Dental Health in Northern Chile's Atacama Oases: Evaluating the Middle Horizon (AD 500–1000) Impact on Local Diet

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ABSTRACT As one of the few areas apt for horticulture in Northern Chile's arid landscape, the prehistory of the Atacama oases is deeply enmeshed with that of the inter-regional networks that promoted societal development in the south central Andes. During the Middle Horizon (AD 500–1000), local populations experienced a cultural apex associated with a substantial increase in inter-regional interaction, population density, and quantity and quality of mortuary assemblages. Here, we test if this cultural peak affected dietary practices equally among the distinct local groups of this period. We examine caries prevalence and the degree of occlusal wear in four series recovered from three cemeteries. Our results show a reduction in the prevalence of caries for males among an elite subsample from Solcor 3 and the later Coyo 3 cemeteries. Dental wear tends to increase over time with the Late Middle Horizon/Late Intermediate Period cemetery of Quitor 6 showing a higher average degree of wear. When considered in concert with archaeological information, we concluded that the Middle Horizon was marked by dietary variability wherein some populations were able to obtain better access to protein sources (e.g., camelid meat). Not all members of Atacameño society benefited from this, as we note that this dietary change only affected men. Our results suggest that the benefits brought to the San Pedro oases during the Middle Horizon were not equally distributed among local groups and that social status, relationship to the Tiwanaku polity, and interment in particular cemeteries affected dietary composition. Am J Phys Anthropol 148:62–72, 2012. ©2012 Wiley Periodicals, Inc.

The development of societies in the prehistoric South-Central Andes was dependent on inter-regional connections and exchange networks that grew together with agricultural practices (Janusek, 2007; Núñez, 2007). However, these numerous and long-standing interconnections varied over time, and as a consequence, the prehistory of the region is marked by oscillating periods of greater and lesser long distance integration, loosely associated with the rise and fall of complex societies such as the Tiwanaku and the Inca Empire (Isbell and Silverman, 2002). The nature of these centralizing forces varied not only temporally but also geographically (Kolata, 1993; Stovel, 2005; Janusek, 2007; Núñez, 2007). As a result of their strategic location on routes connecting northwest Argentina, southern Bolivia, and northern Chile, the San Pedro de Atacama oases, located in northern Chile's Atacama Desert (Fig. 1), present an interesting case study of the cultural and lifestyle changes associated with Tiwanaku influence during the Middle Horizon.

Traditionally, the Middle Horizon (AD 500–1000) is linked with a cultural apex in the Atacameño oases seen through substantial increases in inter-regional interaction, population density, and the quantity and quality of grave goods (Llagostera, 1996; Núñez, 2007). This period is characterized by the inclusion of the oases into a regional network centered on the Tiwanaku polity, suggesting the growing prominence and influence of this foreign culture on the oases (Bravo and Llagostera, 1986; Berenguer and Dauelsberg, 1989; Llagostera and Costa, 1999; Núñez, 2007; Hubbe et al., in press). Certain scholars have suggested that this apogee was not restricted to cultural features, but resulted in a general improvement in quality of life, especially overall nutritional status (Neves and Costa, 1998; Costa et al., 2004).

Tiwanaku influence, however, was not equally distributed among the inhabitants of the Atacama oases both in space and time, something suggested by differences seen in the quality and diversity of mortuary goods in the excavated cemeteries. Recently, one of us (Torres-Rouff, 2011)

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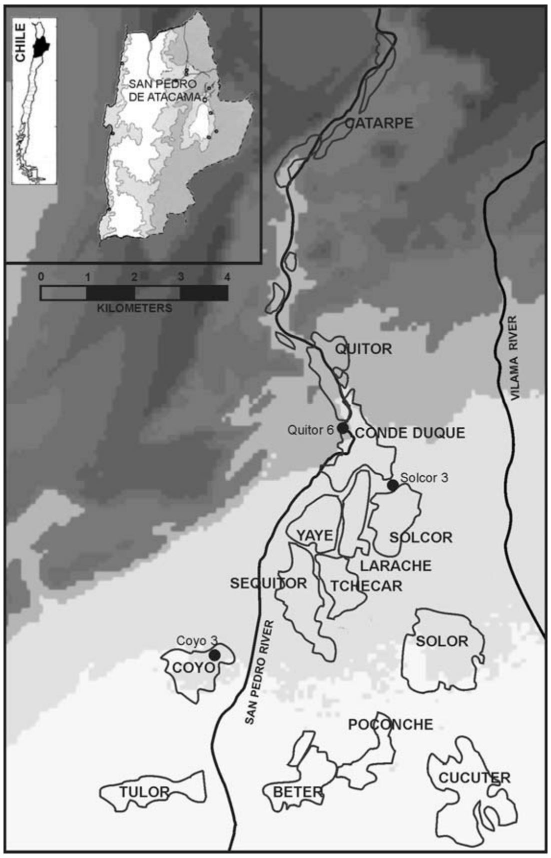

Fig. 1. Location of the San Pedro de Atacama oases and the cemeteries included in this study.

suggested that social differences played an important role in the prosperity of groups from this period, resulting in significant differences in the prevalence of cranial trauma among high- and low-status cemeteries. Here, we further explore the local inequalities associated with the Middle Horizon by investigating the dietary composition of individuals buried in cemeteries with differing relationships with the powerful foreign polity.

Our approach rests on the assumption that social inequalities are reflected both in the richness of cultural paraphernalia as well as in aspects of an individual's quality of life (Hillson, 1996; Dansforth, 1999; Kellner and Schoeninger, 2007, 2008). Here, our goal is to analyze the prevalence of macroscopic markers commonly associated with dietary composition and food preparation (caries, antemortem tooth loss (AMTL), and occlusal wear; Hillson, 1996; Larsen, 1999) and test the hypotheses that 1) there existed an important heterogeneity in the composition of local diet during the Middle Horizon; and 2) that a closer association with the Tiwanaku polity was associated with better access to valued food items.

THE MIDDLE HORIZON IN THE ATACAMA OASES

The modern town of San Pedro de Atacama (Fig. 1) comprises a series of small oases at the northern tip of the Salar de Atacama, at an altitude of nearly 2500 masl. Despite the extreme aridity (Errázuriz et al., 1987; Niemeyer, 1989), the drainage of the San Pedro and Vilama Rivers into the Salar near the oases provides beneficial conditions for agriculture (Llagostera and Costa, 1999; Núñez, 2007).

