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The altitude of the depths: use of inland water archaeology for the reconstruction of inundated cultural landscapes in Lake Titicaca

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ABSTRACT

Andean societies have undergone abrupt climate changes that have affected their water resources and habitable or cultivable land. This is the case for Lake Titicaca, which has experienced fluctuations up to 20 metres during the last three millennia. Although paleoenvironmental reconstructions have provided valuable data on these lake level variations, their resolution is often not sufficient to assess their impact at the human time scale of land-use patterns. In this study, we provide a description of recent methodological developments in underwater archaeology that allows great advances in such reconstruction. Our results highlight that the level of the lake rose globally with multiple events of transgression and regression over the last two millennia. We also show that certain abrupt lake variation coincide with major transformations of the societies such as the emergence of the Tiwanaku state in the 6th century during a major transgression.

KEYWORDS

Inundated cultural landscapes; climate change; Tiwanaku and Inca cultures; geoarchaeology; shoreline transgression

Introduction

In the high-altitude Andes, the presence of hundreds of lakes and lagoons has favoured the settlement and development of primary state formation (Kolata 1993; Stanish and Levine 2011; Delaere, Capriles, and Stanish 2019; Delaere 2022). In particular, the Lake Titicaca watershed, located at 3810 m above sea level (a.s.l.), has been the place of a unique cultural development due to its attractive ecosystem inside a semi-arid area (Binford and Kolata 1996; Dejoux and Iltis 1992; Newell 1949). Archaeological research conducted over the lasts decades has identified key periods, including the emergence of agricultural villages during the Middle Formative period (~1500 BC; MF), the development of regional socio-political entities during the Late Formative period (250 BC – AD 550; LF), the formation of state during the Tiwanaku period (AD 550–1150; TIW), the division of the territory into regional chiefdoms during the Altiplano or Colla-Pacajes period (AD 1150–1400; ALT PAC), and the territorial expansion of the Incas to the Lake Titicaca (AD 1400–1532; INC) (Bandelier 1910; Janusek 2008; Bauer and Stanish 2001).

Along this archaeological period, climate in the tropical Andes has been marked by abrupt changes (Marchant and Hooghiemstra 2004; Baker et al. 2005; Guédron et al. 2018) that have impacted this high-altitude lake which is mostly subject to evaporation (~90% of its water output). This has resulted in large variation of the lake levels, up to 20 metres during the late Holocene

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(Mourguiart et al. 1998; Baker et al. 2005; Abbott et al. 1997), that have lasted from the decennial to the secular scale. In the shallow and gentle slope areas of the southern part of the lake, these variations have resulted in the flooding or desiccation of large areas, which have had an impact not only on ecosystems and natural resources (Dejoux and Iltis 1992), but also on the cultural developments of the Titicaca region (Kolata 2003; Bruno et al. 2021).

The reconstruction of Lake Titicaca level variations has been studied mainly through paleoenvironmental studies using sedimentary archives. These reconstructions are elaborated via the study of the distribution of paleoproxies such as (i) paleobiotics proxies [i.e. diatoms (Fritz et al. 2006, 2012; Weide et al. 2017), ostracodes (Mourgiard et al. 1998), fossil pollen and charcoal (Hanselman et al. 2011)], (ii) stable isotopes (Rowe et al. 2003; Baker et al. 2009; Guédron et al. 2021), and (iii) sedimentology (Abbott et al. 1997). These methods are highly relevant and provide variable degrees of information at various scales which depend on the temporal resolution covered by the archive (i.e. sedimentation rate, resolution of the age-depth model, hiatuses), and the number of collected cores to constrain the spatial variability. Thus, although some archives provide high-quality information, some archaeological periods, such as those of the first millennium AD (i.e. beginning and development of the Tiwanaku culture), are insufficiently resolved to assess the possible impact of paleoenvironmental changes on the cultural trajectory.

Portions of lake territories that are currently inundated, including ancient shores, can be studied by the techniques and methods of inland water archaeology. The underwater material remains of the lake socio-ecosystems, therefore, represent a valuable source of information that can complement paleoenvironmental studies (Conolly and Obie 2021). Indeed, the sedimentary burial of artifacts and macro-remains have allowed exceptional conservation (i.e. constant temperature, anaerobic conditions, and absence of light) (Huybrechts, Declerck, and Delaere 2015), of both the cultural and the paleoenvironmental context that have punctuated the history of the Andes. The geoarchaeological approaches make it possible to create a dialogue between the fine observations obtained at small scale (e.g. core slice surface of about 30 cm^2) in sediment cores, with those from large excavated surfaces of decametric size in archaeological test pits. In addition, the transposition of geoscience analytical tools in the large excavated underwater surfaces provides not only contextual information (e.g. walls or fireplaces), but also enables collecting more macroremains (e.g. charcoal and seeds) for radiocarbon dating and analysis of anaerobically preserved land covers. Their combination with the chronological information provided by the ceramology makes it possible to refine the chronology of the studied sedimentary units, and to move away from debates related to the reservoir effect. However, archaeological excavation in Lake Titicaca does not allow access to areas deeper than 30 m, which is possible with sediment cores.

In this study, we describe an innovative underwater archaeological methodology which combines geoscience (i.e. sedimentology, chronology, and altimetry) and archaeological (i.e. cultural remains and their context of deposition) information obtained in excavated test pits to reconstruct Lake Titicaca's shoreline transgression and regression through times. We then discuss the challenges and benefits of employing such tools to investigate the nature of the archaeological levels with the different cycles of events that have marked the history of Lake Titicaca. We demonstrate here that the identification of remains and shoreline facilities currently inundated make it possible to give a chronology and an absolute altitude value of the changes in the shoreline over time. Other studies deploying this methodology on a larger scale will soon complement this work and improve our understanding of the relationship between climate change and cultural events.

