Ice Friction for Moving the Heavy Stones at the Ancient Pumapunku Complex. A First Technological Approach to the Age Problem

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In this work, ice-lubrication for moving the lithic material at the Tiwanaku complex and particulary at the ancient Pumapunku site is discussed. Ice friction (sliding stones on a sheet of ice) is identified as the most feasible technology for the transport of heavy stones at Pumapunku which is much in line with the inventiveness and technological approach used by this civilization not only because the propitious climatological conditions of the Titicaca basin but also because their most than proved technical inventions and knowledge in crops frost protection technology (*raised-field systems* also called *suka kollo* in Aymara), which is believed modified drastically the entire microclimate of the basin. Indeed, it is very justified to think that if ancient Tiwanaku people were able to develop a completely efficient technology to face the negative effects of frost in the entire basin region, on the contrary, it becomes very difficult to believe that the same people either inadvertent or deliberately don't took advantage of frost to move the heavy stones from the quarries. Because ice friction provides the maximum reduction in the number of men required to pull the heaviest stone and because Andean civilizations lacked draft animals before the arrival of Europeans, then by utilizing an available population growth model -derived from plausible crop-yield estimates, it is possible to asses a technologic upper limit for the age of the Tiwanaku civilization. Finally, for the specific case of andesite blocks which are believed to be quarried at the foot of the Mount Ccapia (90 km away from the Tiwanaku site) and sailed on large rafts or totora reed boats across lake Titicaca, the alternative possibility of an ancient ice-corridor in the Gulf of Taraco is analyzed.

Keywords. *Tiwanaku site; Pumapunku site; Andean Archeology; Titicaca Lake Region (Peru and Bolivia);*
Tiwanaku culture. Tribology

• Significance

Built thousands of years ago in Bolivia, the ruins of the Pumapunku complex have puzzled experts for decades and although researchers have worked to determine its age by a variety of different dating methods the exact origin and age of the site is still in dispute. Here we investigate for first time the Pumapunku problem but from a pure technological point of view. To do so, we identified ice-lubrication as the more feasible and probably technology used by the Tiwanaku people taking into account not only the climatological conditions at the Titicaca basin but also very in line with the proved inventiveness dealing with frost. Finally the disquieting hypothetical case of an ancient ice-corridor to transport the andesite stone is addressed.

I. INTRODUCTION

Built thousands of years ago in Bolivia, the ruins of Tiwanaku and particulary of Pumapunku site have puzzled experts for decades and although researchers have worked to determine its age by a variety of different dating methods the exact origin and age of the site is still in dispute. The age of the site has been significantly refined over the last century. Back to 1910, Arthur Posnansky maintained that the site was over 11000-17000 years old, [1],[2], based on comparisons to geological eras and archaeoastronomy; beginning in the 1970s, first radiocarbon dating concluded that the site was first occupied around 1580 BC,[3], and more recent radiocarbon records (1999), [4] are dating the site around AD 540-600. Nevertheless the study cannot be taken as conclusive, because radiocarbon results -which was based in analysis of the organic material from the lowermost and oldest layer of mound-fill forming the Pumapunku site, could only account, in the best case, for the moment in which the foundation stones were placed but cannot firmly be extrapolated as the moment in which the stone was transported from the quarries, because it seems clear that it is not required that both times must identically match, and in fact it seems that each constructive period at the Pumapunku site is

