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# Ancient geopolymers in South-American Monuments, Part IV(*): use of natural andesite volcanic sand (not crushed).

Joseph Davidovits and Frédéric Davidovits

*Geopolymer Institute, 02100 Saint-Quentin, France.*

*e-mails:* joseph@geopolymer.org, frederic@geopolymer.org.

## ABSTRACT

The studies carried out in 2017-2018 on the monumental stones constituting the Pumapunku site in Bolivia (South America) provided evidence that the stones are ancient artificial geopolymers (Parts I to III). To make geopolymer andesite stone, around AD 600 to AD 700, the builders could have transported an andesite stony material having the consistence of sand from the Cerro Khapia volcano site, and added an organo-mineral geopolymer binder manufactured with local biomass ingredients. They did not use the many quadrangular volcanic blocks, the famous "*piedras cansadas*", the tired stones, which are still lying on both sides of the lake Titicaca. The present paper describes how the builders of Pumapunku / Tiwanaku exploited a natural volcanic andesite sand from the volcano Cerro Khapia, transported and stored it at the shore village of Iwawe, Stratum (V) in the excavation by Isbell & Burkholder, (2002). For the making of their andesite geopolymer monuments, they did not need to crush andesite rock. This andesite sand is similar to one of the pozzolana sands found in the best ancient Roman mortars and coined in Latin "*carbunculus*", 2000 years ago.

***Keywords:*** *ancient geopolymer; South-American monuments; andesite sand, carbunculus, gas-pipes, piedras cansadas.*


(*) *Part I:* Davidovits *et al.* (2019a);
*Part II:* Davidovits *et al.* (2019b);
*Part III:* Davidovits *et al.* (2019c).

## 1. Introduction

Tiahuanaco, (Tiwanaku), in Bolivia, is a village known throughout the world for its mysterious monolithic Gate of the Sun (*Puerta del Sol*) made out of volcanic stone, andesite. It comprises an earthen pyramid and is located south-east of Lake Titicaca at 3820 m above sea level. It belongs to the civilizations of the pre-Columbian Americas. Archaeologists name this site "*Tiwanaku*" and consider that it was built well before the Incas, around 600 to AD 700, 1400 years ago. The site of Pumapunku is right next door with the ruins of an enigmatic pyramidal temple built at the same time (see Figure 1).

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Because it is not restored and developed for touristic activity, Pumapunku (also written Puma Punku) is less known to the general public. However, there are two architectural curiosities there: four giant red sandstone terraces weighing between 130 and 180 tons (Figure 1) and small blocks of andesite, an extremely hard volcanic stone, whose complex shapes (the *H*-blocks) and millimetric precision are incompatible with the technology of the time (Figure 2).

And for good reason, since archaeology tells us that the Tiwanakans had only stone tools and no metal hard enough to carve the rock. But they would have carved the gigantic blocks of red sandstone (these ancient blocks are the largest of all the American continent!) and they were able to carry these hundreds of tons to the site, then to adjust them precisely. Also, they would have been able to carve the "H" blocks made of volcanic andesite, an extremely difficult-to-carve stone with an incredible finish perfectly flat faces at exact 90° interior and exterior right angles!