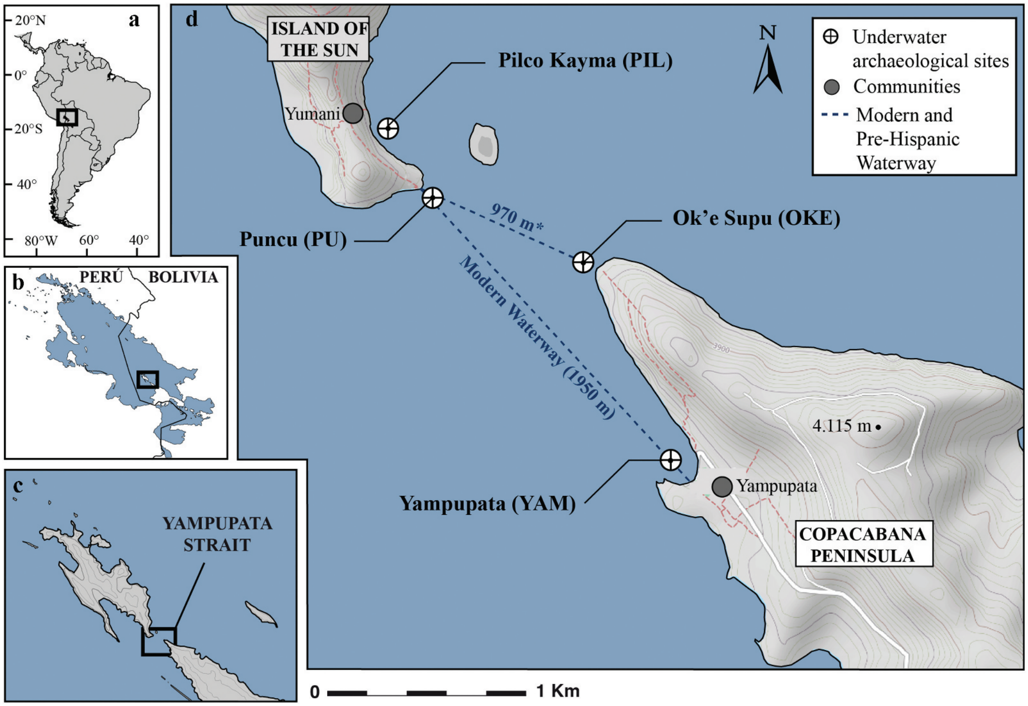

Figure 1. A) Location of Lake Titicaca in South America at 15°S within the Andean Cordillera. B) General map of the lake, which covers an area of 8,560 km^2 at the border between Peru and Bolivia. C) Location of the Yampupata strait between the Copacabana peninsula and the Island of the Sun in the Bolivian part of the northern Lake Titicaca Basin. D) Location of the prospected areas (crossed circles) including Ok'e Supu (OKE) at the tip of the Copacabana Peninsula, Yampupata (YAM) in the Copacabana peninsula, and Puncu (PU, Delaere 2017) and Pilco Kayma (PIL) at the southern tip of the Island of the Sun. The 970 m* section is the most likely pre-Hispanic waterway.

Prospection strategy and context of the ok'e supu pre-Hispanic lakeside settlement

To identify the location of potential archaeological sites in Lake Titicaca (Figure 1, A-B), eight archaeological field campaigns were conducted between 2012 and 2018, combining underwater stratigraphic test pits excavations (vertical analysis, chronological analysis) and bathymetric surveys (horizontal analysis, spatial analysis) following published methodologies (Delaere 2017; Delaere and Capriles 2020, 2021; Pieters and Delaere 2020).

Among 25 identified underwater archaeological sites, the site of Ok'e Supu (Municipality of Copacabana, Bolivia, Figure 1, C-D) has particularly attracted our attention because it combines archaeological remains and geomorphological criteria favourable for this study. First, its location at the tip of the Copacabana Peninsula, and about 970 metres from the coast of the Island of the Sun, makes Ok'e Supu site a good candidate as a major pre-Hispanic lakeside settlement on the axis of the waterway connecting the mainland to the Island. The site is an analogue of the Puncu site (Figure 1C) located on the other side of the strait (Delaere 2017). Second, the depth of the Yampupata Strait, located between the Island of the Sun and the Copacabana Peninsula, reaches 112 metres deep at 300 metres from the coast of the archaeological site. This strait has therefore always been in water since the first evidence of settlement, because the earliest reported ^{14}C age associated with ceramic production on the Island of the Sun dates to 1405–1275 BC (Stanish and Bauer 2004), and because the amplitude of lake level fluctuations over the last 3 millennia has never exceeded 20 metres (Abbot et al. 1997).

Third, the geomorphology of the lake bottom at the Ok'e Supu site is characterized by steep slopes (30% in average) which increases the altimetric contrasts and favours the identification of ancient shorelines.

Geoarchaeological methodology for the identification of inundated cultural landscapes

To get a representative spatial view of the site, 21 archaeological test pits of 4 m^2 (Figure 2) were completed laterally along an isobath, and longitudinally along the slope at a depth between 3 and 15 metres to provide transect descriptions.

Each excavated test pit was characterized in detail with both archaeological and geosciences tools following the sediment lithostratigraphy to provide; (i) sedimentological (ii) contextual, (iii) ceramological, (iv) chronological, and (v) altimetric resolution information (see below). The altimetric and lithological correlations (see Moulin 1991; Billaud, Langenegger, and Brigand 2012) allows then to create a composite section. The integration of chronological and contextual information from the analysis of archaeological remains allows the identification of ancient shorelines or the historical relative water levels above the sediment. These successive steps, and the use of various analytical techniques provide an innovative methodology allowing not only to have a double reading grid (cultural and natural), but also to evaluate the relationship between anthropogenic and environmental data.

First, the characterization of sediment lithostratigraphy allows documenting the limnological context at the time of sedimentation. Based on published information on the sedimentology in Lake Titicaca (Dejoux and Illtis 1992; Guédron et al. 2020), sedimentological stratigraphy and facies were characterized together with unconformities using sedimentological markers. Briefly, the presence of dark organic rich, and carbonate depleted layers were taken as indicators of paleosoil (i.e. gleyed soil) typical of non-depositional surfaces. Scour marks and coarser-grained sediment were used as proxies of erosion surfaces typical of paleo-shorelines (Abbott et al. 1997). In contrast, shell lags provided information about very shallow water depositional context (below 2-meter-deep), whereas light carbonate rich sediment was taken as indicators of shallow to moderately deep water columns (between 2 and 10 m deep) where the benthic macrophytes (*Characeae*) results in high productivity of calcium carbonate [up to 70% of their dry mass (Guédron et al. 2020)]. Hence, the lithological description of subaquatic archaeological test pits has been synthesised into four categories; (i) paleo-soil (emerged level), (ii) the paleo-shorelines, (iii) erosive or detrital input levels caused by strong erosion of the drainage basin, and (iv) carbonate sediment levels (submerged level).

