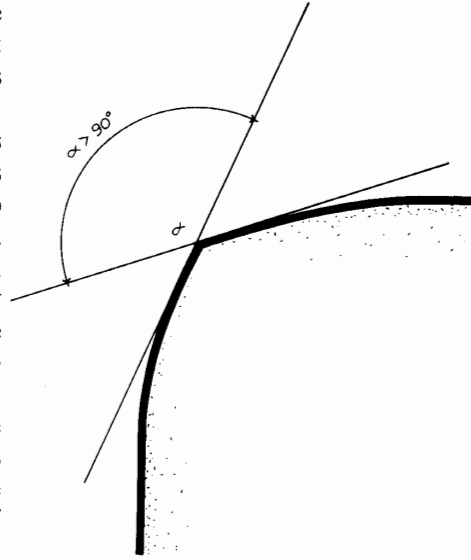
After drafting the edges, I dressed two more faces, trying out a few more hammers between 3.5 and 4 kg. (fig. 18). Not all hammers used yielded the same results. One in particular was badly balanced, which made it bounce back at unpredictable angles and very difficult to control. Others did not bounce high enough to be used without effort. Nevertheless, dressing of three sides and the cutting of five edges took no longer than ninety minutes.

I had noticed that, on most blocks, the dihedral angles between two adjacent faces, measured at the edge, seemed to exceed 90° (Diagram 2). Verification on a group of 31 blocks yielded an average dihedral of 117° , with a range from exactly 90° to an extreme of 132° . This dihedral appears to be a direct consequence of the technique of drafting edges. The resulting protruding faces have the advantage of protecting the edges during transportation and handling. This technical detail of stone cutting accounts for the sunken joints that produce

the chiaroscuro in Inca masonry.

The experiments show that stones can be mined, cut, and dressed with simple tools, yet with little effort and in a very short time. Is that the way the Inca stonemasons worked? The physical evidence that they used techniques close to those developed in the experiment is abundant and ubiquitous. Pit scars similar to those obtained on the andesite block at Rumiqolqa are to be found on all walls, regardless of rock type (fig. 19). On limestone, the pit scars show a whitish discoloration of the stone. These white spots are the result of a partial metamorphosis of the limestone produced by the heat generated by the impact of the hammer stone (fig. 20). In each case, the pit marks towards the edge or joint are finer than in the middle of the face of the stone, suggesting the use of smaller hammers to work the edges.

Diagram 2



If the exotic stones I found were indeed used as hammers, there should be indications of wear not only on the hammers themselves but also on the ground, in the form of chips or slivers struck off them. To check this point, I marked off an area 1.8×1.8 m. near 4 partially buried hammer stones and combed through the surface rubble of andesite flakes. Limiting myself to chips I could pick up with my fingers, I found 43 slivers, all of which match petrologically the hammer stones found.

The only doubt about the technique of pounding arises if I want to explain sharp concave edges, such as those observed in the steps at the "Throne of the Inca" at Saqsawaman (fig. 21). How would one pound out concave angles? At Rumiqolqa, I found a small, elongated tool, which dissipated my reservations. This tool, made of quartzite, could have been used as either a hammer or a chisel, as it shows wear on both the pointed and the blunt ends (fig. 22). The shape of the tool is such that it could also have served as a wedge.

At many Inca sites one finds eye-holes cut into stones: eye-bonders to tie down roofs, as at Machu Picchu; eye-holes of unknown use, as at the Inkawatana in Ollantaytambo and at the Qorikancha in Cuzco. All holes that I have investigated are pounded out. The holes show the characteristic pit marks and exhibit a conical shape on either side of the perforated stone. This suggests that the pounding was started from both sides and continued from both sides until the central portion of the stone was thin enough to be punched out. I know of only one eye-hole, in a stone in the courtyard of the Museo Arqueológico in Cuzco, that could possibly support Bingham's suggestion that eye-holes were bored "probably by means of pieces of bamboo rapidly revolved between the palms of the hands, assisted by the liberal use of water and sand" (Bingham, 1930, p. 68).

The technique of pounding is reported in at least one documentary source. "El Inca" Garcilaso de la Vega wrote in his *Comentarios reales* (1604): "They had no other tools to work the stones than some black stones they called hihuana [*sic* for *hihuaya*] with which they dress the stone by pounding rather than cutting" (Garcilaso de la Vega, lib. 2, cap. XXVIII; 1945, tomo I, p. 126; Lyon translation).

Alternative techniques

Although there is no doubt that the technique of pounding was the predominant method of dressing stone, there is evidence in the area I have investigated that the Inca stonemasons had knowledge of other techniques to work stone.

Many of the building blocks at Ollantaytambo exhibit highly polished edges, while the faces show the familiar pit mark. This polish may have been achieved with bars of pumice, of which I found a few fragments.

Close to the so-called religious sector of Ollantaytambo, there is a stone block that appears to have been sawn into. In fact, this stone has not been cut at all. The alleged saw cut, which is shown to every tourist and is referred to by Ravines in an editorial footnote to Outwater's article "Edificación de la fortaleza de Ollantaytambo" (Ravines, 1978, p. 584 footnote 6a), is only a quartz vein which has partially weathered out. However, a few hundred meters from this stone, at the place known as Inkamisana, there is a number of genuine cuts forming a pattern of lozenges. These cuts result from abrasion, not from crushing or pounding. They may have been made with some kind of saw or file, but clearly not with a wire or string, as the cuts abut onto a vertical wall through which no wire could have been pulled. The cuts are, in fact, made of two smaller channels with a fine ridge between them that has been broken off (fig. 23). Similar cuts forming similar patterns can be found on stones labeled paving stones in the Archaeological Museum in Cuzco.

Some 12 m. to the northeast of the Sun Temple in the religious sector of Ollantaytambo, there is a purplish fountainlike stone of meta-arkos(?) that features interesting abrasion marks (fig. 24). Ravines suggested that this stone is in a state of a "*roca a medio pulimentar*" (Ravines, 1978, p. 584 footnote 6b). There are, at Ollantaytambo, good examples of polished blocks, most blocks of red granite lying around show areas of almost mirrorlike polish, to indicate that the marks on the stone in question result not from polishing but from some form of sawing. But again, the cuts could not have been made with a string or wire, the curvature of the cut is contrary to what one would obtain with a string. There is more evidence throughout the territory that I have explored to show that the Incas did on occasion saw into stones. What tools they used for this I do not know.

Fitting and Laying

The next and most intriguing questions about Inca stone masonry concern the precision fitting of the blocks. For the purpose of the discussion, a distinction will be made between the bedding joints, i.e., the joints through which most of the weight of a block is transmitted to the course below, and the lateral or rising joints.

Bedding joints

With regard to the bedding joints, I have made an observation that can be formulated as a general rule:

The bedding joint of each new course is cut into the top face of the course already laid below it.

The rule is manifest, for example, at Saqsawaman (Diagram 3), and gives a simple

explanation of the wall section at Machu Picchu that so attracted Bingham's attention (fig. 25). Of this wall he wrote:

In the course of time such a house, whose attic was entirely above the level of the Beautiful Wall, would tend to lean away from the wall, and the seams would open. Consequently the stone mason ingeniously keyed the ashlar together at the point where the greatest strain would occur, by altering the pattern from one which is virtually rectangular to one containing hookstones, thus making a series of braces which would prevent the ashlar from slipping and keep the house from leaning away from the ornamental wall. (Bingham, 1930, p. 92).

If indeed the two story house were to lean away from the Beautiful Wall, this would create an uplift, rather than a slip motion, against which the "hookstones" would be useless. The particular configuration is better explained by the bedding joint rule, and may be interpreted as a "seam" where wall sections started from opposite ends meet.

The rule, according to which the upper course projects into the lower course, does, like any good rule, have its occasional exceptions, for example at Ollantaytambo (fig. 26). But even exceptions like this do not preclude that it is primarily the lower course that is cut to adapt to the upper course.

Wherever walls have been dismantled, one can clearly see the cuts made to receive the next course of blocks (fig. 27). Cuts like these are the manifest refutation of the often advanced hypothesis that neighboring stones have been ground against each other to achieve the perfect fit (Ravines, 1978, p. 559). Obviously, grinding would not have left marks like these. How then was the fit achieved?

Again, I tried to do it myself to get a better understanding of the technique involved. The experiment required two blocks of andesite, the one used in the dressing experiment and a larger one into which the bedding joint was to be cut. The face of the smaller stone shown in fig. 28 is the one for which the bedding joint was to be cut.

I started by putting down the face to be fitted onto the lower block and outlining its contours. Contemporary quarrymen dig up the root of a ubiquitous bush, named *llawlli*, which has a deep yellow sap, and use this root for marking in the manufacture of paving tiles. After outlining the bedding joint, I pounded it out. In the process a lot of dust is produced, which is quite useful, for when one puts back the upper block to check the fit, the dust compresses where the two faces of the joint touch, while it remains loose elsewhere. Where it is compressed is where one has to continue the pounding. Through repeated fitting and pounding, one can achieve a fit as close as one wishes. Figs. 29 and 30 compare the fit I achieved in this fashion with an actual fit in the Inca wall of the Amarukancha in Cuzco.

The technique for fitting two stones is thus one of trial and error. I concede that this technique appears to be tedious and laborious, especially if one thinks of the cyclopean blocks at Saqsawaman or Ollantaytambo. It should be remembered, however, that to the Incas time and labor were probably of little concern, and my experiments show that with some

practice one develops a very keen eye for matching surfaces, so that the number of trials can be reduced considerably. The suggested method works, and it has the advantage of not postulating the use of tools and other implements of which no traces have been found. Finally, it has the support of at least one sixteenth century observer. José de Acosta wrote in 1589:

Y lo que más admira es que no siendo cortadas estas [piedras] que digo de la muralla, por regla, sino entre sí muy desiguales en el tamaño y en la facción, encajan unas con otras con increíble juntura sin mezcla. Todo esto se hacía a poder de mucha gente y gran sufrimiento en el labrar, porque para encajar una piedra con otra, según están ajustadas, era forzoso proballa muchas veces, no estando las más de ellas iguales ni llenas. (Acosta, lib. 6, cap. 14; 1962, p. 297)

And what one most admires is that, although these [stones] in the wall I am talking about are not cut straight but are very uneven in size and shape among themselves, they fit together with incredible precision without mortar. All this was done with much manpower and much endurance in the work, for in order to fit one stone to another so precisely it was necessary to try the fit many times, the stones not being even or full. (My translation)

The emphasis here should, of course, be on the phrase "it was necessary to try the fit many times."

Rising joints

The lateral or rising joints differ from the bedding joints in that the fit observed from the front is often only a few centimeters deep, the interior of the joint being filled with rubble (fig. 27). Harth-terré hailed this method of fitting stones as the technical secret of the "wedge-stone" (*piedra-cuña*) which allowed the Inca stonemason to reduce the fitting work to only a thin band around the edges of the stones (Harth-terré, 1965, p. 155 fourth and fifth paragraphs). While this shallow fit is common, it rarely applies to bedding joints and is by no means the rule for rising joints. In many instances the blocks are fitted with the same care over the entire joining plane (fig. 27). Nevertheless, as I shall show below, "wedge-stones" do play an important role in Inca stone masonry.

The technique for fitting lateral joints I assume to be similar to that used for the bedding joints:

The new block to be laid is fitted into, and the joint cut out of, the lateral block or blocks already in place.

