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IDENTIFICATION OF PASSIVE SOLAR DESIGN PRINCIPLES AT MACHU PICCHU, PERU

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ABSTRACT

This research paper identifies the passive solar principles found at Machu Picchu Ruins, Peru. This is done through a combination of climatic data collection, detailed architectural drawings, and field observations by the author since 1978. The results show that Machu Picchu can be viewed as a study model of energy and resource conservation on a large-scale. It also sets grounds for future quantitave analysis of the features presented.

1. INTRODUCTION

The potential of analyzing the way by which primitive architecture responds to regional environmental conditions to understanding how former cultures utilized natural energy and resources in architecture and urban design has been pointed out in several research papers and books. However, the majority of the reports available so far have been qualitative or concentrated on the design of a single building. On the contrary, there have been very few studies of this nature that were quantitative and analyzed a primitive urban setting. Moreover, this line of architectural research has been limited to the utilization of specific natural resources, such as solar and wind energy. Also, these studies have been carried out in specific geographic areas, such as North Africa, North America, and the Middle East.

It is important that the above-cited architectural research be conducted at the urban scale in a quantitative way at geographical and climatological settings other than the ones previously studied. This is relevant due to the fact that the densely populated areas of the world are among the most vulnerable areas in case of a major future energy crisis. The many primitive settlements found throughout the world offer an exeptional opportunity to evaluate energy and resources conservation at the urban scale.

This research paper presents an analysis of the architecture and urban design found at Machu Picchu Ruins, Peru as it responds to the utilization of natural resources. The aim of this report is to identify the architectural and urban design features that can be interpreted in the context of today's passive solar principles.

2. SITE LOCATION AND BACKGROUND

The area of study consists of the well known Machu Picchu archaeological site. It is located within the Vilcabamba Cordillera and along the Urubamba River in the Eastern Slopes of the Southern Andes of Peru. More specifically, its coordinates are latitude 13° 09' S and latitude 72° 32' W. The topography is rugged with slope angles ranging from near level to perpendicular. The altitude varies from about 1,450 to 2,800 meters (4,780 to 9,240 feet). The ruins are located at 2,200 meters.
The region under study is situated within the boundary of the sub-tropical and tropical latitudinal zones (1) and in the "Tierra Templada" altitudinal zone (2). The climatic regime of the eastern slopes of the Andes is chiefly controlled by southeast trade winds, which carry a large amount of moisture that originates in the Atlantic Ocean and is reclycled over the Amazon Basin (1,3). The climate of the region of study is broadly classified as Cw (4); that is, a mild-humid climate with a dry winter (June-September) and a wet summer (December-March) having about ten times the amount of precipitation of the dry season (5). Moreover, local climatic conditions are modified by topography and wind patterns(1).

The ruins of Machu Picchu were found in the most preserved state among all the archaeological sites of Peru. It was discovered by Hiram Bingham in 1911 (6). Subsequently, there was recovery of most of the archaeological material. The site has been explored as the major touristic attraction of Peru.

3. INCA CULTURE

The Inca Empire occupied a vast region of the Andes Mountains of South America, reaching from Quito, Ecuador to Tierra del Fuego, Argentina (8). The city of Cusco became the capital of this vast and powerful society. The Empire emerged from a period of harsh environmental conditions (9,10,11). Pachacuti, the first Inca, reorganized the previous Andean culture at ca. A.D. 1400 (12). It was then that he changed the agricultural calendar from lunar to lunar and solar. He also ordered that four columns be built on the hills east of Cusco for carrying solar observations from the central plaza bellow. Moreover, he determined that the agricultural practices and environmental management had to be different for different locations of the Empire. These practices had to change according to latitude and and altitude (9,10). Of course these two terms were not in use at that time. The latitudinal and altitudinal references were made with respect to well known cities of the Empire.

The calendric system and ecological practices set forth by Pachacuti became the roots of the Inca culture in about 100 years. The gods of Inca religion included astronomical and physical environment elements. The principal astronomical deity was Inti, or the sun in Quechua (13). The other gods included the moon, the earth, the ocean, hail, rain, mountains, and river. By the time of the Spanish conquest, A.D. 1532, the Empire had a strong ecological management system throughout the Andes. This system was made up of soil, wood, forestry, wild animal life, and fertilizer conservation (9,12). It is worthwhile to note that these facts have been kept within the fields of anthrolpology and archaeology thus far.

