Research Article

How Do Surficial Lithic Assemblages Weather in Arid Environments? A Case Study from the Atacama Desert, Northern Chile

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Archaeological sites composed only of surficial lithics are widespread in arid environments. Numerical dating of such sites is challenging, however, and even establishing a relative chronology can be daunting. One potentially helpful method for assigning relative chronologies is to use lithic weathering, on the assumption that the most weathered artifacts are also the oldest. Yet, few studies have systematically assessed how local environmental processes affect weathering of surficial lithics. Using macroscopic analyses, we compared the weathering of surficial lithic assemblages from seven mid-to-late Holocene archaeological sites sampled from four different microenvironments in the Atacama Desert of northern Chile. Changes in polish, texture, shine, and color were used to establish significant differences in weathering between two kinds of locations: interfluves and canyon sites. Lithics from interfluve sites were moderately to highly weathered by wind and possessed a dark coating, whereas canyon lithics were mildly weathered despite greater exposure to moisture, often lacked indications of eolian abrasion, and lacked dark coatings. Our results show that lithic weathering can be used as a proxy for relative age, but only after considering local environmental factors. The power of such chronologies can be improved by combining archaeological, paleoenvironmental, geomorphological, and taphonomic data. © 2015 Wiley Periodicals, Inc.

INTRODUCTION

Surficial materials are widely used in archaeology to date and assign chronological and cultural affiliation to sites. Although this can be facilitated when diagnostic artifacts are recognizable within a particular culture history framework, such instances are rare. In the central Andes, diagnostic lithic artifacts, and projectile points in particular, have been used for chronological purposes (Lanning & Hammel, 1961; Núñez, 1983; Klink & Aldenderfer, 2005). Despite its potential, lithic weathering *per se*, typical of desert environments, has not been examined as an independent or complementary proxy for determining relative ages and site formation. Weathering, a process that progressively destroys the archaeological record, affects stone artifacts (lithics), which, either buried or exposed, can undergo significant changes over time (Schiffer, 1983, 1987; Hiscock, 1985; Sheppard & Pavlish, 1992; Cackler et al., 1997). Some of these modifications contain information about the depositional history of lithic assemblages, and about atmospheric and climatic processes (Dincauze, 2000: 51).

Table I Cultural chronology for the Atacama Desert.

Period	Age Range (cal. yr B.P.)
Early Peopling/Paleoindian	13,000–11,500
Early Archaic	11,500–8000
Middle Archaic	8000–6000
Late Archaic	6000–3700
Formative	3700–1400
Middle Horizon	1400–800
Late Intermediate	800–500
Late	500–400
Colonial/Historic/Modern	400–0

Archaeological evidence suggests humans occupied the hyperarid Atacama, arguably one of the driest and most stable surfaces on the planet, at least 13,000 yr ago (Núñez, Grosjean, & Cartajena, 2002; Grosjean, Núñez, & Cartajena, 2005; Latorre et al., 2013; Table I). Weathering features[1] are readily recognizable on lithic materials left behind by these early groups, and surface assemblages are both numerous and conspicuous. These remains have been exposed to shifting hydroclimatic regimes throughout the Holocene at millennial and centennial timescales (Latorre et al., 2007; Gayo et al., 2012a,b). Such climate changes have left behind a "lag" of ecological and cultural evidence that offers a unique opportunity to study site formation processes.

Here, we explore the relationship between the degree of weathering and relative age of cultural material. Specifically, we seek to identify the principal agents of weathering that affect surficial lithic artifacts in the Pampa del Tamarugal (PDT) in northern Chile (Figure 1). We also evaluate the potential for differential taphonomic processes in different geomorphic contexts, and identify those that generate distinctive traces on artifacts.

REGIONAL SETTING AND CLIMATE

The PDT is a large inland basin located within the hyperarid core of the Atacama Desert where elevations reach ~1500 m above sea level (asl) on the east and ~900 m asl in the Coastal Cordillera to the west. The axis of the basin extends over 200 km between 19°17′ and 21°30′ S. latitude. Average relative humidity varies 29.2–46.4% throughout the year, and evaporation is 2000–3400 mm/yr (Lanino, 2005). Although this area is today characterized by scarce rainfall (<1 mm/yr; Lanino, 2005), recurrent coastal fog—locally called *camanchaca*—occurs during the austral winter and reaches the western portion of the PDT (Cereceda et al., 2008). The *camanchaca* penetrates inland mostly along breaches of the Coastal Cordillera and reaches the PDT very infrequently in areas where this mountain range exceeds 1200 m asl (Rech, Quade, & Hart, 2003). Between 1995 and 2003, the mean annual temperature was 20°C with an average maximum monthly temperature of 33.9°C in December and a minimum of 0.2°C in June. Winds blow predominantly from the southwest (PRAMAR-DICTUC,

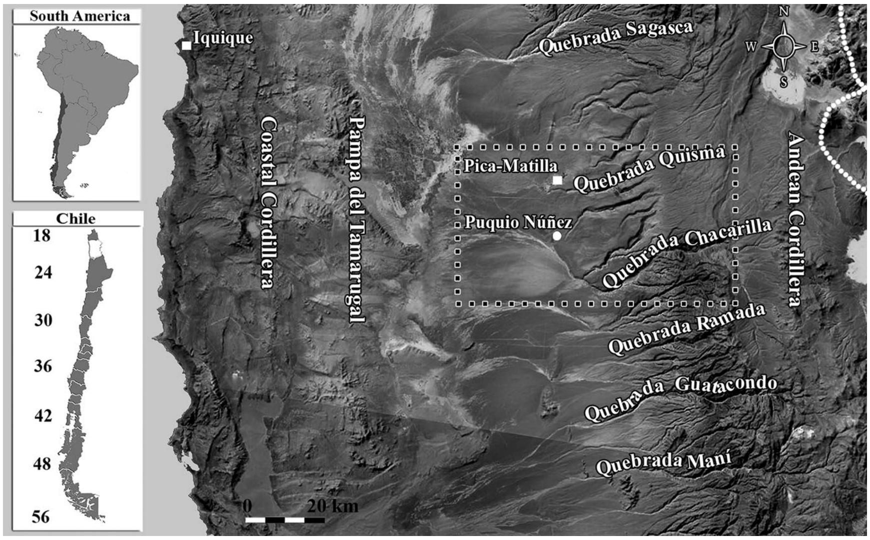

Figure 1 Study area (black dashed line) showing major canyons (*quebradas*). The towns of Pica-Matilla (square) and the oasis of Puquio Núñez (circle) are shown for reference. White dashed line corresponds to the border between Chile and Bolivia.

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[1] We are using a broad definition of weathering to refer to modification of the original surface of lithic materials, including processes that are not chemical and mechanical weathering *sensu stricto*.

2007) with average speeds of 2.2 km/h (Lanino, 2005), although strong wind gusts of up to 60 km/h are known to occur (URBE, 2003). In this area, winds occur predominantly between noon and 7 pm, peaking at 12.6 km/h by 4–5 pm (Arenas-Charlin, 2009). Monthly average wind speeds are higher during the austral summer (2.2–2.7 km/h) and decrease through the year reaching minimum values (~1.6 km/h) by June (Lanino, 2005; Arenas-Charlin, 2009).