The beginning of the Middle Horizon in the Atacama oases (~ AD 500) is associated with the appearance of altiplano or altiplano-inspired grave goods in local cemeteries (Tarragó, 1968, 1976; Serracino, 1980; Browman, 1980a; Berenguer et al., 1988; Llagostera et al., 1988; Núñez, 2007). During the Middle Horizon, grave wealth is more abundant and of a higher quality than that seen in previous or subsequent periods, with the presence of gold objects and decorated ceramic fineware, in addition to elaborate textiles and wooden snuff trays intricately carved with Tiwanaku iconography (Torres, 1987, 1992; Berenguer and Dauelsberg, 1989). Foreign grave goods are found throughout Middle Horizon cemeteries, even though access to these resources appears to have been mainly restricted to the elite (Rivera, 2008; Torres-Rouff, 2011). Material culture related to ritual shows tremendous development during the Middle Horizon and also suggests some ideological syncretism between Tiwanaku and the population in San Pedro (Llagostera et al., 1988). This general increase in wealth is associated with a significant increase in the exchange area of the Atacameño oases, which likely played a strategic role for the camelid caravans that linked Tiwanaku's heartland with its far periphery (Oakland, 1992; Kolata, 1993; Llagostera, 1996).

The expansion of interaction networks during the Middle Horizon was not restricted to contact with Tiwanaku. During this period, there is evidence of increasing exchange with other regions, as objects are found in San Pedro that originate in the Bolivian lowlands, the Pacific coast, and northwestern Argentina (Bravo and Llagostera, 1986; Berenguer and Dauelsberg, 1989; Torres and Conklin, 1995; Berenguer, 2000; Uribe, 2002; Stovel, 2005; Rivera, 2008). It has been argued that exchange was not limited to material culture and may also have included the migration of individuals into the Atacameño oases. Varela and Cocilovo (2000, 2009) describe an increase in biological diversity (reflected in craniometric data) supporting the possibility that either people were migrating into the oases during the Middle Horizon, or that there was a significant demographic increase at this time.

Archaeologists have long debated the nature of Tiwanaku's relationship with San Pedro (Browman, 1980b; Berenguer and Dauelsberg, 1989; Oakland, 1992; Kolata, 1993; Torres and Conklin, 1995; Torres-Rouff, 2002). Recent research has indicated that the oases were within Tiwanaku's sphere of influence and that this relationship was peaceful in nature (e.g., Goldstein, 2005). There is no indication of investment in military activities during the period (Berenguer et al., 1980; Núñez, 2007), or of an increase in interpersonal violence during these phases (Torres-Rouff and Costa, 2006). Nevertheless, Tiwanaku influence in the oases had other impacts on Atacameño life. Neves and Costa (1998) demonstrated a significant increase in adult stature at the time, suggestive of improving nutritional status. However, when they calculated the prevalence of postcranial trauma (associated with high risk activities), there was no improvement in the Middle Horizon sample (Costa et al., 1999). Similarly, they found no significant differences in their analysis of nutritional indicators in the form of prevalence of linear enamel hypoplasia and porotic hyperostosis between periods (Neves and Costa, 1999). Finally, Da-Gloria et al. (2011) have shown an increase in

TABLE 1. Skeletal samples included in the study

Site	Males	Females	Total N	Chronology (2σ ^{14}C Cal AD)[a]	Source
Nonelite Solcor 3	13	11	24	465–769 673–867[b] 781–981[c]	Llagostera et al., 1988:64
Elite Solcor 3	13	15	28	433–774 607–865 689–986 775–1024 909–1176	Llagostera et al., 1988:65
Coyo 3	20	13	33	897–1202 855–1216 1016–1207	Costa and Llagostera, 1994:75
Quitor 6	10	14	24	899–1211 889–1485 1228–1487	Costa, 1988:105
Total	56	53	109		

[a] Dates were calibrated from the reported measured radiocarbon age using the southern hemisphere calibration curve (SHCal04) in Calib 6 (Stuiver et al., 1993).
[b] Date generated for this study (BETA-305869).
[c] Date generated for this study (BETA-305870).

nonspecific infections during the peak of Tiwanaku influence in San Pedro de Atacama.

The Middle Horizon ended around AD 1000, a time that is marked by the collapse of Tiwanaku as a complex polity, possibly due to a combination of internal strife and a period of intense drought in the South-Central Andes (Binford et al., 1997; Berenguer, 2000; Janusek, 2007). The dismantling of Tiwanaku's extensive trade network brought an end to their economic and ideological influence in Northern Chile.

Despite the general view that the local populations were prosperous during the Middle Horizon, recent studies have focused on the burgeoning social inequalities that characterized the Atacama oases in this period. Analysis of individuals and goods recovered from the numerous excavated Middle Horizon cemeteries shows considerable diversity in the quality and quantity of grave goods, suggesting important social differences between groups living in the oases and in their relationship with the Tiwanaku polity. Torres-Rouff (2008, 2011) has shown that social differences are reflected in the distribution of material wealth and foreign goods as well as in patterns of violence between individuals recovered from differing Middle Horizon cemeteries. She argued that people did not share equally in the benefits of this period's affluence, and that there were tensions in Atacameño society despite seemingly widespread prosperity. This study aims to further explore the social inequalities of this period, assessing general differences in dietary composition in the Atacama oases during the Middle Horizon.

MATERIALS

We examined adult skeletal samples from three cemeteries from the Atacameño oases, which were occupied during the Middle Horizon and the beginnings of the subsequent Late Intermediate Period: Solcor 3, Coyo 3, and Quitor 6 (Table 1). The Middle Horizon occupation of these cemeteries is attested to by radiocarbon dates (Table 1), typological classification of ceramic pots (Berenguer et al., 1988) and the presence of Tiwanaku-related objects among the grave goods. All three cemeteries were excavated during the 1980s and 1990s by a team of archaeologists from the Instituto de Investigaciones Arqueológicas y Museo Le Paige in San Pedro de Atacama, where the remains are currently curated. Individuals were interred in cylindrical pits with their bodies wrapped in textiles. Most burials were individual inhumations although a few communal graves were distributed throughout the cemeteries. These patterns hold for all the cemeteries discussed here.

