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First dendroarchaeological dates of prehistoric contexts in South America: *chullpas* in the Central Andes

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ABSTRACT

Despite the existence of long-lived tree species with excellent tree-ring characteristics, the use of dendrochronological techniques for dating archaeological contexts has been very limited in South America. Recent research in the Bolivian Altiplano of the Central Andes has yielded a network of *Polylepis tarapacana* chronologies that goes back to the 13th century. This species was regularly used by local populations since pre-Columbian times as raw material for beams, lintels, hooks and other architectural features in houses, storage chambers, and sepulchers. The aim of this study is to argue in favor of the potential of *P. tarapacana* for providing high resolution dates of significant archaeological events during the pre-Columbian era. The chronology of *chullpas* (burial towers and storage chambers) in the southern Andean Altiplano is used as a case study. Growth rings from *P. tarapacana* have provided several centennial-length dendrochronological records including a reference regional chronology covering the last 786 years in the Central Andean highlands. Based on this long reference chronology calendar years were assigned to woody pieces from pre-Hispanic *chullpas*. Dendroarchaeological results are consistent with contextual evidence and most radiocarbon dates from woody samples and related archaeological items. Our results indicate that *P. tarapacana* has a high potential for providing annually-resolved tree-ring dates for archaeological contexts in the Altiplano since the early 13th century.

1. Introduction

Dendrochronology is the highest-resolution technique available for dating archaeological objects (Baillie, 1995; Nash, 2002). To date, dendroarchaeology has only been used to establish the antiquity of prehistoric contexts in the Northern Hemisphere, where several tree species with precise dating potential were used by ancient people. In the North American Southwest and in Northern Europe, this technique has allowed relating the age of wood specimens with archaeological materials and associated phenomena. In South America, successful crossdating has been achieved on long living species such as *Fitzroya cupressoides* (Boninsegna and Holmes, 1985; Lara and Villalba, 1993), *Araucaria araucana* (LaMarche et al., 1979; Mundo et al., 2012) and *Austrocedrus chilensis* (Boninsegna, 1988; Villalba and Veblen, 1997; Morales and Boninsegna, 2000; Le Quesne et al., 2006, 2009; Christie et al., 2011). However, none of these species have been used to date prehistoric human activity or related events. This relates primarily to the fact that exposed woods tend to decompose rapidly in the humid environments where these trees grow,[1] but may also reflect the fact that these woods were seldom employed in the manufacture of artifacts or structures by Native American people.

A network of tree-ring records from *Polylepis tarapacana* – the highest growing tree in the world – has recently been developed in the Bolivian Altiplano, Central Andes of South America. These records go back to the 13th century AD (Solíz et al., 2009; Morales et al., 2012). *P. tarapacana*, growing between 4000 and 5200 m elevation, shows annual tree-ring resolution and consistent responses to interannual climate fluctuations (Argollo et al., 2004; Morales et al., 2004; Christie et al., 2009; Solíz et al., 2009; Morales et al., 2012). Given the scarcity of wood in this arid region, *P. tarapacana* was regularly used by local populations since pre-Columbian times as raw material for beams, lintels, hooks, and other architectural features in houses, storage chambers, and sepulchers (Nielsen and Berberián, 2008).

The use of *P. tarapacana* wood by Altiplano populations provides a unique opportunity for obtaining high-precision dates of prehistoric events which are difficult to situate chronologically with

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[1] *Fitzroya cupressoides* is an exception since well-preserved sub-fossil remnants of long dead specimens have been found (Lara and Villalba, 1993).

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enough accuracy on the basis of the dating techniques previously used. Examples of these events abound during the Late Prehistoric Period (AD 1000–1600)[2] of the Central Andes because it was a time of rapid social transformation, as attested by the construction of hilltop fortresses, the growth of conglomerated villages, the expansion of irrigation systems, the emergence of new styles of pottery, textiles and houses, and the spread of Inca material culture (e.g., ceramics, buildings, roads), among other lines of evidence. The historical processes underlying these phenomena, however, are difficult to reconstruct – at least in part – due to the lack of dating techniques with adequate resolution to establish the timing, duration, and/or chronological order of events.

Two dating methods are currently used by archaeologists working in this area, radiocarbon (^{14}C) and thermoluminiscence (TL) techniques. Radiocarbon dating is by far the most popular, but its relatively low resolution makes it ineffective to resolve many of the substantive questions raised by archaeological evidences. Moreover, almost a century-long wiggle in the ^{14}C calibration curve around the 14th century AD significantly diminishes the resolution of radiocarbon dates for this period when key events took place in the region. TL dates have similar or even less precision, and have shown significant dating differences when compared to radiocarbon estimates of the same materials or deposits (Angiorama, 1998; Bárcena, 1998). These discrepancies raise doubts about the possibilities of comparing dates resulting from these two methods. In this situation, the utilization of a dating technique with annual resolution like dendrochronology represents a major contribution to Andean archaeology.

The goal of this article is to demonstrate the potential of *P. tarapacana* for providing high resolution dates of significant archaeological events of the pre-Columbian era in the Central Andes. The chronology of burial towers and storage chambers (collectively referred to as *chullpas* in this paper) is used as a case study. The article is organized in three sections. The first section characterizes the *chullpa* architecture, its significance, and approximate chronology. The following section presents the materials, methods, and dendrochronological dates of wood samples extracted from *chullpas* at three different sites. A regional composite tree-ring chronology, which extends back to AD 1226, is used for dating purposes. In the final section all these lines of evidence are brought together to argue for the feasibility of dendroarchaeological dating based on *P. tarapacana* for the Andean highlands, including preliminary conclusions in relation to *chullpa* chronology.

2. *Chullpa* architecture of the Central Andean highlands

An outstanding characteristic of the late pre-Hispanic archaeology of the Central Andean highlands is the presence of countless tower-shaped structures that served, *inter alia*, as sepulchers. Given the high quality of their construction, these features – known as *chullpas*: "containers in which they placed their dead" in Aymara (Bertonio, 1984[1612]) – are some of the best preserved examples of prehistoric architecture in the area. They are found in isolation or forming discrete groups close to settlements or to farming areas, usually on highly visible places where they are still perceived as prominent landmarks.

[2] This term refers to the time between the end of the Middle Period by AD 900–1100 (depending on the region) and the consolidation of the Colonial regime during the late 16th and early 17th century, thus encompassing the Late Intermediate Period (AD 1000–1450), the Inca Period (AD 1450–1550) and the era of initial European contact. A broad chronological category like this is necessary because in many respects, material culture shows great continuity during these centuries; therefore, in the absence of absolute dates, many archaeological units cannot be situated more accurately in time.

The *chullpas* caught the attention of the Spanish conquistadors in the 16th century, who noted that the Indians put more effort in building sepulchers than their own houses (e.g., Cieza de León, 1996 [1553], chapters 62–63). This was just one among many curious practices they observed, which revealed the great importance that ancestors had in Andean cosmology and society. These powerful spirits were conceived as owners of the land and ultimate sources of authority and well-being for the community of their descendants (*ayllus*). *Ayllu* members periodically addressed their ancestors through rituals that involved direct, physical interaction between the living and the dead, represented by their mummies, body parts (bones, hair), and other objects, such as textile bundles or monoliths (Duviols, 1979; Kaulicke, 2001). These practices played a central role in the reproduction of ethnic identities, territorial rights, and political hierarchies. Whether used as open sepulchers that granted physical access to the corpse (Isbell, 1997), elite burials (Hyslop, 1977), ancestral altars (Aldunate and Castro, 1981), and/or landmarks (Kesseli and Pärssinen, 2005), *chullpas* afford the possibility of tracing archaeologically the origins and development of a distinctive Andean form of corporate social organization.