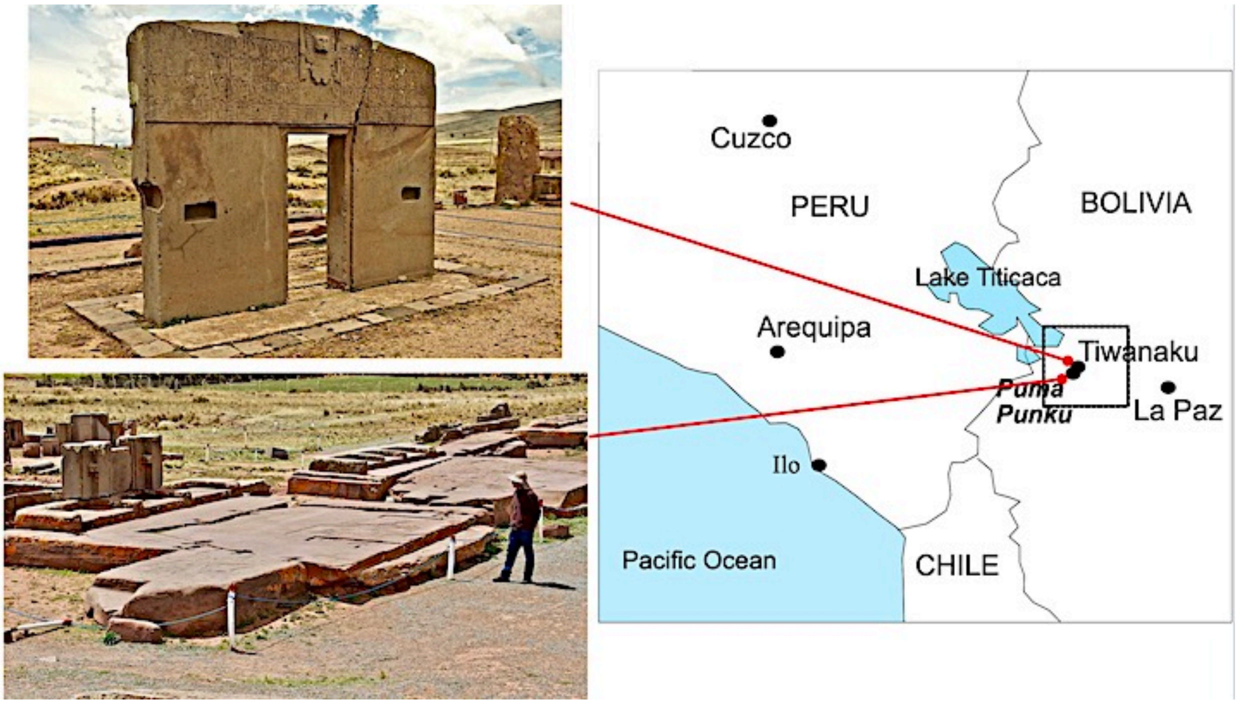


**Figure 1:** South American Andes Altiplano with Tiwanaku (*Gate of the Sun*) / Pumapunku.

**Figure 2:** the famous "H" blocks: 1 meter high andesite stone, Mohs hardness 6-7 (7=quartz), density d=2.58 kg/l). Right: precise reproduction by Stüble and Uhle (1892).

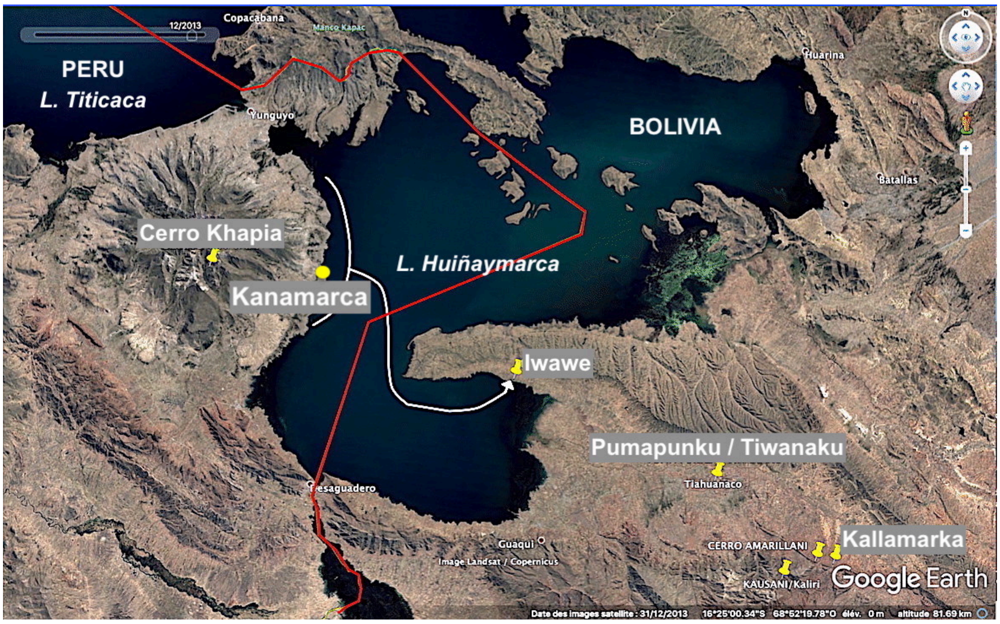


**Figure 3:** Map showing the border (in red) between Peru and Bolivia, Pumapunku / Tiwanaku and the volcano Cerro Khapia, the small lake Huiñaymarca, part of Titicaca Lake. Bottom right, the site of Kallamarka.

