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Prehispanic water pressure: A New World first

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ABSTRACT

Ancient cultures have a wide range of water control management techniques, each associated with a particular purpose, including water for consumption, agriculture, flood control, drought relief, and rituals (Scarborough, 2003). One technique that has received limited archaeological attention is the purposeful creation of water pressure to perform useful work. Perhaps the earliest such example was found on the island of Crete in a Minoan palace and dates as early as 1400 BC. Terracotta pipe segments with graded diameter reductions were used to create fountains (Evans, 1921–1935). Although gravity and the weight of water are the most efficient means of generating water pressure in a closed conduit, natural conditions (climate, geology, topographic slope, etc.) that might lead to the construction of water pressure systems are less clear. Here we show that the Classic Maya (AD 250–600) constructed a water pressure system with the potential to control the flow of water within an urban area. By burying a conduit along a steep ephemeral channel passing through a residential group, upland springs could be diverted to build pressure in the conduit to provide a dry-season supply of water. Up to 6 m of hydraulic head could have been recovered to lift water from the pressurized conduit to a point of use. Water pressure systems were previously thought to have entered the New World with the arrival of the Spanish. Yet, archaeological data, seasonal climate conditions, geomorphic setting, and simple hydraulic theory clearly show that the Maya of Palenque in Chiapas, Mexico had empirical knowledge of closed channel water pressure predating the arrival of Europeans.

1. Introduction

The ancient Maya are renowned as great builders, but are rarely regarded as great engineers. Their constructions, though often big and impressive, are generally considered unsophisticated in terms of engineering techniques and knowledge, as we understand them today. Most large Maya constructions required only a simple grasp of building techniques as well as a good supply of unskilled laborers. One major exception to this widely held view relates to water control and manipulation. Many Maya centers exhibit sophisticated facilities that captured, routed, stored, or otherwise manipulated water for various purposes.

Palenque, one of the best known Classic Maya centers, has what is arguably the most unique and intricate system of water management known anywhere in the Maya Lowlands. Years of archaeological research, including intensive mapping between 1997 and 2000, reveal that this major center, situated on a narrow escarpment at the northern boundary of the Chiapas Plateau. The site began as a modest settlement about AD 100. Then, during the seventh and eighth centuries, Palenque experienced explosive growth, mushrooming into a dense community with an estimated population of 6000 and approximately 1500 structures — residences, palaces, and temples — under a series of powerful rulers (Barnhart, 2001).

The first official acknowledgment of the ruins at Palenque appears in a letter written by Ramón Ordoñez y Aguiar to the president of the Real Audiencia of Guatemala in 1773 (Gonzáles, 1986). Historical research sheds light on a much earlier discovery by Fray Pedro Lorenzo de la Nada (ibid.). In 1560, Fray Domingo de Azcona invited Fray Pedro to work with the Indians in and around the colonial city of San Cristóbal de las Casas. For 6 years Fray Pedro worked closely with the Chol and Tzeltal Indians before visiting the Palenque area. During that time, he became fluent in their native languages. When he reached the lowlands, he assisted the Indians by setting up a new town near the Chacamax River, 8 km southeast of the ruins. Fray Pedro named this new town Palenque, meaning, according to Spanish dictionaries, "palisade or stockade of wood."

Miguel Angel Fernández, Palenque's head archaeologist during the 1930s, comments in his field reports that "the natives of the area referred to Palenque [ruins] by the name of Otolum" (Gonzáles, 1986: 5). This name is a word of Chol origin, derived from: *otot* (house); *tul* (strong); *lum* (land), together meaning "strong house land" or "fortified place" (Gonzáles, 1986; Becerra,

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1980: 243). Thus, a strong affinity exists between the words "Palenque" and "Otolum."

Fray Pedro Lorenzo de la Nada is the only person in the early history of Palenque's rediscovery who could have named the town after the ruins. He had a firm enough grasp of the Chol language to search for a similar Spanish translation (Gonzáles, 1986). The word Otolum is still used today as the name of the precious stream that flows through the site's center.