In the southern Altiplano (Lípez region) and some of the adjacent high valleys (e.g., Upper Loa [Castro et al., 1984]), towers coexisted with dome-shaped chambers used for storing quinoa, pottery, farming tools, and other goods. Chambers, which are found mostly inside caves and rock shelters, share many characteristics with towers, e.g., in their elaborate construction techniques and in distinctive formal details such as regularly sized, finely made openings. Moreover, it has been documented in Lípez that some towers were also used for storage (Nielsen, 2006). These resemblances and functional overlaps indicate that, despite their differences, these two kinds of structures were closely related for their users (Berenguer, 2004; Sillar, 1996), perhaps invested with common meanings or infused with similar ancestral agency (Nielsen, 2008). Therefore, in these southern regions at least, it is better to think of a generic "*chullpa* architecture", which with some variations in form and location participated in different activities that were closely related in the ideology of ancestor worship, like housing the dead and protecting the crops.

Chullpas show great variation across space in shape, size, and formal details, a pattern that is also noticeable in other cultural materials, such as ceramics, textiles, and domestic architecture, which during the late pre-Hispanic period conformed to distinctive "regional styles". In the Lípez region of the southern Altiplano, these structures typically have thick (0.6–0.9 m), double walls made of stone set with mud mortar, flagstone pavements, vault roofs often reinforced with *Polylepis* or *Trichocereus* beams, and a square or rectangular opening of regular size (40 × 40 cm), just enough to allow the passage of an adult (Fig. 1). Tower shapes range from circular or elliptic to rectangular plans (Fig. 1a, b, f, g, h), while chambers tend to be irregular, probably because of the restrictions imposed by the rock shelters and outcrops in which they were most frequently built (Fig. 1c, d, e).

In terms of chronology, contextual evidence and radiocarbon dates indicate that *chullpa* construction in the South-Central Andes began during the 13th century, continued during the Inca period (AD 1450–1550), and persisted for some time after the European invasion (Nielsen and Berberián, 2008; Castro et al., 1979). The formal, locational, and functional changes that *chullpa* architecture may have experienced during these centuries of dramatic cultural changes, however, are poorly known. In the southern Altiplano, for example, there is some evidence to suggest that rectangular towers began to be constructed during the Inca period, an innovation that would parallel the change from circular/elliptic to rectangular houses (Nielsen, 2001), reinforcing the analogy of *chullpas* as "houses of the dead".

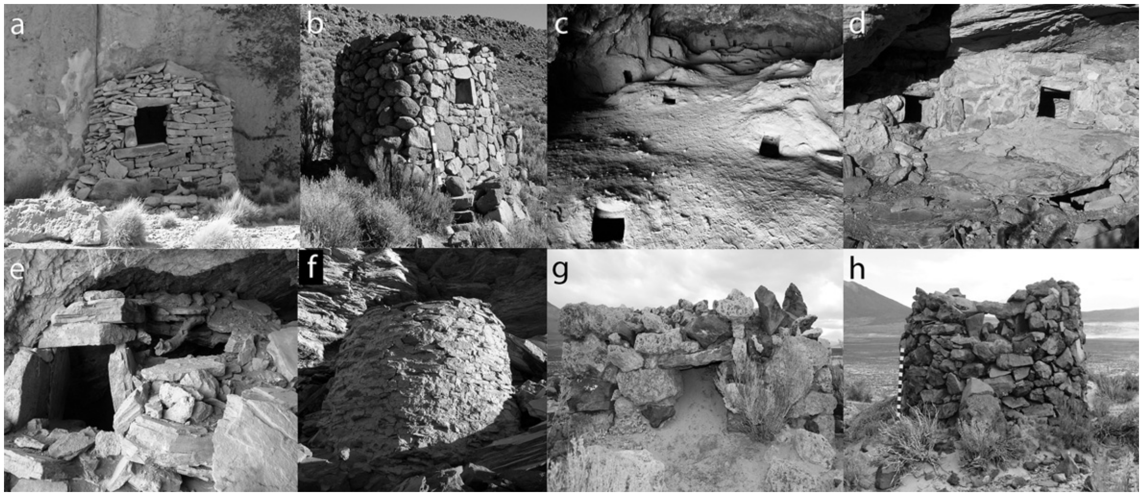

Fig. 1. The *chullpas* (stone chambers or towers) from the Lípez region, Bolivia: (a) Pukara de Mallku; (b) Laqaya; (c) Cueva del Diablo; (d–f) Llacta Qaqa 1; (g–h) Sia Moqo.

The role in ancestor worship attributed to these monuments also raises interesting temporal questions. According to early colonial sources, *ayllu* members periodically opened the sepulchers of their ancestors, taking out their remains to participate in various activities among the living, renewing their offerings and incorporating new bodies to the graves. Testing this hypothesis and exploring its applicability to various regions and periods would require dating different materials in order to compare the chronology of the sepulchers, the bodies inside, and the associated objects, and would clearly benefit from the use of high resolution techniques.

3. Materials and methods

3.1. Species and sample collection

P. tarapacana grows between 4000 and 5200 m elevation on volcanic slopes along the western Andean cordillera of Bolivia and adjacent areas of Peru, Chile and Argentina (16–23°S). Its upper elevation range represents the highest treeline worldwide (Kessler, 1995; Kessler and Schmidt-lebuhn, 2006; Schmidt-Lebuhn et al., 2006). *P. tarapacana* occurs as scattered trees on rocky environments and is well adapted to cold and dry conditions at high elevations. Centennial-aged (ca. 600 yrs) individuals have been sampled in the open woodlands of the Altiplano (Solíz et al., 2009). The extreme environmental conditions of the region not only determine a low rate of radial growth but also the preservation of sub-fossil wood for several centuries (Argollo et al., 2004; Christie et al., 2009).

Samples of *P. tarapacana* were initially collected from Caquella and Uturunco volcanoes on the eastern side of the Cordillera Occidental in southern Bolivia (Fig. 2). Chronologies from these sites were originally reported by Argollo et al. (2004) and Solíz et al. (2009). These sites were re-visited, incorporating new samples that were used to update and extend back in time the original chronologies. Cross-sections and wedges were obtained from dead and living trees. A careful selection of areas with dead and subfossil trees was conducted to improve the robustness of the chronologies during pre-Hispanic centuries. The occurrence of fire was observed at some places, so tree wedges were collected on the less-affected sectors of the stands. The highly significant correlation ($r > 0.69$) between both chronologies over the common interval 1242–2006 indicates a strong common signal between these records. Samples from both sites were merged in a regional tree-ring chronology consisting on 147 tree-ring series.