The Solcor 3 cemetery is located in the core of the oases. This cemetery seems to represent one of the burial places for an elite population (Bravo and Llagostera, 1986; Torres-Rouff, 2008, 2011). Solcor 3 was in use during the period of Tiwanaku influence (Table 1) in the oases and a portion of the individuals was buried with goods bearing Tiwanaku iconography. Although between 15 and 20% of the population had Tiwanaku goods, these individuals tend to have only one object from the altiplano polity among a mortuary assemblage that also includes occasional grave goods from other foreign areas (predominantly northwest Argentina) and a larger suite of local material. Regardless, Tiwanaku is the dominant foreign presence in this cemetery. Excavation of Solcor 3 yielded the remains of nearly 150 individuals and 52 adults with well-preserved dentition are analyzed here.

In this study, the Solcor 3 sample was considered as comprising two series—elite and nonelite—according to individual burial offerings. These categories are based on the work of the excavating archaeologists, Bravo and Llagostera (1986). They performed a detailed analysis of cemetery organization, ceramic seriation, and the mortuary contexts and argue for the existence of at least two groups that were interred at the cemetery. The portion we denominate the elite Solcor 3 series includes individuals buried with Tiwanaku objects as well as particular burnished black ceramic styles. Nonelite Solcor 3 comprises individuals with evident lack of Tiwanaku or other foreign objects in their burials and more rough-hewn pottery. Individuals that presented unclear association to Tiwanaku objects, even when associated with other foreign objects were not included in this study as we used an established grouping. Bravo and Llagostera conclude (1986:331) by noting the closer tie of their Group B, our elite series, to the altiplano polity. Previously, the presence of Tiwanaku goods in only a portion of the graves had been assumed to be evidence of the use of the cemetery before the arrival of Tiwanaku influence in the area (Bravo and Llagostera, 1986; Neves and Costa, 1998; Costa et al., 2004). However, new dates generated for this study in concert with a recalibration of extant dates with the southern hemisphere curve (SHCAL04; Stuiver et al., 1993) (Table 1), suggest otherwise. These dates have also shown a preponderance of individuals interred in the oases during this time who have no evidence of interaction with the altiplano polity. The elite sample considered in this study comprises 28 adult individuals and the nonelite 24 adult individuals (Table 1).

The two remaining cemeteries are considerably smaller and were occupied during the end of the Middle Horizon and the initial Late Intermediate Period (AD 1000–1450; Table 1). The excavation of Coyo 3 revealed 51 tombs with 80 individuals. The later date of this cemetery is reflected in the tomb contents, which are of diminished quality and quantity although they still show some influence from the Tiwanaku polity (Costa and Llagostera, 1994). Thirty-three adult individuals from Coyo 3 are considered here. Finally, Quitor 6 represents the excavation of a later portion of the Quitor 6 cemetery (the northern sector), one that also displayed considerable wealth during the peak of the Middle Horizon (Costa, 1988). The 42 tombs excavated from this portion of the cemetery belong largely to the Late Intermediate Period, show scarce to nonexistent mortuary goods and no evidence of interaction with Tiwanaku. In this analysis, we included 24 adult individuals from Quitor 6. In sum, 109 individuals from the three cemeteries are included in this analysis.

METHODS

To help control for the effect of age in the samples (see below), we only analyzed individuals whose dentition was relatively complete. Consequently, we included only adult individuals who had at least 25% (eight teeth) of the dentition preserved, resulting in a total sample of 109 individuals (Table 1). Sex and age at death determinations were made by two of the authors (W.A.N. and M.A.C.) through the analysis of traditional osteological markers of sex in the pelvis and skull (Buikstra and Ubelaker, 1994). Age at death was considered in ranges of $\sim$ 5 years in an attempt to obtain a more accurate view of the age distribution in each skeletal sample and to elucidate age-dependent elements of our analysis, such as patterns of dental attrition. These age distributions were used in the correlation with age and regression analyses presented below.

In an effort to reconstruct broad patterns of dietary behavior between individuals with access to Tiwanaku goods as well as between cemeteries, we analyzed the prevalence of caries and the degree of dental wear. To correct for the effects of AMTL on dental pathology, we used the Lukacs (1992, 1996) correction factor discussed below.

Caries

Although several factors influence the prevalence of dental caries, they are most frequently used as an indicator of the amount of carbohydrates ingested by a population (Hillson, 1979, 1996; Turner, 1979; Newbrun, 1982; Larsen, 1987, 1999; Alt et al., 1999). A diet low in animal protein but high in carbohydrates enhances the onset of cariogenic activity and vice versa. In this study, caries were analyzed by visual inspection with the help of a dental probe and were positively scored when the demineralization process reached the dentine. Prevalence of caries was calculated as the number of decayed teeth divided by the total number of teeth observed (Turner, 1979). The caries index was calculated for the total dentition as well as for the anterior (IC, IL, and C) and posterior (P3–M3) dentitions separately due to differential risks for dental caries (Hillson, 1996; Larsen, 1999).

Although widely used, this caries index often underestimates the prevalence of caries, because it does not take into account the percentage of tooth loss as a consequence of severe carious infections. As proposed by Lukacs (1992, 1996), one way to correct for this underestimation of caries prevalence is to consider the number of teeth lost antemortem, a process that may have resulted from pulp exposure due to severe carious lesions. The correction factor is calculated as the number of teeth presenting pulp exposure resulting from caries divided by the total number of teeth presenting pulp exposure. This frequency is subsequently multiplied by the observed number of teeth lost antemortem and added to the number of carious teeth observed in the sample. The corrected caries frequency is obtained by dividing the corrected number of carious teeth by the total number of observed teeth plus the total number of teeth lost antemortem (Lukacs, 1992, 1996; Duyar and Erdal, 2003). Although this correction factor rests on the somewhat simplistic assumptions that pulp exposure is the primary cause of AMTL, and that it only results from severe carious lesions or heavy dental wear, it does present a better estimation of real caries prevalence, especially in cases such as this where AMTL is frequent (Lukacs, 1992, 1996).

