Quaternary International 619 (2022) 56–71

Contents lists available at ScienceDirect

Quaternary International

journal homepage: www.elsevier.com/locate/quaint

Comprehensive mapping and compositional analysis of the Alca obsidian source, Peru

Kurt Rademaker [a,*], Michael D. Glascock [b], David A. Reid [c], Ermitaño Zuñiga [d], Gordon R. M. Bromley [e]

[a] Michigan State University, East Lansing, MI, USA
[b] University of Missouri Research Reactor, Columbia, MO, USA
[c] University of Illinois at Chicago, Illinois, USA
[d] Independent Researcher, Chuquibamba, Peru
[e] National University of Ireland, Galway, Ireland

ARTICLE INFO

Keywords:
South America
Archaeological geology
Obsidian
Neutron activation analysis
X-ray fluorescence

ABSTRACT

The Alca obsidian source in southern Peru is one of the largest and most geochemically complex sources of volcanic glass in South America. Hunter-gatherers first discovered and used Alca obsidian for stone tools at the end of the Pleistocene. Alca later became one of the three most economically important and widely distributed sources of obsidian in the Central Andean region. Systematic mapping and geochemical characterization efforts spanning 20+ years have revealed an extensive high-elevation source region composed of six geographically and compositionally distinct sub-sources. Here we synthesize research documenting the 2000 km^2 spatial extent of the Alca obsidian source, and we present expanded geochemical datasets for six Alca sub-sources (n = 238 geologic samples) obtained using neutron activation analysis (NAA), laboratory x-ray fluorescence (XRF), and portable (p)XRF. Results for Alca and for six other obsidian sources in the Peruvian Andes illustrate the efficacy of these techniques to discriminate Peruvian obsidian sources, including Alca sub-sources. Comprehensive compositional data from the Alca source area, examined against accumulating obsidian artifact datasets from throughout Peru, reveal past human use of various Alca sub-sources. These cases contribute fine-grained behavioral information, made possible by a complex obsidian source with geographically patterned geochemical variation and a >12,000-year sequence of human interaction with this geologic resource.

1. Introduction

Compositional analysis of archaeological artifacts from throughout Peru has revealed a long sequence of human use of obsidian from various geologic sources for stone toolmaking. One of the first artifact characterization efforts, conducted in the 1970s, employed destructive neutron activation analysis (NAA) and energy-dispersive (ED) x-ray fluorescence (XRF) to 855 obsidian artifacts from nearly 100 archaeological sites spanning the past 12,000 years (Burger and Asaro, 1977, 1978, 1979). These efforts were designed to identify the number of geochemically distinct obsidian sources in the Peruvian Andes and, based on geographic clustering of artifacts with shared geochemistry, to suggest probable areas where geologic sources of obsidian would be located. Exploration of those areas could then pinpoint the location of source outcrops, the outcrops could be geochemically characterized and archaeologically studied to learn about extraction behavior, and geographic distributions of obsidian artifacts through time could reveal the evolution of Andean mobility and exchange systems.

The initial artifact characterization studies identified eight distinct sources of obsidian, though >80% of the samples derived from only three sources. The Quispisisa source supplied most of the analyzed obsidian from sites in central and northern Peru. Two other major sources, the Titicaca Basin Type and Cuzco Type, were named based on the geographic areas where artifacts of these obsidians were most prevalent. For example, over 90% of the analyzed flakes from the Cuzco valley were made of Cuzco Type obsidian, with relatively fewer artifacts of Cuzco Type identified in the Lake Titicaca Basin or other areas of the southern Peruvian highlands (Burger et al., 1998b). This systematic approach was highly effective for identifying region-scale geochemical groupings, though in general few samples per archaeological site were

* Corresponding author.
E-mail address: radem103@msu.edu (K. Rademaker).

https://doi.org/10.1016/j.quaint.2021.11.029
Received 13 September 2021; Received in revised form 29 November 2021; Accepted 30 November 2021
Available online 3 December 2021
1040-6182/

analyzed.

Over the next two decades, Burger and colleagues continued to analyze obsidian artifacts from archaeological sites while searching for the geologic sources (see references in Glascock et al., 2007). By 2000, the source areas for Peru's three largest obsidian sources had been discovered and characterized (Fig. 1). The Titicaca Type's source was located at 4950 m above sea level (masl) east of the town of Chivay in the department of Arequipa (Brooks et al., 1997; Burger et al., 1998a). Some ~140 km northwest of the Chivay source, the Cuzco Type's source was identified at 2850 masl near the town of Alca in the Cotahuasi valley (Burger et al., 1998b). The Quispisisa source was discovered at 3900 masl south of the town of Huanca Sancos in the department of Ayacucho (Burger and Glascock, 2000, 2002). Additional Peruvian obsidian sources have since been identified and characterized (Schreiber, 1992; Frye et al., 1998; Burger et al., 1998c, 2006, 2021; Burger and Glascock, 2001; Glascock et al., 2007; Craig et al., 2010; Giesso et al., 2020; Nesbitt et al., 2021).

If the identification of distinct obsidian sources using geochemical analyses of artifacts constituted a first phase of Central Andean provenance research, and the second phase involved discovery of the geologic sources, the third phase has been archaeological and geochemical studies of obsidian source regions. Tripcevich and colleagues carried out systematic mapping, archaeological investigation, and geochemical characterization of the Chivay (Tripcevich, 2010; Tripcevich and Mackay, 2011) and Quispisisa (Tripcevich and Contreras, 2011, 2013) source areas. At both sources these teams mapped and described primary and secondary outcrops, documented and sampled quarry pits, workshops, and roadways connecting to the sources, and conducted sampling and analysis to examine intra-source geochemical variation. Both source areas were mapped over considerable horizontal extent and elevation range. Chivay included >25 km^2 of obsidian exposures between 4700 and 5050 masl. Quispisisa spanned a 75 km^2 area, with a 20 km^2 core area containing 34 large quarry pits, attesting to extraction of large volumes of material. Yet, despite larger source areas and extensive sampling, analyses at each source demonstrated relatively little intra-source geochemical variation (*i.e.*, a single geochemical signature).

Investigation of Peru's third major source, Alca, has taken place over the past 20+ years by various teams, each describing different areas of the source region and providing geochemical datasets (Burger et al., 1998b; Jennings and Glascock, 2002; Tripcevich, 2007; Wasilewski, 2011; Rademaker et al., 2013). This cumulative research has documented Alca obsidian within an extensive, high-relief volcanic field in which multiple sub-sources, or geochemically distinct outcrops, are distributed. Here, drawing from these investigations by our team and others, we synthesize the geographic and geologic setting of the Alca source region and we present expanded geochemical datasets for Alca sub-sources (n = 238 geologic samples) obtained using NAA, laboratory ED-XRF, and portable (p)XRF.

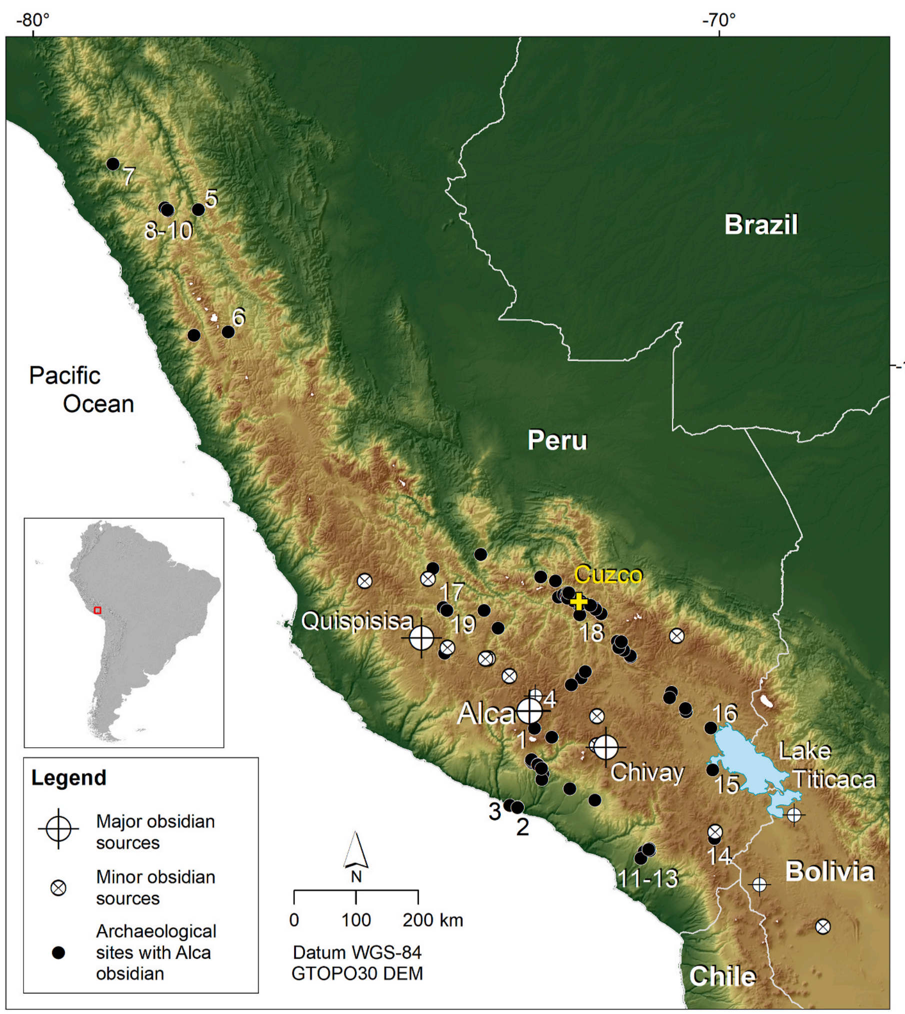

Fig. 1. Map showing major and minor Peruvian obsidian sources and archaeological sites containing Alca obsidian. The numbered sites are mentioned in the text: 1-Cuncaicha; 2-Quebrada Jaguay; 3-Pampa Colorada; 4-Wayñuna; 5-Manachaqui; 6-Chavín de Huántar; 7-Kuntur Wasi, 8-Cerro Amaru; 9-Huamachuco; 10-Marca Huamachuco; 11-Cerro Baúl; 12-Cerro Mejía; 13-Omo; 14-Quelcatani; 15-Incatunuhuiri; 16-Taraco; 17-Campanayuq Rumi; 18-Minaspata; 19-Yanawilka.