4. NATURAL ENERGY, URBAN DESIGN, AND ARCHITECTURE AT MACHU PICCHU

The author has recognized four levels of evidence that indicate the presence of utilization of natural energy in architecture and urban design at Machu Picchu. These were first observed in 1978. The levels found are site selection, land use, urban design, and building design. A discussion of each of the levels is presented below.

4.1 Site Selection

The Urubamba River has an unique configuration in the area of study. The river has a deep valley and it encircles the site at nearly 360 degrees. Therefore, the site where the citadel of Machu Picchu developed has unusual topography and climate. The configuration of the river valley allows for mountain-valley wind to occur at almost every orientation. The general flow pattern of mountain-valley wind throughout a typical day at Machu Pic-Picchu is shown in Figure 1. The valley winds have fairly uniform velocities from all directions during the mornings, but the strongest component comes from the SW in the afternoons. The SW valley wind reach velocities of about 10.5 m/s (34.7 ft/s).

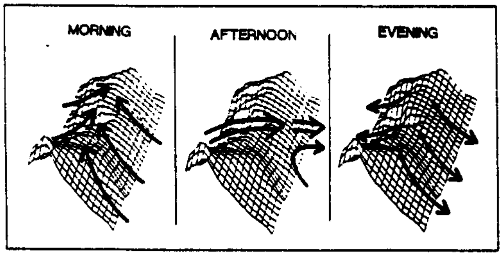

Fig. 1. Typical wind flow patterns.

Moreover, the ruins are surrounded by higher peaks. The combination of mountain-valley wind, remarkable topography, and marked regional seasonal cloud cover contributes for the development of unique seasonal cloud cover and climate at Machu Picchu. This seasonal cloud cover is illustrated in Figure 2 .

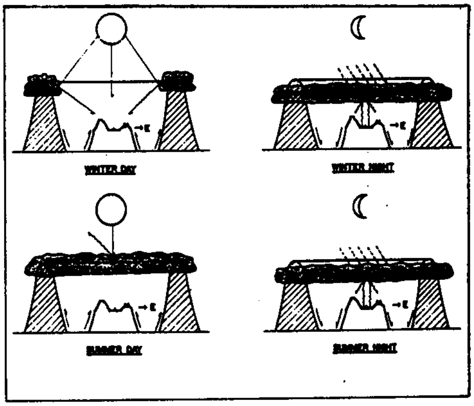

Fig. 2. Cloud cover configuration.

The valley is filled with fog in the earliest hours of the day. As the day progresses, the barometric gradient is gradually established and clouds begin to form and rise in layers. The sky conditions directly above the ruins begin to change rapidly from overcast to partially clear, and clear. This process reverses by early evening and the clouds begin to descend. The effect of the mountain-valley wind on the altitude of low clouds and relative humidity during the day is shown in Figure 3.

Therefore, there is the formation of a cloud ring on winter days, which which contribute to an increase of difuse solar radiation. On the other hand, a cloud cover prevents overheating of the site during a summer day, and reflects longwave radiation on a typical night preventing frost to occur at Machu Picchu. The clouds that form at the site include stratus, stratus cumulus, and cumulunimbus, and cumulus humilis. It should be mentioned that sky conditions are very dynamic at Machu Picchu and the cloud configuration depicted in Figure 2 for each season of the year is an instantaneous average picture.

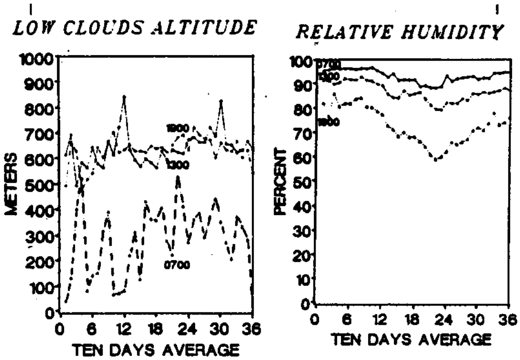

Fig. 3. Cloud altitude and relative humidity at 0700, 1300, and 1900.

This distinct seasonal cloud cover acts as a natural greenhouse. The total solar radiation arriving at a horizontal surface during typical clear, partially clear, and overcast day is found in detail in Figure 4. It is interesting to note that there are several instances when there is more total solar radiation available on a partially clear than on a clear day due to the presence of the above-cited cloud ring.