All of the aforementioned environmental factors affect processes that can significantly alter surficial lithics. On one hand, eolian sand blasting causes erosion (among other taphonomic effects) which can blur or erase the technological characteristics of lithic artifacts (e.g., ridges, cracking ripples, and hackles), sometimes making their cultural classification difficult (Lancaster, 1996; Borrazzo, 2004, 2006). On the other hand, saline fog, possibly combined with other factors such as sandblasting and thermal oscillations, may result in lithic pitting, that is, cavities or holes associated with mechanical weathering (see Huckleberry & Billman, 2003).

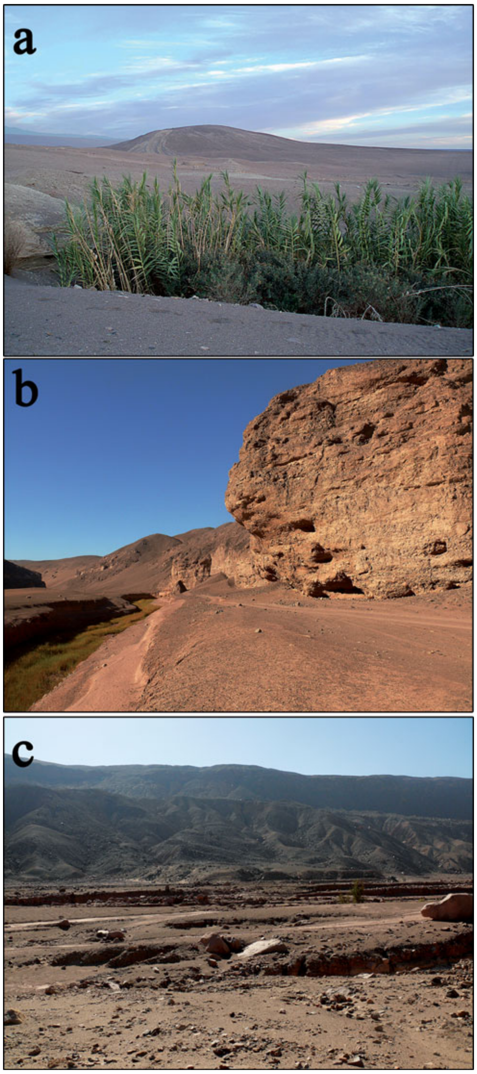

Figure 2 Photographs of some of the sampled locations: (a) interfluves near the Puquio Núñez oasis (view is from a wetland toward PQN3, PQN10, and PQN23 lithic clusters). (b) Canyon environment located along the lower section of Quebrada de Chacarilla (view from CH2 site). (c) Canyon environment along the middle sector of Quebrada de Chacarilla (view is from an unpaved road toward CH4 and CH5 sites).

Due to prevailing extreme hyperaridity and the almost complete absence of macroscopic life (Arroyo et al., 1988; Gayo et al., 2012a), this landscape is termed absolute desert. Plants, however, can be found around local freshwater springs or in deep canyons where the groundwater table is near the surface (Gajardo, 1994; Villagrán et al., 1999; Luebert & Pliscoff, 2006). Groundwater is recharged by summer rainfall that takes place at elevations over 3500 m asl on the western flank of the Andes and in high-Andean basins (Magaritz et al., 1990; Houston, 2006a,b). Local emergence of groundwater through capillary migration and evaporation forms extensive salt pans along the western (distal) margin of the PDT (Grilli, 1985; Risacher, Alonso, & Salazar, 1999). Common plants found here include tamarugo trees (*Prosopis tamarugo*) as well as several halophytic shrubs and grasses such as *Distichlis spicata, Atriplex madariagae*, and *Tessaria absinthioides* (Briner, 1985; Luebert & Pliscoff, 2006). Hygrophytic vegetation such as pampa grass (*Cortaderia atacamensis*) can also establish in areas where phreatic levels intercept surface slopes and/or in areas of irrigated crops. This is the case of Puquio Núñez, one of our sampled locations (Figures 1 and 2a), where a 6–8 km wide depression with permanent groundwater discharge (Galli & Dingman, 1962) supports vegetable crops, fruit trees, and a natural population of cane grass (*Phragmites australis*). Riparian ecosystems (Gajardo, 1994; Villagrán et al., 1999; Luebert & Pliscoff, 2006) occur in perennial or intermittent streams north of 21°S in canyons that are deeply incised, the larger ones marking the northern boundary of the PDT basin (Taltasse, 1973; Houston, 2006a; Muñoz et al., 2007). Quebrada Chacarilla is one such canyon (Figures 1, 2b, 2, and c) drained by a perennial-to-intermittent river (Houston, 2001, 2002) where riparian vegetation occasionally develops on low fluvial terraces. We sampled four archaeological sites here (Chacarilla 2 [CH2], Chacarilla 15 [CH15], Chacarilla 4 [CH4], and Chacarilla 5 [CH5]), all of them located outside of the current riparian vegetation zone.

The proximal (eastern) sectors of the PDT are characterized by relict alluvial fans that developed during the upper Oligocene to the Late Pleistocene (Nester et al., 2007; Blanco & Tomlinson, 2013; Figure 3). These fans are commonly dissected by large canyons with

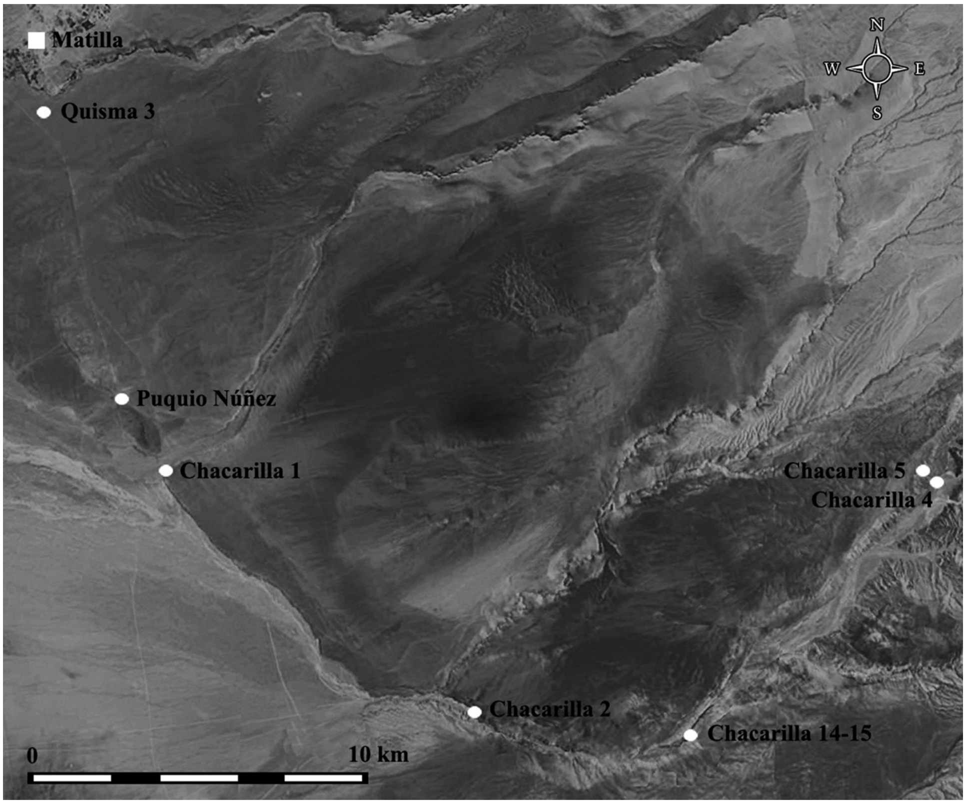

Figure 3 Aerial photograph (Earth Explorer) indicating location of sampled archeological sites.

headwaters located farther to the east in areas of volcanic rock and marine sediment outcrops within the Andes. These alluvial fans vary in morphology, slope, and magnitude of dissection. The older Oligocene fan remnants (locally mapped as the Altos de Pica Formation, a source of lithic raw material) occur to the east, whereas younger inset fans extend westward into the PDT basin. This alluvial landscape is often interrupted by local tectonic or structural features such as faults, often exposing older sediments, such as occurs at Puquio Núñez (Figure 3).