Second, the archaeological context indicates the nature of occupation or activity at the archaeological site. It provides information on the site's anthropization nature considering taphonomic factors (Brochier 1997), whether by direct action (e.g. presence of fireplaces on a paleosoil) or indirect action (e.g. fall of an object from a boat into a submerged sedimentary level). Thus, the contextual information is complementary to the sediment lithostratigraphy, and allows to identify or validate the presence of palaeo-soil and/or submerged surfaces in the sediment pile. This information is based on *in situ* observation of excavated surfaces that consider the knowledge of cultural land-use patterns in Lake Titicaca (Delaere 2020). Each unit is also characterized by photography, photogrammetry (Figure 3), and surface surveys illustrating the connection of artifacts and ecofacts within a contemporary surface.

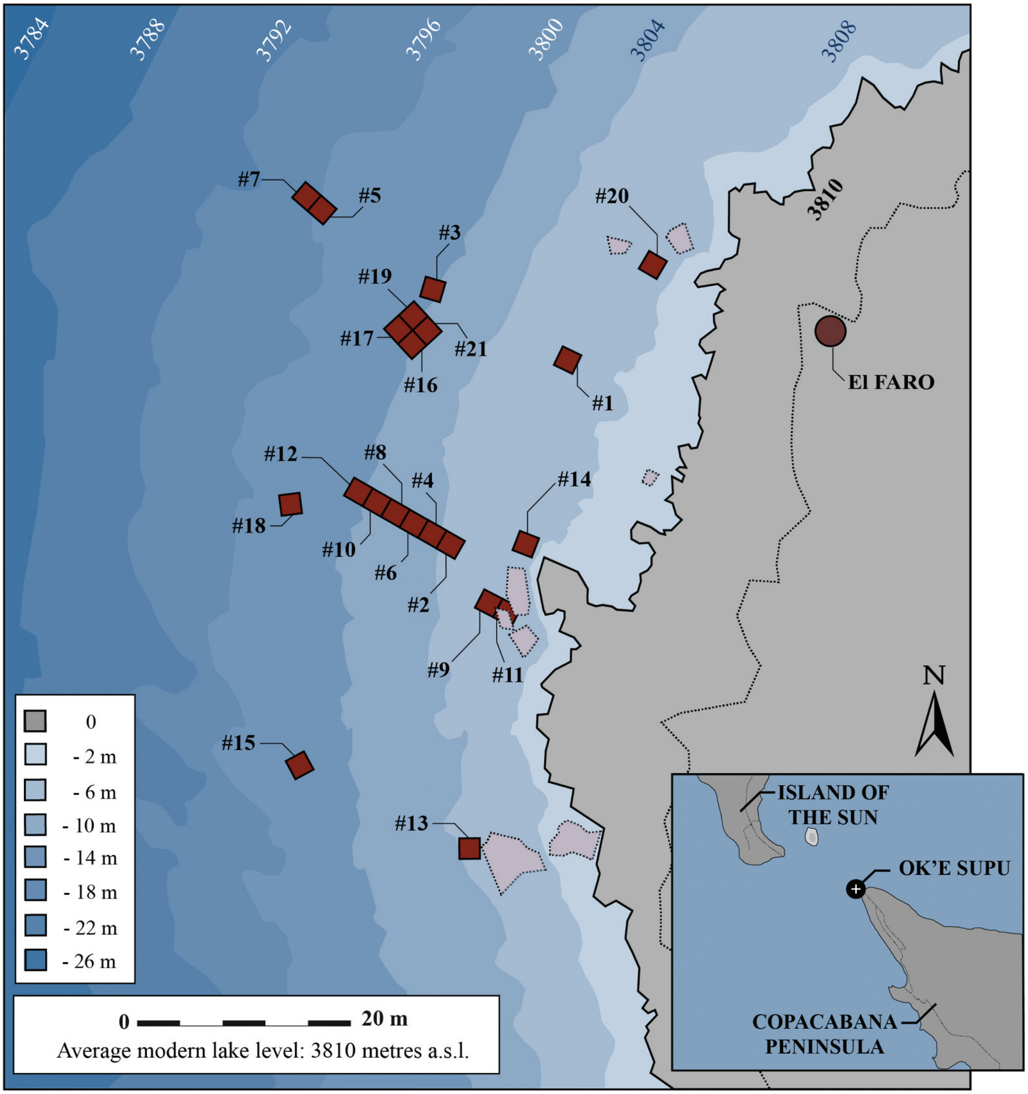

Figure 2. Bathymetric map of Ok'e Supu site with the location of underwater archaeological test pits (#) excavated for 24 days in 2016 and 13 days in 2018, representing a total of 330 immersions and 398 hours of cumulative diving for a total excavation area of 84 m^2 (Topography: L. Masselin, ULB; Map: C. Delaere).

Third, the analysis of the ceramic material from each identified lithological unit brings information on both the archaeological period covered by the unit (chronological value), and the relative degree of anthropogenic occupation when the information is spatialized (anthropization rate assessed by the abundance of material). The underwater contexts are characterised by the almost exclusive proportion of ceramic material (97% of the artifacts), but also by the almost systematic absence of construction or primary contexts. Consequently, ceramics are the main cultural indicator in underwater contexts. The method of analysis and classification of the ceramic fragments is based on a stylistic examination that takes into account the correlation of the following different identification

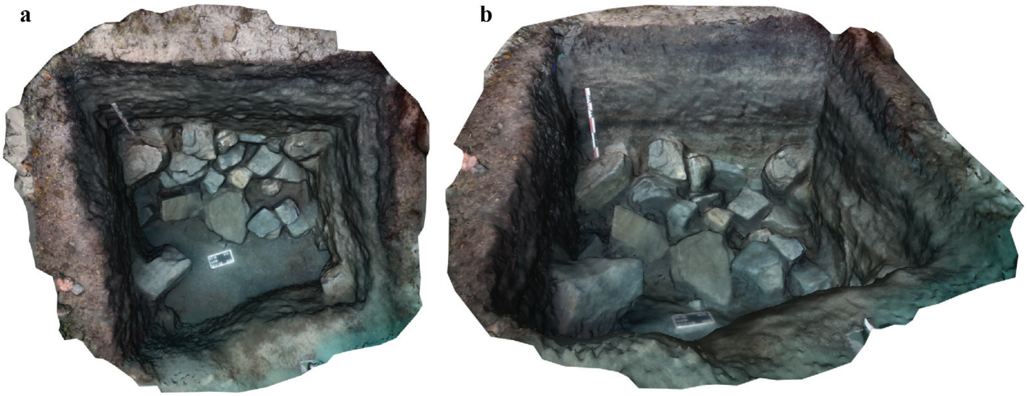

Figure 3. Photogrammetry of a 4 m^2 underwater archaeological test pit in Lake Titicaca (SAM_#11; Photography: B. Debrand, ULB). A) Plan view, and B) 45° view. The scale ruler visible in the photo is 50 cm long. Sediment stratigraphy can be seen overlying a detrital level of natural block stones.

criteria: (i) shape, (ii) type of fragment (rim, base, body of the ceramic, modelled elements), (iii) thickness of the fragment, (iv) firing (oxidising or reducing), (v) colour of the paste, (vi) composition of the paste, and (vii) iconography (Janusek 2003; Roddick 2009). This allows the identification of the cultural affiliation of all the ceramic fragments, and provides a chronological value to each lithological unit. In addition, the calculation of the anthropogenic activity rate (AAR) gives complementary information about the occupation of the site. From the total number of artifacts per test pits and their chronological affiliation, the AAR allow identifying both events/cultural periods and locations/depth of significant anthropization, and establish diachronic land use patterns.