Consequently, we analyzed prevalence of AMTL in each sample. AMTL was defined as teeth lost during an individual's life, usually resulting from inflammatory reactions in the alveoli due to pulp exposure (Lukacs, 1992; Hillson, 1996). AMTL was scored each time a tooth socket was empty and presented signs of alveolar reabsorption. In the absence of these signs, we scored the missing tooth as a postmortem loss. AMTL was used in this study only to correct the caries factor and was not analyzed as an independent variable. The percentage of AMTL due to caries exposure at each cemetery was used to correct the caries prevalence for each site's sample. Independent caries correction factors for each sex were not calculated because the small sample size for some of the subsamples would yield unreliable results. Consequently, female and male corrections were performed using the total rate of pulp exposure due to caries. However, differences in the estimated percentage of AMTL due to caries exposure between samples was minimal, and accordingly, sex differences, if present, would likely have been very small. Lukacs' correction was not performed independently for the anterior and posterior dentition, as the corrections did not change the pattern of caries prevalence between series (see results).

Caries, although cumulative over the course of an individual's life and usually correlated with age, surprisingly did not show significant correlations with age in our sample (Spearman's $r = 0.007$; $P > 0.05$), likely because of the high rate of AMTL (Table 2). The lack of an age correlation allows us to compare the prevalence of caries in each sample without having to correct for age differ-

TABLE 2. Prevalence of caries, antemortem tooth loss, and rates of dental wear in each of the series

	Nonelite Solcor 3			Elite Solcor 3			Coyo 3			Quitor 6		
Incidence	Total	Male	Female	Total	Male	Female	Total	Male	Female	Total	Male	Female
Caries	44.69% (143/320)	43.75% (98/224)	46.88% (45/96)	32.37% (168/519)	22.74% (68/229)	45.45% (100/220)	31.24% (189/605)	24.42% (94/385)	43.18% (95/220)	52.33% (269/514)	47.93% (104/217)	55.56% (165/297)
Caries corrected	65.34% (369/565)	62.75% (231/368)	70.17% (138/197)	52.05% (381/732)	37.57% (139/370)	66.85% (242/362)	50.93% (483/949)	44.62% (257/575)	60.63% (227/374)	63.44% (429/677)	61.41% (182/296)	65.02% (248/381)
Caries anterior dentition	33.80% (48/142)	34.04% (32/94)	33.33% (16/48)	20.20% (40/198)	8.04% (9/112)	36.05% (31/86)	22.06% (62/281)	13.22% (23/174)	36.45% (39/107)	34.96% (79/226)	21.17% (25/92)	40.30% (54/134)
Caries posterior dentition	53.37% (95/178)	50.77% (66/130)	60.42% (29/48)	39.88% (128/321)	31.55% (59/187)	51.49% (69/134)	39.20% (127/324)	33.65% (71/211)	49.56% (56/113)	65.97% (190/288)	63.2% (79/125)	68.10% (111/163)
AMTL	39.01% (245/628)	35.82% (144/402)	44.69% (101/226)	25.39% (213/839)	17.19% (71/413)	33.33% (142/426)	34.19% (344/1,006)	30.89% (190/615)	39.39% (154/391)	21.22% (163/768)	24.69% (79/320)	18.75% (84/448)
Average wear (corrected residuals)	3.73 (3.71)	3.79 (3.64)	3.58 (3.80)	3.02 (3.51)	3.05 (3.47)	2.98 (3.56)	4.09 (3.70)	4.27 (3.72)	3.76 (3.65)	3.34 (3.39)	3.86 (3.42)	3.86 (3.37)
IC	5.87 (5.22)	5.73 (5.07)	6.07 (5.44)	3.88 (4.79)	3.75 (4.65)	4.02 (4.94)	5.64 (5.13)	5.84 (5.20)	5.32 (5.01)	4.30 (4.5)	4.91 (4.64)	4.91 (4.53)
IL	5.04 (4.80)	4.86 (4.67)	5.31 (4.99)	3.58 (4.49)	3.69 (4.44)	3.45 (4.56)	5.52 (4.79)	5.72 (4.85)	5.20 (4.69)	4.03 (4.34)	4.70 (4.38)	4.70 (4.30)
C	4.96 (4.58)	5.07 (4.50)	4.83 (4.67)	3.58 (4.30)	3.58 (4.24)	3.58 (4.34)	4.95 (4.54)	5.29 (4.60)	4.43 (4.44)	3.97 (4.07)	4.43 (4.12)	4.43 (4.03)
PM1	4.14 (3.93)	4.65 (3.89)	3.50 (3.98)	3.11 (3.80)	3.05 (3.75)	3.17 (3.85)	4.39 (3.98)	4.64 (4.03)	4.01 (3.90)	3.57 (3.66)	4.10 (3.70)	4.10 (3.63)
PM2	3.07 (3.19)	3.18 (3.15)	2.95 (3.23)	2.70 (3.06)	2.72 (3.03)	2.67 (3.09)	3.67 (3.18)	3.39 (3.19)	4.17 (3.15)	2.88 (2.95)	3.42 (2.96)	3.42 (2.94)
M1	3.00 (3.17)	2.85 (3.13)	3.21 (3.24)	2.82 (3.01)	2.91 (2.99)	2.72 (3.03)	3.46 (3.19)	3.60 (3.17)	2.66 (3.25)	3.00 (2.92)	3.92 (2.93)	3.92 (2.92)
M2	1.97 (2.54)	2.07 (2.54)	1.50 (2.51)	2.41 (2.51)	2.56 (2.51)	2.23 (2.51)	2.63 (2.55)	2.91 (2.55)	2.20 (2.56)	2.83 (2.48)	3.22 (2.49)	3.22 (2.48)
M3	1.76 (2.22)	1.89 (2.20)	1.33 (2.29)	2.09 (2.14)	2.15 (2.13)	2.04 (2.16)	2.47 (2.21)	2.74 (2.21)	2.06 (2.22)	2.14 (2.11)	2.20 (2.11)	2.20 (2.10)

ences. The prevalence of caries in males, females, and in the total sample was analyzed through pairwise χ^2 comparisons. As multiple comparisons between all possible pairs of frequencies affect the efficacy of statistical analyses, the alpha value adopted here was adjusted using Bonferroni's Correction (Sokal and Rohlf, 1995), so that only P values lower than 0.0083 (0.05 divided by six pairwise comparisons) were considered significant. Within each sample, the prevalence between males and females was also contrasted using χ^2 tests. In this case, the traditional alpha of 0.05 was used as the significance threshold.