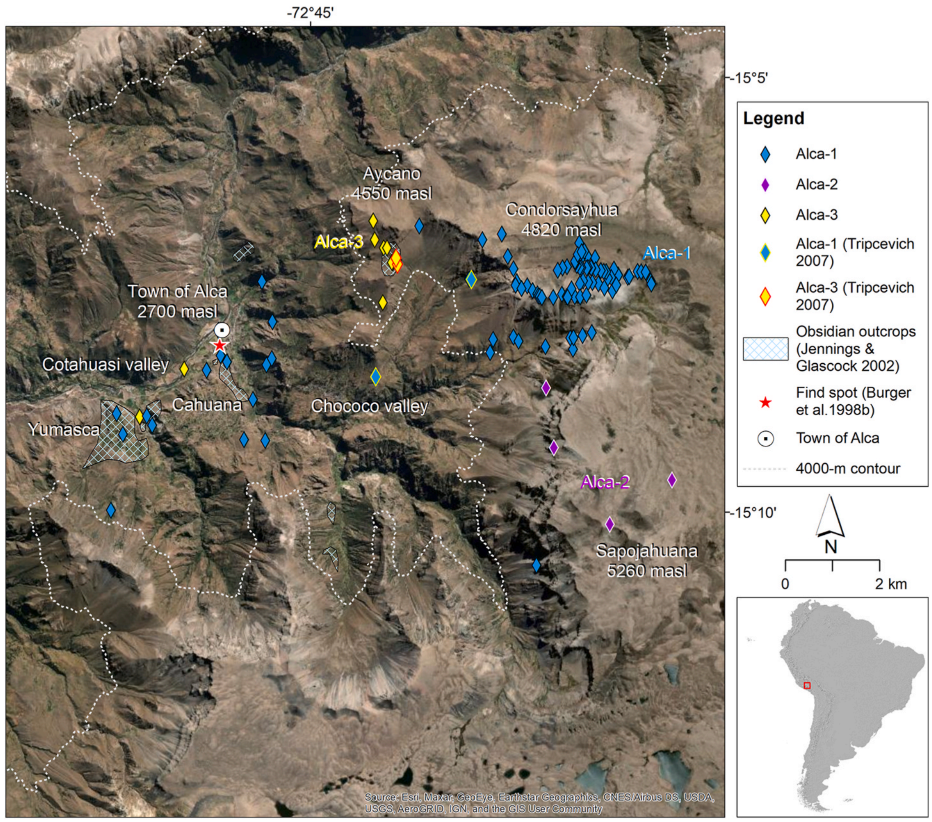

Fig. 2. Map of the Cotahuasi valley showing Alca obsidian sample locations reported in this study and previously published samples (Burger et al., 1998b; Jennings and Glascock, 2002; Tripcevich, 2007).

2. History of investigations of the Alca source

Burger et al. (1998b) published the first study of the geologic source of Cuzco Type obsidian using samples collected near the town of Alca in the Cotahuasi valley of Arequipa. The first samples were collected respectively near the towns of Yumasca (2900 masl) and Cahuana (3500 masl), ~200–800 m above the Cotahuasi River (Fig. 2). These samples were obsidian nodules from a cliff face of poorly consolidated volcanic tuff, with obsidian also observed in talus at the base of the cliff. The obsidian included black, brown, red, and multicolored nodules typically 20 cm but up to 60 cm in diameter. Short- and long-count NAA conducted at Lawrence Berkeley National Laboratory confirmed that the five geologic samples from Cahuana and Yumasca were geochemically identical and matched artifacts of the Cuzco Type (Table 1) (Burger et al., 1998b).

Jennings (2002) identified additional obsidian outcrops around the town of Alca between 2600 and 4200 masl as part of an archaeological survey of the upper Cotahuasi valley. Only limited areas above 4000 masl and >4 km from the Cotahuasi River were visited. These efforts documented two obsidian-bearing strata, a lower stratum from the valley floor to 3300 masl described as a volcanoclastic flow and an overlying stratum of tuff with rare obsidian extending to 4300 masl. Jennings mapped and sampled 16 distinct exposures containing obsidian nodules from 5 to 30 cm in size. These outcrops were distributed within an area of ~50 km^2 in the lower elevations of the Cotahuasi valley and the west-draining Chococo tributary drainage that joins the Cotahuasi River at the town of Alca (Fig. 2). Local residents mentioned that large obsidian deposits existed at the headwaters of the Chococo River, though Jennings did not visit the area (Jennings, 2002).

Jennings and Glascock (2002) reported short- and long-count NAA results from the University of Missouri Research Reactor (MURR) for 34 obsidian samples collected from six outcrops (Table 1). The

Table 1
Published geochemical datasets for the Alca obsidian source.

Reference	ED-XRF	NAA	WD-XRF	pXRF	n = geologic samples	Alca sub-sources
Burger et al., 1998c		5			5	Alca
Jennings and Glascock (2002)		34			34	Alca-primary, Alca-X, Alca-Y
Tripcevich (2007)		5			5	Alca-1, Alca-3
Wasilewski (2011)	18	13			31	Alca-1, Groups 1-6
Rademaker et al. (2013)	252	33	66	35	258	Alca-1, Alca-2, Alca-3, Alca-4, Alca-5, Alca-7
Current study	*53	23		*230	238	Alca-1, Alca-2, Alca-3, Alca-4, Alca-5, Alca-7
Total analyses = 767	**323**	**113**	**66**	**265**		

* Include new analyses of 34 geologic samples previously analyzed with ED-XRF.
** Include new analyses of 35 geologic samples previously analyzed with pXRF (Rademaker et al., 2013).

compositions of 30 samples matched the geologic samples analyzed by Burger et al. (1998b). The other four samples indicated two distinct geochemical signatures. The 30 samples matching Burger's samples were referred to as "Alca-primary," and two samples each collected from ~3350 masl defined provisional Alca-X and Alca-Y sub-sources. The two Alca-X samples came from a slope just north of the town of Alca. The two Alca-Y samples were collected from an outcrop on the south side of the Chococo River. This work indicated a larger extent of the Alca obsidian source and hinted at geochemical variation within the source region, though the spatial distribution of the three geochemically distinct sub-sources remained unknown.

In 2001 Tripcevich explored east into the Chococo valley to Cerro Aycano, a pyramid-shaped peak northeast of the town of Alca. He collected five obsidian samples, including one from 3760 masl north of the Chococo River and two from 4200 masl on a slope below Cerro Condorsayhua. Tripcevich also collected two obsidian samples at ~4300 masl from tuff exposed in a landslide scar on the ridgeline of Cerro Aycano (Fig. 2). The five samples were analyzed with NAA at MURR (Table 1). The Cerro Aycano samples provided a match with the Alca-X sub-source that Jennings and Glascock (2002) had identified. The other three samples matched the Alca-primary source (Tripcevich, 2007).

Building on these efforts, beginning in 2004 Rademaker explored east from the town of Alca to the headwaters of the Chococo River and collected obsidian samples for characterization using Electron Probe Microanalysis at the University of Maine and Laser Ablation-Inductively Coupled Plasma-Mass Spectrometry (LA-ICP-MS) at the Field Museum Elemental Analysis Facility. Above 4000 masl obsidian became abundant in tuff deposits with increasing elevation, extending to the 4830 masl summit of Cerro Condorsayhua, an eroded rhyolite dome (Fig. 2). Obsidian exposures here exceeded 400 ha, with angular blocks and nodules of obsidian up to and exceeding 50 cm. Nearly all of the 102 samples analyzed appeared to match the Alca-primary sub-source, indicating its bedrock outcrop was Cerro Condorsayhua. A few obsidian samples collected from tuff outcrops on Cerro Aycano exhibited a distinct geochemistry. Unfortunately, comparison of compositional data between LA-ICP-MS and NAA proved challenging, and integrating the new and previous datasets had to await additional analysis (Rademaker, 2006). At this point three geochemically distinct Alca sub-sources were known and numbered: Alca-1 (Alca-primary) (Glascock et al., 2007) with bedrock outcrops at Cerro Condorsayhua, Alca-2 (Alca-X) whose primary bedrock outcrops remained unidentified, and Alca-3 (Alca-Y) with primary outcrops at Cerro Aycano.