3.2. Regional reference tree-ring chronology

Standard dendrochronological procedures (Stokes and Smiley, 1968; Fritts, 1976) were used to date dendroarchaeological samples and develop the regional tree-ring chronology. Wedges and cross-sections were carefully sanded and dated following the techniques in Stokes and Smiley (1968). The Schulman's convention (1956) for the Southern Hemisphere, which assigns to each ring the date of the calendar year in which radial growth starts, was used for dating purposes. Ring widths were measured under a binocular microscope using a Bannister measuring machine (0.001 mm precision) connected to a computer (Robinson and Evans, 1980). The computer program COFECHA (Holmes, 1983) was used to detect measurement and cross-dating errors. Ring-width series were detrended to remove the biological trends inherent to radial growth and minimize the growth variations not related to climate. In order to date the dendroarchaeological samples against the regional reference chronology, all tree-ring series were autoregressively modeled and detrended using a 32-year cubic spline filter.

To assess the quality of the regional chronology, including the temporal variability in the strength of the common signal in tree-ring series, the Mean Sensitivity (MS; Fritts, 1976), the mean correlation between all series (RBAR; Briffa, 1995), and the Expressed Population Signal (EPS; Cook et al., 1990) statistics were estimated using the program ARSTAN (ARS40CWIN version; Cook, 1985). The mean sensitivity is a measure of the relative change in ring-width variations from year to year and is calculated as the absolute difference between adjacent indices divided by the mean of the two indices (Fritts, 1976). The RBAR statistics is the mean correlation coefficient for all possible pairings among tree-ring series from individual cores in the chronology, computed for specific time intervals (Briffa, 1995). The EPS quantifies the degree of similarity between a finite-sample chronology and a hypothetical chronology infinitely replicated (Briffa, 1995). There is no level of significance for EPS, however values above 0.85 are accepted as a good level of common signal fidelity between tree-ring series (Wigley et al., 1984). To calculate the RBAR and EPS, we used a 50-year window with an overlap of 25-year between adjacent windows.

3.3. Dendroarchaeological samples and contexts

Ten wood samples recovered from three archaeological sites in the Lípez region (Potosí, Bolivia) were successfully cross-

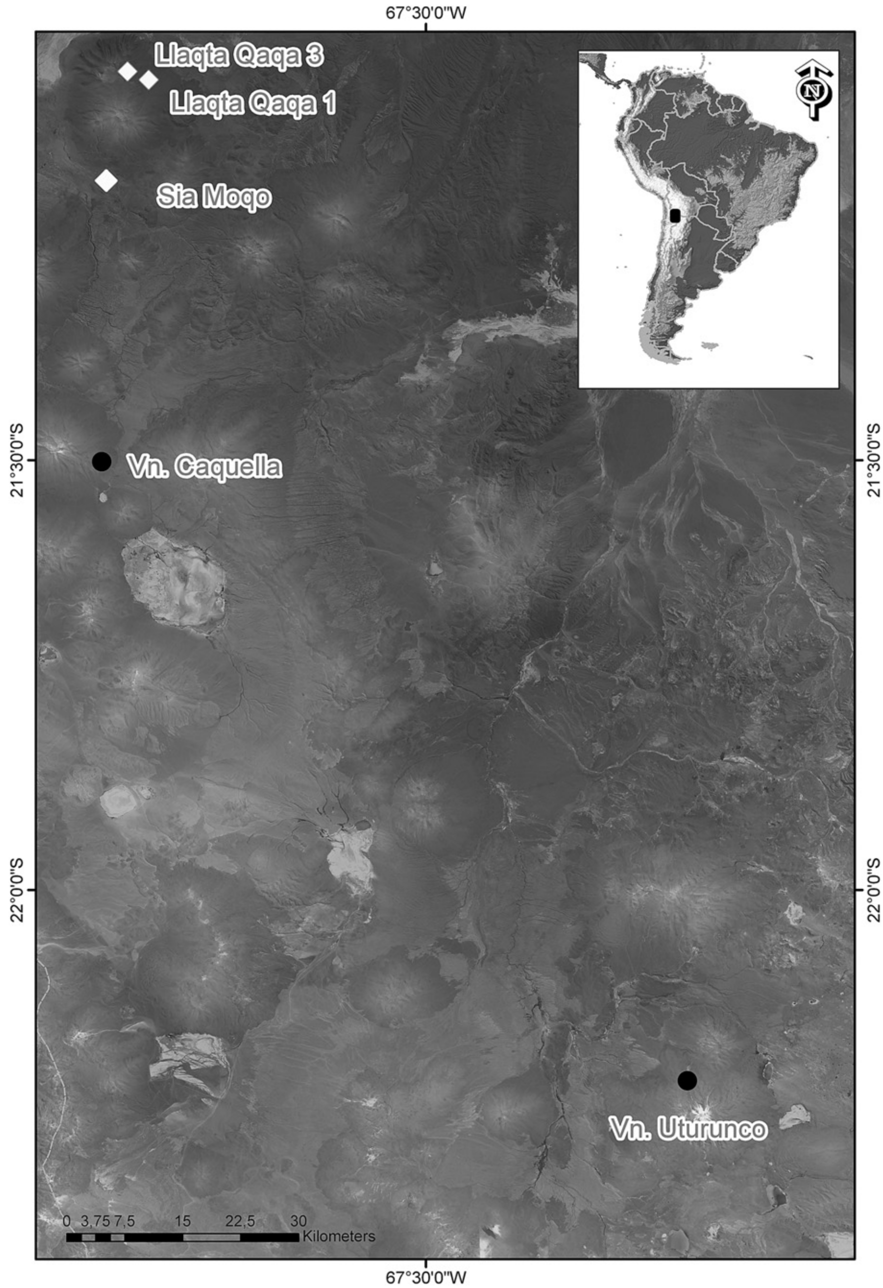

Fig. 2. Geographical location of site collections for tree-ring chronologies (black circles) and dendroarchaeological woods (white diamonds) across the Bolivian Altiplano.

dated. The Llacta Qaqa 1 site (21°06′ S, 67°52′ W, 4240 m, Community of San Juan, Fig. 2), is a cave on the northern slope of Cerro Chiguana. This site contains approximately 25 *chullpas* of different shapes ranging from free-standing cylindrical towers (Fig. 1f) to irregular, semi-subterranean domes built against the back wall of the cave (Fig. 1d,e). The Llq1-50 sample was the only remaining beam in a cylindrical tower (*chullpa* 50). Samples Llq1-22, Llq1-23 and Llq1-24a were taken from three different beams that supported the stone roof of an irregular chamber (*chullpa* 20, Fig. 1e). The two additional samples from this site (Llq1-2A1and Llq1-A2) were 20 cm-long hooks that were sticking out inside a cylindrical tower (*chullpa* 2). Surface inspection revealed no human remains in any of these structures or anywhere else in the cave. Surface artifacts were not particularly diagnostic, but consistent with a late pre-Hispanic chronology.

The Llacta Qaqa 3 site (21°02′11″ S, 67°51′50″ W, 4220 m, Fig. 2) is also a cave located 1 km to the southwest of Llacta Qaqa 1. It has two structures inside, a recently disturbed chamber and a subcylindrical tower built against the cave wall and ceiling. The wood we dated was found on the surface; probably it was a beam that had been removed from the chamber. It is important to note that among the ceramics observed on the surface there were fragments of distinctive Inca pottery (e.g., a bird-shaped plate handle).