Palenque was first excavated by Count Frederick Waldeck in 1832. During his 2-year stay at the ruins, this eccentric character set up quarters in a temple that was later named in his honor, the Temple of the Count (Trujillo, 1974). A lithographer, Waldeck produced beautiful illustrations of the site, although many of his drawings cast the bas-reliefs and stuccos in a Hellenistic light. News of a great Mediterranean civilization, complete with elephants, in the New World sparked enormous interest back in Europe.

In 1840, Patrick Walker and John Caddy journeyed to Palenque. While working in British Honduras (Belize), Walker and Caddy learned of a large-scale scientific investigation of ancient Maya cities that was to be conducted by an American team led by John Lloyd Stephens and Fredrick Catherwood. Britain did not have the resources to support an expedition of such magnitude. "England, despite her reputation for scientific research, was about to become outdone by a representative of that upstart colony to the north" (Pendergast, 1967: 30). The British knew Stephens and Catherwood were traveling to Copan first and thought it possible to precede them to Palenque. Indeed, Walker and Caddy arrived in Palenque 2 weeks prior to Stephens and Catherwood. Caddy created a number of remarkable sepia sketches of buildings and sculptures. He published his work promptly in 1840, a full year before Stephens and Catherwood.

During his expedition through Central America in 1890–1891, Alfred P. Maudslay explored the ruins of Palenque. His report on the site occupies the entire fourth and last volume of *Biologia Centrali-Americana*. "It contains plans of the ruins, photographs and drawings of all the buildings and sculptures known at that time" (Saville, 1926: 153).

In 1923, the Dirección de Antropología of the Mexican government sent an expedition to Palenque (Blom, 1926: 168). Frans Blom was asked to develop a rough map to determine the extent of the site's size and density. The data collected from this expedition are still used today by archaeologists. Blom's map was the most thorough survey conducted of Palenque until August 2000.

Before Rodrigo Liendo's (1999) project on agricultural production in the mid-1990s, archaeological work included a few regional surveys and test excavations (Rands, 1974; Rands and Bishop, 1980; Ochoa, 1977; Fernandez et al., 1988; Grave Tirado, 1999). Without question, the majority of the research at Palenque has focused attention on monumental construction (i.e. temples and palaces) while paying little attention to households or the hinterlands. All previous surveying and mapping was similarly limited.

The Proyecto Grupo de las Cruces (PGC), which began in May 1997, was a continuation of archaeological investigations conducted over the last 100 years. A joint venture of the Pre-Columbian Art Research Institute (PARI), based in San Francisco, California, and Mexico's Instituto Nacional de Antropología e Historia (INAH), the Proyecto Grupo de las Cruces aimed to utilize all available resources to bridge gaps in the archaeological record and to increase understanding of the communal and dynastic histories, as well as the architectural diversity, of Palenque. Under the direction of art historian Merle Greene Robertson and INAH archaeologist Arnoldo Gonzáles Cruz, the PGC made some of the most important finds in the last 30 years. Over a 3-year period, archaeologists uncovered the architectural complex of a hitherto unknown king, Ahkal Mo Nahb III, the 14th ruler of Palenque.

A more complete map of Palenque was needed for a better understanding of the site's density and architectural character. In 1998, Edwin Barnhart and team began the task of creating the first complete structural and topographical map of Palenque. The Palenque Mapping Project (PMP) was sponsored by Florida's Foundation for the Advancement of Mesoamerican Studies, Inc. (FAMSI). Throughout a 3-year period, the PMP mapped a total of 1481 structures within a 2.2 km^2 area. The earlier map published by Robertson (1983) portrays only 329 structures. The new data generated by the PMP more than quadruples the known size of Palenque, giving it the second highest structure density of all the Classic Maya sites.