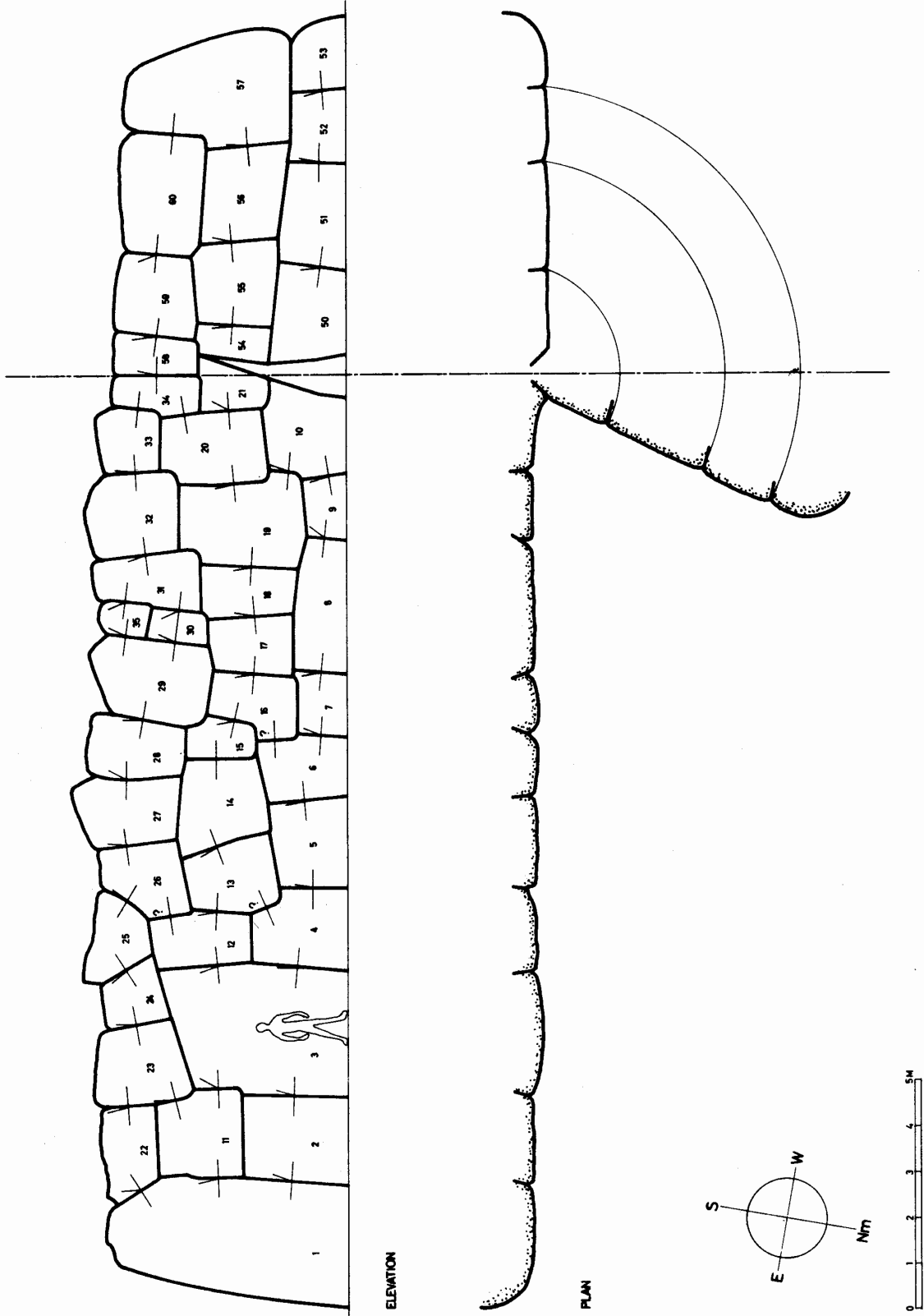
The combined effect of the fitting of bedding joints and lateral ones is neatly illustrated at Saqsawaman (fig. 31), and it takes some of the magic out of the famous "twelve angle stone" in the retaining wall of Inka Roka's palace.

Laying sequences

The matter of lateral fitting raises some questions about the sequence in which the blocks were laid. The sequence may not matter so much for masonry with a regular bond, but it certainly becomes critical in masonry with an irregular bond. To investigate laying sequences, I have surveyed one of the fortification walls at Saqsawaman. The unfolded view of walls 26 and 27 of the first rampart

Diagram 3

Plan and Unfolded Elevation of Wall Sections 26 and 27 of the First Rampart at Sagsawaman Showing the Angles Formed by the Joining Planes and the Plane of the Face of the Wall



shows the orientation and magnitude of the angles formed by the joining planes and the plane of the face of the wall (Diagram 3).

Assuming that the laying of the first course, with the exception of block 1, was straightforward, one can reasonably assert that blocks 16 and 19 were laid before either 15 or 20, and that block 34 must have been in place before the laying of 33, and 26 in place before the laying of 25.

Inspecting the second course (blocks 16 to 19) in detail, one notes again how the bedding joints are cut into the lower course, and how rising joints are cut into the laterally adjoining blocks. The change in the angle of the joints between 19 and 10 and between 19 and 20 supports the argument that 19 was fitted to 10 first and 20 cut into 19 later. As for the sequence in which blocks 16 to 19 were set, I would argue that this course was started from both ends, with block 18 as the last stone. Its shape would have allowed it to be lowered into position from the top, but more likely it was pushed in from the front. Block 18 is wedge-shaped and acts as a sort of a keystone, just as Harth-terré described it (Harth-terré, 1965, p. 155). That some keystones were introduced from the front is manifest in a gap found in the second rampart at Saqsawaman (fig. 32). The tapering sides of the gap indicate that it was a keystone that had fallen out of the bond. Since the width at the bottom of the gap is broader than at the top, the keystone must have been introduced from the front. If, as I suspect, the Incas used earthen embankments to raise the building blocks into position, then it would make sense to assume that keystones were always inserted from the front. Each of the courses in these walls proves to have a block that can reasonably be regarded as such a keystone: blocks 15, 58, 30, and 35, and possibly 28 and 25. The course formed by blocks 20 and 57 does not have a keystone because it does not need one. Block 57 is a corner stone which could easily be put in place last. Corner stone 1 was most likely erected after blocks 2 and 11 were in place.

These conclusions about laying sequences are not meant to be definitive for a number of reasons. First, more walls need to be analyzed for sequence; one wall is simply not enough of a sample. Second, because of the fit, which does not allow one to introduce even a knife blade into the joints, I have not been able to measure all the internal angles and in particular those of the bedding joints. Where I have succeeded in making such measurements, I often could do so only to a depth of about 5 cm. This depth is not sufficient, as the joining planes quite frequently are not flat but warped, with the result that farther in the direction of the joining plane might be different from what I have measured on the surface. Third, and most importantly, firm conclusions about the laying sequences can only be reached after careful motion studies have been conducted.

The problem of laying sequences leads me to a set of questions regarding the handling and transportation of the stones, a subject that I have not taken up yet, not because I find it uninteresting or unimportant, but simply because I have neglected it in favor of the issues addressed here.

Acknowledgements

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I owe very special thanks to John Rowe. Not only has he encouraged me to pursue the study of Inca stonemasonry, but he has been very generous with suggestions and criticism, and has reviewed earlier versions of this paper. Without his interest in my project and his support I would never have embarked on this enterprise.