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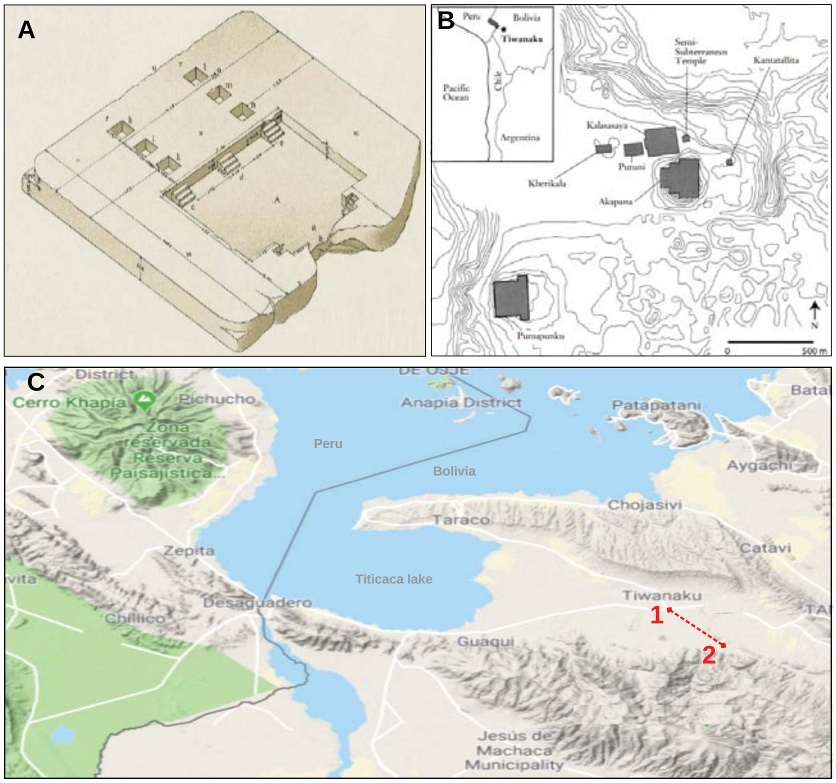

FIG. 1: Tiwanaku topography from the Centro de Investigaciones Arqueologicas en Tiwanaku CIAT. **A)** Plataforma Lítica at Pumapunku site. **B)** Global location of the Tiwanaku complex. **C)** The distance between the Tiwanaku Complex (1) and the Quebrada Kausani quarry (2) located about 10 km where it is believed the heavy sandstones were quarried

separated by a considerable space of time and has its own particular technique and conception, [1]. Moreover, from the scattered lithic material found lithic material could be relocated or reassigned to a purpose different than initial, a fact which can be easily observed today by visitors which can find Pumapunku stones scattered nearby by people quarrying stone for building, churches or railroad construction.

The object of this work was first of all to identify the most suitable, efficient and available technic for ancient Tiwanaku people for moving the heavy stones compatible not only with the climatological conditions of the Titicaca basin but also with the kind of inventiveness shown by this civilization. Once identified this technique, to tackle the problem of its age assessed from a purely technological point of view which, as far as the author knows, has not been done before. The proposed method, although certainly, cannot provides an absolute figure for the age of the Tiwanaku complex, nonetheless can provides an upper maximum limit for its age and then is worthy to be considered. Indeed, it is well known that the Andean civilizations lacked draft animals before the arrival of Europeans, and therefore whatever the technology used it only could be accomplished by pure human force. Therefore by knowing the ultimate technology which reduces at maximum the number of men required to transport the heavy stones of the complex and knowing the evolution of the population with time, it is possible to set an upper estimate of the age of Tiwanaku limited by pure technological considerations.

II. MATERIALS AND METHODS

A. The use of ice for moving the lithic material at Pumapunku

The largest of Pumapunku's stone is a sandstone block 7.81 meters long, 5.17 meters wide, averages 1.07 meters thick, and is estimated to weigh about 131 ton and is part of what is called the Plataforma Lítica, [5]. Based upon detailed petrographic and chemical analyses of samples from both individual stones and known quarry sites, archaeologists concluded that these and other red sandstone blocks were transported up a steep incline from a quarry near Lake Titicaca roughly 10 kilometres (6.2 miles) away (see Fig. 1), [5].
Archaeologists argue that the transport of these stones was accomplished by the large labor force of ancient Tiwanaku. Several theories have been proposed as to how this labor force transported the stones but nowadays all of them remain speculative. Two of the more common proposals involve the use of llama skin ropes and ramps and inclined planes and using sliding sledges considering that rollers were unknown for Andean civilization, [4],[5]. Using this lubrication condition (i.e., stone transported on a wood sledge sliding on the ground), it is