Fourth, the organic (charcoals, seeds and plant remain) and inorganic (mollusc shells) macroremains collected within or at the edges of each sediment unit which allow (i) refining the period covered by each stratigraphic unit or (ii) identifying gaps in sedimentation (hiatus) typical of non-depositional surfaces resulting in a change in radiocarbon activity. All radiocarbon ages were obtained using Accelerator Mass Spectrometry (AMS) at the radiocarbon facility of the Belgian Royal Institute for Cultural Heritage (RICH) and calibrated using the SHCal20 southern hemisphere curve (Hogg et al. 2020) in OxCal 4.4.4 (Ramsey 2009, 2021). Ages are presented with a 1 sigma (68.2%) and 2 sigma (95.4%) age uncertainty.

Fifth, the altimetric positioning of each archaeological test pit, here named geoarchaeological profiles, were performed in four stages; i) a bathymetric survey from a boat of the prospected area was performed with a multibeam echo-sounder Panoptix™ PS30 and GPSMAP®7410, ii) the position of all the underwater archaeological test pits were georeferenced by *in situ* underwater trilateration, iii) the altimetric and bathymetric values were mapped based on the reference modern lake level arbitrarily fixed at 3810 metres a.s.l. The seasonal and annual fluctuations were therefore considered based on the monthly lake level record data published by the Huatajata station of the National Meteorological and Hydrological Service of Bolivia (SENHAMI). Finally, the altimetry of each sedimentary unit within each geoarchaeological profile was determined from the depth of the unit (top and down) below the georeferenced sediment/water interface.

Results

The 18 analyzed geoarchaeological profiles have been combined in a lithostratigraphic cross-section following the morphology of the currently submerged coastal slope at Ok'e Supu (Figure 4).

This cross-section, is established by correlating the sedimentary units on a chronological basis (Harris matrix), constructed from ceramological and radiocarbon ages, and not on the basis of their sedimentary lithology, which is known to change with the height of the water column. Thus, it allows the reconstruction of the altimetric evolution of the paleo-shore-lines and lacustrine sedimentary units for each defined cultural period. Overall, the occurrences of submerged sediment facies in this cross-section show an increasing lake level over the last two millennia. The lake was ca.

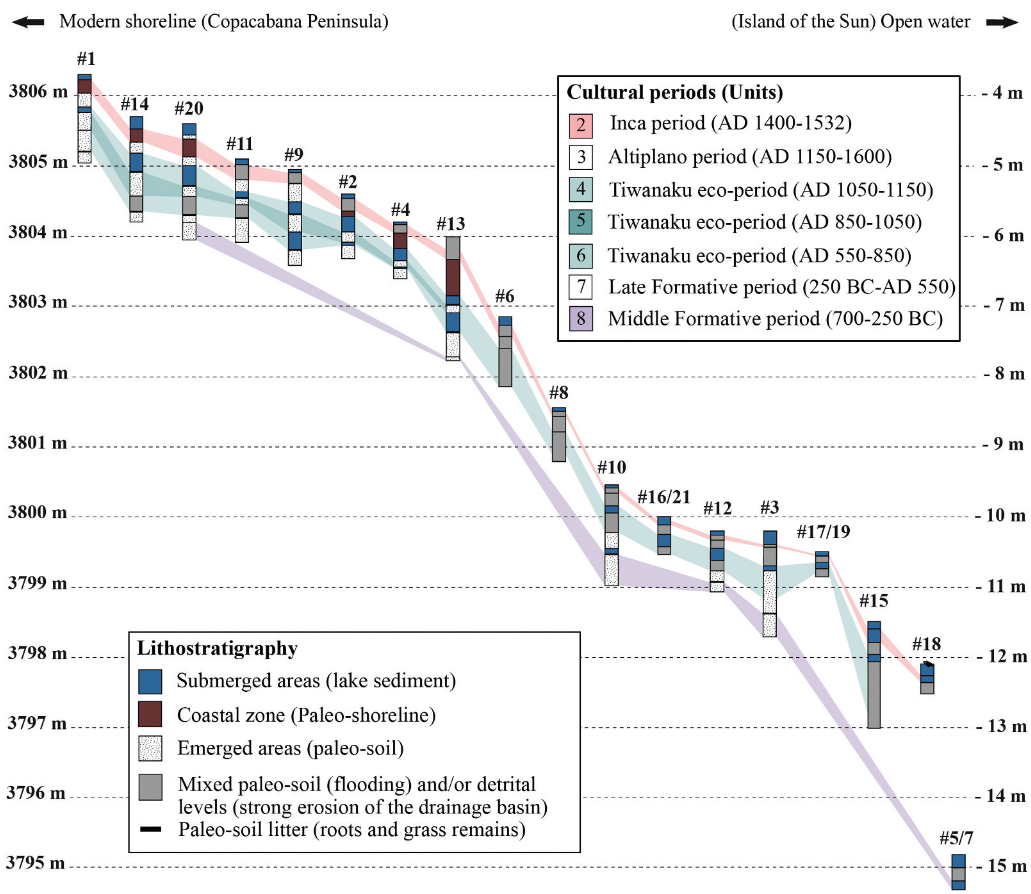

Figure 4. Composite geoarchaeological transect of underwater archaeological test pits (#) excavated at Ok'e Supu site with their respective altimetric values below the modern lake level (3810 m a.s.l.). Stratigraphic units are correlated to each other by cultural period (colored bands) obtained from stylistic examination of the ceramic material (cultural proxy) and validated by radiocarbon ages (Table 1). In lithostratigraphic profiles, blue colour refers to carbonate rich lake sediments (i.e. shallow water level between 2 and 15 metres), grey colours to very shallow environments (mixed layers composed of paleo-soil and detrital materials), dark red colour to paleo shore-line coastal sediment; and black colour to emerged areas (paleo-soil). Note that the altimetric values are determined from the Huatajata-Senamhi station (Bolivia) database which is always 0.7 m below the one provided at the Puno-Senamhi station (Peru).