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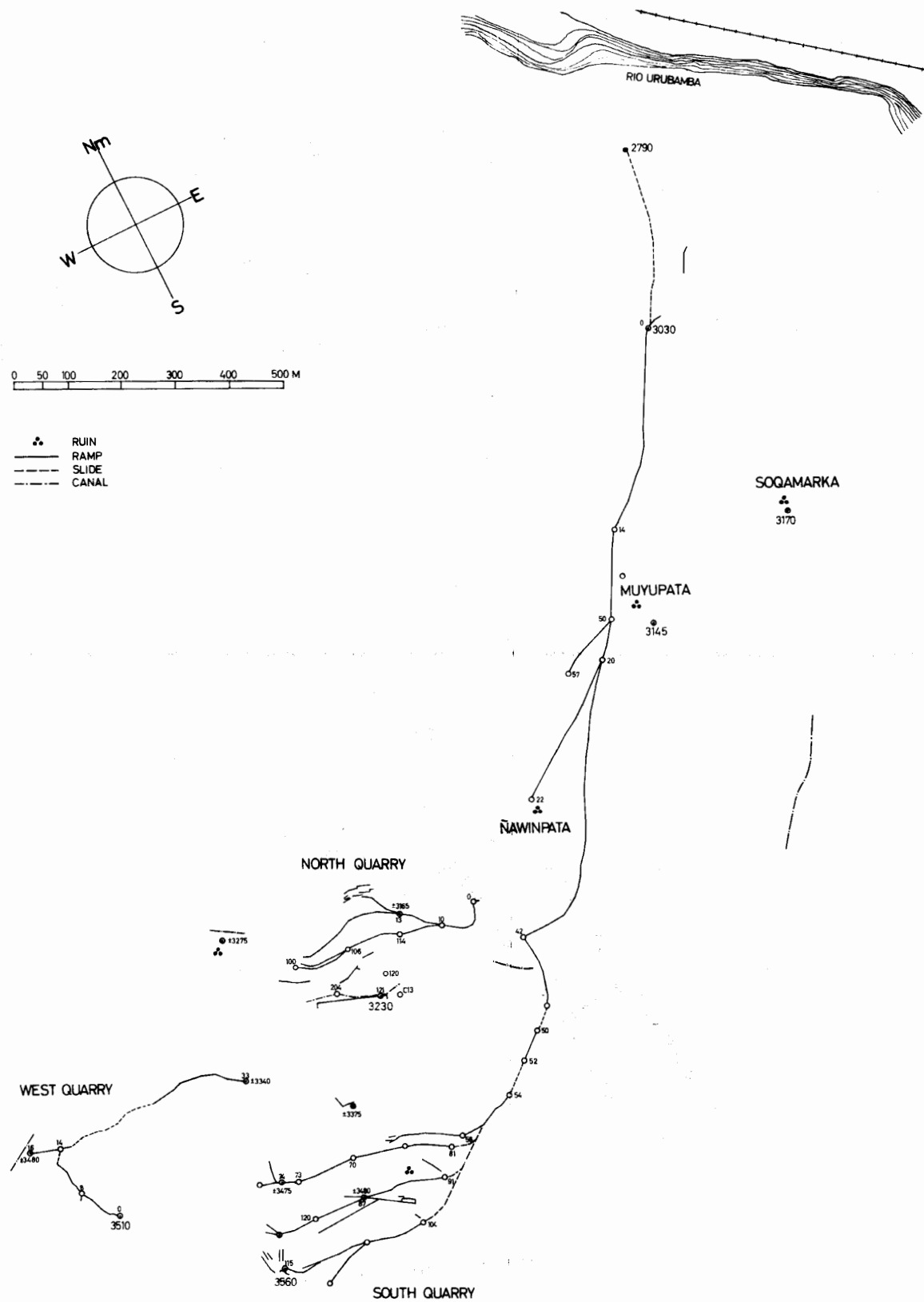
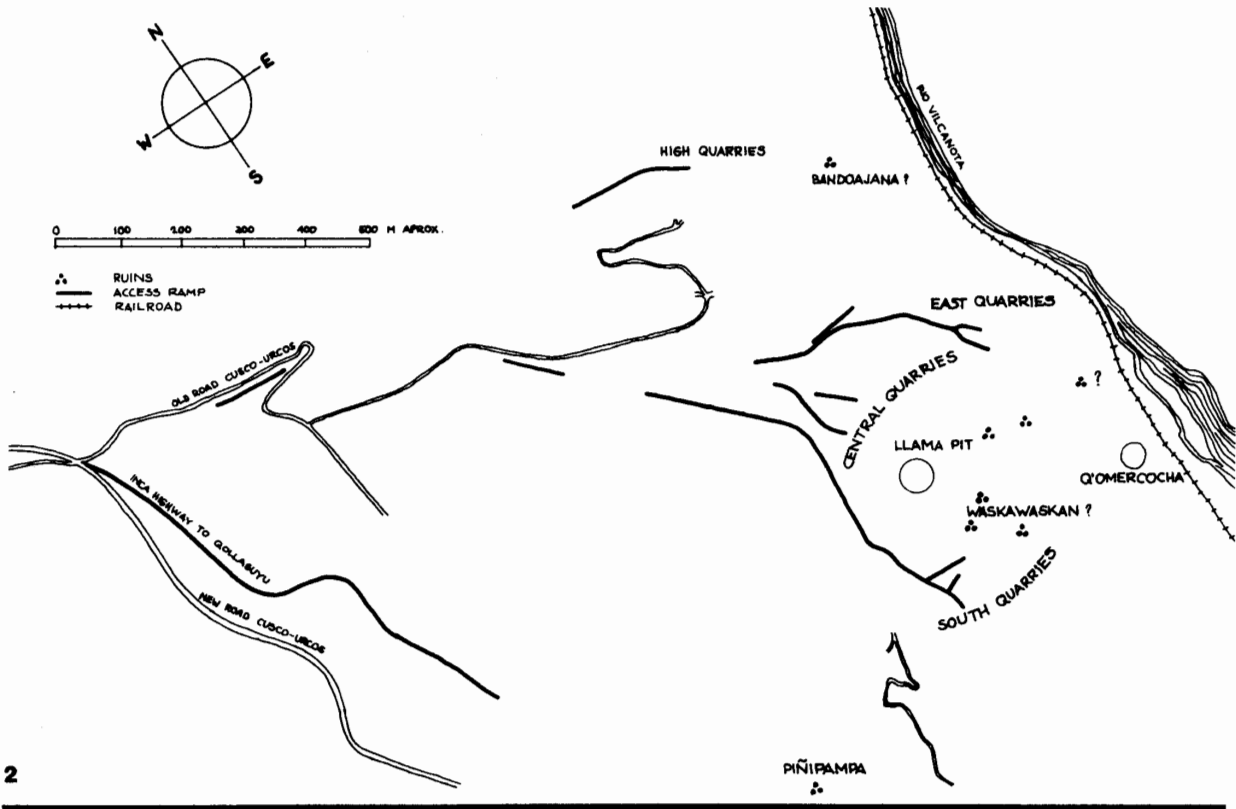
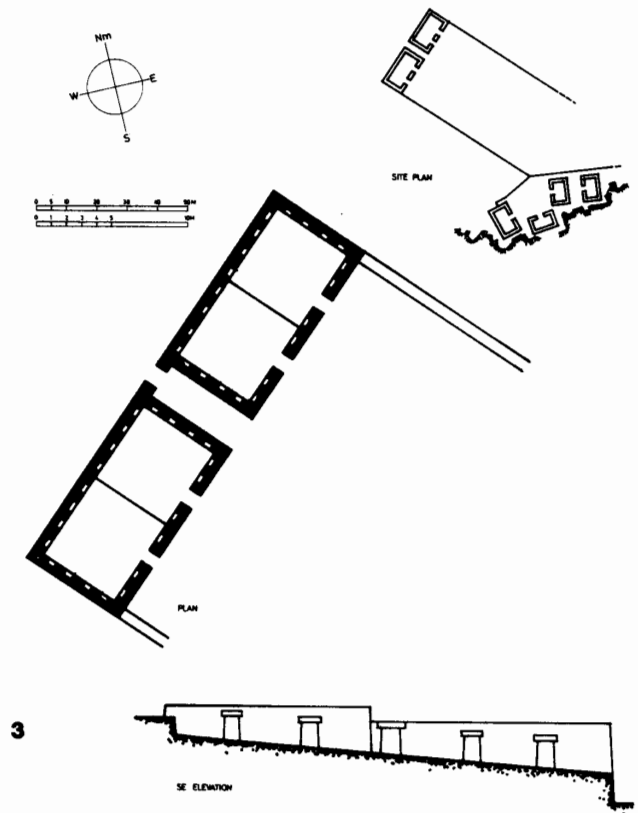


Fig. 1, map of the quarries of Kachiqhata near Ollantaytambo.



2



3

Fig. 2, sketch map of Rumiqlolqa quarries; fig. 3, Harth terré's plan and elevation of quarrymen's houses in the Kachiqhata quarries (details redrawn from Harth-terré, 1965, gráfico 2).

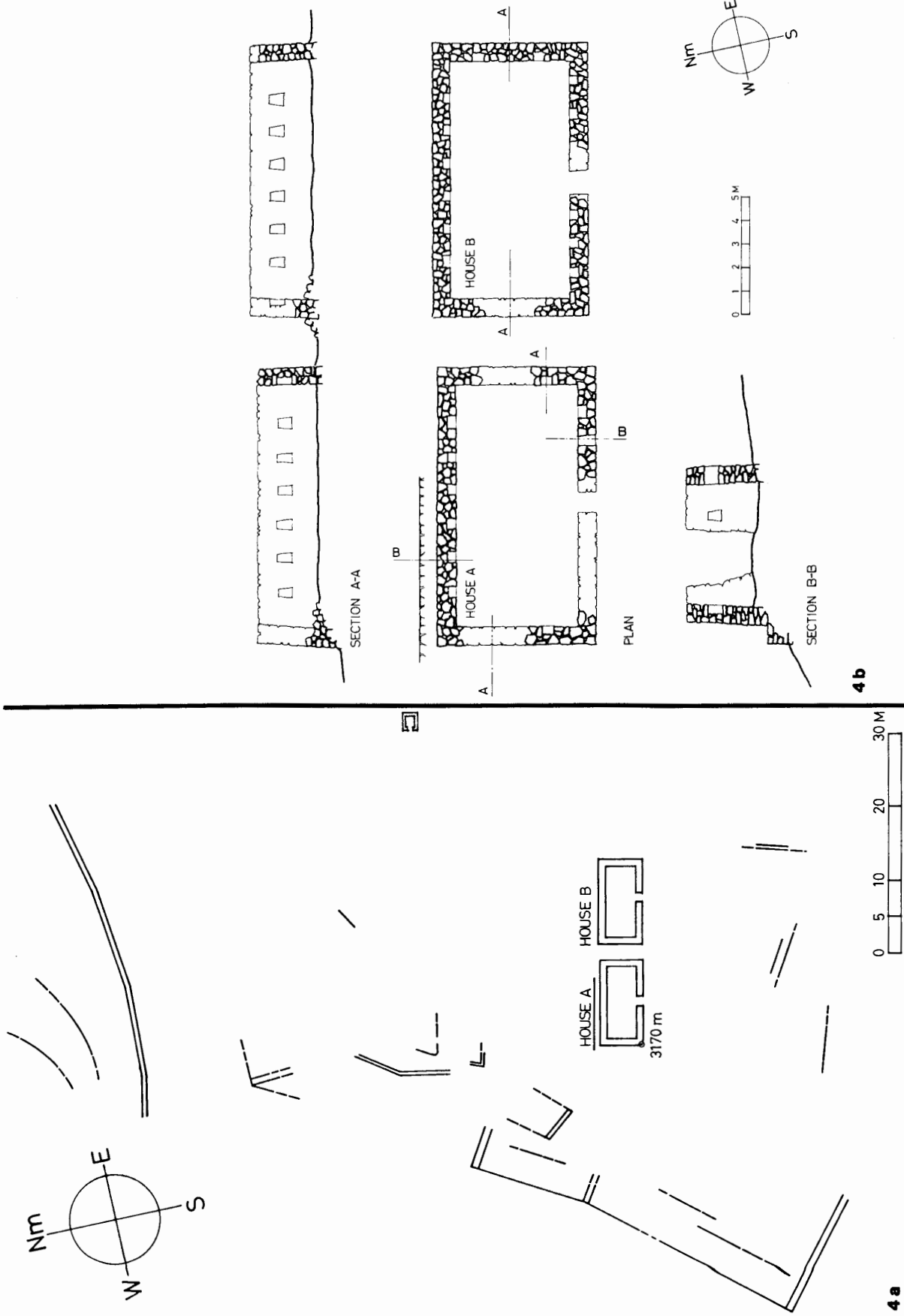


Fig. 4a, site plan of Soqamarka; fig. 4b, plan and sections of houses A and B at Soqamarka.