The Sia Moqo site (21°10′26″ S, 67°52′;23″ W, 3730 m, Community of Copacabana, Fig. 2) is a settlement on top of a hill with good visibility. Surface ceramics correspond to the late phase of the Late Intermediate period (AD 1250–1450) and to the Inca period (AD 1450–1550). This village is likely the Aymara community of Chea, which was mentioned in a demographic record (*padrón de reducción*) of 1603 (Martínez, 1995). It includes two sectors, a residential area and a cemetery. The residential area is composed by numerous agglomerated stone houses, most of them rectangular with gables, and a few irregular enclosures used as corrals or open domestic areas. The cemetery includes two kinds of burials, i.e., below-ground internments at the bottom of a rock outcrop on the northern side of the hill and over twenty *chullpa* towers of different sizes, showing both circular and rectangular plans.

The first sample from this site (Sm-ch1) came from a beam supporting the stone roof of a low (0.65 m), prismatic tower (*chullpa* 1, Fig. 1g). This structure was excavated. It contained the incomplete skeletons of at least two, stratigraphically superimposed, female adults accompanied by chañar (*Geoffrea decorticans*) fruits, textile fragments, a series of weaving tools (two spindle-whorls, cactus kneedles, three wooden loom parts), a large sherd, a calabash fragment, a wooden spoon, an obsidian flake, a hafted andesite hoe, and a bronze axe with bent stem (Inca period according to González, 1979). All these objects were found over a layer of llama dung. The floor of the sepulcher was prepared with a bed of clay and straw. The second sample (Sm-ch3) was the beam of a similar tower (*chullpa* 3) located 20 m to the east. A third sample (Sm-ch6) came from a roof beam inside a circular tower (*chullpa* 6; 2.1 m-high, 2.4 m-width; Fig. 1h). The excavation of the 0.4 m-thick sandy fill of this structure uncovered a well-prepared clay floor but rendered no macroscopic cultural remains.

Archaeological samples were polished and measured following the standard dendrochronological techniques used for the development of the regional tree-ring chronology (Section 3.2). On the basis of two radii per sample, a mean ring-width series was developed for each cross-section. The program COFECHA (Holmes, 1983) was used to assist in the cross-dating of these samples. All archaeological tree-ring series were autoregressively modeled and detrended using a 32-year high pass filter. Finally, each mean ring series was compared and cross-dated against the *P. tarapacana* reference chronology over the past 786 years.

Five of the archaeological woods were submitted to the Radiocarbon Laboratory of the University of Arizona for conventional radiocarbon dating. These samples included approximately one fifth of the rings in each piece of wood, including the last preserved ring. Results of radiocarbon dates are shown in Table 2.

A control sample without archaeological association from the Uturunco Volcano (UT0228) was also radiocarbon dated. This 39 rings sample (1450–1488), is the internal sector of a longer sample that spans from 1450 to 1779 (330 years) and shows a mean correlation of $r = 0.53$ with the master *P. tarapacana* tree-ring chronology.

4. Results

4.1. Regional reference tree-ring chronology

The regional reference chronology includes the tree-ring samples from the Caquella (21°30′ S, 67°34′ W) and Uturunco (22°32′ S, 66°35′ W) volcanoes (Fig. 3). The high degree of similarity recorded in both *P. tarapacana* chronologies ($r = 0.69$; $N = 765$; $P < 0.0001$; common time span 1242–2006) suggest that variations in the records are predominantly induced by large-scale environmental factors. Our results are consistent with Solíz et al. (2009), who showed large-scale common patterns in a network of 14 chronologies of *P. tarapacana* across the Altiplano.

The regional chronology is composed by 147 tree-ring series. Samples were cross-dated and yield a 786-year long chronology, the longest Polylepis record for the Andean Altiplano (Fig. 3). The chronology covers the period AD 1226–2009, but is best replicated since AD 1288 ($N > 8$ tree ring width series). The statistics to assess the quality of the chronology show a remarkable common signal between the individual samples in the chronology (Fig. 3b, c). The regional *P. tarapacana* chronology shows values of RBAR (0.35) and mean sensitivity (0.2) similar to those previously recorded by Solíz et al. (2009) and Morales et al. (2012) for the Bolivian Altiplano. The EPS remains above the threshold of 0.85 until the year 1251 (Fig. 3c).

4.2. Dendrochronological and radiocarbon dates

The tree-ring series from each archaeological sample were cross-dated and plotted against the reference chronology (Fig. 4). Cross-dating results are shown in Table 1, whereas the radiocarbon ages for the control samples are displayed in Table 2. Fig. 5 compares the dates resulting from the two methods.

The outer tree-ring of the six pieces of wood from Llacta Qaqa 1 were dated between AD 1328 and 1355 (Table 1, Fig. 4a–f), consistently placing the construction of the site around the mid-14th century. The Llq1-50 sample shows traces of bark, suggesting that the last growth ring is preserved in this sample. Based on the cross-dating against the regional chronology, this sample was cut in the year AD 1328 (Table 1). This cutting date falls within the 2σ calibrated range AD 1310–1440 obtained for the radiocarbon date of the outer rings of the sample (Fig. 5).

Samples Llq1-22, Llq1-23, and Llq1-24a were supporting the roof of the same chamber. The presence of bark in Llq1-22 and Llq1-24a allows establishing the cutting dates for both samples, whose

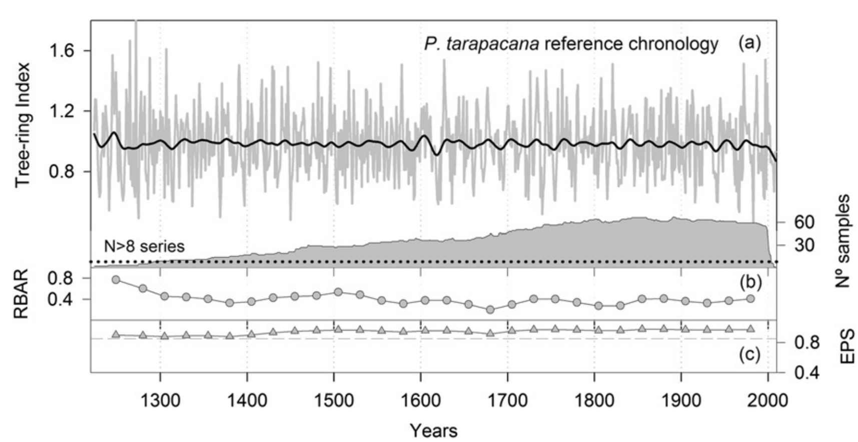

Fig. 3. A 786 yr tree-ring chronology of *P. tarapacana* from the southern Bolivian Altiplano (a). The correlation coefficient (RBAR) for all possible pairings among tree-ring series from an individual chronology and the Expressed Population Signal (EPS), computed for 50-year window with an overlap of 25 years between adjacent windows (b, c).