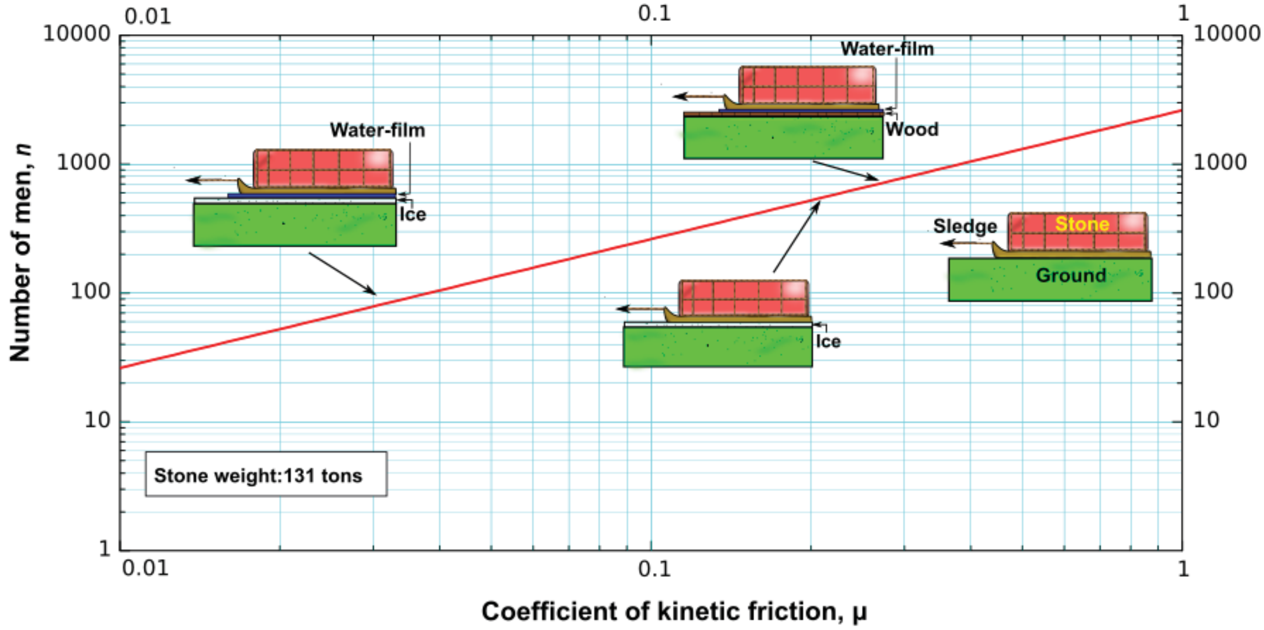

FIG. 2: Number of men as a function of the coefficient of kinetic friction for a 131 ton stone.

agreed that the required number of men to pull the heaviest stone of 131 tonnes required around 2620 persons or thereabouts,[6].

This large number of persons, however, seems troublesome. One one hand, even 1200 men to pull a huge stone is considered impractical for an ancient Egyptian case,[7], On the other hand, in a recent study for the case of the Forbidden City in 15th and 16th century China for moving a lighter 123 ton stone, the number of 1200 men (i.e., less than a half of the required persons claimed for the Tiwanaku case), is observed as impractical not only because the efficiency of the total pulling force but also because organization of masses of men, [8]. However, to difference of Egypt, the number of men can be drastically reduced if climatological conditions are favorable.