We have observed well-developed desert pavements on alluvial fan interfluves, particularly on the older Oligocene and Miocene surfaces. Desert pavements are a common feature of the Atacama, typically made of clasts of diverse sizes and rock types that develop over a fine matrix of gypsum and anhydrite, locally known as *chusca* (Rech, Quade, & Hart, 2003; Ewing et al., 2006). Desert pavements are well-known geomorphic features of many arid regions of the world, and are commonly linked to eolian dust flux such that the pavements are typically accretionary rather than deflationary in origin (McFadden, Wells, & Jercinovich, 1987; Quade, 2001; Matmon et al., 2009). Their degree of development is often used as a proxy for age, although many factors, such as the density of plant cover and animal activity, can disrupt their formation (Quade, 2001). Very few archaeological studies have included desert pavements as a source of information regarding archaeological site formation (although see Ahlstrom & Roberts, 2001; Adelsberger et al., 2013). This is despite the fact that diagnostic archaeological artifacts have been used as a means to provide minimum age of desert pavement formation (Matmon et al., 2009). In the Atacama Desert, diagnostic surface lithic artifacts have been tentatively associated with "specific lake and stream terrace levels" to derive age estimates for their formation and to understand settlement patterns (Lynch, 1990: 213). The relationship between archaeological sites and desert pavements, however, has not been studied in the Atacama.

The PDT possesses an extreme hyperarid climate that has lasted for millions of years (Jordan et al., 2014). This, however, does not preclude important past climate fluctuations and paleoenvironmental changes at millennial–centennial timescales since the Late Pleistocene (Latorre et al., 2007, 2013; Nester et al., 2007; Gayo et al., 2012a,b). Positive hydroclimatic anomalies (Gayo et al., 2012a,b) have generated increases in surface and groundwater discharge from the adjacent highlands at 17,600–14,200, 12,100–11,400, 2500–2040, 1615–1350, and 1050–680 cal. yr B.P. These anomalies created oases composed of riparian and phreatophyte vegetation that attracted prehistoric human groups to the hyperarid core of the Atacama (Santoro et al., 2011; Gayo et al., 2012a,b; Latorre et al., 2013). It is likely that these pluvial events constrained the times of human occupation in this extreme environment, and through their positive demographic effects may have also stimulated cultural innovations (Williams et al., 2008; Marquet et al., 2012; Gayo, Latorre, & Santoro, 2015).

CONCEPTUAL FRAMEWORK

Wind is an important process for modifying surficial cultural remains and has two primary taphonomic effects. The first one is eolian abrasion or corrasion (Camuffo, 1995), which is a destructive process that occurs only on exposed surfaces and is produced by wind-borne particles striking the artifact surface. This results in the polishing of ridges and sharp edges, the shining of surfaces, and the rounding of conspicuous microtopography on freshly fractured rock (Borrazzo, 2006). The second effect is the formation of a dark coating known as "rock varnish", a biogeochemical form of weathering that consists of an accretionary growth through atmospheric precipitation of wind-borne organic and mineral particles to an exposed surface (Dorn, 1998, 2007; Watchman, 2000). These particles, often clay-sized, become fixed to rocks in the form of microstrata, through joint biotic and abiotic mechanisms that are still discussed. Rock varnish can be identified by the superficial darkening of lithics and may be glossy, the latter due to a smooth micromorphology combined with manganese enrichment (Dorn, 2007). Rock varnish as a numerical dating method has been the subject of debate, particularly when applied to petroglyphs and archaeological lithic materials (Liu & Broecker, 2000, 2007, 2008; Watchman, 2000; Dorn, 2004, 2007; Baied & Somonte, 2013; Somonte & Baied, 2013; Whitley, 2013).

Wind abrasion is the most prevalent process altering surficial lithics in our study area, although lithic weathering due to atmospheric and soil moisture is also possible on geomorphic surfaces close to river beds, hill slopes exposed to infrequent surface runoff, and areas subject to winter fog. Periodic exposure to moisture commonly results in coatings or patinas caused by mineral alteration and replacement on buried and surficial artifacts (Burroni, Donahue, & Pollard, 2002; Borrazzo, 2006). Patinas commonly form on cherts as a uniform or blotchy white layer that leaves a rough and dull surface (Hiscock, 1985). However, clearer or brighter patinas have also been identified (Kelly & Hurst, 1956; Frederick et al., 1994).

Similar taphonomic effects on artifact surfaces can sometimes be produced by human use, for example, polishing of edges and ridges, and changes in color, complicating efforts to identify post-depositional alterations. This possibility was minimized from our assemblages as most of the sample was composed of lithic debris. In the case of tools, we excluded active edges or surfaces prone to use wear (Semenov, 1981; Mansur-Franchomme, 1986). The changes we observed were present over the entire exposed face of the artifact. Aside from this, we found lithics that were partially buried, and their buried sections did not show these changes, or they were less intensely developed. Thus, we believe that the observed changes in texture, shine, and color of lithic samples from our study area were the consequence of post-depositional weathering.

METHODS

Fieldwork

Sites were selected considering natural factors that may have acted differently upon surface lithic artifacts. These include:

(1) Distance to water sources such as perennial or intermittent rivers and springs. Some sites are located 30–400 m away from water whereas others are situated on hyperarid interfluves, far from potential moisture sources.
(2) Distance to vegetation to help evaluate its effect on patina formation and reduced sandblasting. Sites are located 30–400 m away from vegetation, or in areas completely devoid of visible plant life.
(3) Elevation to help to evaluate possible differential weathering caused by variability in rainfall. Sampled sites are located 1200–2000 m asl; elevations <1500 m asl are considered to receive no rainfall.
(4) Topography to help evaluate differences in wind intensity on lithic surface properties. Selected sites are located on inclined and level surfaces.
(5) Landform type to help evaluate possible differences between lithics deposited on diverse geological materials. This includes alluvial surfaces containing soils with organic content, desert pavements, and dunes.

Finally, cultural associations were also considered as the presence of surface diagnostic materials other than lithics was crucial to establish the chronological context of each site (for further details see Table II).

To control for internal factors of weathering and to facilitate comparisons between sites, only silicified ignimbrite lithic artifacts were selected. Ignimbrite is a high

Table II Geographical, surficial, and cultural characteristics of sites included in this study.