Occlusal wear

Occlusal wear can originate from contact between opposing teeth or as a result of the action of abrasive foods on the surface of teeth and is characterized by the presence of wear facets on the occlusal plane (Molnar, 1971, 1972; Hillson, 1996; Kaifu et al., 2003). The severity of dental wear in a population depends on a number of different factors including the amount of fibrous food ingested, degree of food processing, and/or the use of teeth as tools on a regular basis (Smith, 1972; Kieser et al., 1985; Molnar and Molnar, 1985; McKee and Molnar, 1988; Kaifu, 1999). In this study, dental wear was analyzed using Molnar's scale (1971, 1972), which stipulates a nonmetric scale ranging from 1 to 8 (1 corresponding to absence of wear and 8 to complete attrition of the crown). Molnar's scale was adopted to allow for the eventual comparison of these series with other series in South America that have been studied with the same scale (e.g., Hubbe, 2006). However, Molnar's scale is comparable in efficiency and reliability with other ordinal scales (Smith, 1972, for example).

Like caries, occlusal wear is a cumulative process and is strongly correlated with age. However, the degree of dental wear also varies greatly between tooth types due to different eruption times and differential usage of each tooth during mastication (Hillson, 1996; Deter, 2009). These characteristics make comparison of occlusal wear difficult among samples with large age differences or with differential preservation of tooth types.

Our samples not only show a high prevalence of AMTL as well as some postmortem tooth loss (data not presented here), resulting in differential preservation of tooth types, but they also show significant differences in age (Kruskall–Wallis test; $P = 0.0009$), with individuals interred at Quitor 6 being younger than those at the other sites. Thus, to correct the observed correlation between occlusal wear and age in the samples (Spearman's $r = 0.313$; $P < 0.05$), we worked with the residuals of the regression between age and wear for each individual. We chose to perform regressions instead of comparing series for each age class because this would reduce sample size considerably, limiting the power of our statistical analyses. We performed one regression for each tooth type, as the correlations with age changed accordingly, with posterior teeth showing a smaller correlation with age than anterior teeth. In each regression, an individual's degree of wear for each tooth type was calculated as the average wear between all teeth of the same category (e.g., superior and inferior left and right M3s). Although averages are not generally recommended for representing ordinal data (Sokal and Rohlf, 1995), the variation within each tooth type was small and averages did not result in substantial variation from medians (difference between means and medians is less than 1.0 in all cases). Therefore, we chose to work with averages, which are easier to calculate and manage in a database.

The residuals of regressions for each tooth type were averaged within each series, presenting the mean degree of occlusal wear for each. As each tooth type responds differently in the rate of dental attrition, we determined that each tooth type should only be directly compared to the same tooth type from the other series. As such, we considered them to be repeated measurements and comparisons between sites was performed using a nonparametric Analysis of Variance (ANOVA) for repeated measures (Friedman test; Sokal and Rohlf, 1995) and comparisons between pairs of sites were performed with Dunn multiple comparisons tests (Sokal and Rohlf, 1995). Similarly, differences between the sexes at each site were compared using a Wilcoxon Matched Pairs Test (Sokal and Rohlf, 1995), considering the average degree of each tooth type as a repeated measurement. Finally, all analyses were done in Statistica 7 (Statsoft).

RESULTS

Table 2 presents the prevalence of caries, AMTL, and the degree of dental wear at each site. Caries prevalence in the series varies between 31 and 52% of teeth evidencing at least one lesion. When the caries correction factor is applied, these frequencies jump to extremely high values (51–65%). It is of note that, despite considerably increasing caries prevalence, the correction factor does not alter the pattern of affliction between sites or within sexes. As expected, when posterior and anterior dentitions are observed, the posterior teeth have a much higher prevalence of caries (prevalence ranges between 31 and 68% for posterior dentition and between 8 and 40% for the anterior teeth). However, the pattern of differences between the series does not change from that observed for the total dentition. AMTL prevalence in the series is also high, ranging between 21 and 39%. Similarly, average degree of dental wear is moderately high, and ranges between grades 3 and 4.3, the latter representing teeth with significant dentine exposure.

Figure 2 compares the uncorrected and corrected prevalence of caries between sites. Figure 3 shows the prevalence of caries in the anterior and posterior dentition. Finally, Tables 3 and 4 show the results of the pairwise χ^2 comparisons. As can be seen, the statistical results are similar, independent of the dataset considered, although fewer differences in the anterior dentition are significant due to the generally lower prevalence of caries in these teeth. There is a clear and statistically significant lower prevalence of caries in elite Solcor 3 and Coyo 3 individuals. However, when samples are separated by sex, this significant difference is only observed among males at these sites. Females show a significant difference between Coyo 3 and Quitor 6 (and between elite Solcor 3 and Quitor 6 for the posterior dentition), with Quitor 6 demonstrating a significantly higher prevalence of caries among females. Additionally, when sex differences at each site are examined, we see that these are only significant in the case of elite Solcor 3 and Coyo 3 (again, with the exception of Quitor 6 for the posterior dentition; Table 5).

Figure 4 and Table 6 show comparisons of the degree of expression of dental attrition between sites. As expected, all sites show the same pattern of dental wear, with anterior dentition more affected than posterior.

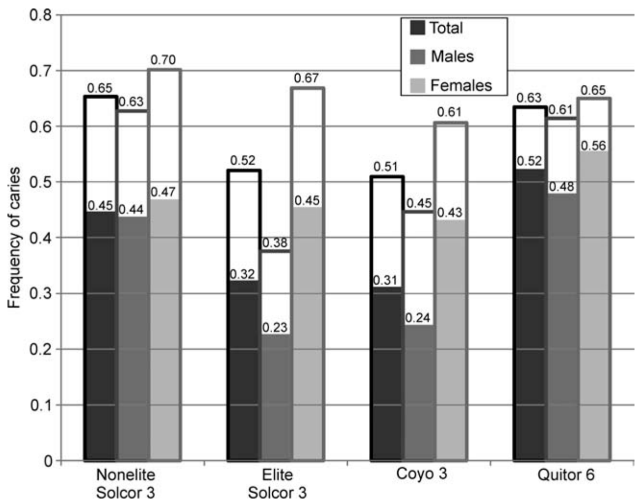

Fig. 2. Caries prevalence observed for each cemetery. Filled bars represent the observed caries prevalence and empty bars show the corrected caries prevalence.