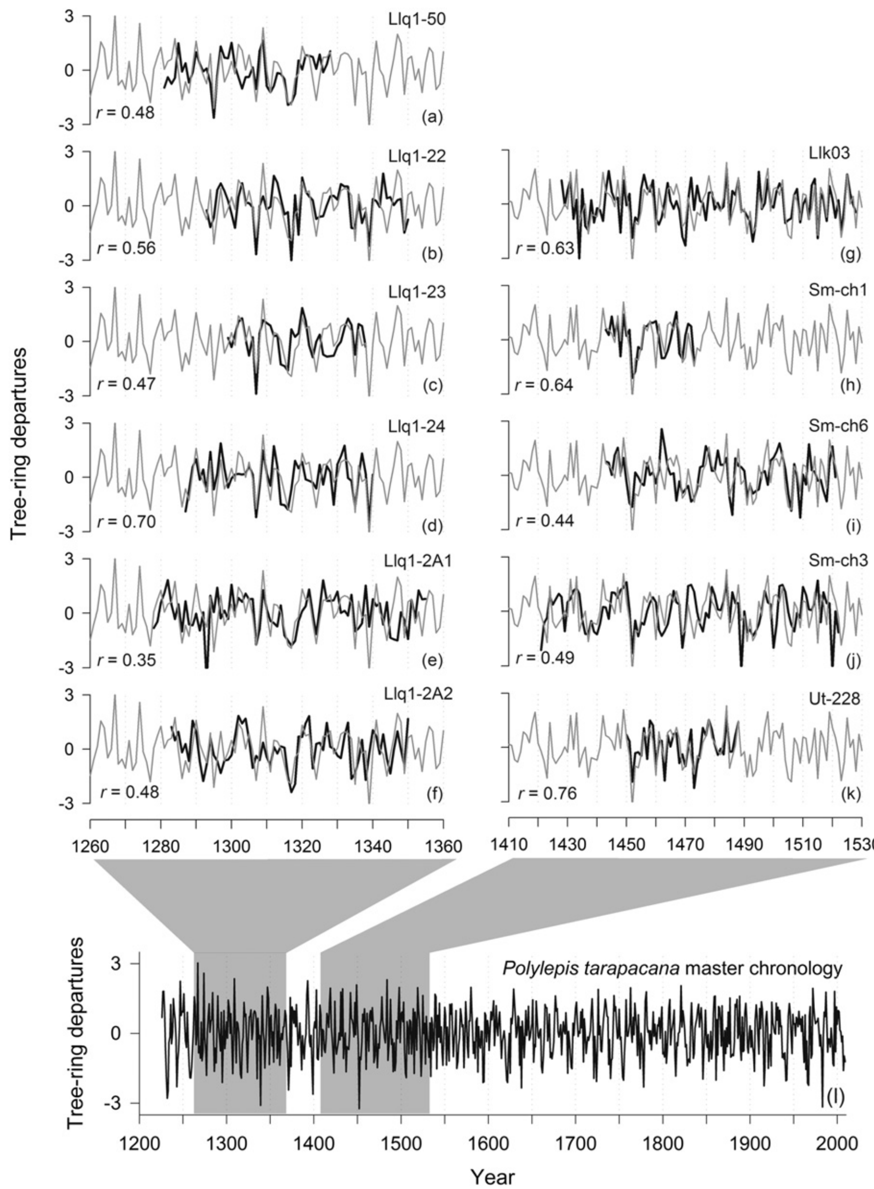

Fig. 4. Comparison between tree-growth variations in the archaeological woods (black line) and the *Polylepis tarapacana* master chronology (gray line; a, k). *r* values correspond to correlation coefficients of each archaeological sample against the master chronology. Shaded sectors in (l) indicate the common time spans between the archaeological samples and the master chronology.

Table 1
Characteristics and descriptive statistics of the dendroarchaeological woods. Terminal ring indicators are: B = Bark presence; vv = Non cutting date.

Tree-ring samples and dates				Statistics					Terminal ring indicators
Site	Structure	Code	Period	yrs	*r*	r^2	*t*	*P*	
Llacta Qaqa 1	*Chullpa* 50, beam	Llq1-50[a]	1281–1328	48	0.48	0.23	3. 7	0.0006	B
Llacta Qaqa 1	*Chullpa* 20, beams	Llq1-22	1293–1350	58	0.56	0.31	5.05	0.000005	B
		Llq1-23	1299–1338	40	0.47	0.22	3.25	0.002	vv
		Llq-24a[a]	1287–1340	54	0.70	0.48	6.96	0.0000001	B
Llacta Qaqa 1	*Chullpa* 2, hooks	Llq-2A1[a]	1278–1355	78	0.35	0.12	3.24	0.002	B
		Llq-2A2	1283–1350	68	0.48	0.23	4.46	0.00003	vv
Llacta Qaqa 3	Beam	Llq3[a]	1428–1528	101	0.63	0.40	8.13	0.0000001	B
Sia Moqo	*Chullpa* 1, beam	Sm-ch1	1443–1473	31	0.64	0.41	4.52	0.00009	vv
	Chullpa 3, beam	Sm-ch3[a]	1421–1491	71	0.44	0.19	4.02	0.0001	vv
Sia Moqo	*Chullpa* 6, beam	Sm-ch6	1443–1521	79	0.49	0.24	4.92	0.000005	vv
Uturunco Volcano	Forest sample	UT228[a]	1450–1488	39	0.76	0.59	7.25	0.000001	Control sample

[a] Samples dated by ^{14}C, see Table 2.

Table 2
Radiocarbon and dendrochronological (outer ring) dates from woods collected at the archaeological sites.

Sample	Lab code	^{14}C AP	Cal 1σ	Cal 2σ	Outer ring date	Archaeological context
Llq1-50	A-15404	595 ± 30	1325–1425	1310–1440	1328	Sub-cylindrical tower in cave
Llq1-24a	A-15133	580 ± 40	1390–1435	1310–1450	1340	Irregular chamber in cave
Llq1-2A1	A-15134	330 ± 40	1500–1650	1480–1670	1355	Sub-cylindrical tower in cave
Llq 3	A-15410	430 ± 40	1440–1620	1430–1630	1528	Sub-cylindrical tower in cave, Inca ceramics
Sm-ch3	A-15407	350 ± 35	1500–1640	1480–1650	1491	Prismatic burial tower, Inca *tumi*
UT0228	A-15405	345 ± 45	1500–1640	1460–1660	1488	Without archaeological association

Note: All calibrations were done with OxCal 4.1 (Bronk-Ramsey, 2010) using the Southern Hemisphere atmospheric curve (McCormac et al., 2004).

ring patterns are strongly correlated with the master regional chronology (Fig. 4b–d). The 10-year difference between the outer rings of Llq1-22 and Llq1-24 beams (Table 1) suggests that the roof of the structure was repaired through the addition of a new beam or that the woods were already dead at the time of construction. The lack of bark in sample Llq1-23 did not allow to establish a cutting date, but cross-dating reveals for the most external ring a date of AD 1338, only two years earlier than the cutting date established for Llq1-24a (AD 1340). Ring variations in the three samples are not only significantly correlated with the master chronology but also among them, allowing the development of a floating chronology for the chamber. The outer ring date of Llq1-24a (AD 1340) is consistent with the 2σ calibrated range provided by the radiocarbon date of this sample (AD 1310–1450; Table 2).