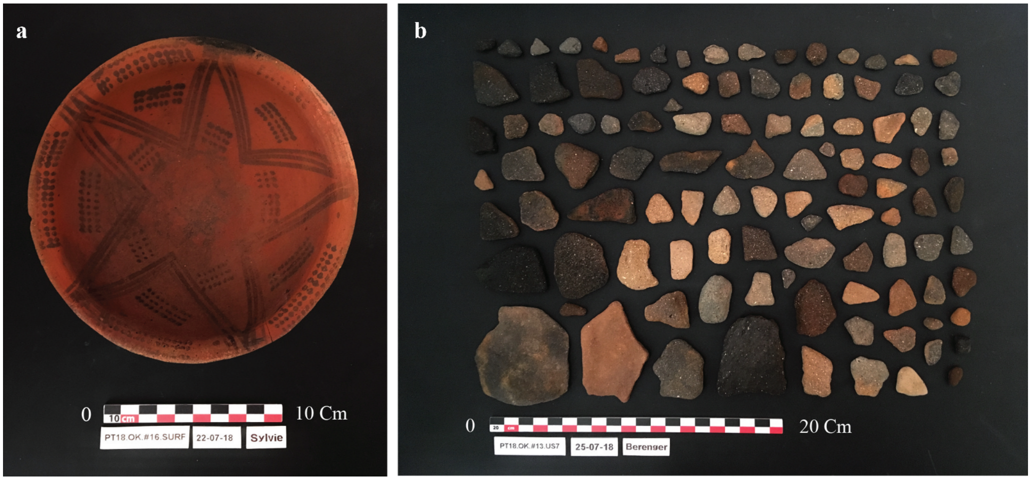

Figure 5. Examples of two distinct taphonomic conditions of ceramics recovered in contrasted stratigraphic units; A) AD a well-preserved cuenco from the Altiplano-Pacajes period (AD 1100–1400), including iconography, recovered in an undisturbed carbonate rich sediment (#16, Unit 2), and B) mixed Late formative and early Tiwanaku ceramic fragments (AD 300–650) recovered in a detrital sediment unit (disturbed) illustrating the shoreline erosion patterns (#13, Unit 7) (Photography: M.-J. Declerck and A. Huybrechts).

13 meters lower than the modern level during the Late Formative period (250 BC – AD 550), increased by at least 7 meters during the Tiwanaku period (AD 550–1150), and reached a level close to the present one after the Inca period (AD 1400–1532).

In details, the 113 sedimentary units identified within the 18 profiles along the transect were compiled into eight main geoarchaeological units (classified per age category) dated from the Middle Formative Period (ca. 800–200 BC) to the Republican Period (ca. AD 1825–1950). These main geoarchaeological units or chronological intervals were obtain mainly from the stylistic examination (Figure 5) of the ceramic material (cultural proxy), and were validated by the 21 radiocarbon ages obtained for the Ok'e Supu site (Table 1), with the oldest ones dating to 700–546 BC (RICH-23405; 2535 ± 32 BP) and the most recent to AD 1673–1900 (RICH-23397; 186 ± 29 BP).

The abundance and stylistic diversity of the ceramic artifacts collected in these geoarchaeological units support a discontinuous but long-term occupation of the site (Table 2). Although indicative, variations in anthropogenic activities rate (AAR) give a first level of information on the location of the palaeo-shoreline as a function of time as well as on the most representative periods of occupation (e.g. 494 TIW fragments at 6 m depth).

The Tiwanaku period of occupation is the most representative, as the ceramic material of this period corresponds to 78% of the assemblage (n = 2959). In addition, peaks in abundance of archaeological material identified at peculiar levels, such as those found at 6 metres depth in #13 (n = 592) and at 10.2 metres depth in #12 (n = 162) dominated by Tiwanaku materials suggest the presence of ancient shorelines used and occupied by Andean populations (Table 2). In contrast, the under-represented periods with low AAR, such as the Middle Formative (MF) period, suggest a lower occupation of the site (at this altitude) but provide sufficient information to establish chronological correlations between each unit in each test pits. It is however important to mention that the imbalance observed in the ceramic assemblage may be affected by taphonomic conditions (greater number of fragmentary

Table 1. AMS Radiocarbon ages of organic macro-remains collected in sediment layers excavated in geoarchaeological profiles or test pits at Ok'e Supu. All ages (presented in calendar year AD/BC) were calibrated using Oxcal 4.4.4 (Ramsey 2009, 2021) and the SHCAL20 curve (Hogg et al. 2020).

Lab Code	^{14}C BP	Error	Material	Provenience	Age AD/BC (68.2%)	Age AD/BC (95.4%)
RICH-23397	186	29	Charcoal	#2, Unit 1	1673–1900	1668-modern
RICH-27931	347	25	Bone (collagen)	#18, Unit 1	1510–1632	1500–1648
RICH-23403	469	30	Charcoal	#6, Unit 2	1436–1483	1425–1615
RICH-23402	476	29	Charcoal	#9, Unit 2	1434–1462	1422–1612
RICH-23404	512	29	Charcoal	#6, Unit 2	1426–1451	1411–1457
RICH-24153	524	28	Wood	#8, Unit 2	1422–1446	1408–1454
RICH-23382	590	30	Charcoal	#12, Unit 3	1330–1425	1322–1437
RICH-23386	597	31	Charcoal	#4, Unit 3	1327–1421	1320–1436
RICH-23406	891	30	Charcoal	#1, Unit 3	1160–1223	1072–1271
RICH-30095	933	25	Charcoal	#13, Unit 4	1054–1211	1046–1220
RICH-30097	940	25	Charcoal	#13, Unit 4	1052–1206	1045–1217
RICH-23398	948	31	Charcoal	#12, Unit 4	1048–1206	1043–1213
RICH-23379	958	30	Charcoal	#9, Unit 4	1047–1181	1032–1208
RICH-30096	959	24	Charcoal	#13, Unit 4	1047–1180	1033–1185
RICH-23384	1002	32	Charcoal	#2, Unit 4	1030–1145	1021–1158
RICH-23381	1221	31	Charcoal	#11, Unit 5	774–954	771–971
RICH-23399	1229	32	Charcoal	#9, Unit 5	774–891	771–970
RICH-23401	1305	31	Charcoal	#10, Unit 6	683–840	678–872
RICH-30098	1569	25	Charcoal	#13, Unit 6	524–590	436–628
RICH-23400	2237	31	Charcoal	#3, Unit 8	361–177 BC	379–154 BC
RICH-23405	2535	32	Charcoal	#5, Unit 8	700–546 BC	785–423 BC

Table 2. Number of Ok'e Supu ceramic fragments for each test pits and each of the identified cultural affiliation, i.e. MF – Middle Formative (700–250 BC), LF – Late Formative (250 BC- AD 550), TIW – Tiwanaku (AD 550–1150), ALT IND – Altiplano indeterminate (AD 1150–1600), ALT PAC – Altiplano Pacajes (AD 1150–1400), ALT INC – Altiplano Inca (AD 1400–1532), and COL – colonial (AD 1532–1825). The anthropogenic activity rate (AAR) corresponds to the sum of collected ceramic fragments per test pit and chronological value.