Recently, (2013), [8], it was proposed that ice-lubrication technique could be used for transporting the huge stones to the Forbidden City in Beijing in the 15th- and 16th-century China. The technique allows a substantial reduction in the coefficient of kinetic friction μ and then into a drastic reduction in the labor force required. Fig. 2 shows the number of men n required to pull a sledge with a 131 ton stone (as the heaviest at Plataforma Lítica) as function of the coefficient of kinetic friction μ given by the specific lubrication technique employed. Referring to this figure, one observes that the coefficient of friction for a direct contact sledge-ground is around $\mu \approx 1$ and the corresponding number of men around 2600 persons or thereabouts which is effectively the number of men currently proposed by archeologists. However, if the stone was not in direct contact with the sledge but using a frozen ice layer, then $\mu \approx 0.22$ and the number of men drops to 400 or thereabouts. Nevertheless this number can be optimized even more. Indeed, the most interesting case is when between the ice and the stone appears a film of water. Such a water film can appears from the heat released by the friction due to the own motion of the stone at low-speed,[8], or by inducing the melt by rubbing and heating the surface in front the stone (as is made in ice sports as skating or curling) or just by pouring water. Whatever the technique, the formation of such a film-water for the motion of heavy stones around 130 ton was demonstrated perfectly feasible, [8].

The importance of the film-water-ice lubrication is that the coefficient of kinetic friction can drops dramatically as low as $0.01 \leq \mu \leq 0.03$, [9], and then for a 130 ton stone the theoretic number of men to pull the ledge can drops from the 2620 men to only 80 men. Because there is not any other conceivable technology -apart from levitation which is of course, discarded at that time, able to reduce the coefficient of kinetic friction to a such extent, then the water-film ice layer set an upper limit to the minimum number of men required to pull the stone.

The key question is to know if actually the climatological conditions of the Titicaca basin allowed the use of a frozen layer technology for moving the heavy stones at the Tiwanaku complex. The answer is affirmative, and not only because the climatological conditions of the basin but because the technology is much in line with the kind of inventiveness developed by Tiwanaku people to such extent that it could be almost incomprehensible that they don't took advantage of the method.

B. Raised fields

Freezing temperatures always have been present in the Titicaca basin. In winter the temperature rapidly falls after sunset, and at night it can drops below freezing temperature. During a typical mild winter season (May

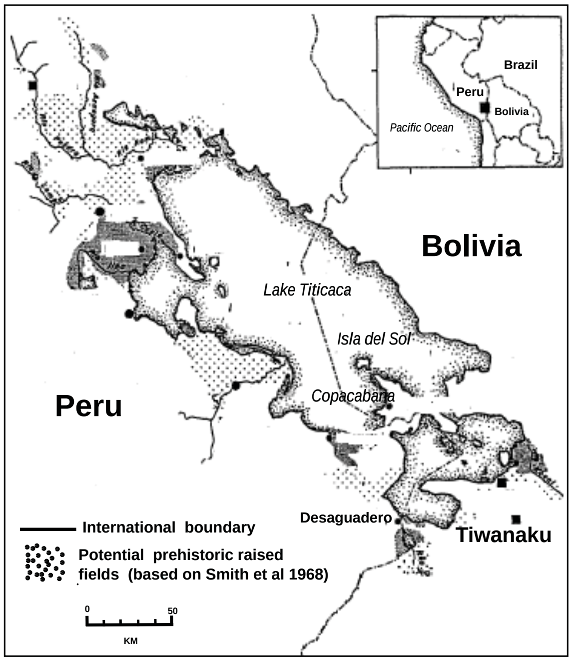

FIG. 3: Map showing the location of prehistoric raised fields (based on Smith et. al, 1968,[10])

to August) in the Titicaca basin, the temperature at the night can be as low as -5^{o}C, however, during severe winters (which are very common) very extreme conditions to indigenous farmers as well as animals are imposed. For example, hundreds of families were affected and more than 250,000 alpacas were killed due to freezing temperatures and snow storms during the winter 2013 in the basin were temperatures of minus 15 degrees Celsius were recorded and Peruvian government had to declare a state of emergency in the region; more recently, in 2016, as many as 50,000 alpacas raised by indigenous farmers in Puno -located at the Titicaca basin and 180 Km from Tiwanaku site, died from the bitter cold winter where temperatures plunged as low as -23 ^{o} C and again Peruvian government had to declare the state of emergency. Therefore, freezing temperatures during winters in the Titicaca basin were if not lower than today at least similar in ancient epoches. This is easy to infer from one of the most ingenious inventions known from ancient Tiwanaku people which is directly related to face the freezing temperatures and is called as *raised fields* or *suka kollo* in the local Aymara language. The impact of *raised fields* on the basin region can not be underrated, and in fact, it is broadly recognized that *raised fields* modified drastically the entire microclimate of the basin. In summary, *raised fields* can be defined as large elevated planting platforms with intervening water-filled canals designed to improve drainage, maximize soil fertility and prevent frost, [11], [12], and they exist at least as early as 1000 BC, [13]. The map of Fig. 3 is showing the location of prehistoric raised fields (baseed on Smith et al, 1968,[10]).