2. Water supply at Palenque

One of the more peculiar findings by French during Barnhart's survey was a small rectangular limestone outlet releasing a low flow (Fig. 1). The similarity of construction to the known aqueducts that are beneath the Main Plaza suggested the need for further investigation. Yet unlike the plaza aqueducts, this feature within the Piedras Bolas was located in steep terrain, had graded reductions in cross-sectional area, and terminated in a small outlet. Several years later French, an archaeologist, and Duffy, a hydrologist, traveled to Palenque to further investigate the feature and began a collaboration.

Palenque's environmental setting is very different from those found elsewhere in the Maya Lowlands. In general, the development of other large Maya centers in the region was unconstrained by topographic limits (with the exception of broad, flat, depressions, called *bajos*, which hold water during the rainy season). Their builders took advantage of extensive areas of well-drained low relief, and as a result cities such as Tikal and Calakmul grew in a dispersed or rambling pattern. The inhabitants of Palenque adapted their burgeoning settlement to a small geomorphological space (ca. 2.2 km^2) confined to a narrow break in slope along an escarpment. This confinement created a much more chaotic and crowded layout than that of most other Maya centers.

Contributing to the difficulties of building on Palenque's spatially confined plateau were the spring-fed streams that naturally divided the landscape. George Andrews (1975) claimed that this irregular natural terrain caused many problems for the city's builders, who were forced to reshape the existing topography in order to maintain a semblance of visual order within the site center. The site required the inhabitants to simultaneously control flooding, reduce erosion, and bridge the divided areas to expand civic space. The Maya of Palenque accomplished this engineering feat by covering portions of the existing streams by constructing elaborate subterranean aqueducts that guided the water beneath plaza floors. This unique technique expanded the size of their plazas by 23% (French, 2007).

The presence of perennial flowing streams provides an important resource in a region where water is a scarce resource during the summer drought. On the other hand, Palencanos were challenged by the need to greatly modify their landscape, in order to take advantage of hydrological resources and to accommodate their growing city. It was this challenge that resulted in a set of complex engineering adaptations unlike those found anywhere else in the Maya Lowlands, or indeed Mesoamerica. While the Maya of most other urban centers were concerned with storing water, the Palencanos were devising ways to manage an abundance of it (French, 2007). With 56 springs, nine perennial waterways, aqueducts, pleasure pools, dams, and bridges – the city truly lived up to its ancient name, *Lakamha'* or "Big Water" (French et al., 2006).

As with many cultures, water possessed a symbolic value for the Maya. Palenque's natural topography mimics the Maya image of the