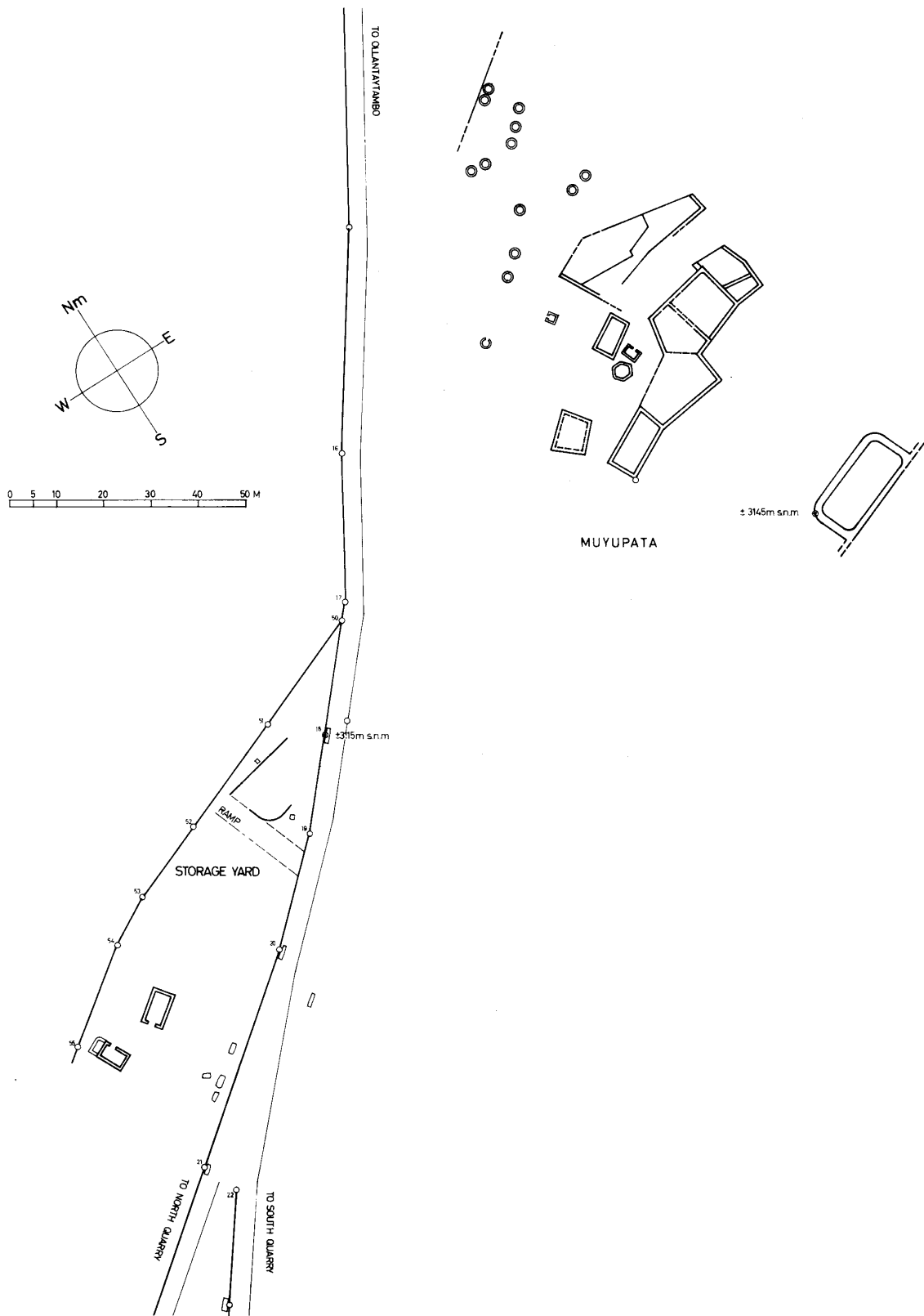
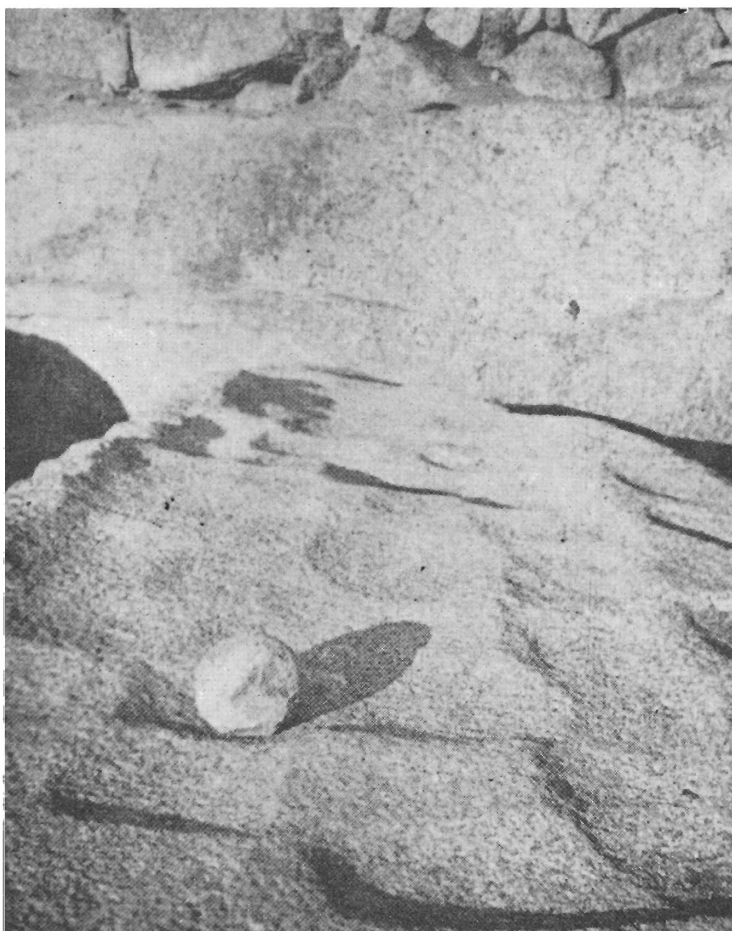


Fig. 5, site plan of Muyupata and of storage yard just below the junction of the access ramps leading to the North and South quarries.



6



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Fig. 6, pouncing marks on red granite block in the South Quarry of Kachiqhata; fig. 7, pouncing marks and hammer stone on obelisk at Aswan (from Clarke and Engelbach, 1930, p. 26).

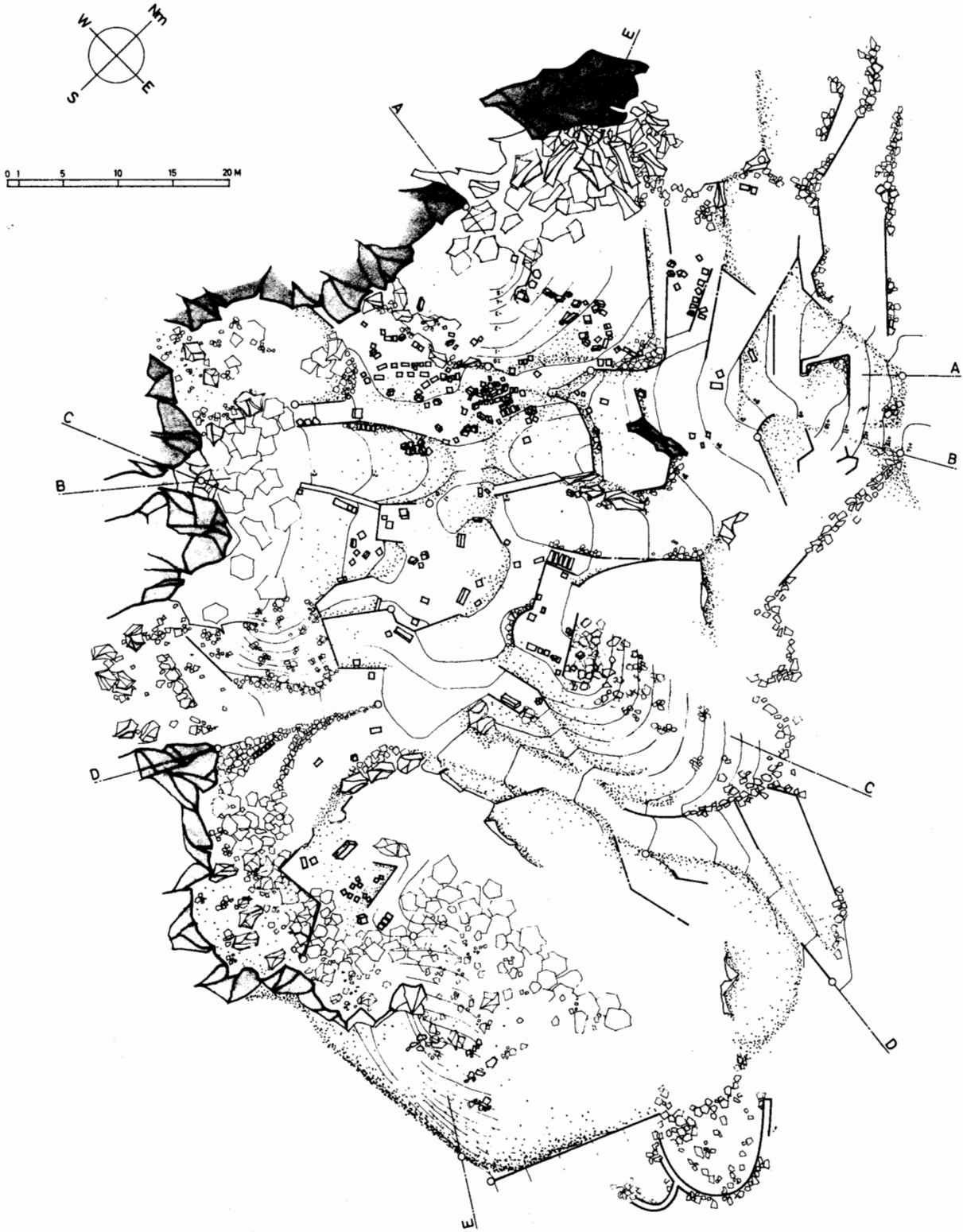


Fig. 8, site plan of Llama Pit in the Rumiqlolqa quarries.