As conclusion, it is very reasonably to think that if Tiwanaku people were able to develop a completely efficient technology to face the negative effects of the ubiquitous problem of frost in the entire basin region, on the contrary, it becomes very difficult to believe that the same people either inadvertent or deliberately don't don't took advantage of the frost layers to move the heavy stones from the quarries, with a drastic reduction of labor force from 2600 men to only 100 men or so, the idea seems almost inconceivable to say the least.

C. A technological approach to the problem of the age of Tiwanaku complex

Because Andean civilizations lacked draft animals before the arrival of Europeans, then by utilizing an available population growth model -derived from plausible crop-yield estimates, it is possible to asses a technologic upper limit for the age of the Tiwanaku civilization. Accurate estimates on the Tiwanaku population, of course, is not possible and vary from author to author, nevertheless, there seems to be an extended consensus that the large rural hinterland of the Titicaca basin transformed into an artificial agricultural landscape is directly associated with the city of Tiwanaku. From plausible crop-yield estimates, archeologist have been able to estimate a population ranging from 20,000 to 56,000 which could have been sustained on a continuous basis by the fields in this immediate hinterland, [14], [15]. Thus, by 1500 BC Tiwanaku was probably a village with no more than 200 households; by 400 AD around 15000 inhabitants; by 800 AD around 30000 and by 900 AD up to 60000 inhabitants with the imperial state, [6] which fit well with an exponential growth model as is shown in Fig. 4. Referring to Fig. 4 , it is seen that, owing only to technological limitations, the maximum age in which the heaviest stone could be transported by Tiwanaku people could be around 2000 BC, i.e., as early as the village period.

D. The transport of Andesite blocks

Whereas sedimentary brilliant red hue sandstone comes from quarries in the Kimsachata-Chilla range located around 10 km away, south of Tiwanaku (see Fig. 1), however, the bluish-gray volcanic andesite was quarried in a more distant region at the foot of Mount Ccapia around 90 km away from Tiwanaku (see Fig. 5 at the top), and despite that they are between 10 ton to 40 ton and not so heavy as the sandstone in Plataforma Lítica , nevertheless the transport of these blocks arise another different problem.

According with the current hypothesis these giant andesite stones (the largest weighing 40 tons) were transported some 90 kilometers across Lake Titicaca