Archaeologists cannot give any rational explanations on how this was possible. Therefore, for the general public, the assumptions generally advanced to explain these wonders are the achievement by a lost ancient super civilization or by aliens' involvement.

To make geopolymer andesite concrete, the builders could have transported non-consolidated volcanic tuff, which is an andesite stony material having the consistence of sand from the Cerro Khapia volcano site, and added an organo-mineral geopolymer binder manufactured with local ingredients (Davidovits *et al*, 2019b). However, we could not determine the source of this volcanic sand.

The present paper describes how the builders of Pumapunku / Tiwanaku found and exploited a natural volcanic andesite sand.

## 2. Results: we found the volcanic andesite sand, it is not crushed stone.

We knew that for the andesite stones, tradition indicated a geological origin in the volcanic region of Cerro Khapia, Peru, on the other side of the Laguna Huiñaymarca, part of the Titicaca Lake (Figure 3). Several archaeologists had detected in the 19th century at this place probable sources for the volcanic stones of Tiwanaku / Pumapunku. Stübel and Uhle (1892) had published their comparative analyses of samples taken, on the one hand, from the *Puerta del Sol* and, on the other hand, from andesite outcrops located at the foot of the Cerro Khapia volcano. There was a strong concordance between the stone of the monument and the geological rock.

### Andesite boulders lying on the lake shores: the "*Piedras cansadas*".

But we had to solve a problem that seemed much more worrisome because it contradicted what we wanted to demonstrate. Despite our scientific discovery, how could we believe in the artificial nature of the andesite rock of Tiwanaku / Pumapunku when there existed everywhere on both sides of the lake shores, many quadrangular volcanic blocks, the famous "*piedras cansadas*", the tired stones? All the travelers and archaeologists of the 19th century already describe them. They try to explain how these blocks of volcanic rock, weighing from 5 to 10 tons, could have been transported from the slopes of Cerro Khapia to the shores of the lake. Then, how they were hoisted on rafts built with *totora* reeds, next unloaded on the other bank and finally transported overland to Tiwanaku / Pumapunku. In Figure 4a, these andesite blocks can be seen on the Peruvian shores near Kanamarca. Figure 4b shows other blocks located on the Bolivian shores, near Iwawe.

However, we had difficulty understanding why the builders of Pumapunku had been forced to transport 10-ton blocks and then cut them into smaller pieces to produce their famous "H" sculptures. It would have been much easier to place these small 300-700 kg blocks on small sleds and small rafts, rather than undertaking this titanic work. It was not logical. There must have been another explanation. This is what we will establish now.


**Figure 4:** *piedras cansadas*, volcanic andesite boulders; a) top, Peruvian shore at Kanamarca; b) bottom, Bolivian shore at Iwawe. *Credit: Ricardo Bardales Vassi (2013)* .

Following the discovery of andesite "*piedras cansadas*" at Iwawe on the Bolivian side of the lake, Ponce Sangines (1968) and his Bolivian and American archaeological colleagues Isbell & Burkholder, (2002), Janusek (2008), Vranich (2005), Isbell (2013), Protzen (2013) had imagined a scenario involving the crossing of the lake by boat from Kanamarca. The village of Iwawe was the port where these blocks were unloaded from the rafts and prepared for transport to Tiwanaku / Pumapunku. See the map of Figure 3. For an unknown reason, they were not transported further to Tiwanaku/Pumapunku.