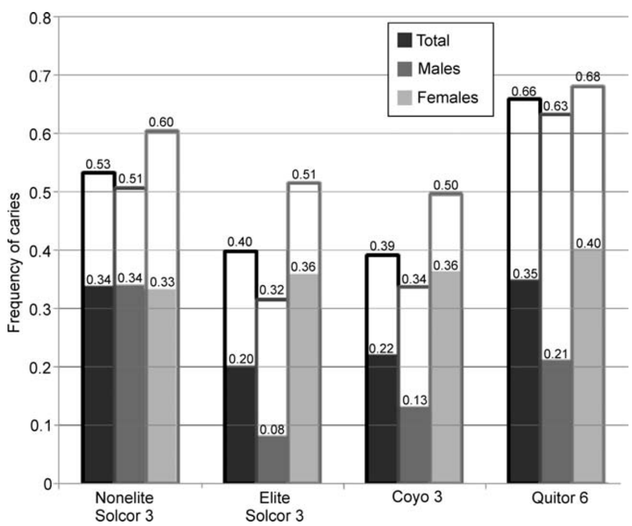

Fig. 3. Caries prevalence observed for each cemetery in anterior and posterior dentition. Filled bars represent the caries prevalence in the anterior dentition (IC, IL, and C), and empty bars show the caries prevalence in the posterior dentition (P3–M3).

Although subtle, significant differences between sites are present. Quitor 6 appears to have the smallest amount of dental wear, a level similar to that seen at elite Solcor 3, whereas nonelite Solcor 3 and Coyo 3 share higher degrees of dental wear. Comparing the prevalence between the sexes at each site (Table 7) shows that with the exception of Coyo 3, males have significantly less dental wear than females. It is interesting to note that these sex differences do not follow the same pattern seen in our analysis of caries prevalence.

TABLE 3. Chi-square probabilities between caries prevalence in pairs of series

	Nonelite Solcor 3	Elite Solcor 3	Coyo 3	Quitor 6
Total				
Nonelite Solcor 3	–	**<0.001**	**<0.001**	0.451
Elite Solcor 3	**<0.001**	–	0.655	**<0.001**
Coyo 3	**<0.001**	0.685	–	**<0.001**
Quitor 6	0.032	**<0.001**	**<0.0001**	–
Males				
Nonelite Solcor 3	–	**<0.001**	**<0.001**	0.734
Elite Solcor 3	**<0.001**	–	0.030	**<0.001**
Coyo 3	**<0.001**	0.610	–	**<0.001**
Quitor 6	0.379	**<0.001**	**<0.001**	–
Females				
Nonelite Solcor 3	–	0.439	0.027	0.222
Elite Solcor 3	0.816	–	0.083	0.595
Coyo 3	0.543	0.631	–	0.211
Quitor 6	0.138	0.023	**0.005**	–

Values above the diagonal show P values for the corrected caries frequency, below the diagonal values present uncorrected frequencies.Values in bold are statistically significant differences ($P < 0.008$; adjusted by the Bonferroni correction).

TABLE 4. Chi-square probabilities for caries prevalence in pairs of series

	Nonelite Solcor 3	Elite Solcor 3	Coyo 3	Quitor 6
Total				
Nonelite Solcor 3	–	**0.002**	**0.001**	0.011
Elite Solcor 3	0.022	–	0.899	**<0.001**
Coyo 3	**0.004**	0.655	–	**<0.001**
Quitor 6	0.891	**0.007**	**0.001**	–
Males				
Nonelite Solcor 3	–	**<0.001**	0.010	0.298
Elite Solcor 3	**<0.001**	–	0.244	**0.006**
Coyo 3	**<0.001**	0.206	–	0.101
Quitor 6	0.342	**<0.001**	**0.004**	–
Females				
Nonelite Solcor 3	–	0.190	0.128	0.455
Elite Solcor 3	0.473	–	0.735	**0.004**
Coyo 3	0.870	0.269	–	**0.002**
Quitor 6	0.508	0.906	0.279	–

Values above the diagonal show P values for the posterior dentition, below the diagonal values are for the anterior dentitionValues in bold are statistically significant differences ($P < 0.008$; value adjusted using the Bonferroni correction).

DISCUSSION AND CONCLUSIONS

Despite decades of study, the nature of the relationship between the Tiwanaku polity and its periphery is not well understood (Kolata, 1993), and archaeologists still debate the strategy or strategies that Tiwanaku might have used in approaching and eventually incorporating smaller communities into their networks (Kolata, 1986, 1991; Torres and Conklin, 1995; Albarracín-Jordan, 1996; Janusek, 2007). In the San Pedro oases, the Middle Horizon is described as a period of local prosperity, peace, and cultural apogee (Berenguer et al., 1980; Browman, 1980b; Berenguer and Dauelsberg, 1989; Oakland, 1992; Kolata, 1993; Núñez, 2004; Goldstein, 2005). However, the role that Tiwanaku played in this is still largely unclear. Theories range from direct Tiwanaku control to indirect benefits from incorporation into the large and well-structured inter-regional network centered on the capital (Berenguer and Dauelsberg, 1989; Oakland, 1992; Kolata, 1993; Torres and Conklin, 1995).

The results presented here suggest that the benefits associated with the Middle Horizon in the San Pedro oases were not equally distributed among the local groups, supporting the first of our hypotheses. Evidence

TABLE 5. Chi-square probabilities for caries prevalence between sexes at each site

Sites	Corrected caries incidence	Observed caries incidence	Anterior dentition	Posterior dentition
Nonelite Solcor 3	0.083	0.606	0.942	0.142
Elite Solcor 3	<**0.001**	<**0.001**	<**0.001**	<**0.001**
Coyo 3	<**0.001**	<**0.001**	<**0.001**	**0.020**
Quitor 6	0.334	0.083	0.056	<**0.001**

Values in bold are statistically significant differences ($P < 0.05$).