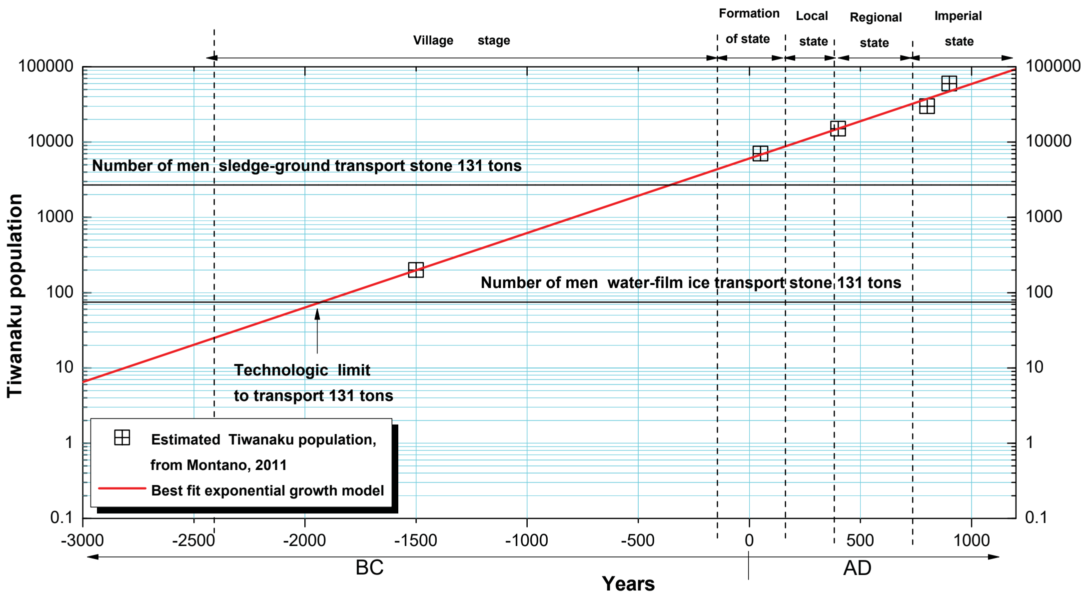

FIG. 4: Tiwanaku population estimation with age. Horizontal curves are the number of men required to pull a stone 131 ton weight by using sledge-ground contact and sledge- water film-ice-ground contact as was depicted in Fig. 2.

on totora reed boats (totora is an indigenous lakeshore reed typically 2-7 meters long and a third as wide), on two possible paths depicted at the top of Fig. 5, [5], then they were dragged another 10 kilometers to the city possible form the Iwawe port. The debatable point is that it is believed that totora reed has not the required rigidity to transport the heavy stones or that the depth of the totora boat´s draft able to withstand a weight around, say, 20 ton could cause had run aground in shallow waters.[5]. As a result it was proposed that andesite blocks had to be transported using balsa tree but because there is not this material in the entire Titicaca basin, it had to be brought from the amazonian located some 80 km north-east away from Titicaca,[5]. Nevertheless, it seems that recent experimental research in 2002 reported success in reproducing the transport of an andesite stone up to 10 ton using totora reed boat, [17].

Nevertheless, within the framework of the present study, it is interesting to investigate the alternative, and yet unexplored, possibility that actually the andesite stones were transported across Lake Titicaca not by using totora reed or balsa boats but actually using an ice-road in more or less fashion as pictorially depicted in Fig. 5 (bottom).

If such hypothetical ice- corridor really existed it could be either a seasonal road or a permanent road. In order to asses this we will proceed as follows: To begin with, we need to asses the minimum effective thickness of the ice sheet able to withstand, say, a 10 ton stone. Although many semiempirical formulations for the bearing strength of ice are available in the literature, however the simplest and most widely used expression due to Gold (1971) [18], seems preferable

$$P = Ah^2 \tag{1}$$

where P is the allowed load (ton); h is the effective thickness of the ice sheet (cm); and $A = 0.01$ ton/cm^2. Therefore assuming a 10 ton andesite stone, it will require a thickness $h \approx 100$ cm. Thus, the point is to know if actually such a thickness could be built during the freezing winter time. From our previous discussions, very low freezing temperatures can be attained in the Titicaca basin, and in fact Titica lake at the Puno has experienced partial freezing on shoe of the lake, therefore, 1 meter thickness for winter in Titicaca Lake could not be ruled out. Nevertheless, there is a factor which almost prevents the idea of a seasonal ice-corridor in the ancient basin, and this reason is precisely the presence of the already discussed *raised fields*. The reason for this is easy to understand if we realize that typical depths of the *raised fields* surrounding the entire Titicaca basin are around 1 meter depth and therefore, it makes not sense using such a depth if during winters all the latent heat stored would be exhausted by freezing the entire *raised field*. As conclusion, if such an ice-corridor already existed in the past and was used for transportation it had to be a permanent ice-corridor and this only seems possible during the glacial retreat in the basin region. Glacial retreat in the Bolivian Cordillera began around 12,000 BP, [19] and was marked by a series of still stands and readvances until about 10,000 BP [20]-[24]. After this time, glaciers rapidly retreated to near-modern limits by 9000 BP, and most valleys were completely deglaciated before 8000 BP. Paleo-lake