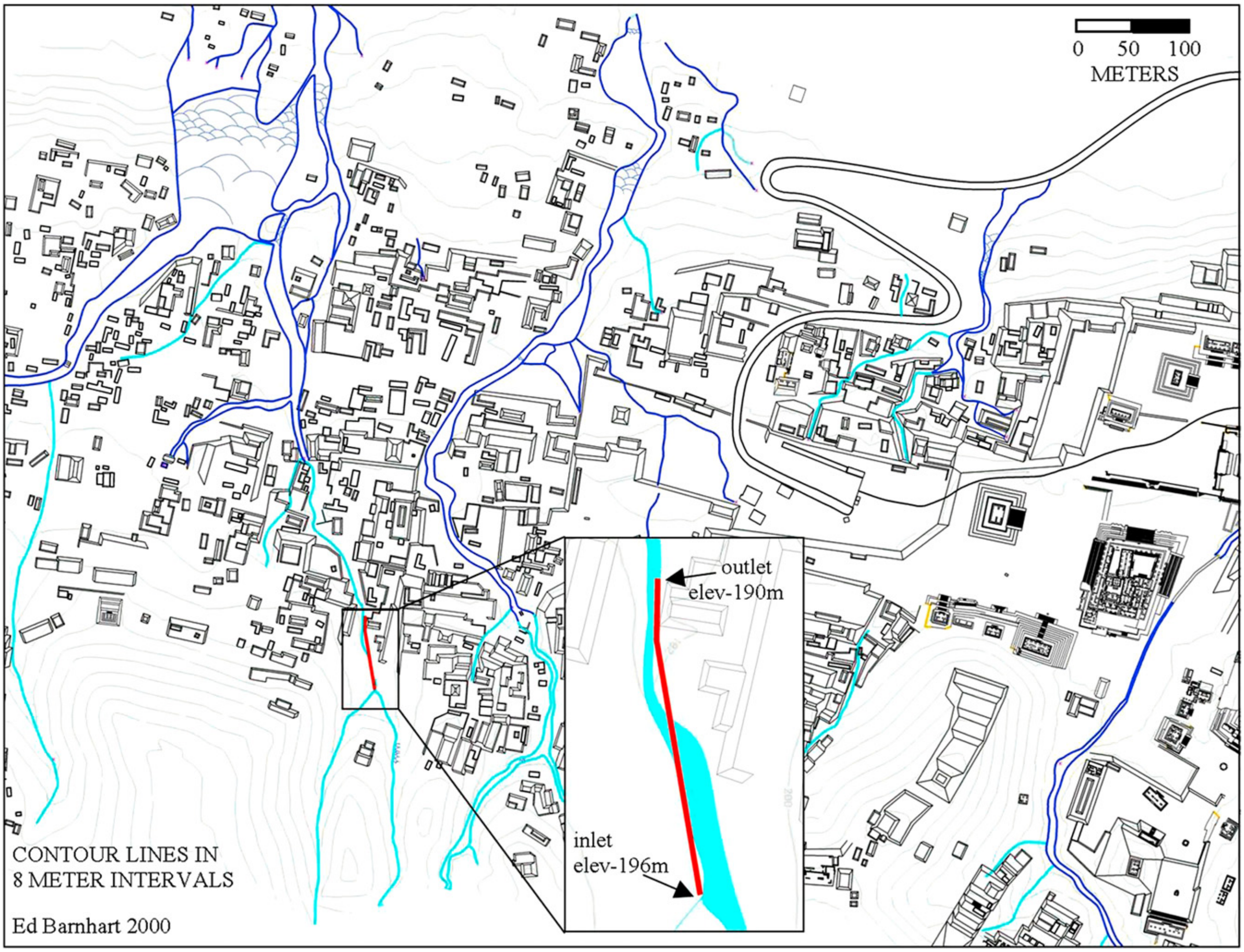

Fig. 1. Palenque site map. The area surrounding PB-A1 inset. Map by Ed Barnhart (altered by author KDF).

place of creation, described in the Maya epic, *Popol Vuh* as the land where waters flow out of the mountains: "The channels of water were separated; their branches wound their ways among the mountains" (Tedlock, 1985: 74). A landscape such as this must have been emblematic to the ancient settlers of Palenque.

Practically speaking, fresh water, and the rains that supplied it, were vital for sustenance. Precipitation in the Maya Lowlands is dominated by seasonality, with low rainfall from December to May (40–250 mm per month) and a rainy season from June through November (300–550 mm a month). October is the wettest month and April the driest. Total annual rainfall for the western periphery of the Maya Lowlands ranges from ~1500 mm a year at the Gulf of Mexico to nearly 3200 mm a year in the foothills of the Sierra de Chiapas at Palenque. Notwithstanding the abundant rainy season precipitation, it still falls short of records in such areas as the Maya Mountains in Belize, which can receive a staggering 4000 mm of rainfall per year (Dunning et al., 1998). It is the distribution of rainfall over the year that impacts human needs and ecological resources. According to Magana et al. (1999), the annual cycle of precipitation over the Palenque area exhibits a bimodal distribution, with maxima during June and September–October and a relative minimum during July and August, a period known as the midsummer drought (MSD). The MSD, or "*canicula*," is associated with fluctuations in the intensity and location of the eastern Pacific inter-tropical convergence zone (ITCZ). Tropical cyclones are a source of heavy precipitation in summer and fall. Convective precipitation and *orographic influence* (when moist air encounters a mountain barrier it is forced up over the mountains, the air then cools as it rises, and the moisture condenses and precipitates as rain) are also significant with increasing distance from the Gulf of Mexico. High levels of rainfall naturally bring very high levels of humidity. The average temperature at Palenque ranges from 22.9 °C in December and January to 28.8 °C in May, with humidity near 100% during the wet season. The great rivers of the region, the Usumacinta and Grijalva, discharge 30% of the total freshwater flow of Mexico. It is not surprising that important Early Classic (AD 150–350), settlements such as Piedras Negras, Yaxchilan, and Bonampak sprang up in those great lowland riverine environments.