Meanwhile, in 2004–2005 Wasilewski conducted a geo-archaeological survey in the Andagua valley, also known as the Valley of the Volcanoes, southeast of the Cotahuasi valley (Fig. 3). This project's goal was to map and characterize obsidian deposits in the northern, upper portion of the valley and surrounding plateau. Wasilewski collected 18 geologic samples from eight locations for ED-XRF (n = 18) and NAA (n = 13) at MURR (Table 1). The geologic outcrops were described as discontinuous layers of nodules up to 12 cm or as small <8-cm pebbles and gravels in colluvium. One notable exception was a 20-cm angular obsidian block found below Cerro Mesani in the upper valley. The block and some of the other geologic samples matched Alca-1. The remaining 10 analyses defined six geochemical groups that did not match any obsidian sources known at that time (Wasilewski, 2011).

Between 2006 and 2012, Rademaker and colleagues characterized previously analyzed and new samples using wavelength-dispersive (WD)-XRF at the University of Maine-Farmington and ED-XRF and NAA at MURR. The new samples were collected in the Cotahuasi valley near the town of Alca, at Cerro Aycano, at the rim of the plateau east of the Cotahuasi valley (Fig. 2), and on the plateau ~20–40 km south of Cerros Aycano and Condorsayhua (Fig. 3). Direct comparisons between the new and previously published analyses (Burger et al., 1998b; Jennings and Glascock, 2002; Tripcevich, 2007) were now possible. These efforts located the bedrock outcrop for the Alca-2 sub-source, mapped Alca-1 and other obsidian in ignimbrites in the Pucuncho Basin, and

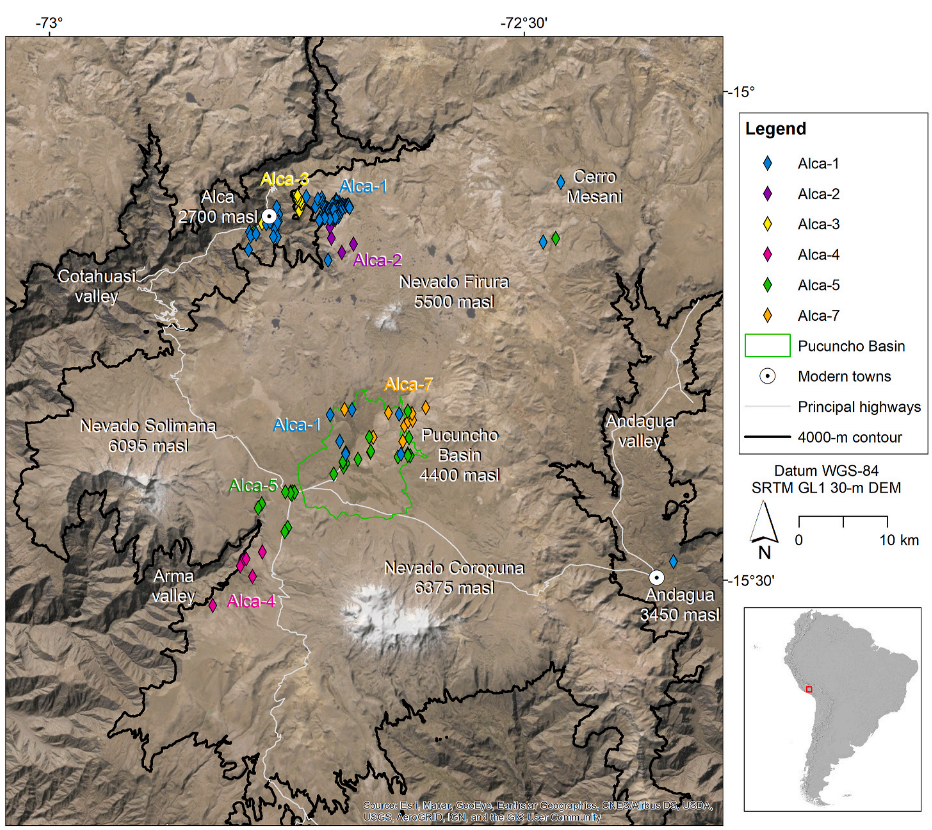

Fig. 3. Map showing all Alca obsidian sample locations. Samples at right (east) side of map from Wasilewski (2011).

identified three new sub-sources (Alca-4, Alca-5, Alca-7) (Table 1). A provisional sub-source, Alca-6, had samples interspersed within the large Condorsayhua Alca-1 outcrops, so Alca-6 was subsumed within the Alca-1 sub-source. Rademaker et al. (2013) integrated these new data with previous work, but unfortunately we were unaware of Wasilewski's (2011) publication on obsidian in the Valley of the Volcanoes.

It was unknown whether expanded NAA and XRF data for additional geologic samples would broaden the known ranges of element concentrations for each Alca sub-source. Moreover, since our 2013 publication, Peru's Institute of Geology, Mining, and Metallurgy (Instituto Geológico Minero y Metalúrgico, or INGEMMET), made available online a revised surficial geologic mapping of the study region (Lajo Soto et al., 2001a, 2001b; Salas et al., 2003). Considered along with geologic mapping and dating efforts by tephrachronologists (Thouret et al., 2016, 2017), the new mapping and geochronologic data now permit a more complete understanding of the spatial extent and age of formation of the Alca obsidian source. At the same time, the patterned geochemical variation documented within the Alca source region has enabled artifacts of various Alca sub-sources to be identified via NAA, ED-XRF, and pXRF at archaeological sites of various time periods throughout Peru (Matsumoto et al., 2018; Hu and Shackley, 2018; Belisle et al., 2020). For these reasons, a more detailed description of the Alca source region and comprehensive geochemical datasets from NAA, XRF, and pXRF are warranted here.

3. Materials and methods

3.1. Field investigations

Rademaker, Reid, and Bromley systematically mapped and sampled Alca obsidian outcrops in the Cotahuasi valley and on the volcanic plateau during pedestrian surveys between 2004 and 2015. Many of the highland plateau areas were explored while conducting glacial geologic and archaeological investigations. Samples were collected judgmentally from surfaces of bedrock outcrops, talus, and secondary fluvial and glaciofluvial deposits. Geographic coordinates for samples were collected with a Trimble global positioning system (GPS), which allowed sample locations to be examined against satellite imagery, INGEMMET geologic maps, and local ignimbrite maps, descriptions, and radiometric ages published by Thouret et al. (2007). Geologic surveys were carried out iteratively in phases, aided by geographic information systems (GIS) and steadily accumulating geochemical analyses. A native of the town of Mauca Llacta in the Pucuncho Basin, Zuñiga discovered new exposures of Alca obsidian and contributed samples. His knowledge of the plateau and surrounding valleys came from leading regular long-distance mule caravan expeditions to transport goods between communities at various elevations in the project area.

Field survey within the Cotahuasi valley targeted the river floodplain north and east of the town of Alca and hillslopes east of the Cotahuasi River accessible by roads and footpaths. The natural topography is rugged, and most land surfaces below 4000 masl have been extensively modified by pre-Hispanic terrace construction and are under cultivation. In these areas, surveys followed drainage systems and ridgelines. Unmodified landforms are more prevalent above 4000 masl.

The high-elevation plateau has little vegetation cover and excellent surface visibility, and distributions of samples (Figs. 2 and 3) accurately reflect the limits of bedrock outcrops. We extended pedestrian surveys outward from outcrops where obsidian was the dominant surface lithology until it was absent. We also explored the plateau from the Cerro Condorsayhua and Nevado Sapojahuana rhyolite domes south to the Pucuncho Basin in an area bounded by the main highway and Nevado Firura (Fig. 3). Additional surveys transected the plateau from the Pucuncho Basin along the north margin of Nevado Coropuna, west of Nevado Coropuna to the Arma River, and southwest of Nevado Coropuna to areas below the 4000-m elevation contour. We did not survey the plateau east of Cerro Condorsayhua, Nevado Firura, Pucuncho Basin, and Nevado Coropuna toward the Andagua valley.

3.2. Neutron activation analysis

Glascock analyzed geological samples with NAA using procedures described briefly here. For more complete descriptions of the analytical procedures see Glascock et al. (1998). All samples were prepared by removing two small portions from each sample for short and long irradiation procedures routinely employed by the Archaeometry Lab at MURR. For short irradiations, 100 mg of sample material was irradiated in a neutron flux of 8×1013 n cm^{-2} s^{-1} for 5 s, allowed to decay for 25 min, and counted for 12 min to measure the short-lived elements Al, Cl, Dy, K, Mn, and Na. For long irradiations, 200 mg of sample material was irradiated using a neutron flux of 6×1013 n cm^{-2} s^{-1} for 70 h. The long irradiation samples were measured twice – after seven days for 30 min each and after 21 days for 2.5 h each. The long-lived elements measured were Ba, Ce, Co, Cs, Eu, Fe, Hf, La, Lu, Nd, Rb, Sb, Sc, Sm, Sr, Ta, Tb, Th, U, Yb, Zn, and Zr. The standard for all analyses was SRM-278 Obsidian Rock.

3.3. Laboratory ED-XRF

Glascock analyzed 53 Alca geologic samples using a Thermo Quantx ARL lab-based XRF spectrometer. The instrument has a rhodium-based X-ray tube which we operated at 35 kV in the mid-Zc mode. The X-rays passed through a thick Pd filter and 3 mm collimator before arrival at the sample position. Samples were mounted on a 20-sample tray and counted for 60 s each by a silicon diode detector (SDD) to measure the emitted X-rays for the following elements Mn, Fe, Zn, Rb, Sr, Y, Zr, Nb, and Th.