Site	Site Setting	Elevation (m asl)	Site Description	Surface Matrix	Site Topography	Other Cultural Features	Distance to Water Source	Distance to Vegetation
CH2	Rock shelter within canyon	1478	Lithic scattering/rock art/ contemporary refuge	Sandy silt and eolian sand	Level	Colonial pottery, animal bones, glass, tin cans	30 m; past floods possibly affected site	30 m (on the river bed)
CH4	Fluvial terrace	2000	Lithic workshop (one lithic cluster sampled)	Sandy silt and clasts	Level	Only lithics	100 m; past floods possibly affected site	100 m (very scarce, on the river bed)
CH5	Fluvial terrace	2023	Lithic workshop (one lithic cluster sampled)	Sandy silt, clasts, and eolian sand	Inclined	Late Archaic morphology bifacial tool; Late Intermediate pottery	300 m; past floods possibly affected site	300 m (very scarce, on the river bed); evidence of bioturbation (roots) at site
CH15	Close to wetland within canyon	1677	Lithic scattering/Late Archaic to Late Intermediate period petroglyphs	Eolian sand	Inclined	Late Intermediate pottery, slags, collar bead	30 m	30 m (on the river bed, and on low fluvial terrace below the site)
PQN3	Close to wetland on interfluve	1198	Cluster from a lithic workshop	Eolian sand	Gently inclined	Two animal bone fragments; human burial with textile found near cluster	200 m	200 m (wetland)
PQN10	Close to wetland on interfluve	1210	Cluster from a lithic workshop	Desert pavement	Inclined	Only lithics	350 m	350 m (wetland)
PQN23	Close to wetland on interfluve	1212	Cluster from a lithic workshop	Desert pavement	Gently inclined	Only lithics	400 m	400 m (wetland)
QUI3	Interfluve	1227	Lithic workshop (selective sampling)	Desert pavement	Gently inclined	Pottery sherd	Absent	Absent
CH1	Interfluve	1211	Lithic scattering	Desert pavement	Level	Only lithics	Absent, but evidence of past water flow near site	Absent

temperature acidic welded volcanic ash, composed of 70–75% SiO_2 (Galli & Dingman, 1962). All the sampled ignimbrites are derived from the Altos de Pica Formation, are silicified and fine-grained, and good for knapping. There are variations in the rock material's original color (2.5YR 5/2; 10R 4/2; 10R 4/1; and 5YR 4/3), and several ignimbrite clasts contain inclusions of other siliclastic materials and phenocrysts. Silicified ignimbrite is highly resistant to weathering compared to other lithic raw materials in the area.

Artifact collection was made by recording *in situ* positions according to two cardinally orientated axes and which surface of the artifact was exposed (i.e., ventral, dorsal, or sideways). Sampled materials correspond in all cases to surficial lithics.

Laboratory Analyses

Technological analysis of the artifacts follows criteria proposed by Andrefsky (2005) and Odell (2000). Afterwards,

Table III Criteria used to establish the relative weathering scale applied in this study (for similar scales, see Hiscock, 1985 and Borrazzo, 2006).

Weathering Stage	Most Common Value Combinations	Lithic Surface Appearance	Polishing of Ridges and Sharp Edges	Texture	Shine	Figure
W-0	(1-1-1)	Fresh	Sharp	Rough	Absent	4a
W-1	(1-2-2; 2-1-2)	Very softly weathered	Sharp or half-rounded	Slightly rough or rough	Slight	4b
W-2	(1-3-4; 1-4-4; and 1-3-3)	Softly weathered	Sharp	Smooth or very smooth	Medium or intense	4c
W-3	(2-3-2; 2-2-2; and 2-2-3)	Soft to moderately weathered	Half-rounded	Slightly rough or smooth	Slight or medium	4d
W-4	(2-3-3; 2-3-4; and 2-4-3)	Moderately weathered	Half-rounded	Smooth or very smooth	Medium or intense	4e
W-5	(3-4-4; 3-4-3; 3-3-4; and 3-3-3)	Strongly weathered	Well-rounded	Very smooth or smooth	Intense or medium	4f
W-6	(4-4-4; 4-3-3; and 4-3-4)	Completely weathered	Completely rounded	Very smooth or smooth	Intense or medium	4g

Weathering stage examples provided in Figure 4.

each lithic was examined for weathering through the evaluation of three variables: (1) polishing of ridges and sharp edges, (2) texture, and (3) shine. Changes in polishing were observed through a 45× binocular magnifier, generating a four-step ordinal scale: sharp (or fresh), half-rounded, well-rounded, and completely rounded (Ugalde, 2009; see also Borrazzo, 2006). Changes in texture were determined by gently touching lithic surfaces. This also generated a four-step scale: rough, slightly rough, smooth, and very smooth. To assess shine, the differences were observed under artificial light, also creating a four-stage scale: absent, slight, medium, and intense. Changes in total or partial coloration were determined using a Munsell color chart, but these were not transformed into a scale.

Each lithic sample was then scored for the first three variables (polishing, texture and shine) considering the four-stage scales: (a) polishing of edges and ridges (scales from 1 = sharp to 4 = highly rounded), (b) texture (1 = rough to 4 = smooth), and (c) shine (1 = absent to 4 = intense). In this way, each lithic would have a combination of three values, for example, 1-1-1 or 2-1-3, etc. (see combinations in Table III). After scoring, lithics were sorted into related groups. When a lithic could not be assigned unequivocally to any of the established groups, the "edge polishing" variable took precedence over the other two variables, as this is one of the clearest evidence of eolian abrasion (see Borrazzo, 2006). This effect of wind erosion has been previously noted on ventifacts, where smoothing and polishing of the rock surface occur on its facets and within its flutes and grooves (Maxson, 1940 cited in Laity, 2011). In our case, it was more accurate to give an ordinal value to the polishing of edges and ridges than to the general changes of texture of the rock. In a few cases ($n = 7$; 1.6% of total assemblage) the degree of edge and ridge polishing was not easy to classify or grade, so this variable was discarded. Instead, these lithics were classified according to their texture, shine degree, and overall weathered appearance.

Related groups of lithics resulted in a six-stage weathering scale (Table III and Figure 4). We added Stage 0 by using an experimental lithic with no signs of weathering (we knapped silicified ignimbrite nodules to obtain flakes and also to evaluate knapping quality). Although four-stage classifications already exist (Hiscock, 1985; Borrazzo, 2004, 2006), we developed our own scale to more accurately reflect the local weathering gradient from less to more intense, assuming that a simpler scale would have reduced the variation for describing these changes.

To statistically test the associations between the three variables used for the ordinal scale of weathering (polishing of edges and ridges, texture, and shine), a Spearman's rank correlation coefficient was computed to assess bivariate dependence between these variables (Spearman, 1904). Also, the *t*-test (Press, 1992) was used in order to determine whether the values of *rho* are significantly different from zero.

Finally, to corroborate differences between types of microenvironments, a Mann–Whitney *U*-test (Mann & Whitney, 1947) was used to evaluate whether weathering is independent of the place where the sample was collected. This test is as a nonparametrical alternative for the two-sample *t*-test (Conover, 1980).