Fig. 2 is a conceptualization of the hydrologic setting and the inferred relation of surface water to groundwater for a typical limestone stream reach. An important feature of the watershed is that along lines of surface drainage, the near- and subsurface limestone exhibit enhanced weathering along natural bedding and fracture planes. As such, the weathered and fractured rock beneath natural channels allows relatively simple manual excavation, and the core-stone (weathered limestone blocks) are relatively easy to excavate and use for construction of the enclosed channel.

3. Creating water pressure

In general, the simplest strategy for constructing a water distribution network in steeply sloping settings is to construct

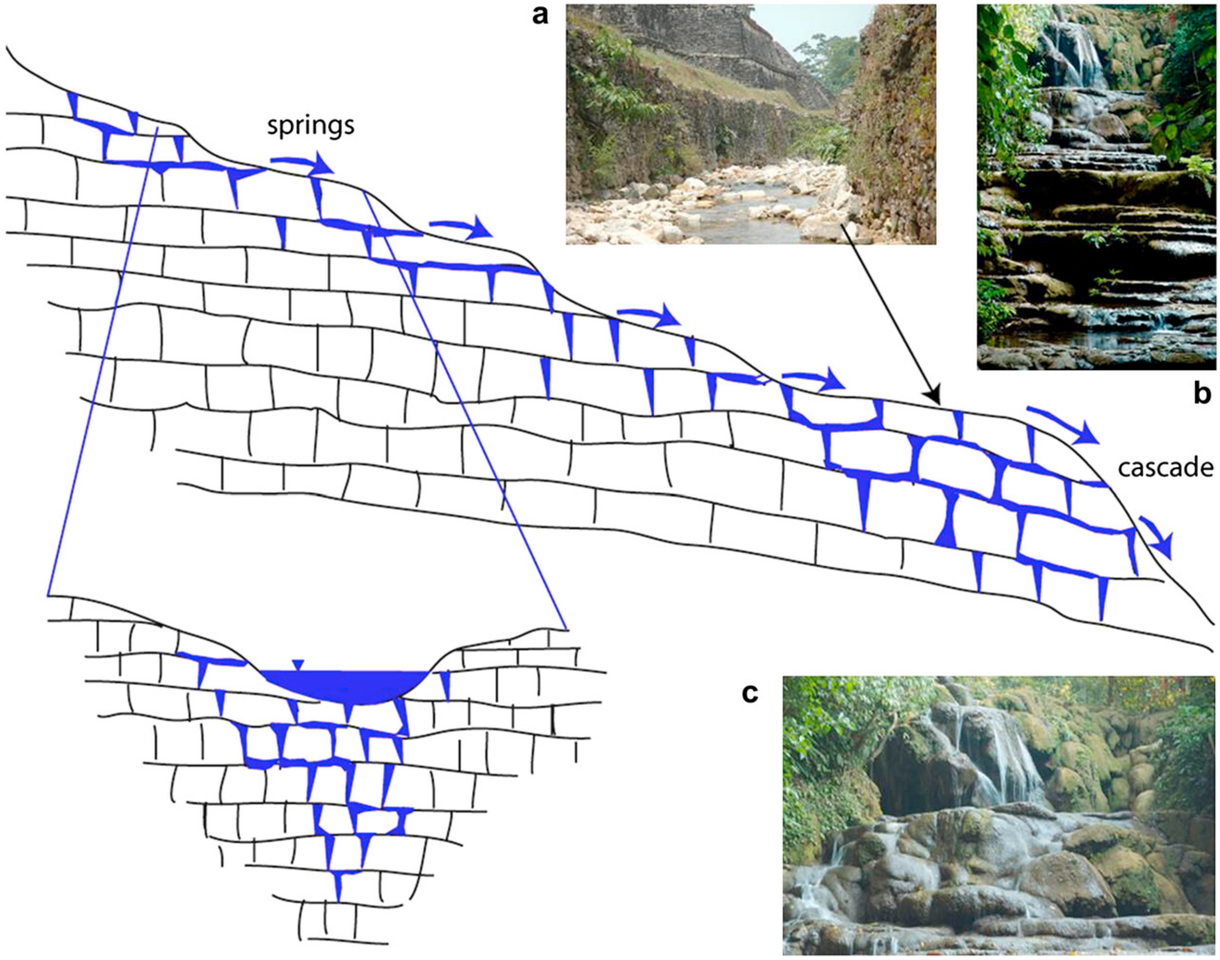

Fig. 2. Hydrologic conceptual model for the Cretaceous limestone watershed at Palenque showing the increased dissolution along bedding planes and fractures below the stream channel bed. (a) Boulder channel crossing the ruins; (b and c) show the pool and ledge cascades and accreting tufa deposits within the groundwater discharge zone. Drawing by author CJD, photos by authors.

lateral open-channel diversion of the upland stream directed along topographic contours away from the main channel. The laterals are constructed with a relatively flat slope to slow the rate of flow and to maximize flexibility to do useful work away from the main stream (e.g. irrigation, stormwater, supply). The main drawback to upland lateral diversion at Palenque is the loss of urban area and the fact that surface channels saturate adjacent land, eliminating even more civic/living space. The limited space, the steep slopes above the site, and the strong seasonality of rainfall makes lateral diversion within the civic area undesirable.