TABLE 6. Probabilities of the Friedman test of dental wear differences between sites and of the Dunn's multiple comparison test between pairs of sites

	Nonelite Solcor 3	Elite Solcor 3	Coyo 3
Total (Friedman test: ***P*** < **0.001**)			
Nonelite Solcor 3	–		
Elite Solcor 3	>0.05	–	
Coyo 3	>0.05	>0.05	–
Quitor 6	<**0.001**	>0.05	<**0.01**
Males (Friedman test: ***P*** < **0.001**)			
Nonelite Solcor 3	–		
Elite Solcor 3	>0.05	–	
Coyo 3	>0.05	<**0.05**	–
Quitor 6	<**0.05**	>0.05	<**0.001**
Females (Friedman test: ***P*** < **0.001**)			
Nonelite Solcor 3	–		
Elite Solcor 3	<**0.05**	–	
Coyo 3	>0.05	>0.05	–
Quitor 6	<**0.001**	>0.05	<**0.01**

Values in bold are statistically significant differences ($P < 0.05$).

from caries and occlusal wear shows that the individuals buried in these three cemeteries had significant differences in their diet. However, there is no clear evidence that the changes in diet were exclusively associated with a closer relationship with the Tiwanaku polity (Hypothesis 2), as the same differences seen between elite and nonelite Solcor 3 individuals are also observed between the later sites (Coyo 3 and Quitor 6), who show scarce or no relationship with the altiplano culture.

Decreases in caries prevalence are usually associated with a lower intake of carbohydrates, and frequently result from greater access to protein sources (Turner, 1979; Hillson, 1996; Larsen, 1999), although it should be stressed that caries are a complex multifactorial pathology and a linear correlation with carbohydrate intake might be overly simplistic (Toverud et al., 1952; Schneider, 1986; Lingstrom et al., 2000; Wu et al., 2001; Lukacs and Largaespada, 2006; Afolabi et al., 2008; Tayles et al., 2009; Cucina et al., 2011). However, overall lifestyle in the San Pedro oases did not change during the period under study, and it is unlikely that factors other than variation of dietary composition caused the difference in caries prevalence reported here.

Local food resources in the San Pedro oases were largely the same throughout their occupation (Llagostera, 2004; Núñez, 2007). Maize has always played a central role in local diet and was complemented by local plants including *chanãr* (*Geoffroea decorticans*) and *algarrobo* (*Prosopis spp.*). It is noteworthy, however, that despite the local diet being dominated by maize, the prevalence of caries reported here is much higher than that seen among maize-dependent cultures from Mesoamerica (e.g., Table 5 in Cucina et al., 2011) and North America (e.g., Schollmeyer and Turner, 2004). Consequently, the differences we note in caries prevalence during the Middle Horizon San Pedro oases can best be explained by an increase in access to protein sources and a concomitant reduction in carbohydrate consumption. Meat by itself also acts as an inhibitor of cariogenic activity, and when associated with a reduction in the intake of carbohydrates can offer a second level of protection against cavities (e.g., Mays, 2010:221).

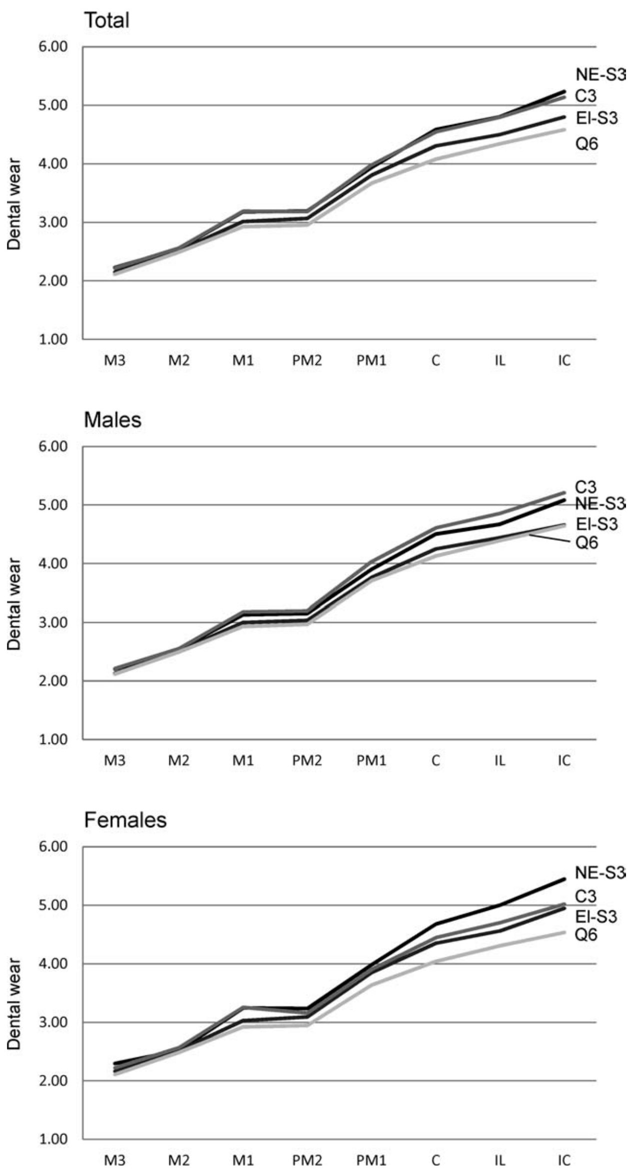

Fig. 4. Mean dental wear observed in each cemetery. NE-S3: nonelite Solcor 3; El-S3: elite Solcor 3; C3: Coyo 3; Q6: Quitor 6.

TABLE 7. Probabilities of the Wilcoxon matched-pairs tests of dental wear differences between sexes in each site

Sites	*P*
Nonelite Solcor 3	**0.017**
Elite Solcor 3	**0.011**
Coyo 3	0.123
Quitor 6	**0.012**

Values in bold are considered as significant differences ($P < 0.05$).

Assuming that differential access to meat is the main cause of the disparity in caries prevalence in the oases (Neves and Costa, 1998), it is possible to explain the patterns of difference observed between the series considered here. First, the lower prevalence of caries among elite individuals interred at Solcor 3 when compared to contemporary nonelite individuals suggests that social differences among individuals occupying the same burial ground are also reflected in the amount of meat to which each group had access. Second, these differences in caries prevalence, and as such in access to meat protein, are also observed at the end of the Middle Horizon and into the Late Intermediate Period between Coyo 3 (lower caries prevalence) and Quitor 6 (higher caries prevalence), despite they both represent sites with impoverished burial contexts (Costa, 1988; Costa and Llagostera, 1994). This may reflect temporal differences or may also suggest that Tiwanaku played some role in diet because Coyo 3 shows some evidence of interaction with the foreign polity. Finally, there are no apparent differences in caries prevalence among the women, suggesting that they had a more standardized diet. The statistically significant differences are caused by the low caries prevalence among men in the two sites with overall lower caries prevalence (elite Solcor 3 and Coyo 3). Sex differences are only observed at these two sites, suggesting that the men interred in these cemeteries are accessing more meat, while in the other series (nonelite Solcor 3 and Quitor 6), there are no differences in caries prevalence between the sexes.