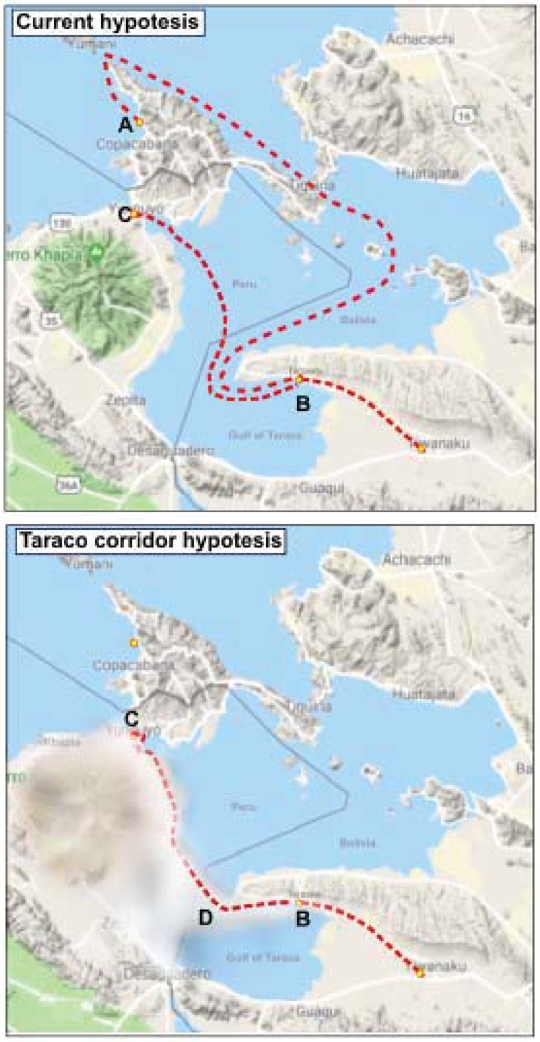

FIG. 5: Transport of the andesite from Mount Ccapia around 90 km away from Tiwanaku. Top. the current path hypothesis, [5]. Bottom: assuming an ice corridor in the Gulf of Taraco.

Titicaca began to drop from its high stand at 5-10 m above modern levels sometime after 11,000 BP, [25], and likely approached modern levels around 9000 BP[21].

Therefore, under the assumption of a hypothetical ice-corridor, the age of ancient Tiwanaku would be around 8000-12000 years old which is much more in agrement with the early calculations by Arthur Posnansky (11000-17000 years old),[1],[2], based on comparisons to geological eras and archaeoastronomy in the Kalasasaya temple.

III. SUMMARY OF RESULTS AND CONCLUSIONS

In this work ice-lubrication for moving the heavy stones at the Pumapunku site is for first time proposed which is much in line with the inventiveness and technological approach used by this civilization not only because the propitious climatological conditions of the Titicaca basin but also because their most than proved technical inventions and knowledge in crops frost protection technology. Ice lubrication allows a drastic reduction in the number of men required to pull the stone which seems very improbable that the Tiwanaku people don't took advantage.

Because ice friction provides the maximum reduction in the number of men required to pull the heaviest stone and because Andean civilizations lacked draft animals before the arrival of Europeans, then by utilizing an available population growth model -derived from plausible crop-yield estimates, it was possible to asses a technologic upper limit for the age of the Tiwanaku civilization around 2000 BC. Finally, for the specific case of andesite blocks which are believed to be quarried at the foot of the Mount Ccapia (90 km away from the Tiwanaku site) and sailed on large rafts or totora reed boats across lake Titicaca, the alternative possibility of an ancient ice-corridor in the Gulf of Taraco was analyzed. It is shown that if such an ice-corridor really exited, it had to be necessarily a permanent ice-corridor and then during the glacial retreat in the Titicaca basin around 8000-12000 years ago.

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