SITE DESCRIPTIONS

In order to compare across different microenvironments, seven archaeological sites with surficial lithic clusters located on the PDT were selected. They represent the

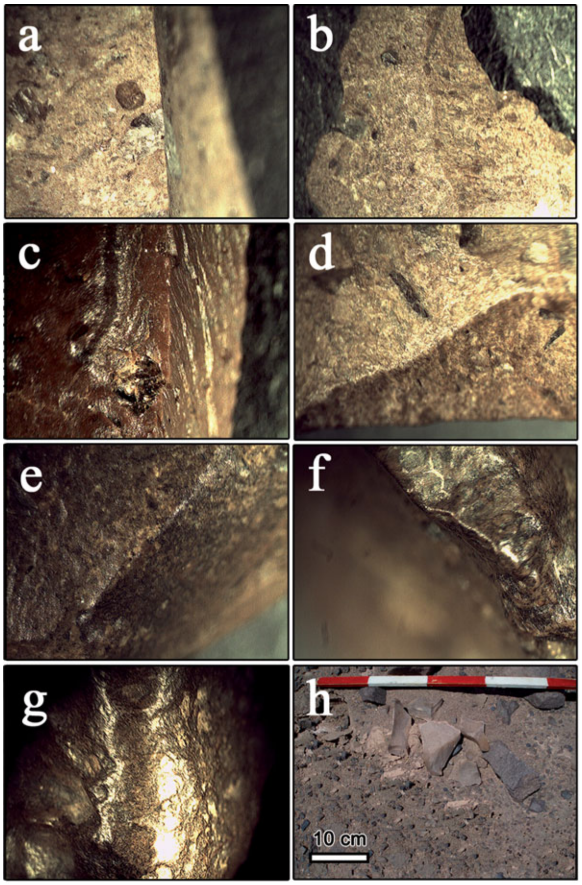

Figure 4 Weathering stages seen under a binocular microscope (focus is on ridges and edges). (a) Stage 0, experimental lithic, 20×; (b) Stage 1, 20×; (c) Stage 2, 20×; (d) Stage 3, 20×; (e) Stage 4, 20×; (f) Stage 5, 15×; (g) Stage 6, 10×; (h) *in situ* lithic debitage, PQN10; scale divided in 10 cm segments.

following four microenvironments: (1) interfluves, (2) past and present wetlands, (3) fluvial terraces inset within large canyons, and (4) rock shelters (Table II). The samples included artifacts from sites CH2, a rock shelter with a lithic scattering located on an ancient fluvial terrace; CH4 and CH5, both open lithic workshops emplaced on ancient fluvial terraces; and CH15, an open site with a lithic scattering and petroglyphs located near a former wetland. All of these sites are located within Chacarilla canyon. Artifacts from the Puquio Núñez site with its lithic clusters Puquio Núñez 3 (PQN3), Puquio Núñez 10 (PQN10), and Puquio Núñez 23 (PQN23) were also collected. This site is an open lithic workshop located near an active wetland on an interfluve. Finally, two sites located on an interfluve, in sections that today are completely devoid of vegetation and water, were sampled. These sites are Quisma 3 (QUI3), an open lithic workshop, and Chacarilla 1 (CH1), a lithic scattering. Artifacts from the interfluve sites are part of the local desert pavement (CH1, PQN3, PQN10, PQN23, and QUI3), and, therefore lay upon of a very stable surface. They are also affected by ocean fog or *camanchaca*. Three of the sampled canyon sites (CH4, CH5, and CH15) were found on ancient fluvial terraces of Late Pleistocene or older, and lack desert pavements. CH2, the remaining canyon site, is located on a lower and more recent (Holocene) terrace that has been exposed to occasional flooding (Houston, 2001). Sites near wetlands or within deep canyons were also subject to possible influences from local vegetation (see Regional Setting and Climate).

Approximate age estimates for our sites are based on cultural traits (Table II) such as ceramic manufacture type, rock art styles (petroglyphs from the Late Archaic up to the Late Intermediate Period at CH15, and pictographs from the Late Intermediate Period at CH2), lithic tool types (a Late Archaic bifacial tool from CH5 site), and lack or low frequency of bifacial knapping debitage and tools, a common lithic technique among early hunter-gatherers which is rather unusual among sedentary groups (Parry & Kelly, 1987; Wallace & Shea, 2006). These cultural traits provide age estimates that span from the Late Archaic period (*ca.* 6000 to 4000 cal. yr B.P.) up to the Colonial Period (*ca.* 500 cal. yr B.P.). This estimated time range of occupation for our sampled surficial sites is further supported by 20 AMS ^{14}C ages obtained from an excavation performed at CH15 which place human occupation between 5580 and 500 cal. yr B.P. (Santoro et al., 2011). In this study, we did not analyze any stratigraphic material.

Puquio Núñez and CH1 are located on top of the Altos de Pica Formation (upper Oligocene–lower Miocene). CH15 is partially buried by talus debris eroding off the Altos de Pica Formation. CH2, CH4, and CH5 occur on Late Pleistocene and Holocene fluvial terraces. QUI3 is situated on Pleistocene and Holocene alluvial fan deposits (Figure 3; Blanco & Tomlinson, 2013).

RESULTS

Lithic Technological Analysis

The analyzed assemblage consists of 426 lithic artifacts, of which 337 (88.5%) are knapping debitage, mostly flakes with no macroscopic signs of use. The rest of the assemblage corresponds to 39 tools (9.2%) and 10 cores (2.3%). Tools are mostly very simply retouched flakes ($n = 23$), but a few bifacial instruments or more elaborate items are identified ($n = 12$). Cores are also very simple, lacking a defined shape, and having unidirectional or multidirectional chipping, as well as mixed platforms (prepared and unprepared). It is interesting to note that

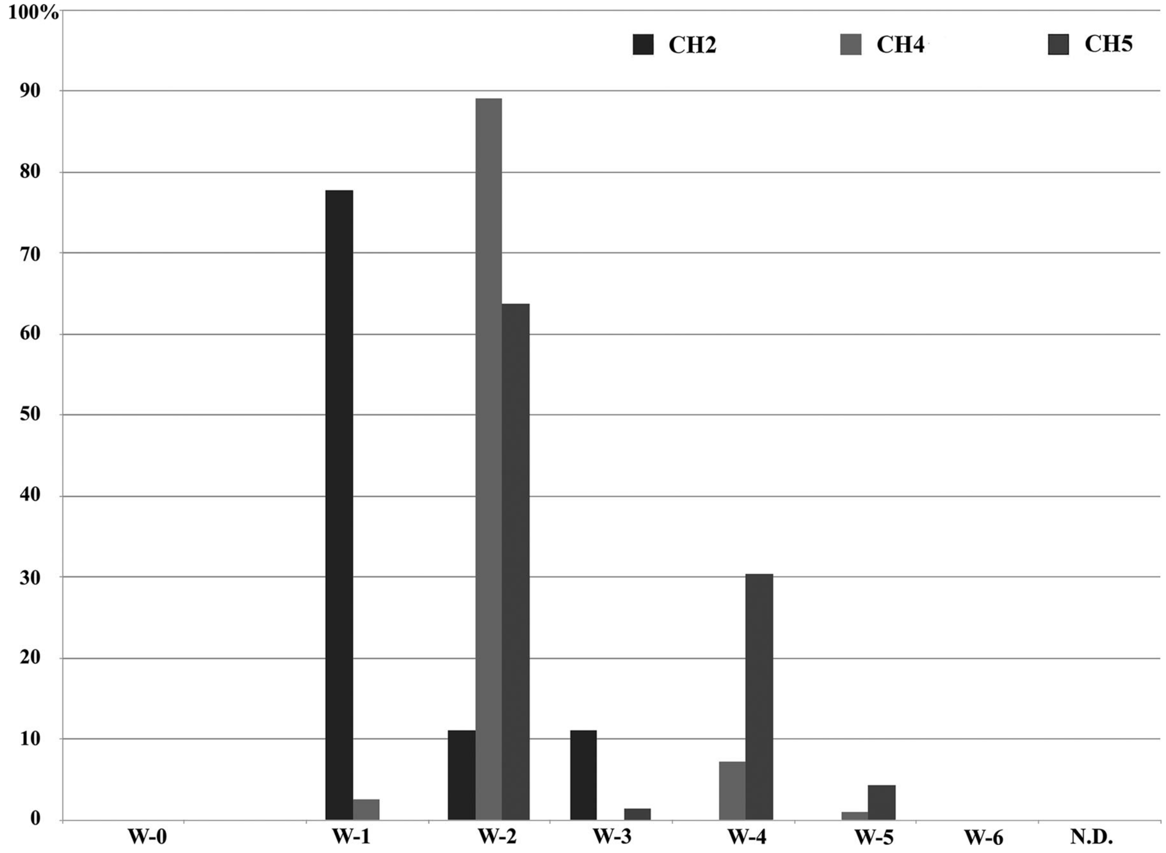

Figure 5 Weathering stages on a total of 271 samples collected from three canyon sites.

the clusters sampled at Puquio Núñez site could correspond to a series of technological stages of the lithic operational sequence: PQN23 extraction of primary or cortical flakes (highest percentage of primary flakes of the site = 37.5% vs. 62.5% of secondary flakes), PQN10 extraction of secondary flakes (7.4% of primary flakes vs. 92.6% of secondary flakes), and PQN3 initial tool manufacture (highest percentage of tools of the site = 22.2%, and 100% secondary flakes; Supplementary Table SI).