This scenario received the support of North American anthropologist William Isbell, a specialist in Andean ceramics who undertook excavations at Iwawe in 2000-2002. Iwawe is a mound not more than 3 meters high. It consists of 9 archaeological layers numbered (I) to (IX) as shown in Figure 5. In the first report published by Isbell & Burkholder, (2002, page 212) one reads: (…) *Stratum V is 15 cm deep and it is frequently broken by big pit excavated through it. (…) Stratum V demand interrogation. It is* *virtually sterile and its distinctive material does not seem to be midden accumulated through domestic activities . At the suggestion of James B. Richardson we submitted samples of Stratum V soil to volcanologist Richard Naslund (personal communication January 1994) of Binghamton University Department of Geology whose thin section microscopic examination conclusively revealed volcanic pumice. Unfortunately, though, the only soil sample available to us in the USA came from a flotation heavy fraction. Consequently, the relative sizes of particles in the original matrix could not be determined. Shanaka de Silva (de Silva and Francis 1991: 138-155 personal communication), who will collaborate with the Iwawi research team in the future, informs us that Stratum V could be volcanic ash rained down on the Altiplano following an eruption in the prehistoric past. In that case the most likely source is the volcano known as Cerro Quemado, 250 km to the southwest of Iwawi. (…) However, volcanic ash is very durable and it can be blown by the wind for long distance. So the Iwawi ash may originate in some other primary tephra.*

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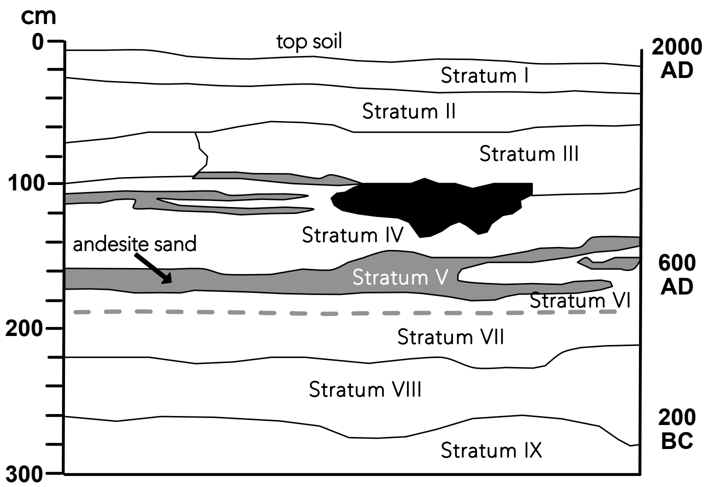


**Figure 5:** Stratigaphy of the Iwawe mound revealed in the archaeological excavations; adapted from Isbell & Burkholder (2002). Stratum V (andesite sand) is in gray and charcoal in black.

This analysis is confusing and not entirely accurate, because the American geologist only had the finest fraction at his disposal. This is why he believed that volcanic ash was present. However, he stated that this Stratum (V) is not a domestic waste (a pile of garbage) but a sand of volcanic origin. How did it get there?

## Andesite volcanic sand.

After completing a new study on the site, Isbell wrote in 2013 on the same subject: Isbell (2013, page 175): "*(…) Iwawe first gained fame as Tiwanaku's port, where great blocks of andesite stone from across Lake Titicaca were landed before being hauled inland to the city. It is also an ancient mound of residential debris about 2.5 m deep on the shore of Lake Titicaca. Excavations yielded nine strata, the lowest sterile soil that appears to have been shaped into raised fields for cultivation before the site was occupied. Stratum V divides the sequence in two. It is composed of andesite sand, probably from intensive work shaping imported stone blocks. Significantly, this grit layer probably represents a moment when construction in andesite was intensive, a major construction time at the capital.*"

The archaeological excavations had discovered that the layer Stratum (V) was made up of sand, andesite volcanic sand. Isbell concluded that this layer was the result of intensive sculpturing of the blocks that had arrived from the Cerro Khapia volcano. However, carving of stones produce rather shards, more or less large or small pieces but no sand.

William Isbell does not mention these andesite splinters in the layer Stratum (V) which for him is made of sand. However, he can distinguish between andesite sand and crushed andesite rock. Indeed, in the stratigraphy of Figure 5 there is a thin layer of crushed andesite between Stratum (VI) and Stratum (VII). It is labeled: "*discontinuous stratum of crushed rock*". He further describes the Iwawe excavation as follows*: " In the deep Stratum VI through VIII, [older than Stratum V], the common cooking pot is accompanied by a wide range of more or less shallow, hemispherical bowls, some with incised rims. These were probably serving bowls, for eating and drinking. But they disappear with the appearance of the sandy debitage that constitutes stratum V and are completely replaced in higher strata by the two most common Tiwanaku shapes, the kero and the tazón.*"

Isbell confirms with the English term "sandy debitage" that the blocks were sawed (how?) and produced a waste material in the form of sand. The Tiwanaku era does not have any saw capable of cutting andesite volcanic rock blocks. Therefore, the Stratum (V) does not contain any splinters or pieces of stone, just sand (in geology, it is called a volcanic sand).