The instrument was calibrated for obsidian by measuring a set of 40 very well-characterized obsidian source samples from geologic sources around the world. The data for calibration were acquired from analyzing the source samples by NAA, ICP-MS, and XRF. Correction for matrix effects from absorbance and secondary emission were made to establish the best calibration curves for each element. For more information, see Glascock (2020).

3.4. Portable XRF

In December 2018 Rademaker analyzed 230 Alca geologic samples collected between 2004 and 2015. Some of these samples were previously analyzed by NAA, WD-XRF, ED-XRF, pXRF, or several of these techniques (Rademaker et al., 2013). Twenty samples previously analyzed via destructive techniques were completely consumed and could not be re-analyzed. A Bruker Titan S1 was used with the following instrument settings: 50 kv, 35 μa, a filter of 75 μm Cu, 25 μm Ti, and 200 μm Al (corresponding to the green filter on Bruker Tracer models), and a 30-s analysis time. Rademaker additionally analyzed geologic samples from other major Peruvian obsidian sources.

Calibration of pXRF photon counts to part per million (ppm) concentrations is based on measurement of the same 40 obsidian specimens used in laboratory XRF calibration (see above) (Glascock and Ferguson, 2012) and evaluated by Speakman (2012). Rademaker analyzed this set of 40 obsidian "standards" using this same Bruker Titan S1 instrument to produce the specific obsidian calibration for this instrument.

Relative standard deviation (RSD) of repeat measurements of an obsidian geologic sample provides a measure of variance, which may include intra-sample geochemical variation and instrumental variance (precision). To evaluate the latter, repeat analyses of the same spot were collected every 10 min on a single geologic hand specimen of Alca obsidian without moving the sample or the instrument over a 3.5-h period, longer than a typical analysis session. The resulting RSD of these 20 measurements for each element provides an estimate of variance due to instrumental fluctuation.

4. Results

4.1. Field mapping

Figs. 2 and 3 show the locations of 280+ Alca geologic samples our team collected from bedrock, talus, ignimbrites, and secondary glacio-fluvial deposits, as well as previously published samples by others (Burger et al., 1998b; Jennings and Glascock, 2002; Tripcevich, 2007; Wasilewski, 2011). We can assign all of these to six Alca sub-sources based on geochemical results discussed below.

4.2. Neutron activation analysis

Previously, Rademaker et al. (2013) reported NAA results for 33 Alca samples representing six sub-sources, though four of the sub-sources had smaller than optimal sample sizes. This study adds 23 new samples to the Alca NAA dataset (Table 1). Table 2 reports NAA mean element concentrations for each Alca sub-source. Individual sample data are presented in Table S1. Fig. 4 plots NAA measurements for the 56 Alca source samples against those for other Peruvian obsidian sources. Mn and Ba concentrations obtainable via short NAA can distinguish some but not all of the Alca sub-sources. Long NAA provides concentrations for multiple trace and rare earth elements that distinguish all six sub-sources from each other and from other Peruvian obsidians. Some of the best elements for discriminating the Alca sub-sources are Fe, Rb, Zr, Cs, Hf, Eu, and Th.

4.3. Laboratory ED-XRF

Rademaker et al. (2013) reported MURR Elva-X ED-XRF concentrations for 252 Alca geologic samples representing six sub-sources. For this study new ED-XRF analyses of 53 Alca geologic samples were obtained with the Thermo Quantx ARL spectrometer. These samples were contributed by Jennings (n = 12) and Rademaker (n = 41). Table 3 summarizes Quantx XRF mean element concentrations for each Alca sub-source and for 72 geologic samples representing other Peruvian obsidians. Individual sample data are presented in Table S2. Fig. 5 plots QuantxXRF measurements for the Alca sub-sources and other Peruvian obsidian sources. The best discriminating elements measured by XRF include Rb, Sr, Y, and Zr. All 37 Alca geologic samples measured with either NAA or pXRF in addition to Quantx XRF produced the same sub-source assignments.

4.4. Portable XRF

The pXRF results include 248 analyses of Alca samples, one for each of 230 geologic samples and 18 replicate analyses. Fourteen other Alca geologic samples were either devitrified, too thin, or had poor geometry that limited contact with the instrument sensor. These analyses were discarded. In addition to the Alca samples, we obtained 44 analyses on samples from the Quispisisa (n = 18), Jampatilla (n = 6), Potreropampa (n = 5), Lisahuacho (n = 5), Chivay (n = 6), and Anillo (n = 4) sources. Table 4 summarizes pXRF mean element concentrations for each Alca sub-source and for the other Peruvian obsidians. Individual sample data are presented in Table S3. Table S4 reports precision. Fig. 6 plots pXRF measurements for the Alca sub-sources and other Peruvian obsidian sources. The best discriminating elements measured by pXRF include Rb, Sr, Y, and Zr. All 45 Alca geologic samples measured with both NAA and pXRF produced the same sub-source assignments.

4.5. Description and spatial patterning of the Alca obsidian source

Integrating the geochemical and geographic data compiled for the Alca source, there is clear spatial patterning of distinct sub-sources. This section describes each Alca sub-source, followed by a summary of geologic data bearing on the spatial patterning and geomorphic history of the source region.

Table 2
Mean element concentrations (ppm) measured by NAA. n = number of geologic samples.

Source	Alca-1	Alca-2	Alca-3	Alca-4	Alca-5	Alca-7
n =	17	7	9	12	9	8
Element	mean ± 1σ	mean ± 1σ	mean ± 1σ	mean ± 1σ	mean ± 1σ	mean ± 1σ
Na (%)	3.08 ± 0.10	3.28 ± 0.06	3.26 ± 0.05	3.23 ± 0.06	3.14 ± 0.06	2.91 ± 0.03
Al (%)	7.07 ± 0.30	7.76 ± 0.30	7.53 ± 0.30	7.27 ± 0.20	7.22 ± 0.18	7.09 ± 0.35
Cl	575 ± 71	555 ± 63	603 ± 34	401 ± 53	538 ± 68	423 ± 29
K (%)	3.75 ± 0.31	3.50 ± 0.18	3.31 ± 0.16	3.04 ± 0.12	3.56 ± 0.16	3.56 ± 0.24
Sc	1.78 ± 0.02	2.01 ± 0.02	1.86 ± 0.02	1.83 ± 0.02	1.76 ± 0.03	1.84 ± 0.02
Mn	473 ± 7	456 ± 16	563 ± 7	558 ± 7	480 ± 4	456 ± 8
Fe (%)	0.546 ± 0.007	0.777 ± 0.057	0.806 ± 0.007	0.585 ± 0.016	0.536 ± 0.016	0.495 ± 0.004
Co	0.26 ± 0.05	0.48 ± 0.09	0.51 ± 0.06	0.37 ± 0.06	0.14 ± 0.02	0.32 ± 0.01
Zn	43.7 ± 2.2	47.9 ± 2.3	47.4 ± 2.2	38.2 ± 1.5	41.8 ± 1.8	31.9 ± 0.8
Br	1.74 ± 0.27	1.78 ± 0.39	1.58 ± 0.19	1.03 ± 0.18	1.73 ± 0.11	0.85 ± 0.23
Rb	137 ± 2	145 ± 3	128 ± 1	107 ± 1	131 ± 2	158 ± 2
Sr	101 ± 14	218 ± 47	280 ± 18	199 ± 19	134 ± 10	184 ± 19
Zr	116 ± 8	188 ± 31	166 ± 6	103 ± 6	112 ± 9	114 ± 7
Sb	0.17 ± 0.01	0.14 ± 0.01	0.27 ± 0.01	0.39 ± 0.01	0.16 ± 0.00	0.36 ± 0.02
Cs	2.79 ± 0.04	2.72 ± 0.07	3.42 ± 0.05	2.69 ± 0.03	2.82 ± 0.06	4.93 ± 0.08
Ba	1002 ± 11	961 ± 20	1031 ± 15	1042 ± 25	1014 ± 18	810 ± 13
La	29.4 ± 0.8	43.4 ± 1.1	37.1 ± 0.5	24.0 ± 0.4	31.4 ± 1.7	30.9 ± 0.3
Ce	58.3 ± 1.3	80.7 ± 2.0	69.4 ± 0.8	45.8 ± 0.6	62.3 ± 3.0	56.6 ± 0.6
Nd	19.7 ± 1.1	26.2 ± 1.9	22.8 ± 0.7	15.7 ± 1.1	20.8 ± 0.9	18.3 ± 0.8
Sm	3.57 ± 0.04	4.22 ± 0.04	3.82 ± 0.04	2.80 ± 0.04	3.64 ± 0.07	3.34 ± 0.05
Eu	0.50 ± 0.01	0.65 ± 0.02	0.70 ± 0.01	0.49 ± 0.01	0.57 ± 0.02	0.47 ± 0.01
Tb	0.35 ± 0.01	0.36 ± 0.01	0.38 ± 0.01	0.29 ± 0.01	0.35 ± 0.01	0.34 ± 0.01
Dy	2.02 ± 0.22	2.11 ± 0.14	2.11 ± 0.29	1.65 ± 0.16	1.96 ± 0.20	2.13 ± 0.16
Yb	1.09 ± 0.05	1.23 ± 0.05	1.31 ± 0.04	0.98 ± 0.02	1.08 ± 0.03	1.21 ± 0.05
Lu	0.17 ± 0.02	0.21 ± 0.04	0.20 ± 0.01	0.16 ± 0.03	0.15 ± 0.01	0.18 ± 0.08
Hf	3.59 ± 0.07	5.09 ± 0.40	4.67 ± 0.07	3.07 ± 0.06	3.31 ± 0.13	3.07 ± 0.07
Ta	0.94 ± 0.01	0.97 ± 0.02	0.90 ± 0.01	0.67 ± 0.01	0.93 ± 0.02	1.14 ± 0.02
Th	13.7 ± 0.2	16.3 ± 0.3	13.7 ± 0.1	7.9 ± 0.1	13.8 ± 0.2	16.8 ± 0.2
U	3.41 ± 0.13	3.91 ± 0.24	3.31 ± 0.12	2.03 ± 0.21	3.61 ± 0.09	4.69 ± 0.19