The two wooden hooks from *chullpa* 2 (Llq1-2A1 and Llq1-2A2), apparently used for storage, were used to develop a floating chronology for this tower. Given the morphological similarities between both samples and the highly significant correlation ($r = 0.60$) between ring width series, it is likely that they come from the same tree. This conclusion is further supported by the chronological proximity of the last ring in both samples dated to AD 1355 for Llq1-2A1 and AD 1350 for Llq1-2A2 with presence and absence of bark, respectively. The lack of bark in Llq1-2A2 could explain the 5-year difference between dates. Both samples show moderately good correlation with the reference master chronology (Table 1, Fig. 4e, f). The radiocarbon date from the Llq1-2A1sample (AD 1480–1670 Cal. 2σ), however, is more than a century younger than the dendrochronological estimate (Table 2, Fig. 3).

The piece of wood recovered at Llacta Qaqa 3 site (Llq3) has 101 rings and is the longest of our samples in the region. Ring variations in this sample are strongly related with the master regional chronology (Table 1, Fig. 4g). The presence of bark in Llq3 indicates a cutting date of AD 1528. The dendrochronological date for Llq3 is consistent with its calibrated radiocarbon age (AD 1430–1630 Cal. 2σ, Fig. 5). These results indicate that Llacta Qaqa 3 was built in the early 16th century, a date that is consistent with the presence of Inca period (AD 1450–1550) ceramics on the surface.

The cross-dating of the three samples collected at Sia Moqo provide ages within this period, a result that is also consistent with the presence of Inca ceramic styles (e.g., Inca Pacajes) on the surface and the high frequency of rectangular plans in both domestic and *chullpa* architecture (Nielsen, 2001). Since all samples were severely weathered and had no traces of bark, cutting dates could not be established (Table 1). The ages for the outermost rings in the samples from the prismatic sepulchers labeled *chullpa* 1 (Sm-ch1: AD 1473; Table 1) and *chullpa* 3 (Sm-ch3: AD 1491; Table 1) are separated by only 18 years, indicating that these sepulchers were built at approximately the same time. This inference is consistent with the form similarity, proximity, and spatial arrangement of both sepulchers. The beam recovered from *chullpa* 6, a tower showing morphological differences with Sm-ch1 and Sm-ch3, approximately 50 m away, yields a somewhat later but still pre-Hispanic date (AD 1521, Table 1).

The calibrated radiocarbon date for Sm-ch3 (AD 1480–1650 Cal. 2σ; Table 2) overlaps with the dendrochronologically estimated age (Fig. 3). Further support for these results comes from the AMS dates of the mandibles of the two individuals buried inside this sepulcher. The stratigraphically earlier individual was radiometrically dated at 478 ± 31 BP (AA-93723) or AD 1410–1610 (Cal. 2σ),

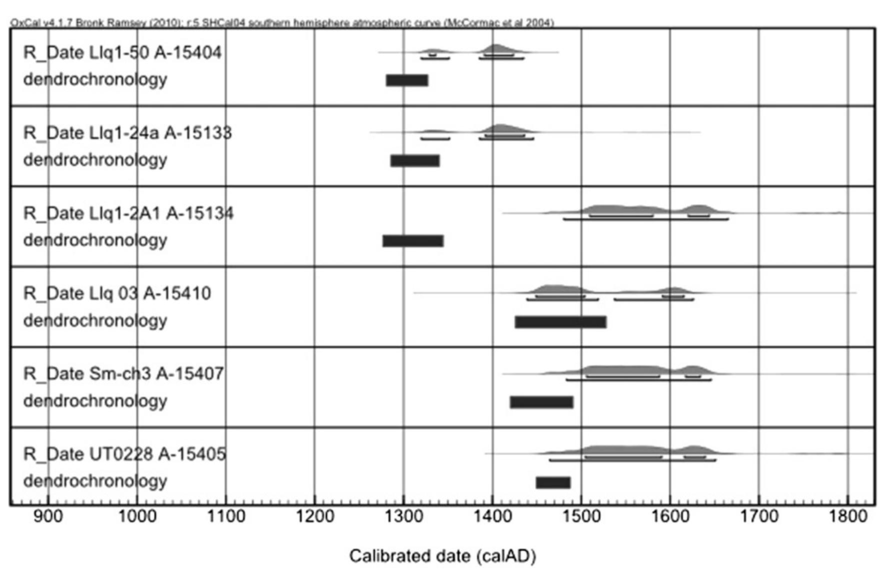

Fig. 5. Comparison of dendrochronological and calibrated radiocarbon dates of archaeological wood samples. Black bars show the calendar dates of the individual wood samples. All radiocarbon calibrations were done with OxCal 4.1 (Bronk-Ramsey, 2010) using the Southern Hemisphere atmospheric curve (McCormac et al., 2004).

whereas the individual found in the upper stratigraphic unit was dated to 346 ± 30 BP (AA-93726) or AD 1490–1650 (Cal. 2σ).

Finally, the control wood collected from the Uturunco Volcano (UT0228) shows 39 rings highly correlated with the master chronology and spanning the AD 1450–1488 interval (Table 1). This result corresponds well with the calibrated radiocarbon date from the outer rings of this sample (Fig. 3).

5. Discussion

Contrasting preservation conditions between *Polylepis* woods collected in caves and at open sites introduce differences in dating quality. Although woods from both contexts were dendrochronologically dated, none of the cross-dating from the Sia Moqo village provide cutting dates. In contrast, most samples from chambers in cave sites such as Llacta Qaqa 1 and 3 retain traces of bark, which provide precise cutting dates, or sapwood in good condition. In addition, the relatively strong clustering of outermost rings dates by contexts, indicate that dendrochronology can provide precise dates for the construction of individual structures and even entire archaeological sites. Since caves with *chullpa* architecture are relatively frequent in the southern Altiplano and the adjacent Rio Grande de San Juan valley, our results indicate that there is significant potential for conducting detailed dendrochronological studies at a regional scale.

Most of the wood samples from the three sites dated by dendrochronology and ^{14}C rendered consistent results. An exception was the sample Llq1-2A1. The dendrochronological age of this wood, however, corresponds closely with the ages of the other five cross-dated samples at the site. Since radiocarbon dates from two (Llq1-50 and Llq1-24a) of these five specimens are also consistent with their dendrochronological ages (Fig. 5, Table 2), we suspect that the radiocarbon date from Llq1-2A1 is misleading. The ^{14}C enrichment of this sample could be related, for example, to the use of this wooden hook to hang hides or meat for drying; in this way, organic substances could have impregnated the wood, affecting the results of the analysis. The AD 1528 cutting date at the nearby Llacta Qaqa 3 site and the presence of an Inca-period settlement (Llacta Kucho), only 500 m to the east (Nielsen and Berberián, 2008), provide evidence of the continuous occupation of the area until the 16th century or later. It is reasonable to think, therefore, that the *chullpas* of Llacta Qaqa 1 were used long after their construction. This apparent discrepancy in ages, which should be further investigated (e.g., through the analysis of residues present in the wood), highlights the importance of combining different dating techniques for understanding the construction, use, and formation processes of these features and sites.

Tree-ring dates are consistent with archaeological contexts based on ceramics, architecture, and background information. This is particularly fortunate in this case given the methodological focus of this study on testing the potential of *P. tarapacana* for accurately dating prehistoric events. As the number, variety, and statistical confidence of dendrochronologically dated contexts increases, it may be possible through this technique to answer some important chronological questions that have been raised in Andean archaeology during the last few decades, such as the construction period of defensive settlements (*pukaras*) or the expansion of the Incas.