According to Isbell and Burkholder (2002), the stratigraphy and the position of Stratum (V), the probable date of the construction period in Pumapunku / Tiwanaku, would be around AD 600. This discovery of volcanic sand was misinterpreted by all archaeologists and anthropologists at the time. Indeed, it is necessary to possess serious knowledge in geology associated with geopolymers in order to understand the implication of this discovery. Apparently, the geologists/volcanologists who were consulted by W. Isbell did not mention that andesite sand was frequently found in association with hard volcanic rock. Such sand can be detected through the phenomenon referred to as "gas pipes". We shall thus try to explain it.

## *Carbunculus*: the volcanic sand in ancient Roman mortar.

The reader should know that, for us, this type of material is not a mystery or an unfamiliar part of our archaeological research. We have known it for more than 30 years. As a matter of fact, it was one of the main constituents (the so-called pozzolana, or "*harena fossicia*") of the best mortars developed by the ancient Roman civilization. It is found in the mortars of the large monuments erected in Rome (Italy), like the Coliseum, that date back to the time of the Roman emperors Julius Caesar, Augustus, Nero or Constantine, 2nd century BC to 5th century AD. According to the Roman architect Vitruvius, the ancient Latin name for this volcanic sand was "*carbunculus*" (Davidovits F., 2020).

In 1994, we started a research program funded by the European Union, called GEOCISTEM (1997), whose partners were the Geopolymer Institute, the B.R.G.M. - Bureau de Recherches Géologiques et Minières in France, the Geology Faculties of the Universities of Barcelona (Spain) and Cagliari (Italy), University of Caen, France (see the caption of Figure 6). The objective of our research was the creation of new ecological geopolymer cements, which would use geological materials like volcanic tuff, Davidovits *et al*. (1999) and Gimeno *et al*. (2003). To achieve this goal, we had chosen to use the same deposits as the ones commonly exploited in Roman antiquity 2000 years ago, in Italy and Spain. This required a multidisciplinary approach, bringing together specialists in geopolymers, geologists studying volcanic rocks, and a researcher familiar with the history of ancient Roman building material techniques. Here is what one of the authors, FD, wrote in 2007 in his doctoral thesis entitled: *Geology and construction in the De architectura of Vitruvius*. The excerpt is available at Davidovits F. (2020):

(...) *To determine the nature of the "materia" carbunculus (volcanic sand), we have to use a discovery that was unexpected - not from a geological point of view, but rather from the humanities - during the GEOCISTEM program, in which we participated for the sampling of Roman mortars. During a meeting in Cagliari (Sardinia, Italy) in September 1996, which involved the five geologists of the partner universities in this project, we were able to visit the volcanic stone quarry of Paringianu, exploited for the extraction of hewn stone (Sheet and Map 3). The "Paringianu tuff", as it is locally called, is a volcanic rock, resulting from a pyroclastic flow.*

*The local volcanic context consists of ignimbrite and rhyolite. The rock is very indurated, i.e., it is solid. It is composed of plagioclase, potassium feldspar, pyroxene, a vitreous matrix and montmorillonite. (...) During the visit, which was instructive on the nature of the Carbunculus "materia", we saw a very striking curiosity for these specialists of volcanic materials: while some tens of meters away, very hard cut stone was being extracted, the geologists showed us an unexploited area of the quarry. And with good reason: the tuff had the same mineralogical and chemical composition as the very hard rock and it contained crystals of identical dimensions, but it disintegrated into sand when we ran our fingernail or finger over it. They explained to us that during the cooling of the volcanic stratum, which has to be done slowly for the rock to harden, a sudden degassing in this tuff layer left columns through which the gases escaped: the stone did not have time to properly solidify as it cooled down. This demonstrated the degree of cohesion between the two types of stone: one cooled slowly and acquired some consistency, while the degassing turned the other into a soft, not very hard rock. According to the geologists who were with us on the site, the difference in hardness between two rocks of similar composition is a common phenomenon.*

**Figure 6:** The GEOCISTEM team visited the site of Paringianu, Sardinia, Italy, on September 27, 1996. From the left: Frédéric Davidovits (Caen Univ., France), Domingo Gimeno (Barcelona Univ., Spain), Philippe Rocher (BRGM, France), Carlo Marini (Cagliari Univ., Italy), Athos Rinaldi (Laviosa, Italy), Joseph Davidovits (Géopolymère, France), Sandro Tocco (Cagliari Univ., Italy), Michel Laval (BRGM, France), Luigi Buzzi (Cementi Buzzi, Italy), Jean Claude Toussaint (E.U Commission, Brussels, Belgium), (GEOCISTEM, Final Technical Report, 1997).