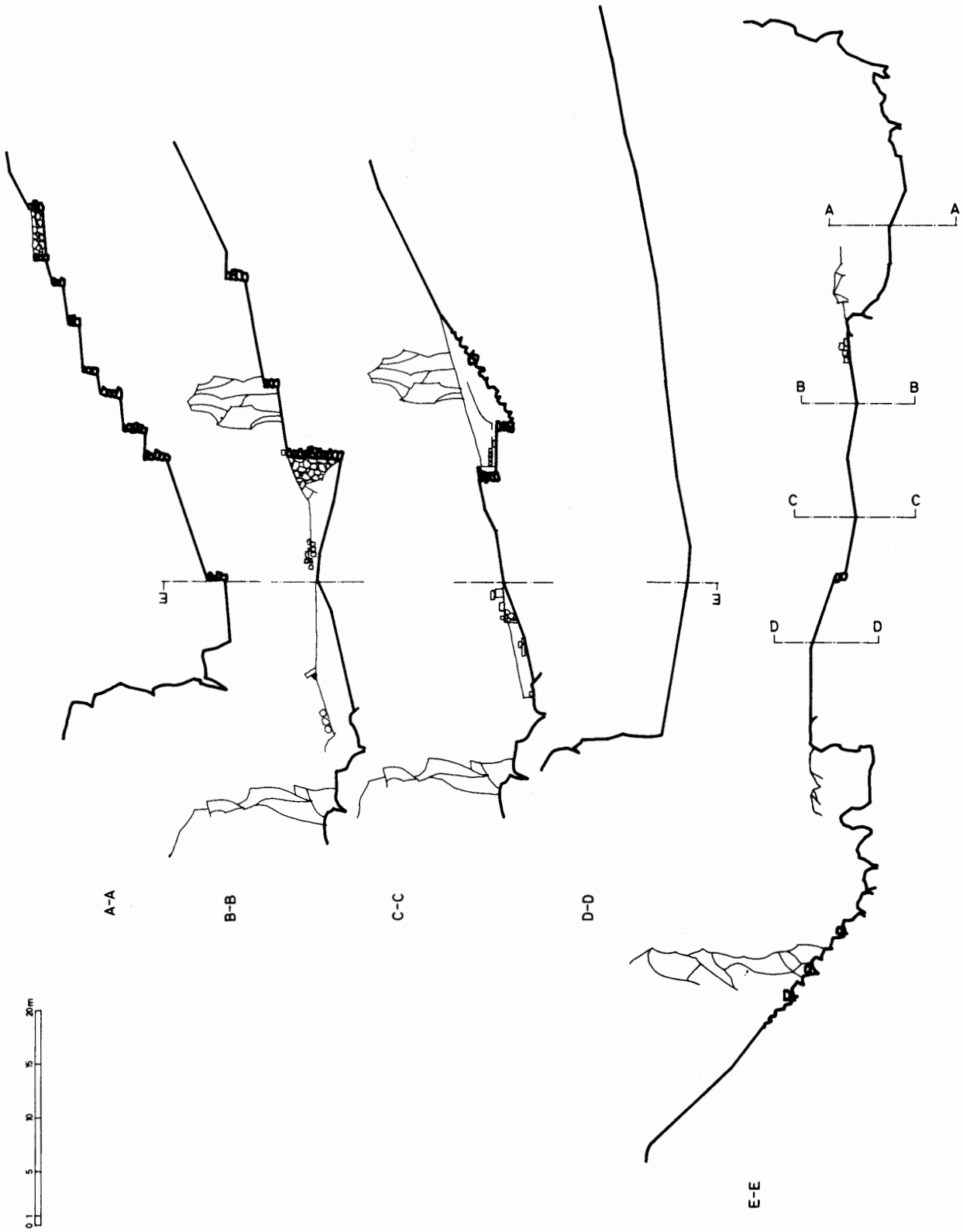
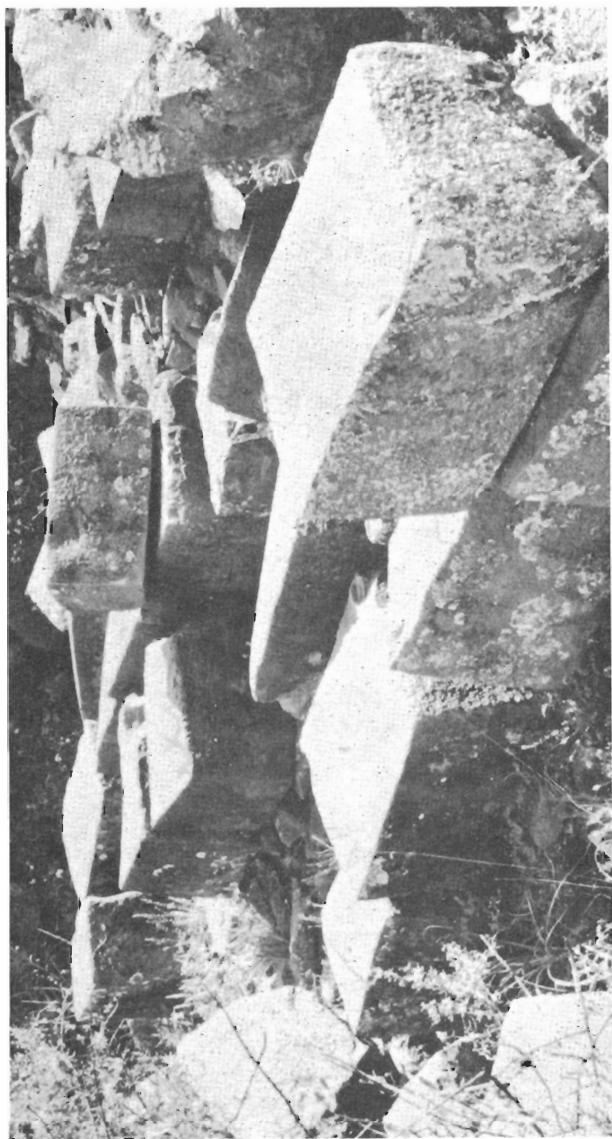
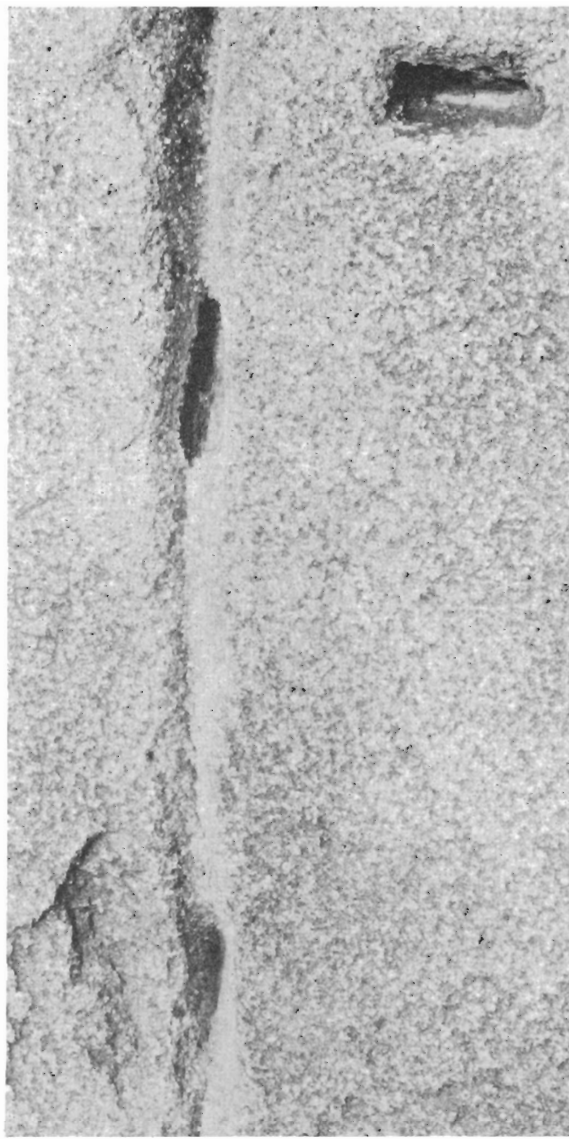


Fig. 9, profiles through Llama Pit in the Rumiqolqa quarries.



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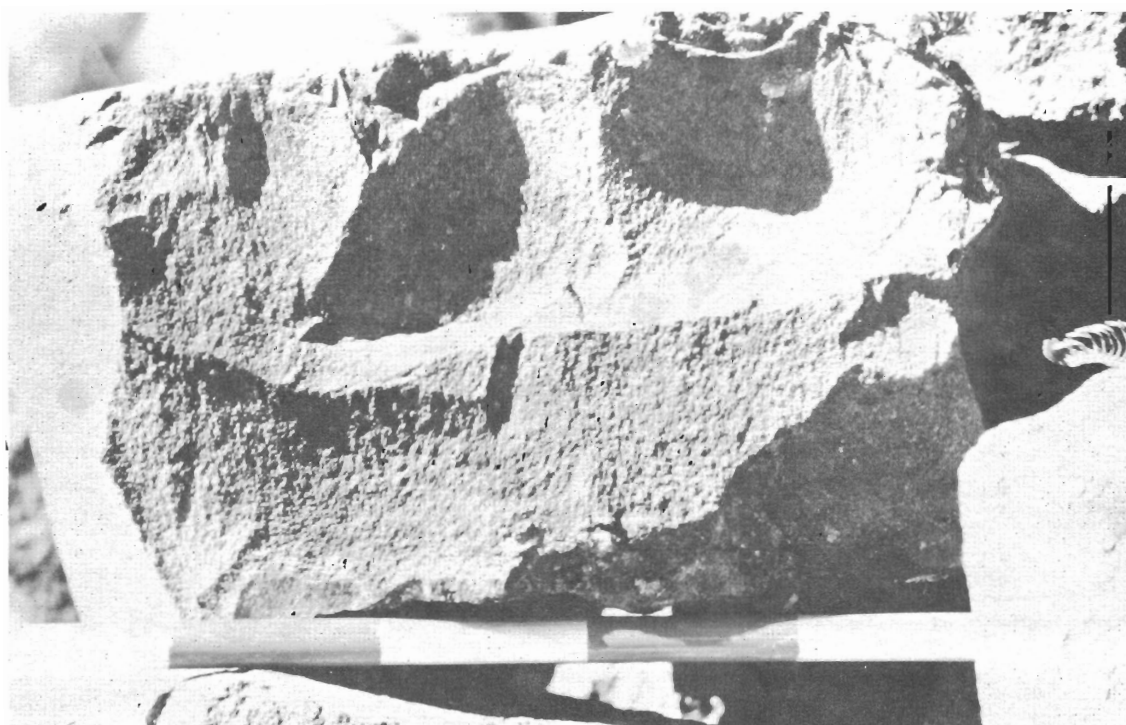


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Fig. 10, ancient cut stones abandoned in Llama Pit; fig. 11, channel and wedge holes in red granite block on access ramp to Ollantaytambo; pit marks and oval wedge holes suggest that holes were pounded out; fig. 12, wedge holes in split rock at Machu Picchu; sharp rectangular shape of wedge holes suggests use of a sharp cutting tool.



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Fig. 13, half buried hammer stones in Llama Pit; fig. 14, flaking scars on block in Llama Pit.

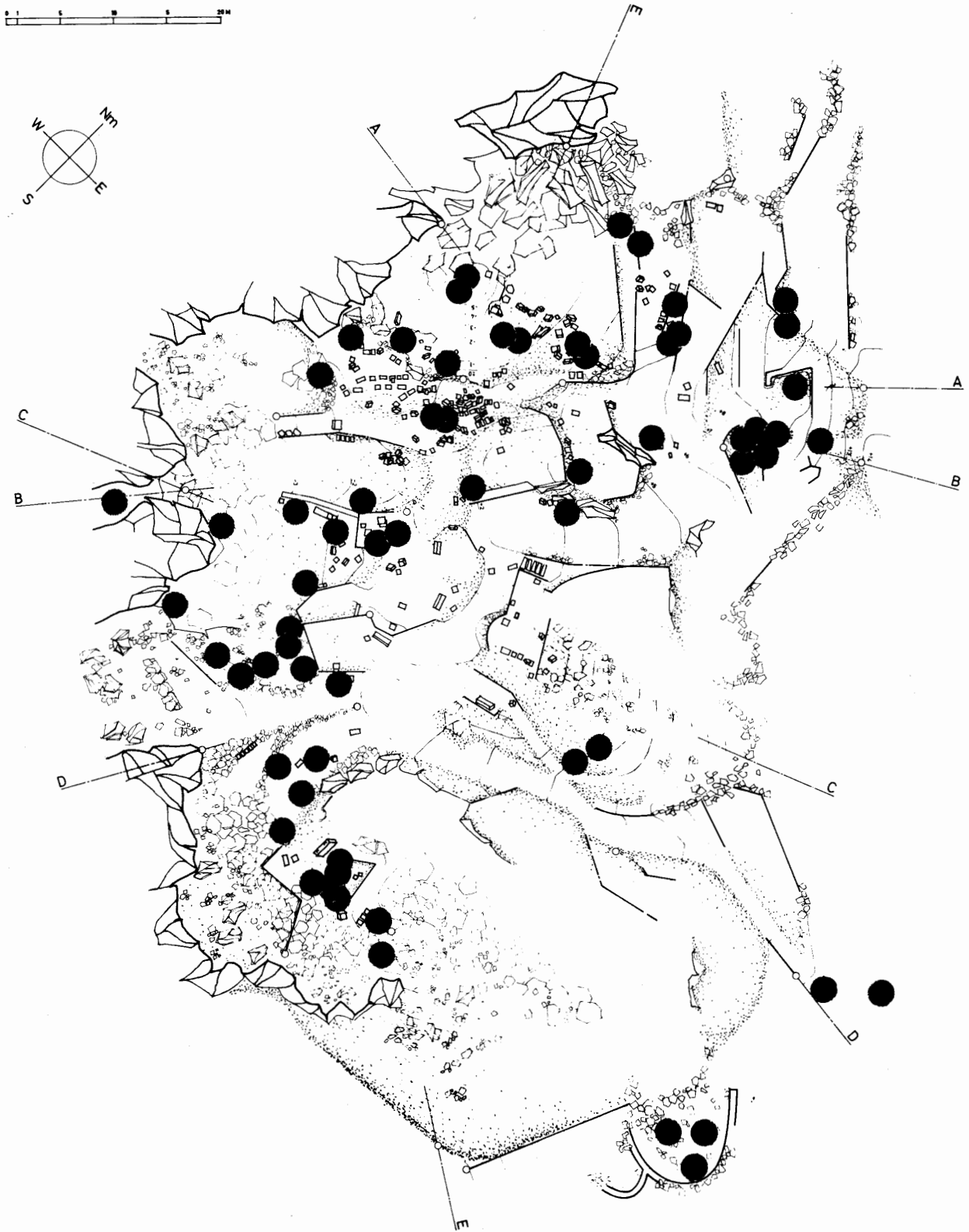
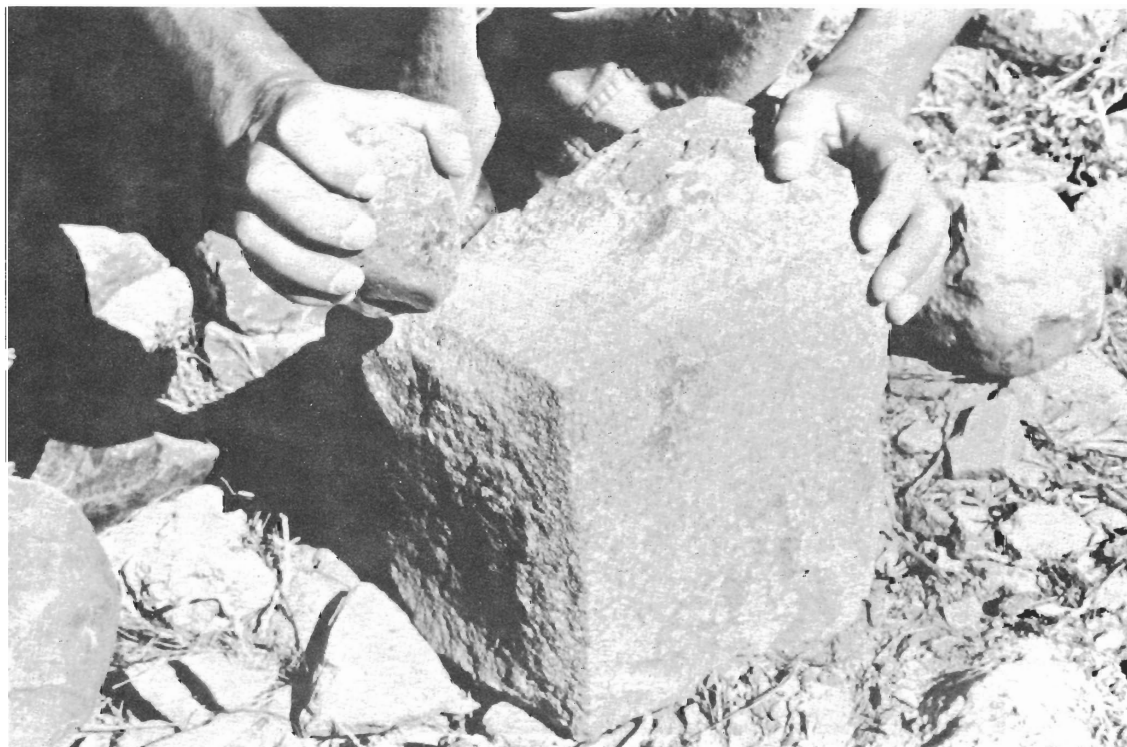