Water diversion using subsurface construction is the preferred method at Palenque due to the shortage of flat civic terrain. Building subterranean conduits beneath the natural channel would be convenient for ease of construction and readily available materials (Fig. 2). There are over a dozen examples in Palenque where subterranean channels were created by excavating the bed of a preexisting stream, constructing limestone conduits and then covering them with fill (French, 2007).

The spring-fed Piedras Bolas – Aqueduct 1 (PB-A1) (Fig. 3) has a unique design when compared to the other aqueducts recorded within the site. Typically subterranean conduits vary in size depending on the flow conditions, while maintaining a constant cross-section from inlet to outlet and generally have a relatively flat bed slope ($<1/100$). The closed conduit, PB-A1 (1.2×0.8 m), is at least 66 m in length, and maintains a topographic slope of $\sim 5/100$. Near the end of PB-A1 there is an abrupt decrease in size to a much smaller section measuring approximately 20×20 cm. This reduction in cross-section continues for another 2 m before re-emerging in the adjacent channel. Today, due to partial collapse and subsequent erosion, very little water passes through PB-A1.

Although only a short segment of PB-A1's original subsurface channel is extant, it is fortunate that the remaining segment includes the terminus of the conduit. We know it is the terminus because a reduction in cross-section (~ 1–0.2 m^2) would be necessary to maintain hydraulic pressure within the upstream buried conduit.

The source of water to PB-A1 appears to be an upslope spring which was diverted into the buried conduit. This source would be especially important during the dry-season when surface flow is ceases. Head losses within the conduit were estimated from reference experimental data for rough stone channels and smooth masonry channels to establish a range of effects (Young et al., 2007).