Dendrochronological dating can also contribute to understanding the formation processes of archaeological structures and sites, as well as the temporality of various practices (Lucas, 2005). Our pilot study not only indicates that storage complexes were built during the Late Intermediate (Llq1) and Inca (Llq3) periods, but also suggests that some of them were built during relatively short episodes. For example, the six dates of Llacta Qaqa 1 span only over 27 calendar years (1328–1355), a result that approaches the time scale of a “construction project,” whereas the three ring dates for burial towers in Sia Moqo span 48 years (1473–1521), a longer temporal distribution that fits well with the notion of a gradually growing cemetery.

Combining different dating techniques may also contribute to resolving some of the issues of timing of these features. As it was mentioned before, the excavation of *chullpa* 3 from the Sia Moqo site exposed partial remains of two individuals deposited in stratigraphically different events. AMS dates obtained from their remains provided ages of 478 ± 31 AP (AA-93723; or AD 1425–1465, Cal. 1σ; 1410–1610, Cal. 2σ), and 346 ± 30 AP (AA-93726; or 1500–1640, Cal. 1σ; 1490–1650, Cal. 2σ), respectively. Although the latest ring in the beam supporting the stone roof of the sepulcher (AD 1491) was not a cutting date, it is likely that the stratigraphically lower burial event was contemporaneous with the construction of the structure, whereas the second internment happened later, but not after AD 1650. Indeed, the three events may have taken place during the Inca Period (AD 1450–1550).

6. Conclusions

There are few millennia-long, tree-ring proxy indicators of past climate in South America (Boninsegna et al., 2009); one of them is ring width series of *P. tarapacana*, a species that grows in the Bolivian Altiplano (Morales et al., 2012). A chronology covering the last 786 years in this part of the Andes was developed on the basis of climatically sensitive tree-ring records from *Polylepis* trees several centuries old in combination with well-preserved wood remains. The lack of alternative sources of wood in the highlands – except for *Trichocereus* cacti in the lowest areas of the Altiplano – resulted in the frequent use of *Polylepis* as construction material by highland populations since pre-Columbian times. The low rate of wood decay in this arid environment facilitates the preservation of wood in numerous archaeological sites that can be dendrochronologically dated using recently developed reference chronologies.

In this study, we assessed the potential of dendrochronology to date wood samples collected from *chullpas* at three archaeological sites (two caves and a village) in the Lípez region, Potosí, Bolivia. Calendar years were assigned to 10 samples, five of them being cutting-dates. Six of these specimens were also dated using the ^{14}C technique, providing in most cases good overlaps between the calibrated radiocarbon and the dendrochronological ages. In addition, all tree-ring dates are consistent with the archaeological knowledge about the chronological contexts in which woods were collected and the general cultural processes they represent.

These results – the first dendroarchaeological dates for South America – demonstrate that *P. tarapacana* can provide annually resolved tree-ring dates for archaeological contexts in the Altiplano since the 13th century. This technique opens new possibilities for Andean archaeology that should be intensively explored. Dendroarchaeological dates cannot only contribute to place significant events of the Late Prehistoric Period accurately in time (e.g., the onset of *chullpa* construction, the shift toward defensive settlement systems, or the expansion of the Incas), but also contribute to insights into the pace and timing of some archaeological processes. In addition, since *P. tarapacana* is a climate-sensitive species, these chronologies provide detailed information on precipitation and temperature changes in the Altiplano (Morales et al., 2012), thus contributing to understand the role of climate in shaping local society.