4.5.1. Alca-1 (2720–4830 masl)

Alca-1 is the sub-source with the broadest exposure and the largest bedrock outcrops owing to explosive and effusive phases and extensive erosion. It is mapped in the rhyolite dome at Cerro Condorsayhua and as pyroclastic material below Condorsayhua in the Chococo and Cotahuasi valleys near the town of Alca, 30 km to the south of Condorsayhua in the Pucuncho Basin, and east of Condorsayhua in the Andagua valley

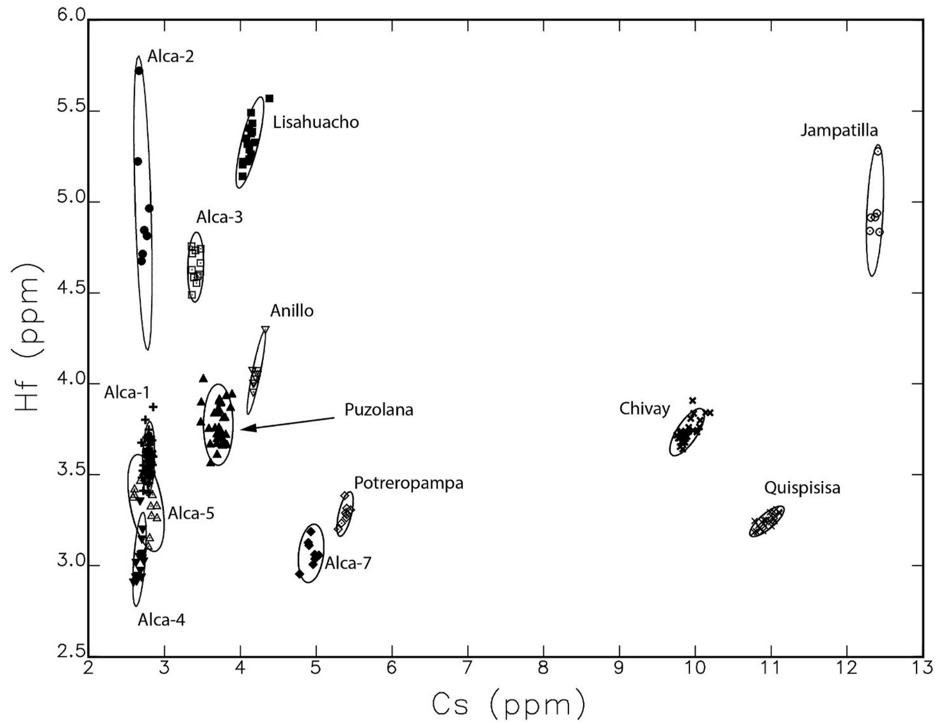

Fig. 4. Scatterplot of NAA results for Cs and Hf showing the major obsidian sources in Peru. Confidence ellipses are 90%. Figure drawn by M.D. Glascock.

Table 3
Mean element concentrations (ppm) measured by ED-XRF. n = number of geologic samples.

Source	Alca-1	Alca-2	Alca-3	Alca-4	Alca-5	Alca-7
n =	26	2	7	9	7	2
Element	mean ± 1σ	mean ± 1σ	mean ± 1σ	mean ± 1σ	mean ± 1σ	mean ± 1σ
Mn	477 ± 43	409 ± 46	535 ± 44	520 ± 28	494 ± 33	473 ± 22
Fe (%)	0.545 ± 0.021	0.672 ± 0.007	0.787 ± 0.022	0.555 ± 0.009	0.540 ± 0.017	0.493 ± 0.005
Zn	45 ± 3	49 ± 0	50 ± 3	40 ± 3	48 ± 2	33 ± 3
Rb	134 ± 3	137 ± 1	125 ± 2	102 ± 2	128 ± 2	152 ± 5
Sr	74 ± 3	149 ± 24	231 ± 5	146 ± 3	110 ± 6	131 ± 1
Y	13 ± 1	15 ± 1	14 ± 1	10 ± 1	12 ± 0	15 ± 1
Zr	89 ± 7	146 ± 6	156 ± 3	82 ± 3	77 ± 9	70 ± 2
Nb	12 ± 1	13 ± 1	12 ± 1	11 ± 1	12 ± 1	11 ± 1
Th	14 ± 1	16 ± 0	14 ± 1	8 ± 1	14 ± 1	16 ± 1

Source	Quispisisa	Jampatilla	Potreropampa	Lisahuacho	Chivay	Anillo	Puzolana
n =	17	6	9	9	22	4	5
Element	mean ± 1σ	mean ± 1σ	mean ± 1σ	mean ± 1σ	mean ± 1σ	mean ± 1σ	mean ± 1σ
Mn	365 ± 33	537 ± 39	497 ± 46	431 ± 27	730 ± 77	505 ± 89	645 ± 88
Fe (%)	0.552 ± 0.022	0.859 ± 0.027	0.463 ± 0.014	0.855 ± 0.014	0.509 ± 0.026	0.638 ± 0.031	0.592 ± 0.082
Zn	34 ± 2	55 ± 2	37 ± 2	57 ± 2	41 ± 3	46 ± 2	38 ± 7
Rb	167 ± 4	147 ± 3	157 ± 3	148 ± 3	241 ± 7	163 ± 10	125 ± 12
Sr	121 ± 3	288 ± 8	72 ± 2	298 ± 4	39 ± 2	153 ± 9	51 ± 3
Y	15 ± 1	26 ± 1	17 ± 1	14 ± 1	28 ± 1	16 ± 1	10 ± 1
Zr	84 ± 2	165 ± 3	63 ± 3	175 ± 6	70 ± 2	115 ± 3	92 ± 3
Nb	11 ± 1	18 ± 1	16 ± 1	16 ± 1	21 ± 1	14 ± 1	29 ± 1
Th	19 ± 2	11 ± 1	17 ± 1	17 ± 1	25 ± 1	19 ± 2	17 ± 1

(Figs. 2 and 7). The south and west edges of Condorsayhua are extensively eroded, with 800 m of obsidian talus extending to the valley floor. Below and north of Condorsayhua's summit, the surface of the eroding rhyolite dome is exposed in an east-west trough. Fractured angular and sub-rounded obsidian fragments up to 30 cm form a pavement on hillslopes and in channels. Obsidian occurs as black, banded, clear, gray, and mottled mahogany, maroon, and red colors and is of variable but generally exceptional quality for knapping.

We documented concentrations of flakes, presumably workshops, but we lacked sufficient time to study these features thoroughly. Along the summit ridge we found extracted nodules and manuported quartzite hammerstones and a stick apparently used to pry large fragments free of the sediment matrix. A more detailed study of associated workshops, quarry pits, camelid corrals, and roadways to examine extraction behavior remains an important avenue for future research at the Condorsayhua locale. Alca-1 obsidian southwest of Condorsayhua is less frequent and occurs as smaller clasts below 4000 masl toward the Cotahuasi River at 2720 masl. Small (<5-cm) sub-rounded obsidian pebbles are present on the river floodplain near the Chococo-Cotahuasi confluence to about 1 km downstream of the town of Alca. Survey along

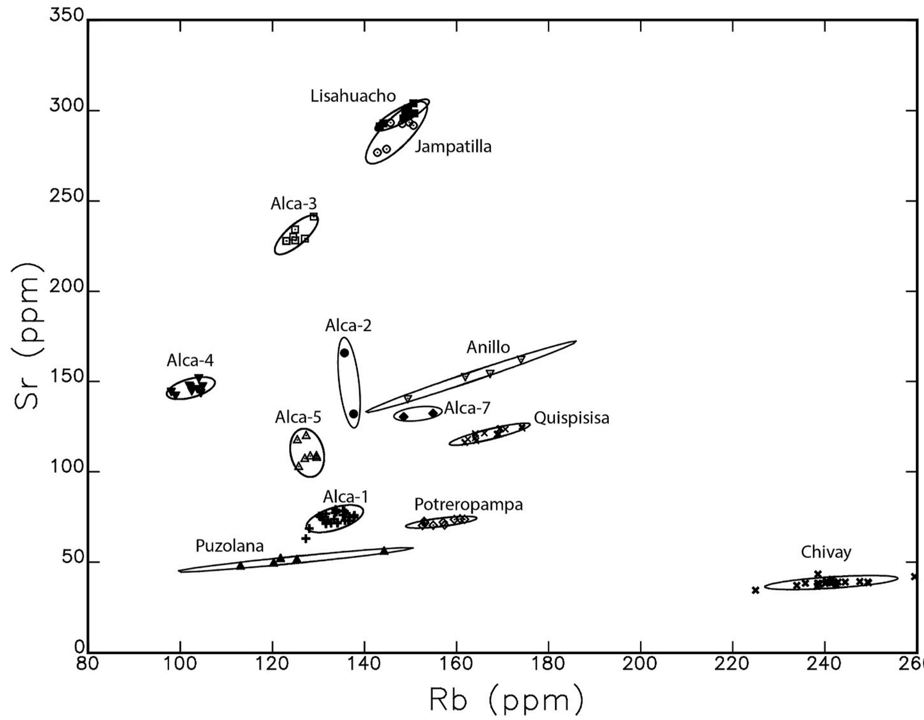

Fig. 5. Scatterplot of QuantX XRF results for Rb and Sr showing the major obsidian sources in Peru. Confidence ellipses are 90%. Figure drawn by M.D. Glascock.