There is a direct effect on the air temperature throughout the day and year at the site. This is also shown in Figure 4. That is, there is a seasonal reversal at Machu Picchu due to the marked seasonal cloud cover. The winter is warmer and the summer cooler. Also, the nighttime temperatures are higher due to the cloud blanket which holds longwave radiation. The average annual maximum (daytime) and minimum (nighttime) temperatures are 20.0° C (69.0° F) and 10.0° C (50.0° F), respectively.

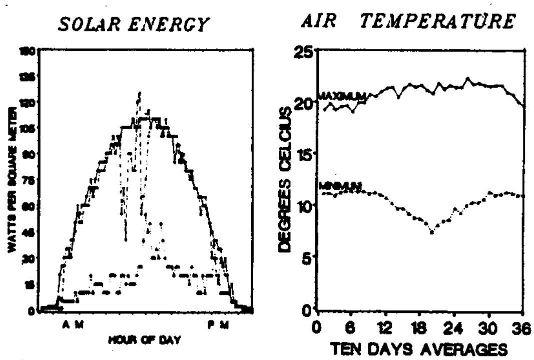

Fig. 4. Total solar energy on typical days and temperature record.

The cloud cover, relative humidity, and temperature conditions presented here are averages taken from a ten-year (1966-1975) data period (14), which was assessed by the author. The total solar radiation are results of repeated measurements by the author at the site since 1978. There are other climatic parameters that are affected by topography and cloud cover at Machu Picchu. A discussion of other parameters and paleoclimatic conditions is outside the scope of this report, and it is given by the author in a more extensive and detailed report (7).

4.2 Land Usé

The citadel was developed in a way that maximized land usage and natural resources. The Incas developed every major accessible alluvial terrace present in the region. The citadel was situated on one of the largest alluvial terraces in that region (7).

The citadel is located on the eastern portion of the mountain top. Its overall orientation is along the north-south axis with the longest portion oriented east-northeast. In such way it takes advange of early morning sun. More significantly, it is within the center of the surrounding peaks, which maximizes utilization of the cloud ring and solar radiation that was described above. Moreover, the location of the citadel on the eastern portion of the mountain top protects most of the structures from the prevailing winds, which come from the southwest.

The citadel is subdivided into two major sectors. These are the agricultural and urban sectors. A general plan of Machu Picchu is shown in Figure 5. Moreover, there are production settlements located at other alluvial terraces nearby Machu Picchu, which explored specific ecological niches (7). Some of these supporting settlements are larger in area than Machu Picchu, but have fewer buildings.

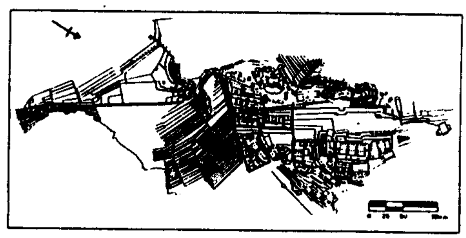

Fig. 5. Genral plan of Machu Picchu.

4.3 Urban Design

The urban design of Machu Picchu shows strong evidence that it was carefully built to take advantage of solar energy and mitigate wind conditions. The urban section that exemplifies these characteristics the most in terms of buildings' arrangement and size is presented in Figure 6.

There are two basic plans shown in Figure 6. The first plan is a building arrangement in which a court yard is achieved with four buildings. The location of this design is critical since it is exposed to the SW winds. Therefore, the buildings open to the inside to maximize solar energy gain and minimize advert wind conditions.

Also, this sector is entirely protected from the SW winds by a wall which surrounds the buildings on the outside. The second plan is found in the wind shadow and have openings to the northeast and east. Moreover, this second plan incorporates solar access allowing equal amount of solar energy to reach the interior of each building. These relationships are shown in Figure 7. There are other building arrangements within the ruins, but a description is limited to the cited plans due to the space allocated for this report.

4.4 Building Design

The majority of the buildings found at Machu Picchu are one and one-half stories high. The structures are rectangular with the longest side facing east, where openings are located. There is a great number of buildings which have earth berms in the west. A cross-section of a typical building is shown in Figure 8.

The walls of the buildings show very interesting features. The walls are

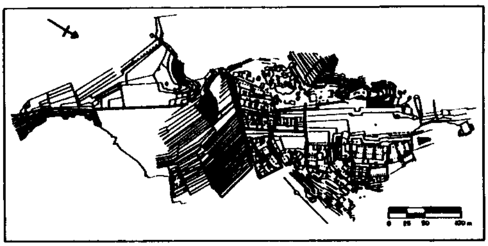

Fig. 5. Genral plan of Machu Picchu.

made out of an assemblage of two granite blocks, one inside and the other outside, which are separated by an insulating layer of soil. There are evidence that show that the walls were covered with a thin clay surface. Moreover, the floors consist of a thick layer of burned clay, which was laid over two other additional layers of sand and burned clay-and-fragmented rocks. These materials are shown in section in Figure 9.