There is no evidence that the Maya plastered the walls of the conduit at the Piedras Bolas site, but there is evidence of this practice at other locations within Palenque. Evaluation of hydraulic conditions was conducted for an assumed channel length of 68 m, the distance from the convergent section to an upstream tributary. Using the assumption of a smooth (plastered) conduit even relatively small discharges $Q < 1$ m/s could maintain a hydraulic head of nearly ~ 6 m between the outlet and inlet which is roughly the elevation difference. For the unplastered case, greater flows are necessary to accommodate leakage and head losses along the

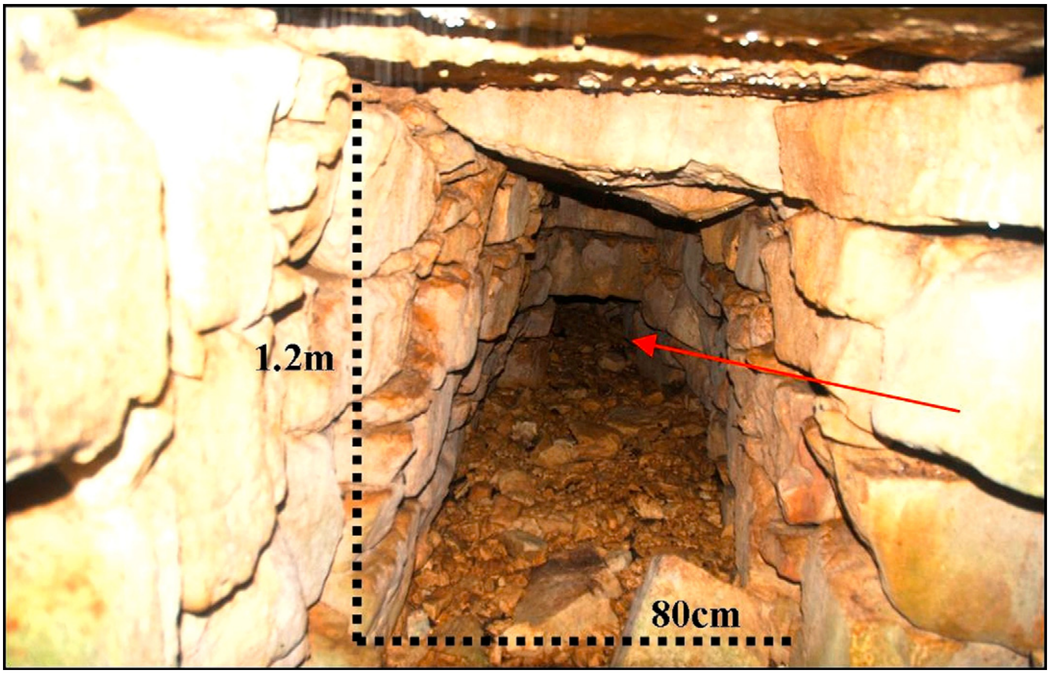

Fig. 3. Interior of PB-A1. Note the abrupt reduction in conduit size. Photo by author KDF.

conduit, but significant useful hydraulic head is still available to lift water at the outlet.

PB-A1 was capable of multiple uses and although the full range of functions are unknown it did create approximately 200 m^2 of civic terrain by allowing the preexisting stream to flow underground while simultaneously bridging several household groups. Furthermore by controlling the outlet the conduit could have also been used to store an estimated 68,000 l of fresh water during low