Test Pits	Depth (m)	MF	LF	TIW	ALT IND	ALT PAC	ALT INC	COL	AAR per test pit
#1	3.7	0	6	349	64	0	6	0	425
#14	4.3	0	10	241	3	57	0	2	313
#20	4.4	0	42	445	16	40	0	0	543
#11	4.9	11	62	367	18	0	0	0	458
#9	5	0	27	423	66	0	1	0	517
#2	5.4	0	30	83	13	0	0	0	126
#4	5.8	0	22	72	5	1	0	0	100
#13	6	0	95	**494**	3	0	0	0	592
#6	7.2	0	27	75	12	0	0	0	114
#8	8.5	0	4	58	3	0	0	0	65
#10	9.6	4	50	97	0	0	0	0	151
#16/21	10	0	5	35	0	1	0	0	41
#12	10.2	2	30	130	0	0	0	0	162
#3	10.2	3	1	16	0	0	0	0	20
#17/19	10.5	0	7	43	0	0	0	0	50
#15	11.5	0	10	10	0	0	0	0	20
#18	12.1	0	6	3	0	0	0	0	9
#5/#7	14.8	1	0	9	0	0	0	0	10
SURF	30	0	0	9	4	0	0	0	13
AAR percultural period		21	434	2959	207	99	7	2	3729

ceramics in erosive zones), but also by cultural factors (no monocausal link between the abundance of artifacts and the intensity of human activities), and circumstantial factors (certain sites are abandoned in favour of others over time).

The oldest period identified along the transect (Figure 5) corresponds to the Middle Formative period (ca. 700 to 250 BC, Unit 8). The presence of paleo-soil layers (i.e. indurated level dominated by silt, plant debris, stone blocks and Middle Formative material) in profiles #20, #13, #10, #12 and #3, and of a carbonate rich sediment (profiles #5/7), informs that the ancient shoreline must have been located between 3798.3 and 3794.7 metres. i.e. between 12 and 15 m below the modern level. During the Late Formative period (ca. 250 BC to AD 550, Unit 7), the lithology reveals the presence of paleo-soil layers at an altitude up to at least 3798.7 metres in profiles #1 to #3, a paleo-beach detrital level at 3797 metres at profile #15, and carbonate rich sediment at 3794.3 metres at profile #5/#7. Hence, the ancient shoreline might have been located at 3797 metres, i.e. 13 m below the modern level.

The sediment unit dated to the Tiwanaku period (AD 550–1150, units 4, 5 and 6), is thicker and better resolved compared to the previous periods, with at least three distinct lithological sub-units (or ecophase) during the 600-year development of the Tiwanaku culture. Significant changes in sediment lithology between these sub-units suggest that the lake as undergone high fluctuations. For the earliest Tiwanaku ecophase (AD 550–850, Unit 6), the presence of a paleo-soil in profile #1, and of paleo-shorelines levels in profiles #14, #20, #11 and #9 determines the shoreline at ca. 6.3 metres below the modern level as all units in profiles below 3803.7 m a.s.l. are constituted of carbonate rich sediment. This result indicates that a large hydrological upheaval occured in the Lake Titicaca at the start of Tiwanaku Period, because the lake level increased by almost 7 metres compared to the previous period. For the second Tiwanaku ecophase (AD 850–1050, Unit 5), the presence of paleo-soils in profiles #1 to #13, and of fire place remains, indicates that the lake level had decreased at least below 3803 metres a.s.l., i.e. at least 7 m below the modern level. Finally, for the latest Tiwanaku ecophase (AD 1050–1150, Unit 4), the presence of carbonate mud in all similar sediment units support a higher lake stand located above 3806.3 m a.s.l., i.e. between the modern level and 3.7 metres below.

In the above unit which corresponds to the Altiplano period (AD 1150–1600, unit 3), the presence of paleo-soil levels in the geoarchaeological profiles #1, #14, #20, #11 and #9, and the presence of two paleo-shoreline layers found in profiles #2, #4 and #13, highlight the presence of the lake shoreline at 3803.2 metres a.s.l. The sediment lithology of this unit gradually shifts from detrital to carbonate rich mud with depth from 3802.6 to 3795.0 metres a.s.l. Hence, after the latest Tiwanaku ecophase (AD 1050–1150) the lake has slightly decreased. Finally, For the INCA period (AD 1400–1532, Unit 2), the presence of scour marks, sandy sediment and shingle at the bottom of the unit in the geoarchaeological profile #1, #14, and #20 support the presence of a paleo-shoreline level with a shoreline located at 3805.2, i.e. at 4.8 m below the modern level. Deeper in the transect, the sediment of this unit changes gradually to a carbonate rich mud consistently with the enhanced production of carbonate with depth in Lake Titicaca. Altogether, this illustrates that the lake has risen in average of at least 2 metres.

Discussion

Archaeological significance of the Ok'e Supu site

In the field of archaeology, the Copacabana peninsula and the Island of the Sun are one of the major crossroads of the region (Bauer and Stanish 2001). Our results, notably the abundance of artifacts discovered underwater at Ok'e Supu (i.e. 6613 artifacts and ecofacts), corroborate the idea that the Island of the Sun had a powerful iconic and economic attraction since the Tiwanaku period, and that it became an empire-wide pilgrimage site during the Inca occupation (AD 1400–1440) following its transformation by the latter (Seddon 1997; Bauer and Stanish 2001; Stanish and Bauer 2004). To reach the Island, it was therefore necessary to cross the strait as reported by 17th-century sources which mention that the '*Yambopata* [Yampupata] landing' was used with 'large boats' (Ramos Gavilán [1621], 1860). Hence, the site of Ok'e Supu (OKE) probably corresponds to the site mentioned in this source, because it is the closest site to the Island (ca. 970 m*, Figure 1. D), and because few artifacts have been found at the site of Yampupata (YAM), the other most likely candidate as an ancient port (Figure 1. D).