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References

Aldunate, C., Castro, V., 1981. Las chullpas de Toconce y su relación con el poblamiento altiplánico en el Loa Superior Tardío. Kultrún, Santiago.
Angiorama, C.I., 1998. Nuevos aportes a la cronología de Condorhuasi-Alamito. Palimpsesto 5, 100–105.
Argollo, J., Soliz, C., Villalba, R., 2004. Potencialidad dendrocronológica de Polylepis tarapacana en los Andes Centrales de Bolivia. Ecología en Bolivia 39, 5–24.
Baillie, M.G.L., 1995. A Slice Through Time: Dendrochronology and Precision Dating. B.T. Batsford, London.
Bárcena, J.R., 1998. Arqueología de Mendoza: Las Dataciones Absolutas y Sus Alcances. Universidad Nacional de Cuyo, Mendoza.
Berenguer, J., 2004. Caravanas, interacción y cambio en el Desierto de Atacama. Sirawi, Santiago.
Bertonio, L., 1984. [1612]. Vocabulario de la Lengua Aymara. CERES, Cochabamba.
Boninsegna, J.A., Holmes, R.L., 1985. Fitzroya cupressoides yields 1534-year long South American chronology. Tree-ring Bull. 45, 37–42.
Boninsegna, J.A., Argollo, J., Aravena, J.C., Barichivich, J., Christie, D.A., Ferrero, M.E., Lara, A., Le Quesne, C., Luckman, B.H., Masiokas, M., Morales, M.S., Oliveira, J.M., Roig, F., Srur, A., Villalba, R., 2009. Dendroclimatological reconstructions in South America: a review. Palaeogeogr., Palaeocl., Palaeoecol. 281, 210–228.
Boninsegna, J., 1988. Santiago de Chile winter rainfall since 1220 as being reconstructed by tree rings. Quat. S. Am. Antarct. Penins. 7, 315–326.
Briffa, K.R., 1995. Interpreting high-resolution proxy climate data—the example of dendroclimatology. In: von Storch, H., Navarra, A. (Eds.), Analysis of Climate Variability. Applications of Statistical Techniques. Springer Verlag, Berlin, pp. 77–94.
Bronk-Ramsey, C., 2010. Bayesian analysis of radiocarbon dates. Radiocarbon 51, 337–360.
Castro, V., Berenguer, J., Aldunate, C., Roman, A., Deza, A., Brito, O., Concha, G., 1979. Primeros fechados arqueológicos por termoluminiscencia en Chile: Toconce. Noticiario del Museo Nacional de Historia Natural XXIII, 270.
Castro, V., Aldunate, C., Berenguer, J., 1984. Orígenes altiplánicos de la fase Toconce. Estudios Atacameños 7, 209–235.
Christie, D.A., Lara, A., Barichivich, J., Villalba, R., Morales, M.S., Cuq, E., 2009. El Niño-Southern Oscillation signal in the world's highest-elevation tree-ring chronologies from the Altiplano, Central Andes. Palaeogeogr., Palaeocl., Palaeoecol. 281, 309–319.
Christie, D.A., Boninsegna, J.A., Cleaveland, M.K., Lara, A., Le Quesne, C., Morales, M.S., Mudelsee, M., Stahle, D.W., Villalba, R., 2011. Aridity changes in the Temperate-Mediterranean transition of the Andes since AD 1346 reconstructed from tree-rings. Clim. Dyn. 36, 1505–1521.
Cieza de León, P., 1996. [1553]. Crónica del Perú. Academia Nacional de la Historia, Lima.
Cook, E.R., Briffa, K., Shiyatov, S., Mazepa, V., Jones, P.D., 1990. Data analysis. In: Cook, E.R., Kairiukstis, L.A. (Eds.), Methods of Dendrochronology: Applications in the Environmental Sciences. Kluwer/IIASA, Dordrecht, pp. 97–162.
Cook, E.R., 1985. A Time Series Analysis Approach to Tree-ring Standardization. Ph.D. dissertation, University of Arizona, Tucson.
Duviols, P., 1979. Un symbolisme de l'occupation, de l'amenagement et de l'exploitation de l'espace: Le monolithe 'huanca' et sa fonction dans les Andes préhispaniques. L'Homme 19, 7–31.
Fritts, H.C., 1976. Tree Rings and Climate. Academic Press, London.
Gonzalez, A.R., 1979. Pre-Columbian metallurgy of northwest Argentina: historical development and cultural process. In: Benson, E. (Ed.), Precolumbian Metallurgy of South America. Dumbarton Oaks, Washington, D.C., pp. 133–202.
Holmes, R.L., 1983. Computer-assisted quality control in tree-ring dating and measurements. Tree Ring Bull. 43, 69–75.
Hyslop, J., 1977. Chulpas of the Lupaca zone of the Peruvian high plateau. J. Field Archaeol. 4, 149–170.
Isbell, W.H., 1997. Mummies and Mortuary Monuments: a Postprocessual Prehistory of Central Andean Social Organization. University of Texas Press, Austin.
Kaulicke, P., 2001. Memoria y Muerte en el Perú Antiguo. Pontificia Universidad Católica del Perú, Lima.
Kesseli, R., Pärssinen, M., 2005. Identidad étnica y muerte: torres funerarias (*chullpas*) como símbolos de poder étnico en el altiplano boliviano de Pakasa (1250–1600 d.C.). Bull. de l'Institut Français d'Études Andines 34, 379–410.
Kessler, M., Schmidt-lebuhn, A.N., 2006. Taxonomical and distributional notes on Polylepis (Rosaceae). Org. Divers. Evol. 6, 1–10.
Kessler, M., 1995. The genus Polylepis (Rosaceae) in Bolivia. Candollea 50, 131–171.
LaMarche, V.C., Holmes, R.L., Dunwiddie, P.W., Drew, L.G., 1979. Tree Ring Chronologies of the Southern Hemisphere: 1. Argentina. University of Arizona, Tucson.
Lara, A., Villalba, R., 1993. A 3620 year temperature record from Fitzroya cupressoides tree rings in Southern South America. Science 260, 1104–1106.
Le Quesne, C., Stahle, D.W., Cleaveland, M.K., Therrell, M.D., Aravena, J.C., Barichivich, J., 2006. Ancient Austrocedrus tree-ring chronologies used to reconstruct central Chile precipitation variability from A.D. 1200 to 2000. J. Clim. 19, 5731–5744.
Le Quesne, C., Acuña, C., Boninsegna, J.A., Rivera, A., Barichivich, J., 2009. Long-term glacier variations in the Central Andes of Argentina and Chile, inferred from historical records and tree-ring reconstructed precipitation. Palaeogeogr., Palaeocl., Palaeoecol. 281, 334–344.
Lucas, G., 2005. The Archaeology of Time. Routledge, London.
Martínez, J.L., 1995. Papeles distantes, palabras quebradas. Las informaciones sobre Lípez en el siglo XVI. In: Presta, A.M. (Ed.), Espacio, Etnías y Frontera. ASUR, Sucre, pp. 285–317.
McCormac, F.G., Hogg, A.G., Blackwell, P.G., Buck, C.E., Higham, T.F.G., Reimer, P.J., 2004. SHCal04 Southern Hemisphere calibration, 0–11.0 cal kyr BP. Radiocarbon 46, 1087–1092.
Morales, M.S., Boninsegna, J.A., 2000. ENSO signal in a new long tree-line chronology from *Austrocedrus chilensis* at Huingango, Neuquén, Argentina. In: International Conference of Dendrochronology for the Third Millenium. Mendoza, Argentina.
Morales, M.S., Villalba, R., Grau, H.R., Paolini, L., 2004. Rainfall-controlled tree growth in high elevation subtropical treelines. Ecology 85, 3080–3089.
Morales, M.S., Christie, D.A., Villalba, R., Argollo, J., Pacajes, J., Silva, J.S., Alvarez, C.A., Llancabure, J.C., Soliz Gamboa, C.C., 2012. Precipitation changes in the South American Altiplano since 1300 AD reconstructed by tree-rings. Clim. Past 8, 653–666.
Mundo, I.A., Masiokas, M.H., Villalba, R., Morales, M.S., Neukom, R., Le Quesne, C., Urrutia, R.B., Lara, A., 2012. Multi-century tree-ring based reconstruction of the Neuquén River streamflow, northern Patagonia, Argentina. Clim. Past 8, 815–829.
Nash, S.E., 2002. Archaeological tree-ring dating at the millennium. J. Archaeol. Sci. 10, 243–275.
Nielsen, A.E., Berberián, E.E., 2008. El señorío Mallku revisitado. Aportes al conocimiento de la historia prehispánica tardía de Lípez (Potosí, Bolivia). In: Rivera Casanovas, C. (Ed.), Arqueología de las tierras altas, valles interandinos y tierras bajas de Bolivia: Memorias del I Primer Congreso de Arqueología de Bolivia. Universidad Mayor de San Andrés, La Paz, pp. 145–166.
Nielsen, A.E., 2001. Evolución del espacio doméstico en el Norte de Lípez (Potosí, Bolivia): ca. 900–1700 d.C. Estudios Atacameños 21, 41–61.
Nielsen, A.E., 2006. Plazas para los antepasados: descentralización y poder corporativo en las formaciones políticas preincaicas de los Andes circumpuneños. Estudios Atacameños 31, 63–89.
Nielsen, A.E., 2008. The materiality of ancestors: chullpas and social memory in the late prehispanic history of the South Andes. In: Mills, B., Walker, W. (Eds.), Memory Work: Archaeologies of Material Practices. School of American Research Press, Santa Fe, pp. 207–232.
Robinson, E.J., Evans, R., 1980. A microcomputer-based tree-ring measuring system. Tree Ring Bull. 40, 59–64.
Schmidt-Lebuhn, A.N., Kumar, M., Kessler, M., 2006. An assessment of the genetic population structure of two species of Polylepis Ruiz & Pav. (Rosaceae) in the Chilean Andes. Flora 201, 317–325.
Schulman, E., 1956. Dendroclimatic Changes in Semiarid America. University of Arizona Press, Tucson.
Sillar, B., 1996. The dead and the drying. J. Mater. Culture 1, 259–289.
Solíz, C., Villalba, R., Argollo, J., Morales, M.S., Christie, D.A., Moya, J., Pacajes, J., 2009. Spatio-temporal variations in Polylepis tarapacana radial growth across the Bolivian Altiplano during the 20th century. Palaeogeogr., Palaeocl., Palaeoecol. 281, 296–308.
Stokes, M.A., Smiley, T.L., 1968. An Introduction to Tree-ring Dating. University of Chicago Press, Chicago.
Villalba, R., Veblen, T.T., 1997. Regional patterns of tree population age structures in northern Patagonia: climatic and disturbance influences. J. Ecol. 85, 113–124.
Wigley, T.M.L., Briffa, K.R., Jones, P.D., 1984. On the average value of correlated time series, with applications in dendroclimatology and hydrometeorology. J. Clim. Appl. Meterol. 23, 201–213.