Fig. 15, distribution of lithic finds in Llama Pit.

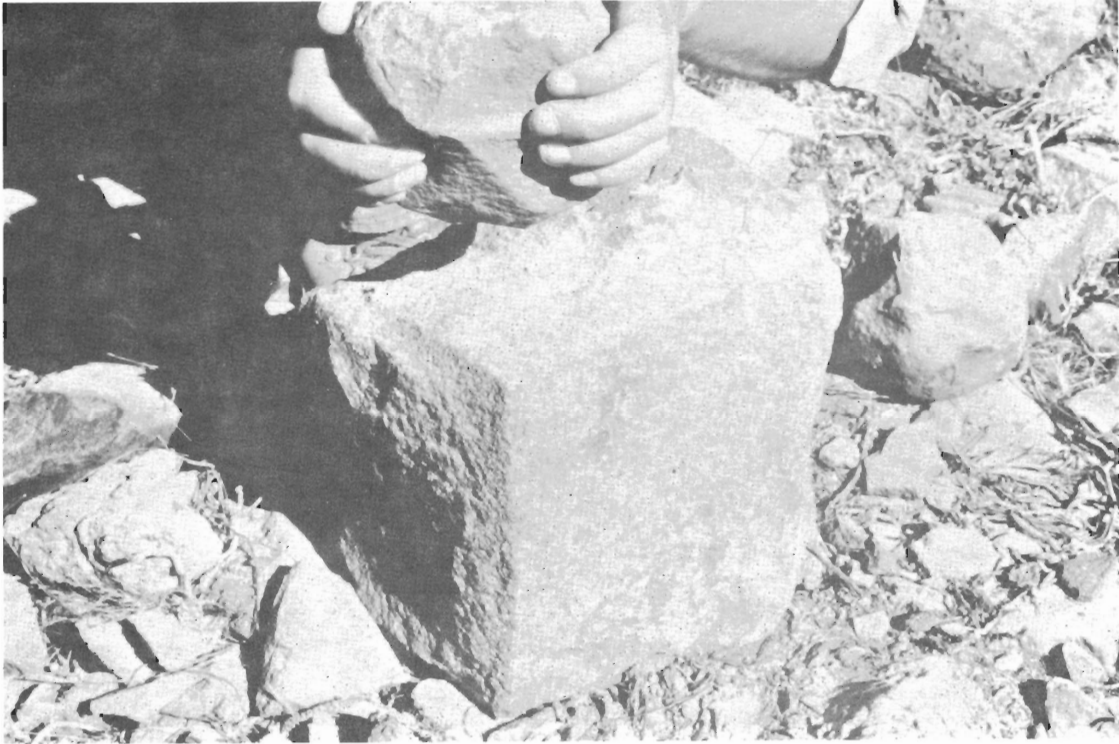


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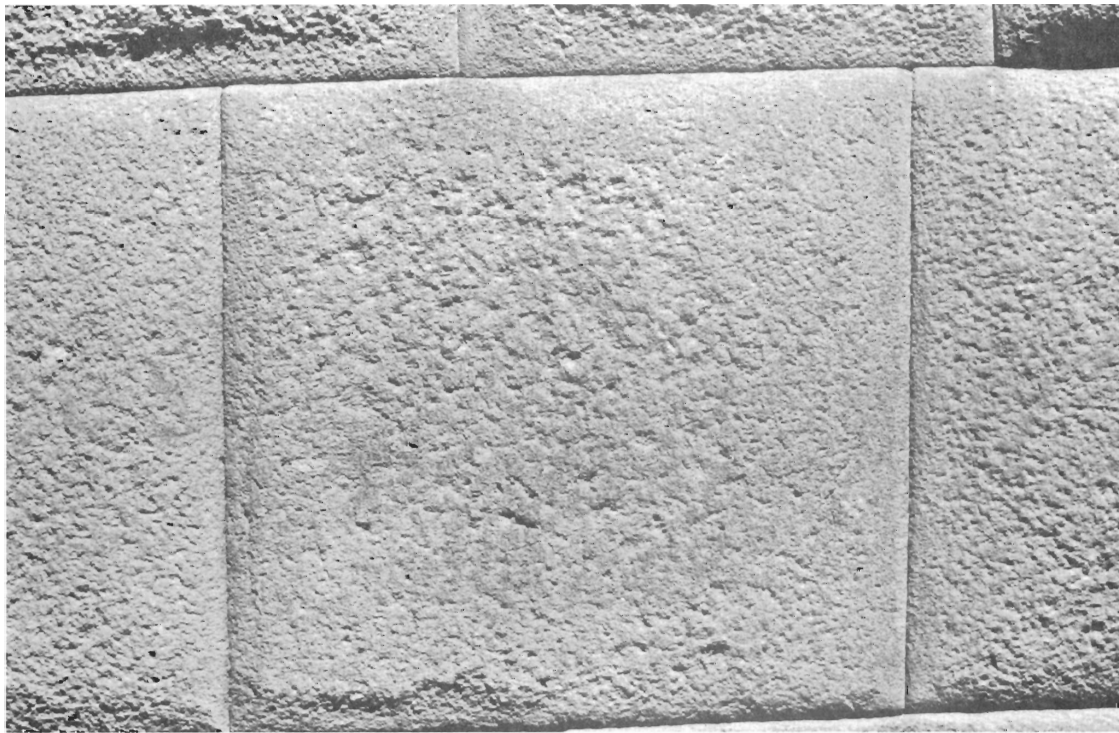


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Fig. 16, raw block of andesite used in stonecutting experiment; fig. 17, drafting an edge with small hammer stone of metamorphosed sandstone.