Reconstruction of paleo-shorelines and relative lake level fluctuation

From what is known about Lake Titicaca level fluctuations (Abbott et al. 1997; Mourguiart et al. 1992; Rowe et al. 2003; Fritz et al. 2006; Weide et al. 2017; Guédron et al. 2021), the lake has fluctuated by at least 20 metres during the last past three millennia. Such lake level variations have resulted in a significant transgression and regression of the shoreline from hundreds of metres to several kilometres depending on the slope of the shoreline (Binford and Kolata 1996). Thus, both the flooding of the inland, or the exondation of submerged areas have likely generated important geopolitical disturbances, as the surface of agricultural land has fluctuated accordingly.

The data provided here (Figure 6) confirm such range of fluctuations and refine previous reconstructions especially for the archaeological period of Lake Titicaca occupation. It is worth mentioning that the altitude of the depth provided in the synthesis Figure 6 do not consider the decadal to centennial oscillations of the lake, but only provides the highest lake level for each considered period. Such information allows going further in the interpretation of the cultural responses induced by climate and environmental changes to explain events in societies (e.g. Lentz et al. 2018; Kennett et al. 2012), whether socio-economic, political, technological, or religious.

At the onset of the emergence of social and political complexity on the shores of Lake Titicaca, i.e. during the Middle Formative and Late Formative periods (700 BC – AD 550), the lake fluctuated little with an amplitude of about 4 metres between 3794 and 3798 m., equivalent to the interannual fluctuations measured over the modern period. This period is however interrupted by a brief flood event occurring during the Initial Late Formative period (#10 US7/8), the amplitude of which could not be precisely defined here.

The following period which corresponds to the emergence of the Tiwanaku culture, i.e. AD 550 to 850, is characterized by a sharp lake rise of almost 7 metres to ca. 3804 metres. This wet period in the Lake Titicaca region (Baker et al. 2009; Thompson et al. 2013; Jiskra et al. 2022) has thus resulted in the inundation of large surfaces of the inland territory, and probably forced the populations to migrate to higher elevations. This may have particularly contributed to the emergence of the Tiwanaku culture, through the migration of the populations towards its capital Tiahuanaco located at 3850 m a.s.l. whose demography underwent a strong development between the 6th and the 8th century (Goldstein 2006; Bandy 2013). Moreover, this period is also reported as the time of the most important development of the agro-pastoral landscape, including that of the raised field systems (Janusek and Kolata 2004; Bandy 2005; Bruno 2014).

The end of the Tiwanaku period (AD 1050 to 1150) was punctuated by another increase in lake level by at least three metres (up to 3806 m a.s.l.) before AD 1100, followed by a decline in lake level of at least three metres which lasted until AD 1300–1400. Unfortunately, the resolution of our reconstruction does not allow us to evaluate precisely the amplitude and duration of these two events. However, the amplitude of these lake fluctuations is less than that of the variations during

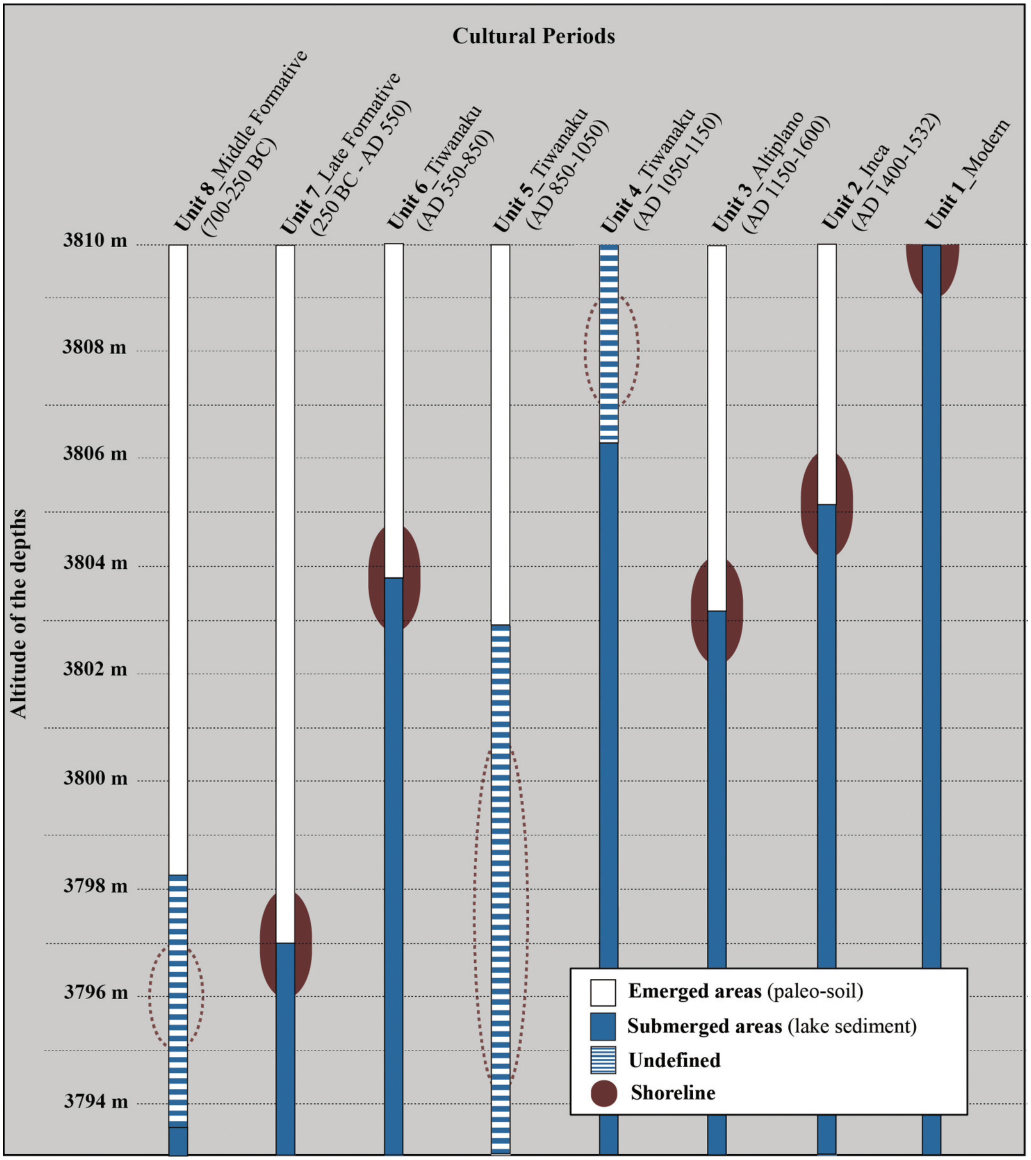

Figure 6. Altitude of the depth. Synthesis of the reconstructed temporal evolution of the Lake Titicaca shoreline by cultural periods (700 BC – present day). White bands indicate the altitude of emerged areas, blue ones the altitude of submerged surfaces, and white and blue dashed bands the most probable range of altitude within which was located the shoreline. For these latter, the lack of data does not permit providing a precise altitude value. Large brown dots indicate the relative interannual oscillation of the shoreline based on last century lake level oscillations (Huatajata-Senamhi station).