In Figure 6, the members of the European project GEOCISTEM are in front of the quarry of hard volcanic rock, and then they will see the gas-pipes and the *Carbunculus* reproduced in Figure 7. Frédéric continues: *"Looking at the degassing columns, one could see that they were vertical and that they created a small system of veins that vertically crossed the entire tufa layer from the bottom to the surface. This was approximately one man's height, and these ducts were a few centimeters wide. This phenomenon is known in geology under the name of "gas pipe" (...).* "

**Figure 7:** The gas pipes in the *Carbunculus* layer, volcanic sand at Paringianu, Sardinia, Italy. Reconstitution after Davidovits F., (2007-2020).

The occurrence of the Stratum (V) in the archaeological stratigraphy leads us to conclude that the ground of the Iwawe village was covered with heaps or mounds of natural andesite volcanic sand. This sand would have been extracted in one or more places in the Cerro Khapia volcano, transported to the shores of Kanamarka. Then it would have crossed the lake on rafts and been stockpiled in the port of Iwawe. We know that the level of the lake could vary with the seasons. Presumably, this activity took place during the rainy season, when the lake level was at its highest. The rafts could easily approach Iwawe's mainland. The andesite sand was poured on the ground, forming a layer several tens of centimeters thick. Isbell indicates that this layer is discontinuous and that it is "*frequently broken by big pits excavated through it*". It is thus a storage area in which workers came to dig and transport the andesite sand to another place (Tiwanaku / Pumapunku).

The *Carbunculus* of the ancient Romans corresponds exactly to the andesite volcanic sand of the Iwawe Stratum (V). Geologists had told us that, in volcanic rocks, the phenomenon of juxtaposition of a very hard stone and a sand was common. But in Iwawe we actually have a volcanic sand coming from the Cerro Khapia volcano. It is not crushed andesite stone. Therefore, logically, in one or more places of this volcano, we should find areas, where there is the juxtaposition of a hard andesite rock and a sand, both having the same mineralogical and chemical nature. But where to do the exploration?

## 3. Discussion: who transported the *piedras cansadas* and when?

We must now find out why, how, when and by whom these *piedras cansadas* had been abandoned on the path leading from Cerro Khapia to Tiwanaku / Pumapunku. For that, we can consult archaeological data and publications describing the use of andesite volcanic rocks in Tiwanaku and Pumapunku. There would be two periods during which these blocks could have been extracted, transported and abandoned on the way to Tiwanaku. The first is around 800-1000 AD., 200 to 300 years after the storage of andesite sand in Stratum (V), either at the end or just after the "classical" period of Tiwanaku. The second is during the Inca Empire, around 1400 AD, 700 years after the construction of Pumapunku.

Although it is difficult to prove it for lack of written texts, anthropologists think that after AD 800., there was a brutal change in the governance of Tiwanaku during this epoch. But the period of the Incas seems to us more appropriate, because it relies on historical and archaeological facts.

We know now that the Incas had undertaken many restoration works, using andesite blocks, on the site of Pumapunku. According to the American archaeologist / Alexei Vranich (2013) these were significant restoration works. Here is what he wrote: " (…) *To make this history tangible, the Inca invested a huge amount of energy in constructions across the entire Titicaca Basin, modifying and enhancing important ritual places. Tiwanaku became the terminal point on an important ritual pilgrimage route that began in the Inca capital of Cuzco. The best-preserved structure at Tiwanaku, the Pumapunku, was renovated and refurbished, and a royal and religious settlement, complete with a palace, bath (essential for Inca rituals), kitchen, and associated plaza, was built against this temple. The Incas even intervened in a more aggressive fashion on the platform, emptying out fill between the retaining walls to form three chambers overlooking the plaza. Arriving in Tiwanaku, visitors and pilgrims would be hosted in the refurbished and Incanized temple, where the mythic history would be told through ritual performance. (…).*