Weathering Patterns

The results suggest that for interfluve assemblages the three variables are positively and significantly correlated (polishing and texture, polishing and shine, and shine and texture are all significantly associated, $P < 0.01$). This implies that as edges and ridges are further polished, the artifact surfaces become shinier and smoother. The same does not occur for canyon assemblages, for which only shine and texture variables are positively and significantly correlated ($P < 0.01$), whereas polishing and shine are negatively correlated ($P < 0.01$; Supplementary Table SII).

The results of weathering analyses suggest that a threshold exists for which a change in the behavior of the ordinal scale occurs between Stages 3 and 4, particularly on the interfluve samples (Figures 6 and 7). We also note that weathering is apparent to the naked eye only from Stage 4 onwards. Stage 6 is composed of highly weathered lithics, sometimes associated with pitting (Figure 4g).

The relative frequencies of weathering stages for Chacarilla canyon and interfluve assemblages are shown in Figures 5–8. The sample from CH2 is the least weathered (Figure 5) and centers on Stage 1 (77.8%). CH4 is closer to Stage 2 (89.1%), as does its neighboring sample from CH5 (63.8%). CH5 also exhibits a large number of samples at Stage 4 (30.4%). Our results clearly indicate that canyon assemblages appear to be only mildly affected by eolian abrasion.

The relative frequencies of weathering stages for lithic assemblages from the Puquio Núñez site (Figure 6) exhibit a predominance of Stage 4. The distinctions between PQN3, PQN10, and PQN23 can be further understood in light of their context. PQN3 is associated with eolian sands, so it could have been repeatedly covered and

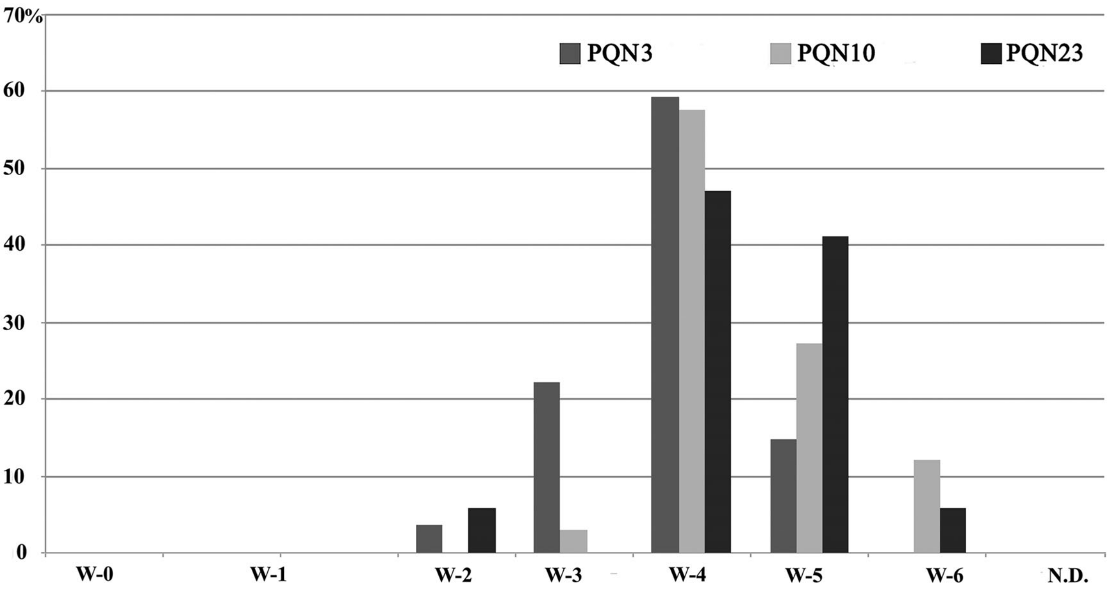

Figure 6 Weathering stages for interfluve lithic concentrations at the Puquio Núñez site (77 samples).

exposed over time. This could explain why 22.2% of the PQN3 artifacts center on Stage 3. In contrast, PQN10 is located on the western hill slope and subject to intense eolian abrasion, which would explain the high frequency of Stage 4 (57.6%), the almost complete absence of lightly weathered lithics, and the presence of artifacts at Stages 5 (W-5; 27.3%) and 6 (W-6; 12.1%). Likewise, PQN23 is atop a hill, the most exposed place to eolian abrasion in the site, and weathering stages observed are clearly very high: Stage 4 (47.1%), Stage 5 (41.2%), and Stage 6 (5.9%).

Finally, the relative frequencies corresponding to the other interfluve sites (QUI3 and CH1) are shown in Figure 7. Both sites exhibit assemblages ranging from

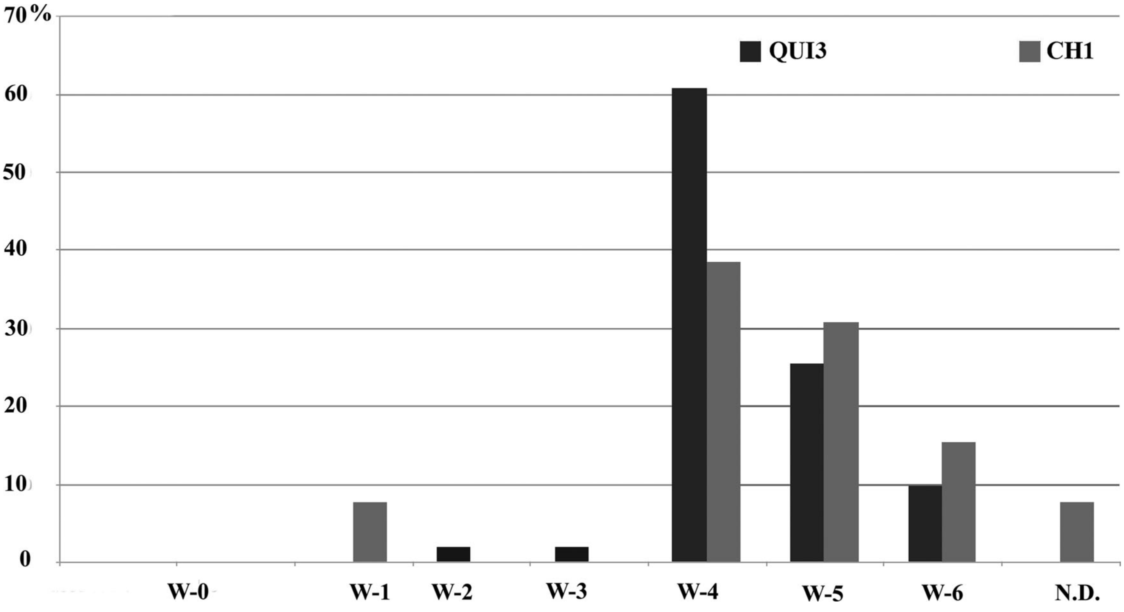

Figure 7 Weathering stages for interfluve sites QUI3 and CH1 (64 samples).