the previous period (unit 6 and 5), and does not support the hypothesis of the fall of Tiwanaku only by environmental changes as such decadal changes in Lake level were likely common in the lives of people residing in this region (Bruno et al. 2021).

Finally, the lithological and altimetric data of the levels affiliated to the period of the conquest of the lake basin by the Incas (AD 1400–1532) show that the water level of the lake was again high (3805 metres a.s.l.).

These results are consistent with the peaks in abundance of ceramic material (AAR) recovered at the different depth levels in the geoarchaeological units (Table 2). In general, the ceramic-rich units are the terrestrial levels, whereas the ceramic-poor ones correspond to the submerged levels. In particular, the Tiwanaku material is very abundant at a depth of ca. 7 metres (consistently with the shoreline identified at ca 3804 m a.s.l.). For the Formative period, the distribution of ceramic material is relatively homogeneous to a depth of 12 metres with peaks of intensity at 6 and 10 metres, consistently with a shoreline located between 3794 and 3798 m a.s.l. Finally, for the post-Tiwanaku period, including the Inca period, the material is restricted to the first 5 metres below the modern level, and confirm a high lake stand around 3805 m a.s.l. Hence, these observations suggest a significant correlation between the abundance of archaeological material and the soil levels or shorelines.

Advantages and limits of the methods

Although this geoarchaeological approach provides unique information that complements the paleoenvironmental reconstructions of the archaeological periods, imperfections inherent to the limitations of the different methods have been identified.

First, although the correlation between geoarchaeological profiles allows some sedimentary gaps to be filled, the amplitude of the lake variations combined with the steep slopes (in the great lake) do not always allow all the information to be covered. Indeed, in the absence of well-preserved homogeneous units in some archaeological test pits (i.e. primary context with preserved terrestrial vegetation or lake organism remains), the presence of heterogeneous or hybrid units (secondary context) formed either by detrital input from the erosion of the shores or from the catchment, or by the disappearance of the original sedimentary matrix (hiatus) do not allow determining with precision the context of both sediment deposition and some artifact burial. Thus, some ecophases have been reworked or eroded, which reduces the resolution of the model (i.e. undefined depth in Figure 6), although it can be contextualized in between the preserved surrounding layers and artifacts.

Second, the stylistic examination of the ceramics allows, in certain cases, to attribute only a large chronological value. This is particularly the case for the Altiplano period (ALT IND, AD 1150–1600), where the significant erosion of the ceramic fragments collected in the upper sedimentary units did not allow a precise distinction between Altiplano-Pacajes (ALT PAC, AD 1150–1400) and Inca production (ALT INC, AD 1400–1532). This difficulty is accentuated by the fact that the Altiplano-Pacajes production continued after the Inca conquest (i.e. AD 1400–1440; Altiplano-Inca) and for several decades after the Spanish conquest in AD 1532 (Altiplano-Colonial). Furthermore, the carbonate-rich sediments are characterised by the presence of chronologically homogeneous artifacts (primary context), which is valuable, but the detrital levels are characterised by the presence of artifacts that may belong to different cultural productions (secondary context). In this case, the chronological value can only be attributed to the most recent objects.

Finally, future methodological developments must focus on the elaboration of continuous age-depth models of Lake Titicaca fluctuations that harmoniously combines data from both geoarchaeological surveys (this study) and the paleoenvironmental approach (sediment cores) using in both cases fine geochemical proxy (e.g. paleobiotic, stable isotopes and chemical proxies) to increase the resolution and provide precise temporal information on the occurrence, the duration and amplitude of lake transgression and regression. This will also allow transposing the results at the scale of the lake basin, with consideration of both bathymetric data and the natural sedimentation rate of the lake (between 1 and 3 cm/year) in order to measure the impact of lake fluctuations on human settlements and key events that punctuate the history of the lake basin.

Conclusion

Although the phenomenon of Lake Titicaca water level fluctuations has been understood for many decades, mainly since the late 1980s (e.g. Mourguiart et al. 1992; Wirmann et al. 1988), the results and projections of paleo-climatic and paleo-environmental data 'beyond the shoreline' had not yet been applied in the domain of archaeology. Conventional sedimentological methods can identify water columns below 2 metres and above 15 metres, but not precisely between 2 and 15 metres, which inland water archaeology can offer. The results of the operations carried out in the waters of Lake Titicaca indicate not only the added value of developing research in the lake, but also of extending it to other lake socio-ecosystems in the Andes in order to multiply the scales and contrasts in the study of aquatic environments.

The coastal area of Lake Titicaca, in particular, is not a common shoreline as the sharp transgression and regression have moved from a few metres to several kilometres through time depending on the slope. The challenge was therefore to spatially assess the rate of transgression and regression of the lake, including the location of ancient's shorelines. The situation of the Ok'e Supu site was an excellent opportunity, and the excavation methods and strategies we employed there in 2016 and 2018 were consequently adapted to collect the necessary data.

The results of this methodological paper demonstrate that the application of this geoarchaeological approach provides new information and opens up many research perspectives, because one can estimate that more than 1.000 km^2 of land exploited and occupied by pre-Tiwanaku communities (ca. ≤ AD 650) are now located in the bottom of the southern basin of Lake Titicaca. Optimal conservation conditions have fixed in time the different facets of these unknown and inundated Andean cultural landscapes.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

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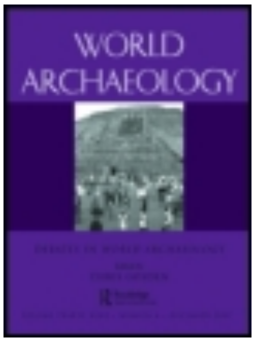

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The altitude of the depths: use of inland water archaeology for the reconstruction of inundated cultural landscapes in Lake Titicaca

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