Table 4
Mean element concentrations (ppm) measured by pXRF. n = number of geologic samples.

Source	Alca-1	Alca-2	Alca-3	Alca-4	Alca-5	Alca-7
n =	78	6	27	13	67	39
Element	mean ± 1σ	mean ± 1σ	mean ± 1σ	mean ± 1σ	mean ± 1σ	mean ± 1σ
Mn	448 ± 89	415 ± 62	579 ± 50	553 ± 131	542 ± 53	512 ± 65
Fe (%)	0.549 ± 0.018	0.770 ± 0.070	0.804 ± 0.016	0.596 ± 0.031	0.545 ± 0.018	0.526 ± 0.048
Zn	38 ± 5	44 ± 4	46 ± 3	34 ± 5	42 ± 5	30 ± 4
Ga	18 ± 1	19 ± 1	18 ± 1	18 ± 1	19 ± 1	18 ± 1
Rb	135 ± 3	144 ± 2	127 ± 2	107 ± 2	130 ± 3	157 ± 3
Sr	74 ± 2	152 ± 15	205 ± 4	141 ± 4	108 ± 5	127 ± 3
Y	14 ± 1	16 ± 1	16 ± 1	14 ± 1	14 ± 1	15 ± 1
Zr	101 ± 4	168 ± 20	153 ± 3	97 ± 4	91 ± 5	86 ± 2
Nb	12 ± 1	12 ± 2	11 ± 1	9 ± 2	12 ± 1	12 ± 1
Th	13 ± 1	15 ± 2	13 ± 1	8 ± 1	13 ± 1	16 ± 1
Source	Quispisisa	Jampatilla	Potreropampa	Lisahuacho	Chivay	Anillo
n =	18	6	5	5	6	4
Element	mean ± 1σ	mean ± 1σ	mean ± 1σ	mean ± 1σ	mean ± 1σ	mean ± 1σ
Mn	292 ± 43	503 ± 33	449 ± 55	332 ± 29	600 ± 43	372 ± 31
Fe (%)	0.550 ± 0.055	0.840 ± 0.039	0.457 ± 0.013	0.825 ± 0.016	0.473 ± 0.014	0.594 ± 0.036
Zn	19 ± 4	45 ± 5	28 ± 3	44 ± 4	31 ± 3	28 ± 7
Ga	16 ± 1	18 ± 1	18 ± 1	17 ± 1	18 ± 1	17 ± 1
Rb	173 ± 6	152 ± 5	161 ± 3	146 ± 4	243 ± 3	165 ± 5
Sr	118 ± 3	238 ± 4	75 ± 1	249 ± 3	38 ± 1	141 ± 4
Y	12 ± 1	28 ± 1	15 ± 1	14 ± 1	19 ± 1	15 ± 1
Zr	98 ± 2	156 ± 3	81 ± 1	163 ± 4	86 ± 1	118 ± 3
Nb	8 ± 1	15 ± 1	12 ± 1	13 ± 1	17 ± 1	9 ± 1
Th	16 ± 2	11 ± 1	15 ± 1	15 ± 1	21 ± 1	17 ± 2

the floodplain did not find any obsidian at greater distance downstream. About 25 km south of Cerro Condorsayhua in the Pucuncho Basin (Fig. 3), Alca-1 obsidian occurs as <5-cm angular and rounded clasts in ignimbrites.

Near the town of Andagua, Wasilewski (2011) reported Alca-1 obsidian clasts up to 12 cm in alluvium. He also discovered Alca-1 obsidian on the plateau north of the Andagua valley and east of Cerro Condorsayhua (Fig. 3). At 4575 masl below Cerro Mesani, Wasilewski collected archaeological artifacts and geologic samples. Among these was a 20-cm angular block of Alca-1 obsidian. Examining the area using Google Earth, the sample location is directly outside a camelid corral, which suggests the large block of Alca-1 might be a manuport brought from Condorsayhua, 24 km west of this location. If large-sized obsidian nodules or bedrock cropped out here, workshop evidence would be expected, but Wasilewski's report does not mention workshops or other large obsidian clasts at Cerro Mesani.

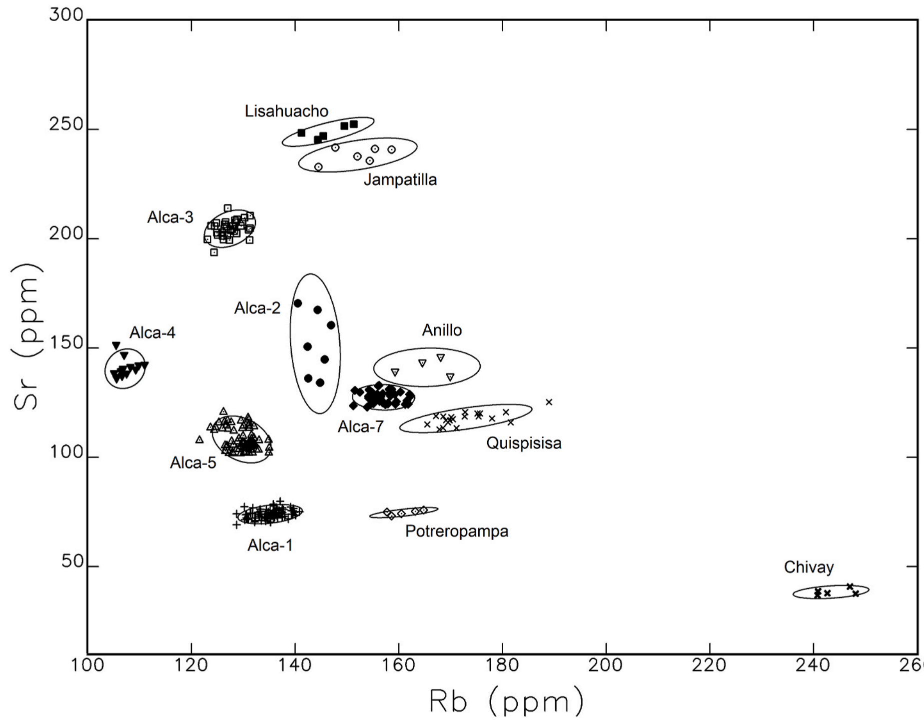

Fig. 6. Scatterplot of pXRF results for Rb and Sr showing the major obsidian sources in Peru. Confidence ellipses are 90%.

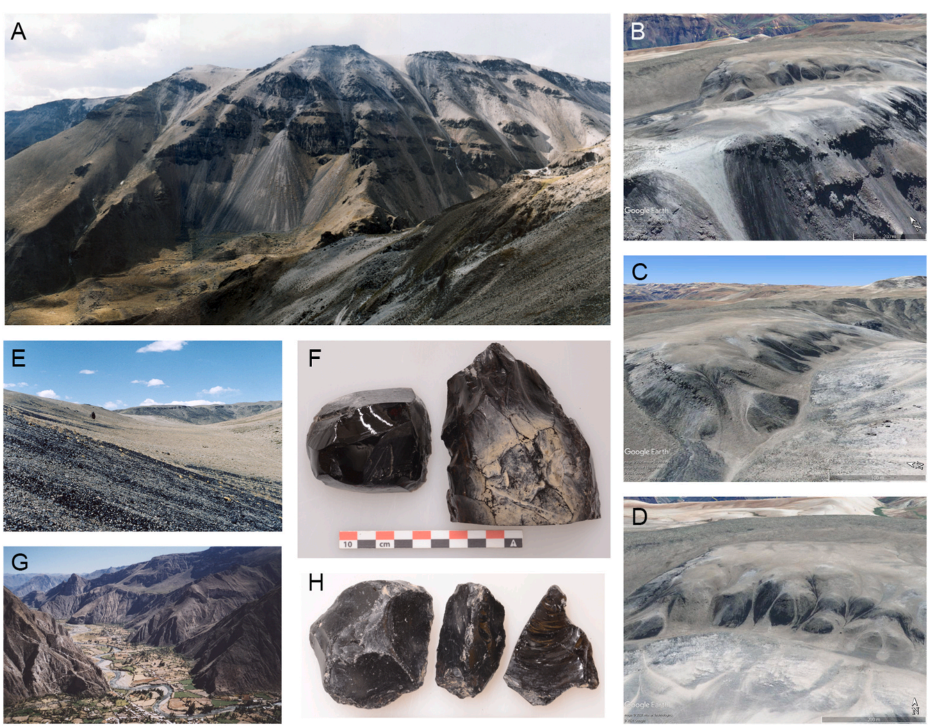

Fig. 7. (A) Photo of Cerro Condorsayhua, facing north. Google Earth images of Cerro Condorsayhua summit and east-west trough north of the summit, where the Alca-1 rhyolite dome is exposed: (B) oblique view of summit, facing northeast, (C) trough, facing east, (D) trough, facing north, showing 600 m-long section of obsidian bedrock and talus outcrops. (E) Photo of obsidian talus in trough, facing east, (F) Alca-1 obsidian hand specimens from Cerro Condorsayhua primary outcrop (KRA-095) cut with rock saw. Note the glassy and exceptional quality of the obsidian and thin weathering rind. (G) Photo of the town of Alca, facing south. The original find spot in valley fill is at left. (H) Alca-1 hand specimens from secondary pyroclastic and alluvial deposits below Condorsayhua near the town of Alca (KRA-001). Note abrasion and faceting on pebbles from secondary deposits.