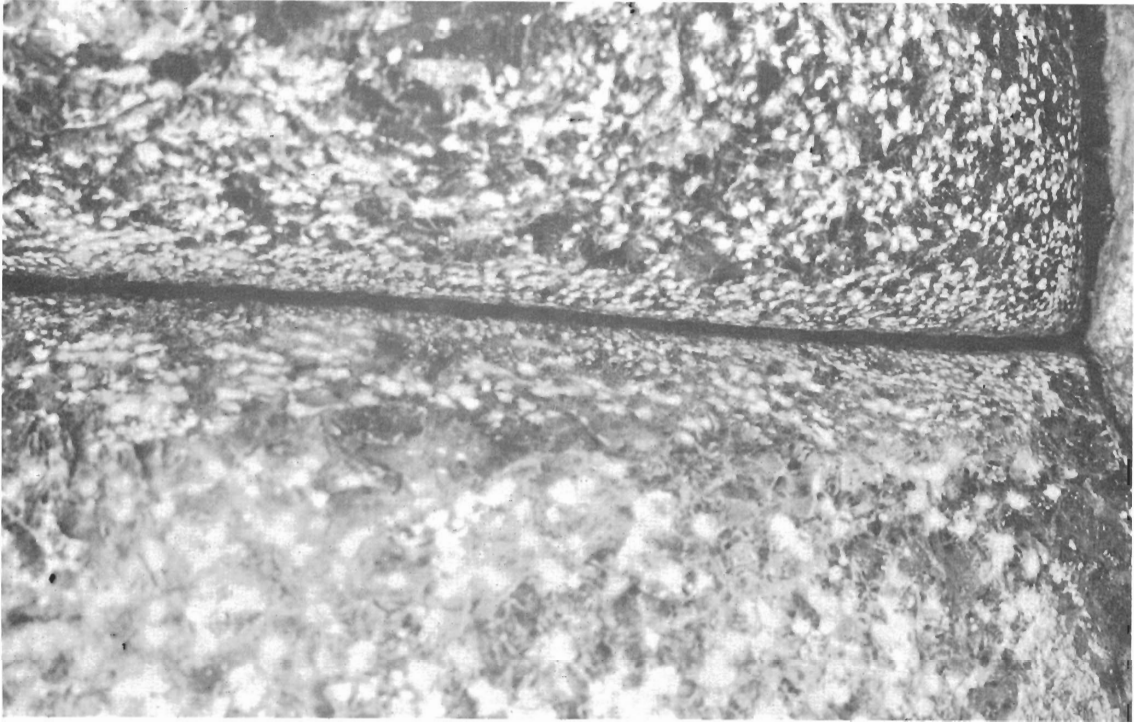


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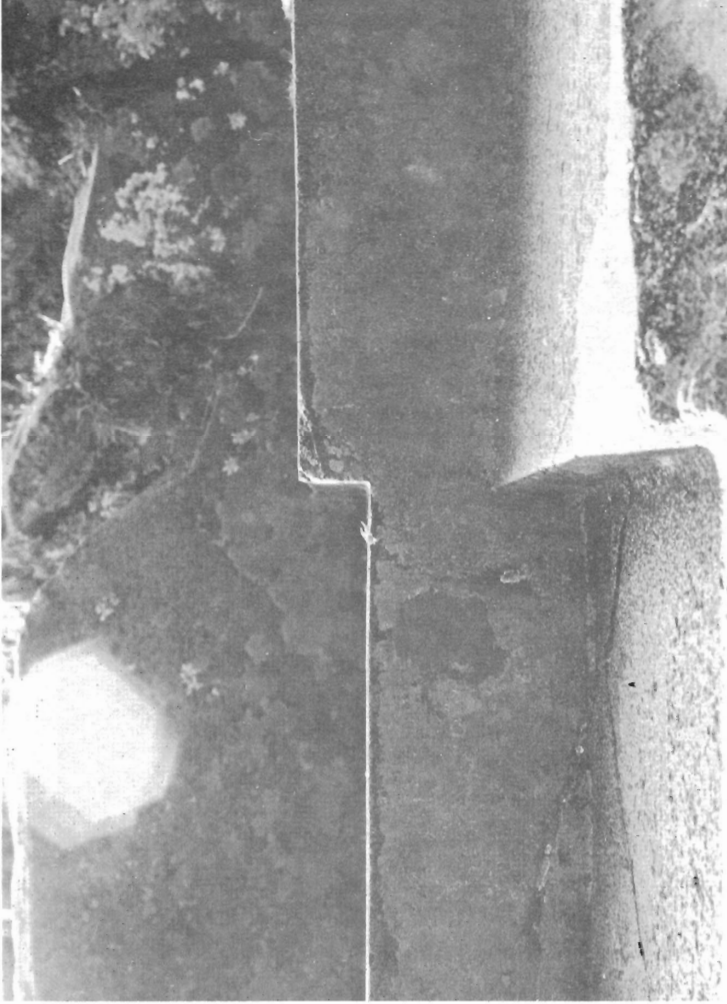


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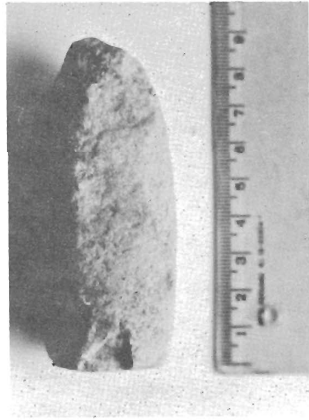
Fig. 18, dressing of a face with hammer stone of metamorphosed sandstone; fig. 19, andesite block in wall of Aqllawasi, Cuzco, showing pit marks from pounding; notice how pit marks get finer around the edges of the block.



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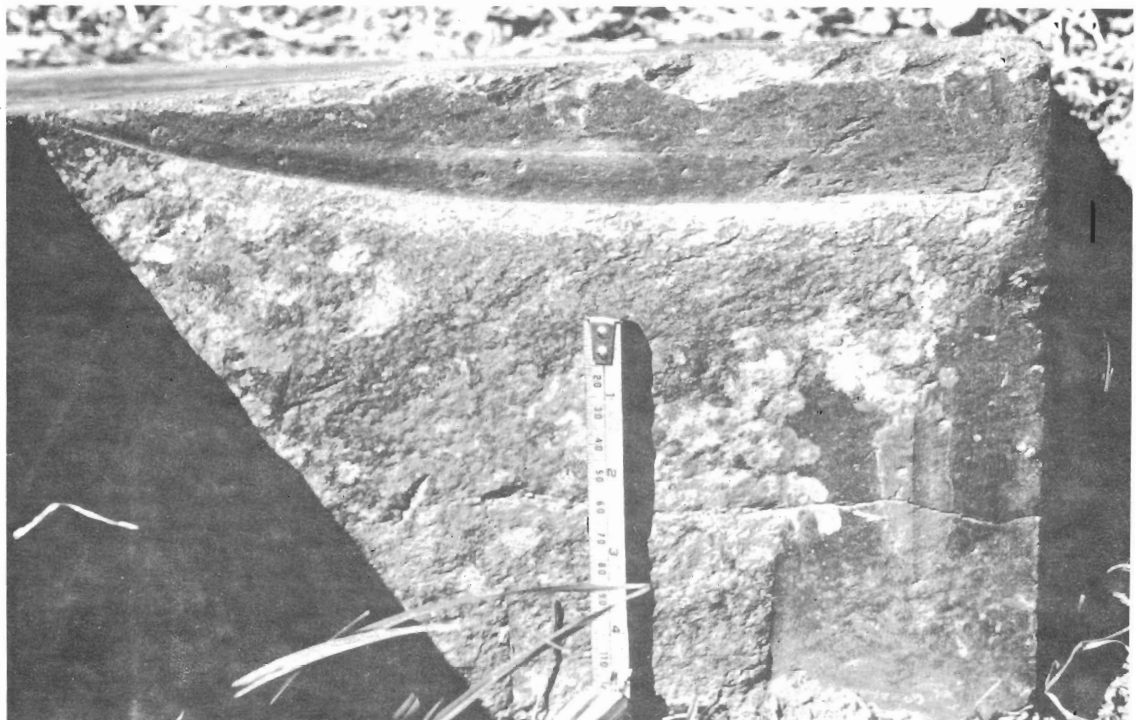
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Fig. 20, pit marks on limestone; whitish spots are produced by heat of impact of hammer stone, resulting in partial metamorphosis of limestone; **fig. 21**, sharp concave corner on steps of the "Throne of the Inca" at Saqsawaman; **fig. 22**, quartzite tool from the Llama Pit that could have served as hammer, chisel, or wedge.

Fig. 23, groove made of two cuts at Inkamisana; cuts are a result of abrasion and not of pounding; fig. 24, cuts made by abrasion with an unknown tool on "fountain" stone at Ollantaytambo.

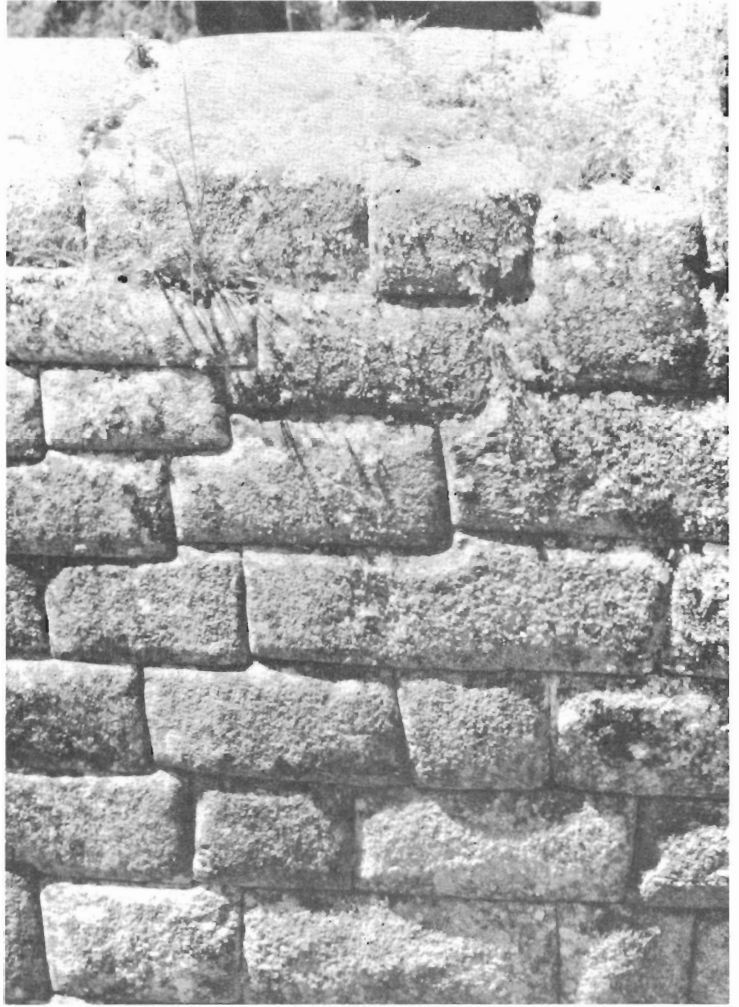


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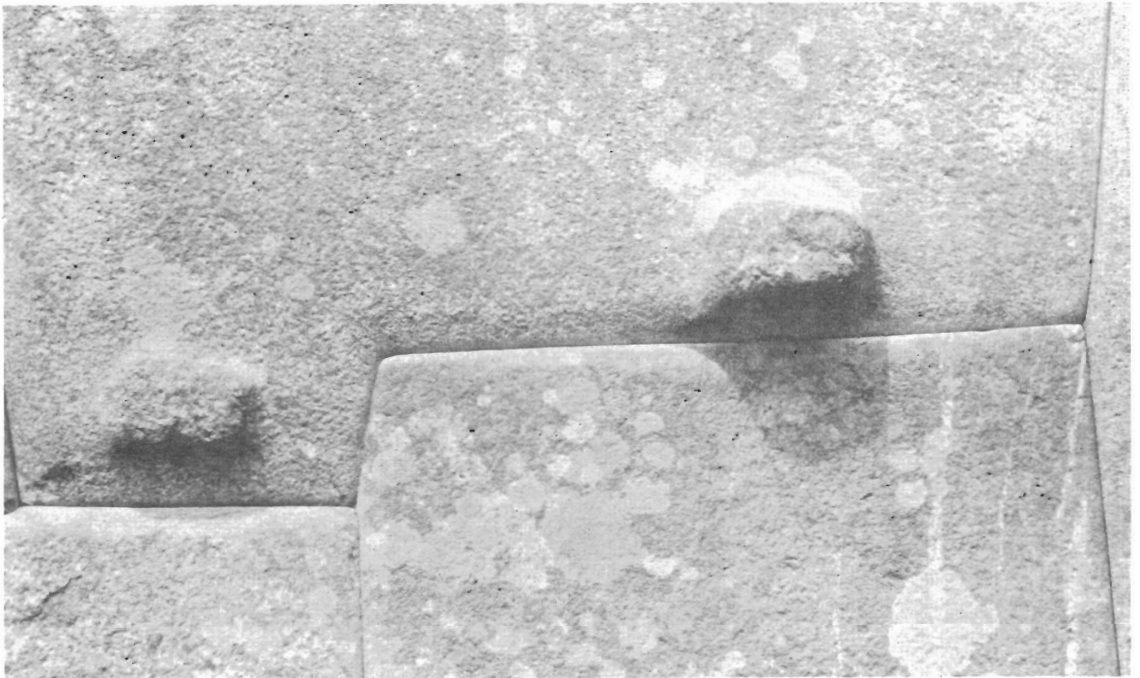