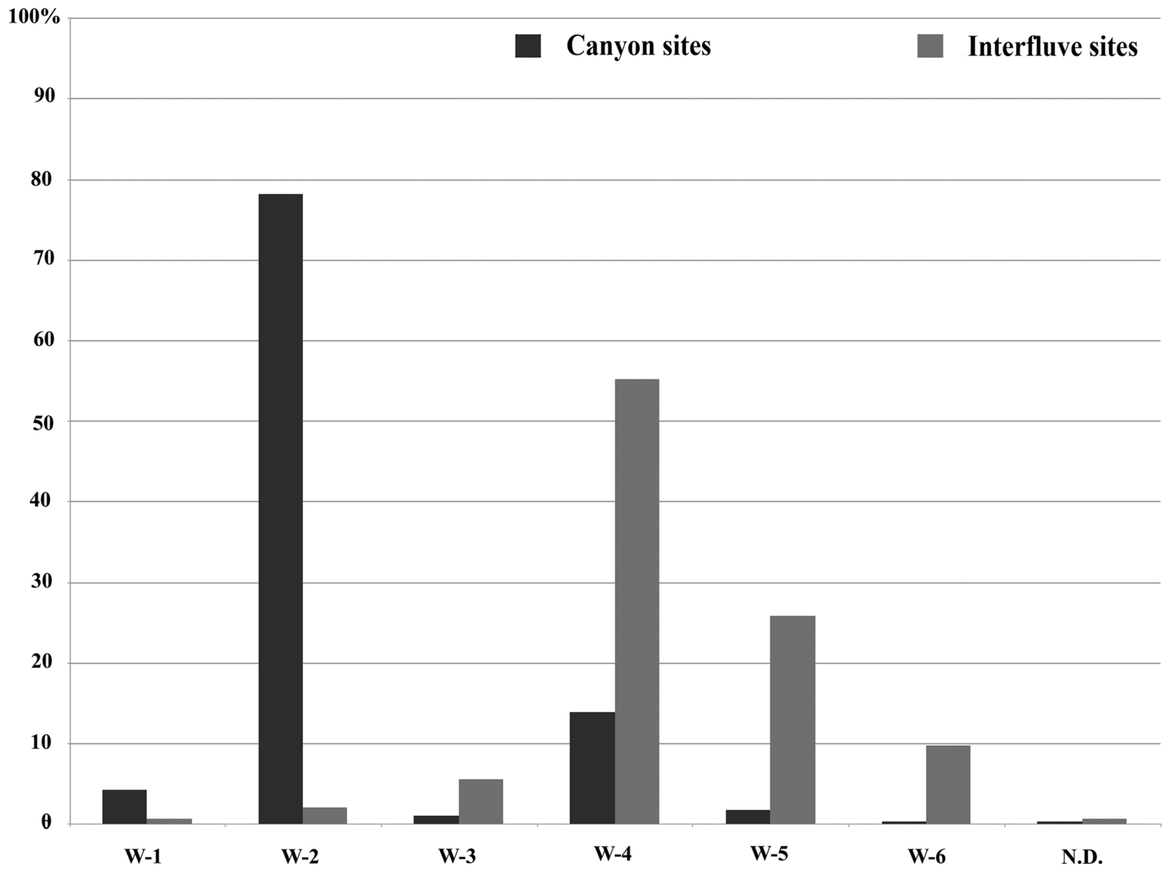

Figure 8 Weathering stages for canyon sites (285 samples) and interfluve sites (141 samples). Note: Figure includes 12 isolated artifacts near the canyon sites.

average to high weathering. QUI3 has 60.8% artifacts at Stage 4, 25.5% at Stage 5, and 9.8% at Stage 6, whereas Stages 2 and 3 have only 2% each. CH1 exhibits percentages of 38.5% for Stage 4, 30.8% for Stage 5, and 15.4% for Stage 6. Stage 1 is present, but with a low percentage (7.7%). The few lithics that are less weathered in both assemblages can be related to lithic production events of different ages within the CH1 and QUI3 sites or, alternatively, to circumstances of selective covering due to burial from shifting eolian sands.

The analyses presented so far show a trend toward increased eolian erosion for assemblages located on the interfluves, out of the canyons, whereas the assemblages within Chacarilla Canyon exhibit a lower degree of weathering (Figure 8). All assemblages, whether they were on the interfluves or within the canyons, were weathered to some extent, making it highly unlikely for any given lithic to not be affected by weathering. Thus, the absence of weathering (i.e., W-0) was not found in any of the assemblages. Even Stage 1 is low for both areas (4.2% inside and 0.7% outside the canyon), but the frequency of Stage 2 increases for sites within the canyon. Interfluve samples are predominant from Stage 3 onwards, and especially for the higher stages of weathering (W-5 and W-6).

Table IV Comparison between probable age and weathering medians for each sampled site.

Site	Site Microenvironment	Probable Age	Weathering Median
CH2	Canyon	Late Intermediate-Colonial	1
CH4	Canyon	Late Archaic to Late Period	2
CH5	Canyon	Late Archaic	2
CH15	Canyon	Late Archaic to Late Period	3
PQN3	Interfluve	Late Archaic to Late Period	4
PQN10	Interfluve	Late Archaic to Late Period	4
PQN23	Interfluve	Late Archaic to Late Period	4
QUI3	Interfluve	Late Archaic to Late Period	4
CH1	Interfluve	Undetermined	4,5

Weathering medians are presented in Table IV. Our results indicate that it is possible to distinguish between canyon and interfluve assemblages based on the degree of weathering. A Mann–Whitney *U*-test indicates that the difference in weathering among these two major assemblages is statistically significant, as the null hypothesis is rejected with 99% confidence ($P < 0.01$). Our data do not support significant weathering differences between artifacts from other microenvironments such as the rock shelter and near wetland sites. Results also show that interfluve lithic assemblages present similar medians of weathering among themselves.

DISCUSSION

Weathering and Microenvironments

The differentiation between interfluve and canyon assemblages indicates a strong relationship between some microenvironments and weathering type and intensity. This could be similar to what happens to soils (e.g., catena concept) where rates of pedogenesis vary due to microclimate and topography (Milne, 1947; Schaetzl & Anderson, 2006). Interfluve lithics are strongly associated with polishing of sharp edges and ridges and with a surficial darkening, which causes them to have a matte shine. For example, at the Puquio Núñez site, the original color of the ignimbrite was 2.5YR 5/2 (pale red), and it usually changes to 10YR 3/3 (dark brown), and 10YR 4/3 (brown-dark brown). According to these indicators, we propose that the interfluve assemblages are affected by eolian abrasion and, possibly, by rock varnish, which are common in desert environments and particularly on desert pavements. In the case of eolian abrasion, the lack of vegetation allows unhindered impact to lithic surfaces by the daily wind-borne sediment load. As far as rock varnish is concerned, this is known to form in different environments, but preservation is favored by surface stability in deserts (Dorn, 2007). The coexistence of eolian abrasion and rock varnish is an interesting topic because abrasion should destroy varnish. For example, after wind abrasion ceases on ventifacts in dryland glacial moraines, rock varnish and other rock coatings may develop over rock surfaces (Dorn, 1995). Wind is present in every desert, however, where varnish is also common. How these two processes balance each other is an open question that requires further research and is beyond the scope of this paper.