Different processes might have contributed to these differences. The rise in prosperity during the Middle Horizon was reflected in demographic increases and in the expansion of settlement into new fertile areas (Llagostera and Costa, 1999; Hubbe et al., in press) in concert with the intensification of connections with the Bolivian altiplano and northwest Argentina (Bravo and Llagostera, 1986; Berenguer and Dauelsberg, 1989; Torres and Conklin, 1995; Berenguer, 2000; Uribe, 2002; Stovel, 2005; Rivera, 2008). It is probable that all of these changes were associated with an increase in agricultural and pastoral productivity. Greater access to animal protein among some of the men could, therefore, have resulted from a novel approach to dealing with the management of local camelid herds, either through the intensification of pastoralism or through the reallocation of this resource from transportation to consumption (as suggested previously by Neves and Costa, 1998). Similarly, it may also reflect men's role in the llama caravans that connected the oases to other regions.

Some scholars have argued that the Middle Horizon was a period when certain men assumed an important role as religious and commercial agents, managing goods and beliefs coming from the Tiwanaku capital (Nuñez, 1992; Llagostera, 2004). The increasing separation between domestic and ritual/commercial activities during the Middle Horizon might be associated with the observed sex differences in caries reported here. It has been argued that the period of Tiwanaku influence in the San Pedro oases saw also the establishment of formal local hierarchies, which may have served to intensify sex-based divisions within these communities (Lessa and Mendonça de Souza, 2004; Torres-Rouff, 2011).

The differences seen in the degree of dental wear, however, do not follow the same pattern observed for caries prevalence. As our results show, the main differences observed here suggest a reduction of dental wear at the Late Intermediate Period site of Quitor 6. Males from elite Solcor 3 show a lesser degree of dental wear than those at Coyo 3, while elite Solcor 3 females show less wear than the nonelite Solcor 3 females. However, there is no statistically significant difference between elite and nonelite Solcor 3 individuals when sexes are pooled. Finally, it should be noted that there is a strong tendency toward higher rates of dental wear among women in the sample.

If caries rate differences are caused by greater access to protein sources, potentially in the form of camelid meat, it is clear that this differential access to meat is not causing differences in the average degree of wear. It seems unlikely that the different wear patterns are a result of the consumption of different (and presumably less fibrous) food items by those individuals buried at Quitor 6 (and to a lesser degree elite Solcor 3) as the archaeological record does not show evidence of changes in this aspect of the local diet (Costa, 1988; Bravo and Llagostera, 1986). The end of the Middle Horizon and the subsequent Late Intermediate Period were marked by increased social strife (Torres-Rouff and Costa, 2006) associated, at some level, with climatic changes that reduced the availability of water, and consequently of fertile areas in the oases (Schiappacasse et al., 1989). It is possible that this tendency toward less attrition in the later period reflects new forms of food preparation that reduced abrasiveness. However, this does not explain the higher degree of dental wear documented among Coyo 3 individuals. As local archaeology has been predominantly focused on cemeteries (Llagostera et al., 1984; Núñez, 2007), no good record for habitation sites currently exists, which impedes our ability to test a hypothesis of changes in food preparation.

Sex differences in dental wear may have resulted from differential use of the dentition as tools in sex-specific tasks (e.g., chewing leather or processing maize for *chicha*, a fermented drink) because differences in dietary composition (i.e., access to meat) seem an unlikely explanation for differences in dental wear (see above). However, given the lack of evidence for task-specific wear at any of these sites, we consider this a hypothesis for future testing and our suggestions must be seen as provisional. It is clear, however, that the factors affecting dental wear are distinct and follow a different logic than those affecting caries prevalence, and consequently might point to distinct processes of change or differences between local groups or sexes during the Middle Horizon.

In conclusion, the Middle Horizon in the San Pedro de Atacama oases was a time of dramatic changes in aspects of local style and quality of life. Our findings complement previous studies of the Middle Horizon in the Atacama (Costa, 1988; Neves and Costa, 1998; Costa et al., 2004; Torres-Rouff, 2008, 2011), by demonstrating significant diversity in the benefits associated with this period. Carious rate data indicate that men from elite groups probably benefitted from increased access to protein sources. However, better access to meat was not restricted to individuals associated with the Tiwanaku polity, as can be attested to by the low prevalence of caries in Coyo 3, a cemetery from the end of Middle Horizon/Late Intermediate Period, characterized by an impoverished burial context.

These results concerning changes in dietary habits in the San Pedro oases during the Middle Horizon give further support to the notion that local populations benefited from Middle Horizon prosperity and their relationship to

Tiwanaku. However, it also suggests that the benefits were segregated and unequal between different sectors of Atacameño society. Our results are strengthened by the fact that the pattern of caries prevalence between sites is consistent regardless of the methods applied to infer it (total, corrected, anterior dentition and posterior dentition caries prevalence). In this study, men particularly benefited from a protein-enriched diet, while women maintained largely the same pattern of high levels of carbohydrate consumption between sites. It comes as no surprise that wealth together with the influence of a foreign culture could be restricted to a small part of society. We now have some evidence for this in the important differences in cranial trauma documented between high and low status cemeteries during the Middle Horizon in the San Pedro oases (Torres-Rouff, 2011).

Our results support the notion that overall changes in a population's wealth are usually accompanied by important changes in basic aspects of their lifestyle such as diet. However, this study is incapable of fully defining the variability that existed in the San Pedro oases during the Middle Horizon. The diversity in the aspects of oral health reported here indicates that the inclusion of the Atacameño oases into the inter-regional networks associated with Tiwanaku did not benefit all sectors of society equally, and likely reflects increasing hierarchy in the local communities (Llagostera et al., 1988; Berenguer and Dauelsberg, 1989). Our future research will focus on an investigation of this potential dietary variation through stable isotope analyses of individuals from a larger number of Middle Horizon cemeteries. We expect that an expanded study of the diversity of this aspect of lifestyle will help shed light on the nature of Tiwanaku's relationship with the groups that inhabited the Atacama oases and help us to explore social inequality at this time.

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