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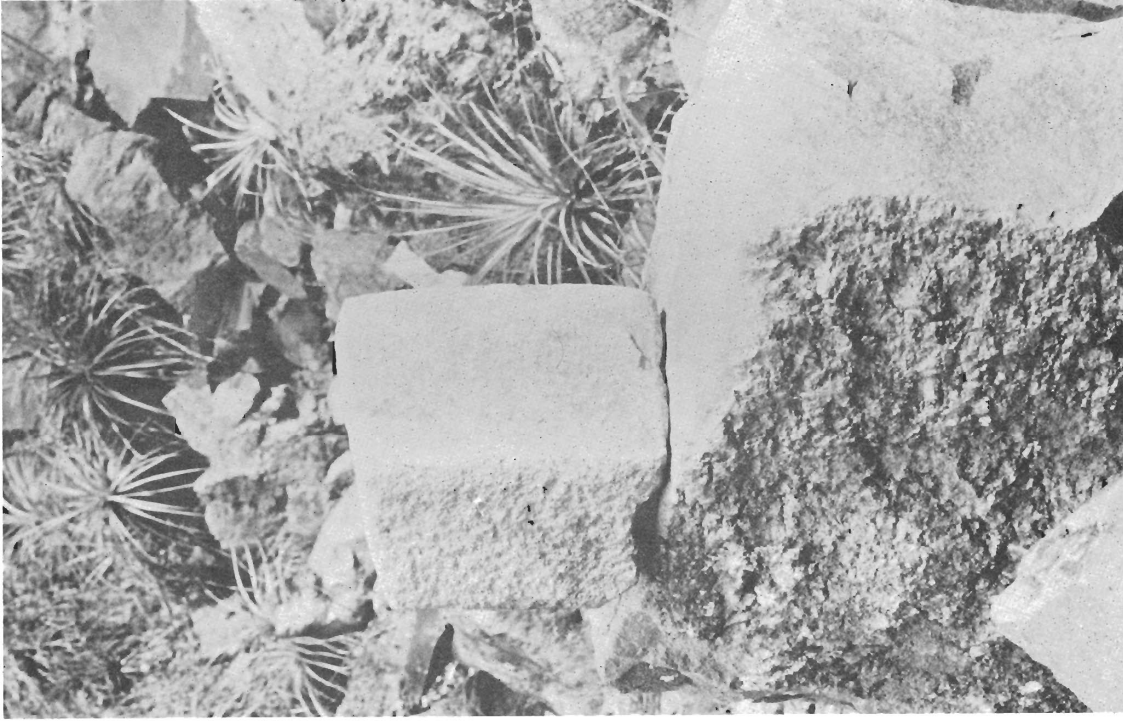
Fig. 25, "hookstones" in Bingham's Beautiful Wall at Machu Picchu are a good illustration of the bedding joint rule; fig. 26, exception to bedding joint rule at Ollantaytambo.



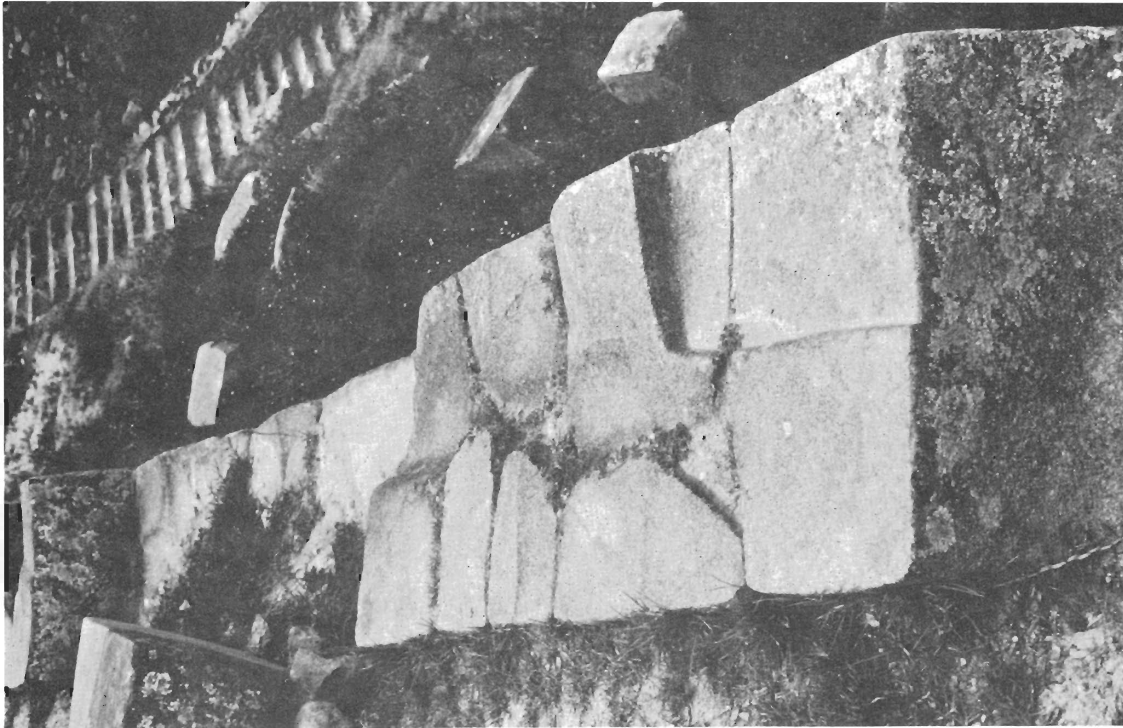
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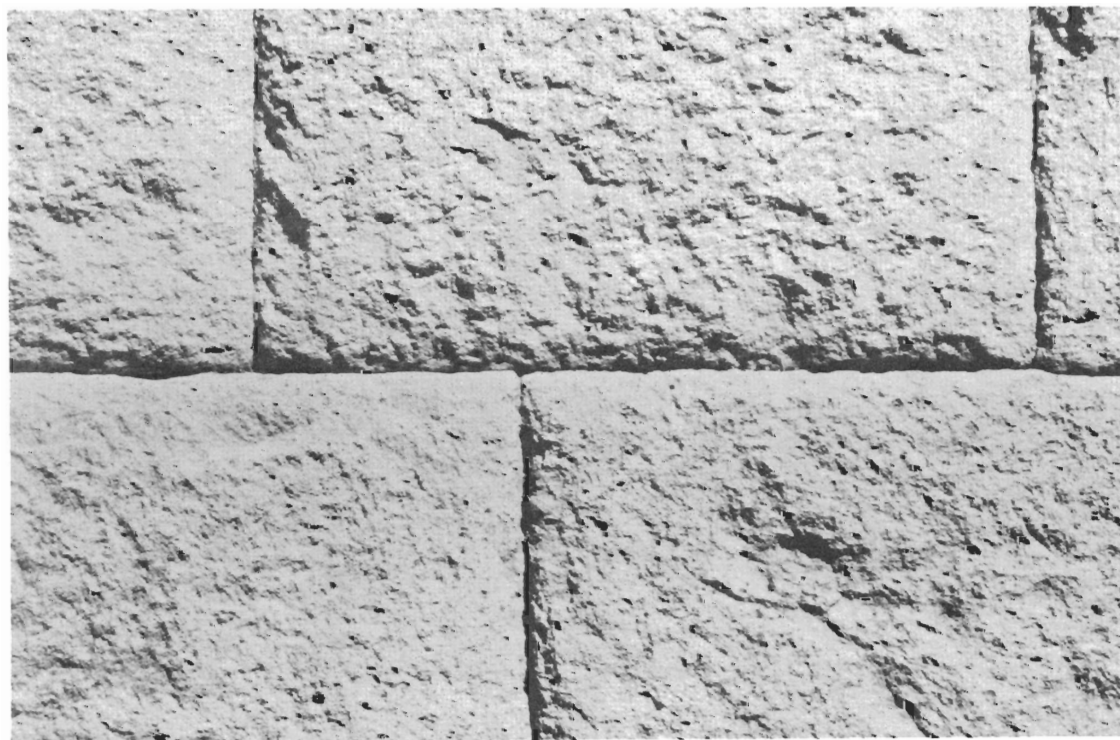


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Fig. 27, bedding joints cut to receive next course of stones; such cuts were not obtained by grinding stone against stone, but were pounded out; fig. 28, two andesite blocks to be fitted in the experiment.



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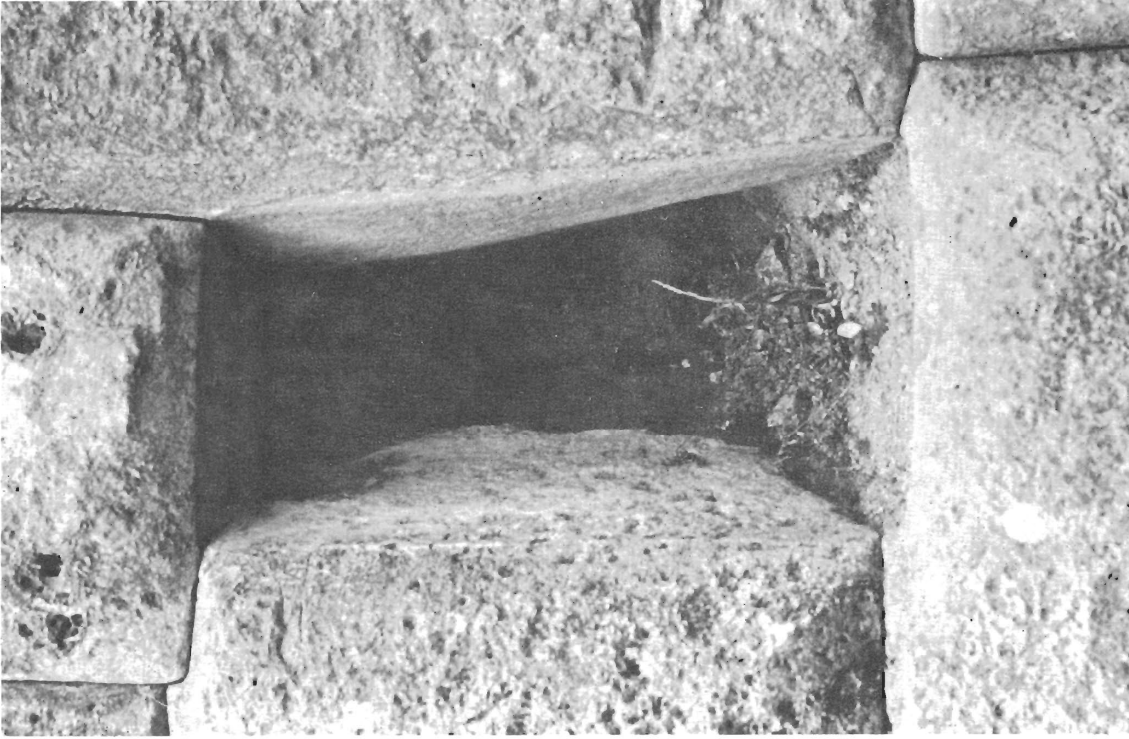


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Fig. 29, fit of two blocks obtained in experiment; fig. 30, fit of andesite blocks in Inca wall of Amarukancha, Cuzco.



31



32

Fig. 31, illustration of the combined effect of the fitting of bedding joints and lateral joints at Saqsawaman; **fig. 32**, gap left by keystone fallen out of bond; notice taper of sides of gap, leaving a wedge-shaped hole; since hole is wider at the bottom than the top, keystone must have been introduced from the front.