4.5.2. Alca-2 (3370–5165 masl)

Six km southeast of Cerro Condorsayhua at the west edge of the plateau Alca-2 obsidian crops out in a rhyolite dome below Nevado Sapojahuana (5260 masl) (Figs. 2 and 8). Alca-2 obsidian is also identified as pyroclastic material in the valley below near the town of Cahuana, 500 m above the Cotahuasi River. Alca-2 matches the Alca-X samples defined by Jennings and Glascock (2002). Nodules of Alca-2 obsidian are <5 cm.

Unlike other Alca sub-sources, Alca-2 obsidian is devitrified, occurring as friable bedrock and small clasts that disintegrate with handling into sub-cm fragments and perlite. Devitrification of the Alca-2 subsource could result from a greater age, but geochemically similar hand specimens from pyroclastic valley fills are less devitrified than those from the high-elevation (>5000 masl) rhyolite dome. Over the Pleistocene, it is likely that these high elevations were episodically occupied by glaciers, which may have contributed to hydration and devitrification of

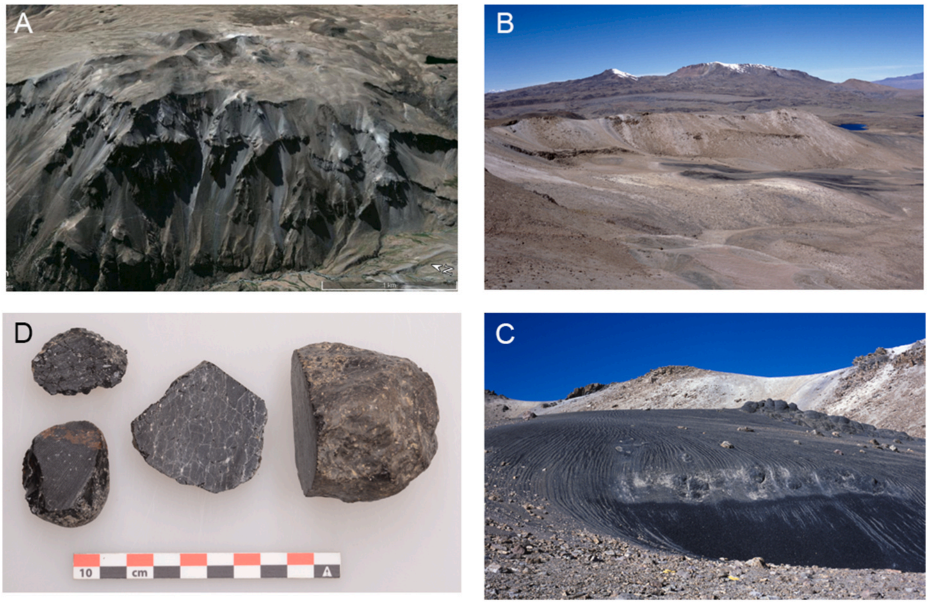

Fig. 8. (A) Google Earth oblique image of Nevado Sapojahuana and Alca-2 rhyolite dome, facing east. Photos of Alca-2 obsidian outcrops, facing south from the summit ridge (B) and east at the outcrops (C). The lake in the background of (B) is the same as the one on the far right side of (A). (D) Rock saw-cut Alca-2 obsidian hand specimens. Bottom left: KRA-151 from pyroclastic valley fill (3368 masl), top left: KRA-268 (5166 masl), right: KRA-267 (5004 masl) sectioned to show interior structure and weathered cortex. Devitrification is prevalent in Alca-2 hand specimens from high elevation.

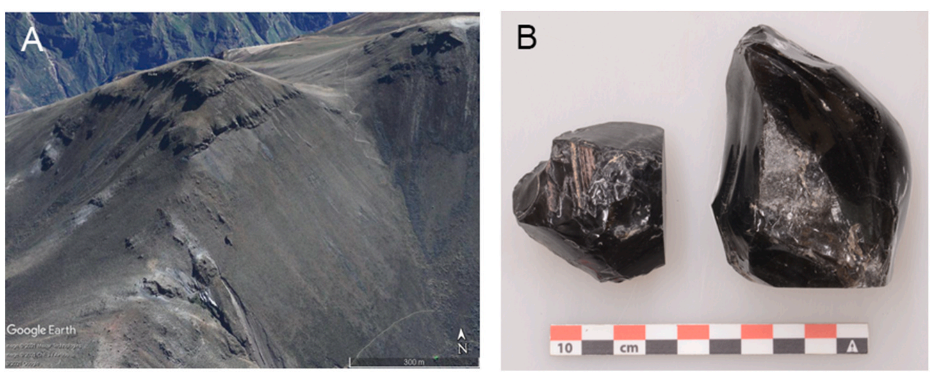

Fig. 9. (A) Google Earth oblique image of Cerro Aycano Alca-3 outcrops, facing northwest. Lighter-colored areas indicate where erosion has exposed tuff with obsidian (B) Rock saw-cut Alca-3 obsidian hand specimens from Cerro Aycano. Left: KRA-167 (4330 masl), right: KRA-161 (4300 masl).

the Alca-2 obsidian outcrops at the base of the peak.

4.5.3. Alca-3 (2710–4340 masl)

Four kilometers west of the Condorsayhua summit is the Alca-3 bedrock outcrop at Cerro Aycano (Figs. 2 and 9). Obsidian crops out in tuff exposed in a ~200-m-thick band on the west and south sides of the pyramid-shaped peak and along the saddle with the neighboring peak Cerro Antag. Pyroclastic Alca-3 obsidian also is found near the towns of Alca, Cahuana, and Lucha below Aycano, from 2710 to 2840 masl. Alca-3 matches the Alca-Y samples defined by Jennings and Glascock (2002). The Cerro Aycano obsidian is glassy and excellent quality for knapping, with nodules up to 10 cm.

4.5.4. Alca-4 (4340–4530 masl)

The Alca-4 sub-source crops out at 4340 masl at the west edge of the volcanic plateau about 900 m above the Arma River, the outlet stream of the Pucuncho Basin (Figs. 3 and 10). Zuñiga first discovered the Alca-4 source in a footpath that cut through the ignimbrite below the plateau edge. Here and in a modern roadcut below the footpath, obsidian fragments and nodules up to 30 cm are found in debris flow deposits. These deposits are only present along a section of roadway beneath a steep gulley descending from the plateau rim. In its upper reaches the gulley cuts through the Alca-4 bedrock deposit, adjacent to a distinct bedrock feature protruding from beneath the horizontal ignimbrites forming the plateau surface. The bedrock feature may be the distal edge of a rhyolite dome. Angular and sub-rounded obsidian fragments up to 30 cm form an extensive pavement here, and a large lithic workshop covers the plateau surface above the outcrop. A large cairn, dry-laid stone habitation structures, a camelid corral, and worked round stone tablets painted with red ocher are located at the workshop.

We also found angular <5 cm Alca-4 obsidian fragments at equivalent elevations to the northeast and southeast of the primary outcrop where drainages dissect older strata (Fig. 10A). Eight km southeast of the primary outcrop at 4530 masl, additional small (<5 cm) angular obsidian fragments were devitrified and could not be analyzed with pXRF. However, hand specimens appear similar to those of Alca-4. The Alca-4 bedrock outcrop may be more extensive but largely buried beneath younger volcanic deposits west of Nevado Coropuna.

Alca-4 obsidian is the only Alca sub-source that is less glassy and rough in texture, and it contains abundant phenocrysts. Wasilewski (2011) defined a geochemical Group 2 based on one characterized sample found near the town of Andagua. Its composition matches Alca-4, but it is not possible to determine from his report whether the sample is an artifact or geologic sample.