5. CONCLUDING REMARKS

The material presented here indicates that careful planning took place at Machu Picchu to take advantage of solar energy, mitigate adverse wind conditions, and utilize other natural resources in architecture and urban design, such as topography and biota.

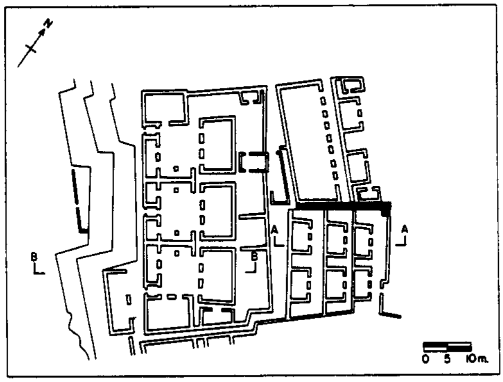

Fig. 6. Typical urban setting, plan.

Among the most relevant planning strategies is the selection of a site that has an unusual cloud cover and climate.

The urban design allows for equal solar access. The individual buildings operate according to the direct gain principle. The buildings are well insulated with earth berms and a layer of soil within the walls. The interior surfaces provide a great heat storage mass.

It should be mentioned that even though the evidence provided here indicates that solar energy may have been employed for achieving

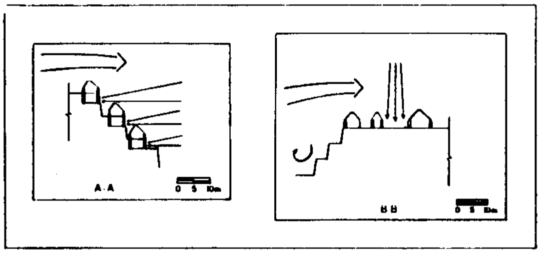

Fig. 7. Typical urban setting, sections A-A and B-B.

human comfort levels, the author has participated in archaeological excavations in which the first hearth was uncovered at Machu Picchu. Therefore, the use of fire for cooking and additional heating was provided by burning small pieces of trees' bran- and twigs. Nevertheless, the use of solar energy may have consisted of the primary source of heat and contributed to wood conservation in that region.

There have been scholars (15,16,17) that have tried to identify solar relationships at Machu Picchu from the archaeo-astronomy point of view, in the same way as found at Stonehenge and other PreColumbian structures (18,19). However, it has never been possible to secure any such relationships because no structural alignments were left by the Inca or pre-Inca populations.

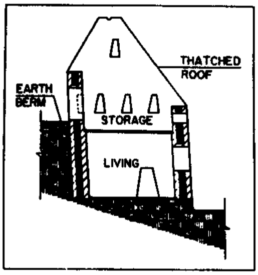

Fig. 8. Typical residential building.

The approach used in the present research deals with utilization of solar energy to maintain human comfort levels and agricultural productivity. It should be added that each of the sections presented here deserves further detailed exposition and future publications are underway.

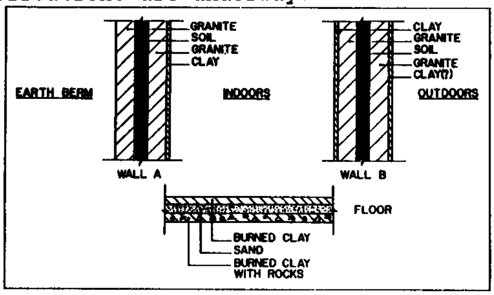

Fig. 9. Typical building materials.

The ruins of Machu Picchu can be viewed as a study model of utilization of natural resources on a large-scale. Also, it sets grounds for evaluating the performance of primitive settlements that are found at unique climates. The marked seasonal atmospheric conditions at Machu Picchu presents us with an opportunity to evaluate the performance of a solar community at clear, partially clear and overcast skies. This research is aimed at generating design tools that coulb eventually be applied to present-day design problems.

The final quantitative results of this research will have practical applications to Andean communities. Moreover, the research methodology used can be applied to any region of the developing world.

This research has already departed from the identification level presented here. The future goals are to advance the quantitative evaluation of the thermal performance of different architectural and urban settings in the Machu Picchu Region.

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