The Incas used a lot of andesite materials to restore Pumapunku and Tiwanaku. For that, they went to seek their blocks in the geological sites which naturally possess this type of quadrangular blocks in the Cerro Khapia crater (see Figure 8b). But we know that the Incas did not drag their stones on the natural surface of the land, but prepared carefully constructed roads. A similar road remains visible at Kanamarca in Figure 8a connecting the Cerro Khapia "quarry" to the shores of the lake (see the location of the village on the map of Figure 2),.

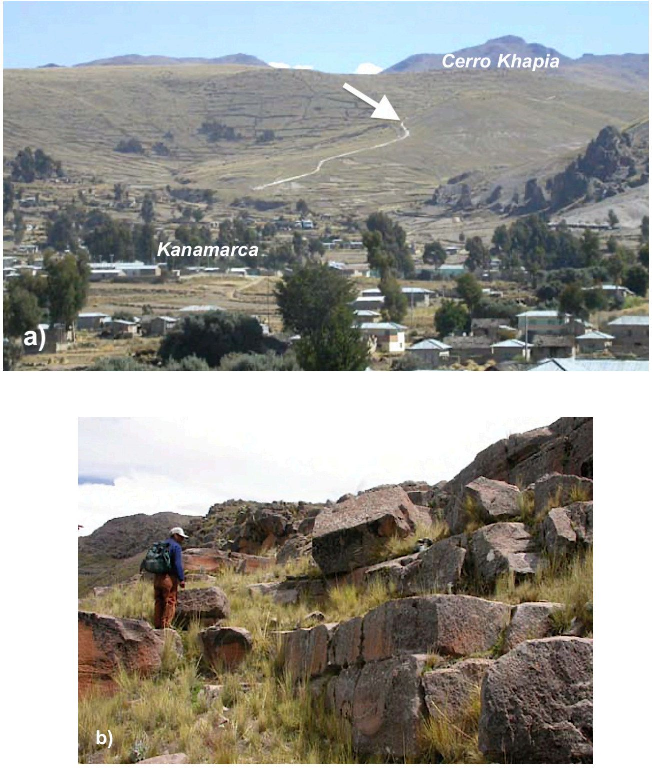


**Figure 8:** (a) top: marked by the arrow the Inca Trail by which the andesite blocks were brought down from the crater area of the volcano Cerro Khapia, (b) bottom: the quarry. *Credit: Ricardo Bardales Vassi (2013).*

## 4. Conclusion.

We now know what geological material was used in the manufacture of the artificial andesite geopolymer blocks in Pumapunku / Tiwanaku, Bolivia, around AD 600. It is not crushed andesite stone but natural volcanic andesite sand, perfectly adapted to this use. It has the same mineralogical and chemical constitution as the andesite blocks of the Cerro Khapia volcano. This sand would have been extracted in one or more places in the Cerro Khapia volcano, transported to the shores of Kanamarka in Peru. Then it would have crossed the lake on rafts and been stockpiled in the port of Iwawe, Bolivia. To produce the andesite geopolymer blocks, the workers of Pumapunku / Tiwanaku added a type of organo-mineral binder manufactured with local biomass (carboxylic acids extracted from maize and plants), guano and reactive alumino-silicate minerals (Davidovits *et al*, 2019b, 2019c).

In the same way, we had already found the geological material used in the manufacture of Pumapunku megalithic terraces. It is a red sandstone that has been disintegrated by climatic erosion and easily transformed into sandstone sand (Davidovits *et al*, 2019a, 2019c). It is associated with Kallamarka / Callamarca (Bolivia), an historical village that is part of the UNESCO World Heritage. It is remarkable!

The next step should involve collecting andesite sand samples from the Stratum (V) of Iwawe and organizing a geological expedition to the Cerro Khapia volcano. We hope to discover the exact source of the materials used to build the monuments of Pumapunku / Tiwanaku.

The construction workers of Pumapunku / Tiwanaku could easily transport these geological materials over great distances, in baskets, by rafts, in llama caravans. In short, it was normal work, on the scale of *Homo sapiens* and his ingenuity.

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