Polishing of sharp edges is rare in canyon lithics, and although changes in their original color (10R 4/1 dark reddish gray) occurred, they are often within color ranges containing red hues (e.g., 5YR 4/1 and 10YR 4/1, both dark gray), along with a brighter gloss. Thus, wind abrasion appears to be almost absent from Chacarilla Canyon. Why would the canyon microenvironment exhibit such low percentages of eolian abrasion? And why was rock varnish absent (or at least one that could be observed macroscopically, as it was for the interfluve lithics) given that silicified ignimbrite was analyzed in both cases? Other kinds of weathering may hold the answer, as white spots representing patinas were observed on the surface of a few canyon lithics. These patinas were not observed on any of the interfluve lithics examined, in spite of the occurrence of occasional winter fog (suggesting that this kind of moisture may not be frequent or intense enough to generate patinas). Vegetation and increased soil moisture along the valley floor in Quebrada Chacarilla could favor certain types of patina growth, albeit not enough to affect lithic artifact morphology through intense rind development. Vegetation also intercepts wind-borne sedimentary particles (Panizza, 1996), the intensity of which is further ameliorated by the deep and narrow Quebrada Chacarilla. Both factors can reduce eolian abrasion. In contrast, the lack of rock varnish on canyon lithics is possibly related to preservation as it forms readily on interfluve lithics. This means that other factors could be either inhibiting the formation of and/or removing varnish. For example, the predominance of fluvial deposition on the lower terrace of Chacarilla (Holocene) would have prevented a constant exposure of the lithics deposited there (site CH2), a necessary condition for varnish formation. The presence of soil moisture or past flooding events can also cause varnish removal or resetting (Dorn, 1998: 28, 2007; Liu & Broecker, 2008). Increased vegetation growth during wetter intervals in the Holocene along the fluvial terraces could have triggered surface instability and mixing of surface artifacts, which would have also prevented varnish formation (see Quade, 2001).

Weathering and Time

Different interfluve assemblages (Table IV) show equal median values of weathering. This suggests that those artifacts have been exposed to similar environmental conditions for more or less the same amount of time. Although the median values of lithic weathering on interfluvial surfaces are the same (W-4), the differences that do exist can be explained by location, burial, and partial uncovering of different assemblages at a site, or by the presence of lithics of different temporality at the same site (Figures 6 and 7). In the case of the lithic clusters from Puquio Núñez, the fact that they could belong to a series of technological stages of the lithic operational sequence, added to the similar weathering medians, indeed suggests similar exposure times, and provides further evidence for assemblage contemporaneity.

A relationship between the degree of weathering and age is also clear (Table IV), particularly when comparing CH2 to all the other sites. The slightly lower weathering rates in CH2 compared to other samples from the canyon can be explained either because CH2 site corresponds to a rock shelter, which provides more protected conditions compared to completely exposed sites, or because these are also younger artifacts from the Late Intermediate to Colonial period. As the chronology is relative and still preliminary, these comparisons must be refined with other lines of evidence.

Relevance for the Atacama and Other Deserts

This study implements a replicable (and of course perfectible) method for constructing an ordinal weathering scale by adapting previous approaches and using a combination of three different variables to assess the degree of weathering: polishing of sharp edges and ridges, texture, and shine. These variables are representative of widespread taphonomic effects seen in lithics in deserts all over the world. We have established how these three variables are positively correlated for the interfluve samples. This reinforces the hypothesis that wind is the major factor behind these changes in surficial lithics. We further point out that a comparison between the degree of weathering among archaeological lithic artifacts and "natural" clasts found in desert pavements (i.e., those deposited by geological processes) could prove useful in providing approximate age estimates for geomorphic surfaces. For example, contrary to what is observed in Old World deserts, such as in Israel (Matmon et al., 2009), current evidence indicates that the Atacama was peopled no earlier than the latest Pleistocene (~13 ka). Hence, depending on the degree of weathering between archaeological and geological samples, studies such as ours could provide either a maximum or a minimum age for desert pavement formation as well as evidence for surface stability. In our case, the sampled archaeological surface lithics were very likely deposited between 6000 and 500 cal. yr B.P., yet observations of "natural" clasts present in the interfluves surrounding our sites indicate that these are more extensively weathered than the archaeological artifacts. This implies that these desert pavements likely formed before 6000 cal. yr B.P. and that the areas altered by humans formed *de novo* after they abandoned the sites. This, of course, requires further studies that compare natural and archaeological samples.

CONCLUSIONS

There is a strong association between the presence of eolian abrasion on interfluve lithic assemblages and an overall lack of surface modification on stone artifacts in canyon sites. Obviously, interfluve sites are more exposed, but can this explain such a large difference in weathering? Since at least some of the canyon assemblages have been exposed to weathering for 6000–4000 yr (as in the case of CH5 from the Late Archaic), there is no *a priori* reason to expect differences between the interfluve and canyon sites. Based on our analyses, we propose two (nonexcluding) hypotheses to explain this differential weathering. First, wind intensity is a major driver of the differences in weathering degree and type, as it is less intense within a canyon than on the interfluves. Second, artifact burial for extended periods could explain the lack of rock varnish and also the diminished eolian abrasion observed in the canyon lithics. In contrast, the stability of desert pavements favors the preservation of surficial sites, the artifacts of which are constantly exposed to eolian erosion with the exception of the smallest (<2.5 cm), which tend to become incorporated into the Av horizon during pavement formation or healing (Adelsberger et al., 2013).

Can these assemblages be used to reconstruct a relative chronology or age sequence of artifacts based on their degree of surface alteration? Because of their extensive polishing and well-developed varnish, interfluve lithics would seem to be a better candidate for such sequences than canyon lithics. Despite minor differences in weathering intensities, interfluve lithics exhibit similar median values of weathering (Table IV), which may indicate that these assemblages have had analogous intervals of exposure under similar climatic conditions. If this were the case, these assemblages would-be comparable and a relative chronology could be defined. Age estimates should not be made when comparing lithics from canyon and interfluve sites as the taphonomic conditions, along with the different types and intensities of eolian abrasion and weathering, would create very dissimilar rates of artifact alteration. Hence, site emplacement, associated microenvironmental features, and taphonomic history are all strong determinants for the type and intensity of weathering exhibited by collected artifacts (see Sheppard & Pavlish, 1992, for a similar conclusion regarding chemical weathering). Our results suggest that relative chronological sequences can be constructed within specific localities based on artifact weathering, as long as they are complemented with other lines of evidence such as stratigraphy, technological features, typologies, and detailed knowledge of past environmental conditions. It is also advisable to explore the potential of weathering studies to visualize and comprehend taphonomic and site formation processes. For instance, for lithic materials from stratigraphic deposits, eolian abrasion indicators can be used to define sustained periods of surface exposure.

Finally, when surveying for surficial early sites, weathering intensity of artifacts and ecofacts should not be used as a proxy for age without previously establishing the depositional environment and taphonomic histories by using a weathering scale similar to the one developed here. Further taphonomic case studies will increase our understanding of the complex site formation histories associated with surficial and stratigraphic archaeological assemblages from northern Chile's Atacama Desert.

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