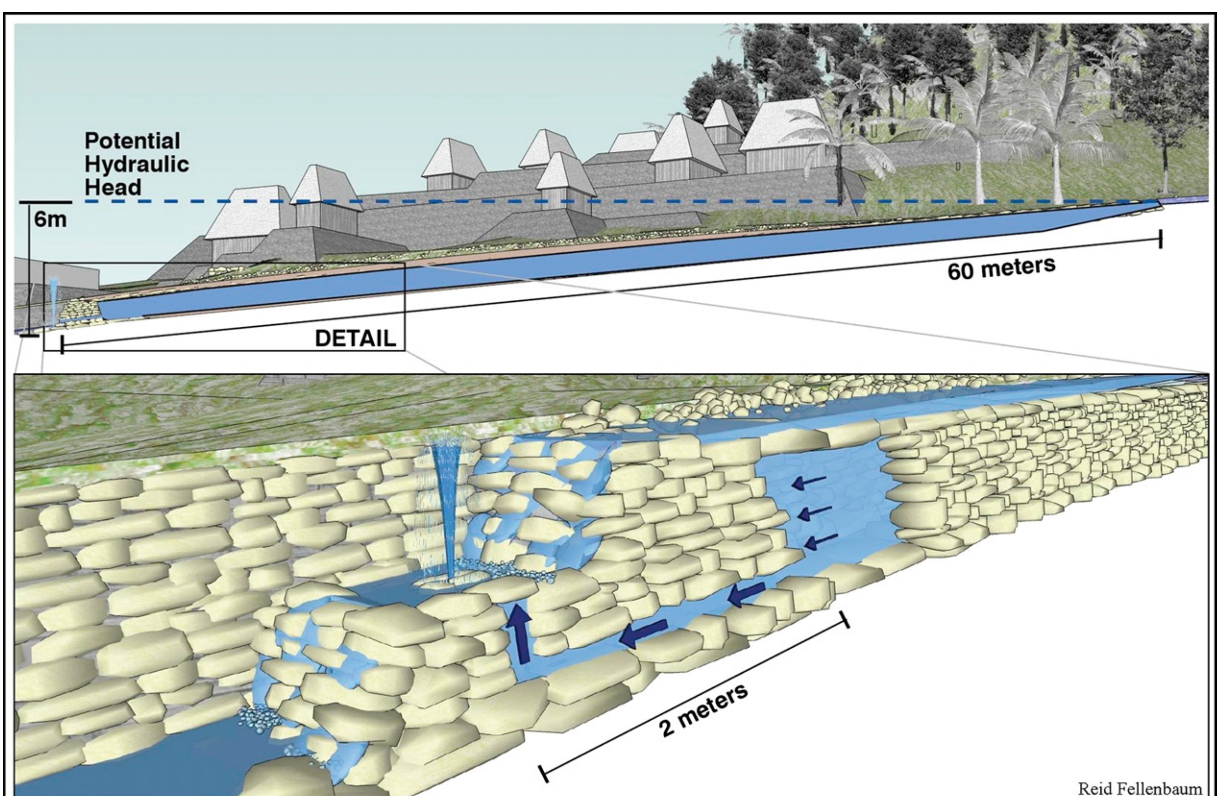

Fig. 4. A depiction of PB-A1 functioning as a fountain. This illustrates one plausible explanation of how the feature utilized water pressure. Details of the use of the pressurized conduit have long been destroyed. Note that during the monsoon excess runoff simply flows over the feature while the buried conduit continues to function. Drawing by Reid Fellenbaum.

flow periods. Another possibility, depicted in Fig. 4, is that PB-A1 created the pressure necessary for an aesthetically pleasing fountain, and perhaps served as an aid in the filling of water jars (Davis-Salazar, 2003).

4. Conclusion

Control of nature's most fundamental resource has been the object of many technological advances of ancient societies. Under natural conditions it would have been rare or difficult for the Maya to witness examples of water pressure in conduit flows. However, the experience in constructing aqueducts for diversion of water and the preservation of urban space at Palenque may have led to a more sophisticated technology, namely the creation of useful water pressure. This method for displaying power through knowledge is similar to approaches used by the ancient Greeks and Romans and is perhaps a very human characteristic.

At Palenque, archaeological data combined with simple hydraulic theory, supports the hypothesis that the Maya of Palenque had empirical knowledge of closed channel water pressure. It is likely that there are other examples of Precolumbian water pressure throughout the Americas that have been misidentified or unassigned. The most promising candidate being the segmented ceramic tubing found at several sites throughout central Mexico (Saville, 1899; O'Brien et al., 1975; Hirth, 2006). These ceramic pipes are tapered, with one segment fitting into the large end of the next, and cemented tightly together (O'Brien et al., 1975; Hirth, 2006). Although these tubes appear to be for drainage they represent the technology necessary to utilize closed conduit water pressure.

We would be remiss if we did not point out the need for new excavations, including test pits of the surrounding residential groups, to better understand the extent and purpose of the unique hydraulic features at Palenque.

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