Fig. 10. (A) Google Earth oblique image of Alca-4 outcrop, facing east, with the Arma River in foreground and Nevado Coropuna in background. Yellow pins indicate Alca-4 samples, and double pins show the Alca-4 bedrock outcrop. Yellow pin at far left is a feldspar sample (34) at 4020 masl dated by $^{40}Ar/^{39}Ar$ to ~8 Ma (Thouret et al., 2016). (B) Alca-4 obsidian hand specimens from primary outcrops at west edge of plateau above Arma River. Left and lower right: Rock saw-cut KRA-100 and KRA-099 (4233 masl), upper right: experimentally produced biface from KRA-308 (4130 masl). (C) Photo of Arma River, facing east and upstream into Pucuncho Basin. (D) Rock saw-cut Alca-5 obsidian hand specimens from the Arma River and Pucuncho Basin. Left to right: KRA-251 (4464 masl), KRA-112 (4295 masl), KRA-212 (4345 masl). (E) Photo facing northeast showing lighter-colored Arma/Sencca ignimbrite surface of the Pucuncho Basin, with darker Barroso andesite lava composing the shrub-covered hillslope in the foreground and at left. The ignimbrite landform shown here contains a Terminal Pleistocene lithic workshop (F) Reconstructed, rock saw-cut Alca-7 obsidian hand specimens from the Pucuncho Basin. Left to right: KRA-269 (4439 masl), KRA-288 (4381 masl), KRA-289. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

4.5.5. *Alca-5 (4080–4520 masl)*

Alca-5 obsidian crops out in the Pucuncho Basin and along the Arma River to just beyond where the Quebrada Angostura tributary joins the Arma River from the north (Figs. 3 and 10). Alca-5 obsidian clasts are frequent from the highway bridge that crosses the river to ~10 km upstream. High-quality obsidian pebbles from <5 cm to >10 cm in size have been reworked from ignimbrite dissected by the Arma River and small tributary streams. Toward the east and north of the Arma River bridge Alca-5 obsidian also is found on alluvial fans, primarily on the margins of the Pucuncho basin (Fig. 10E). Wasilewski (2011) reported Group 3 pebbles on the plateau at 4350 masl, ~25 km northeast of the Pucuncho Basin. The Group 3 composition matches Alca-5, and the material is likely pyroclastic. The larger clasts of Alca-5 near the Arma River bridge suggest the majority of the Alca-5 bedrock outcrop is buried under younger volcanic deposits.

4.5.6. *Alca-7 (4395–4595 masl)*

Zuñiga discovered the Alca-7 sub-source in stream gravels in the Pucuncho Basin. The obsidian occurs as small <5-cm pebbles in ignimbrite exposed primarily at the higher-elevation northeast part of the basin (Figs. 3 and 10). Alca-7 samples crop out in a vertical range of ~200 m, which only overlaps the upper end of the Alca-5 elevation range, suggesting a possible stratigraphic relationship. Wasilewski (2011) characterized four small pebbles as Group 4 collected from three locations on the plateau ~25 km northeast of the Pucuncho Basin, including at Cerro Mesani where the large block of Alca-1 was found. The composition of Wasilewski's Group 4 matches Alca-7 and extends the spatial distribution of the Alca-7 sub-source to 4650 masl. The location of the Alca-7 bedrock outcrop is unknown, but it may be located east of the Pucuncho Basin or buried beneath younger volcanic deposits.

5. Discussion

5.1. *Geologic mapping and geomorphic history of the Alca obsidian source*

Olchauski and Davila (1994) created the first 1:100,000 scale geologic maps and an accompanying monograph for the Cotahuasi and Chuquibamba quadrangles. INGEMMET released digital versions in 1997, facilitating use in GIS. Obsidian samples collected from below 4000 masl in the Cotahuasi valley and the Chococo tributary appeared to be in a formation mapped as Miocene Tacaza Group (Tm-ta), dated to ~19 Ma. Cerros Condorsayhua and Aycano and Nevado Sapojahuana, where our team had identified respective Alca-1, Alca-3, and Alca-2 obsidian bedrock, were mapped as Upper Miocene to Pliocene-age Alpabamba Formation (Tm-al), dated to ~4.8 Ma. Alca-4 sample locations above the Arma River west of Coropuna also were mapped as Alpabamba Formation. A third formation, which corresponded with Alca-1, Alca-5, and Alca-7 obsidian sample locations in the Pucuncho Basin and along the Arma River, was mapped as the Plio-Pleistocene Sencca Formation (Ts-se) (Olchauski and Davila, 1994). It seemed unlikely that geochemically similar Alca obsidian would span 15 my from the Miocene to Pleistocene. Moreover, it would be unexpected for obsidian to survive in useable, non-devitrified form in ignimbrites >10 Ma (Cann, 1983).

The geologic mapping of Cotahuasi and adjacent quads was updated by Lajo Soto et al. (2001a, 2001b) and summarized by Salas et al., 2003. A digital version was made available online by INGEMMET only recently. This update included major revisions to the volcanic stratigraphy. Perhaps the biggest local changes for the Alca source area were the sub-division of Pleistocene Barroso Group lavas surrounding the major stratovolcanoes Coropuna, Solimana, and Firura on the plateau and the new designation *Arma Formation* (Np-ar) for the ignimbrites previously mapped as Sencca Formation along the Arma River and in the

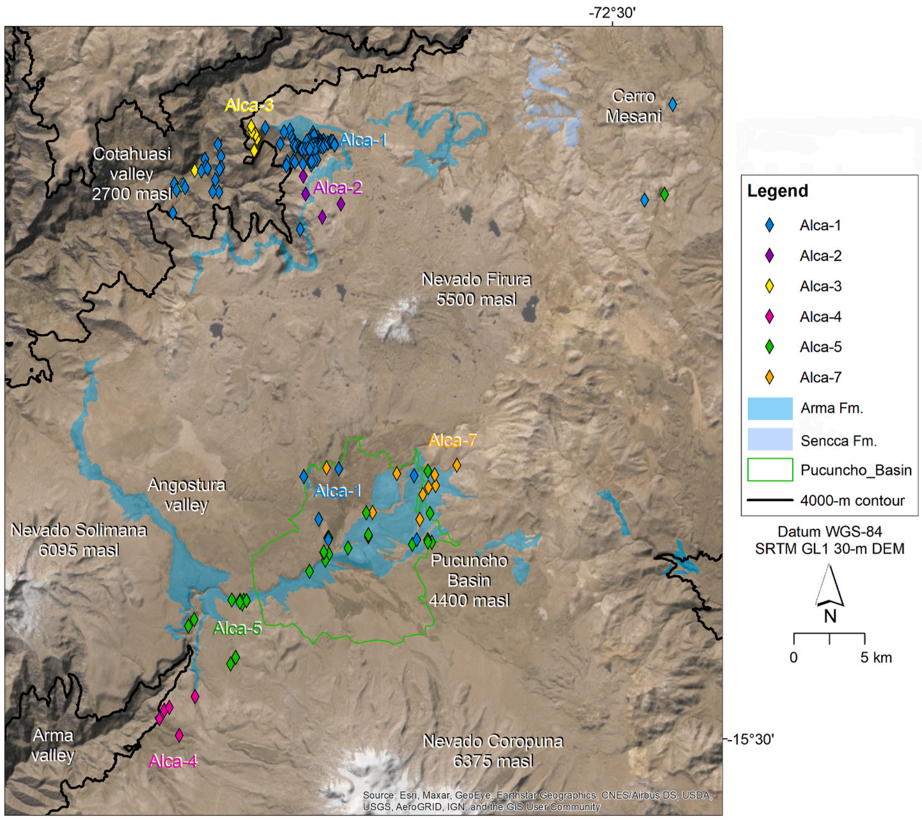

Fig. 11. Map showing Alca obsidian sample locations and the Arma Formation mapped by INGEMMET geologists (Lajo Soto et al., 2001a, 2001b). Detail maps for Cotahuasi and Pucuncho are provided in the supporting material (Figs. S1 and S2).

Pucuncho Basin. The Arma Formation additionally was mapped in areas previously designated as the Miocene Alpabamba Formation, such as at Cerro Condorsayhua and Nevado Sapojahuana, though Cerro Aycano and most of the sample locations of Alca-4 were still mapped as Alpabamba Formation.

Thus, with a few exceptions, the INGEMMET-defined Arma Formation corresponds well to the majority of the locations where our team has identified Alca obsidian (Figs. 11, s1 and s2). The Arma Formation was described as a 100-150-m-thick stratified sequence of pyroclastic materials constituting the base upon which the younger stratovolcanoes Coropuna, Solimana, and Firura were formed. Salas et al., 2003 further suggested the Arma Formation was a stratigraphic equivalent of the Pliocene Sencca Formation and Pleistocene lower Barroso Group.

Thouret et al. (2007, 2016) systematically dated ignimbrites throughout the study area and interpreted the geomorphology of the Cotahuasi valley. Following Late Miocene uplift and the erosion of the Cotahuasi valley system to near-present level ~9–3.8 Ma, volcanic activity on the plateau produced pyroclastic flows that filled adjacent, topographically lower valleys. Subsequent fluvial incision of these fills left remnant hanging terraces along valley margins (*e.g.,* at Cahuana, Fig. 2) and draped younger material on older slopes (Gregory-Wodzicki, 2000; Thouret et al., 2007). Failure of steep slopes and debris avalanches have occurred (Thouret et al., 2017), suggested by lobate scars within the Chococo valley east of the town of Alca (Fig. 2). These processes would have introduced younger pyroclastic material originating at higher elevations to the lower valley. The younger valley fills were K–Ar dated, bracketing them between 3.76 Ma and 1.56 Ma (Thouret et al., 2007). This time range corresponds with ~2.2–1.8 Ma ages for the Upper Sencca Formation ignimbrites on the plateau dated by $^{40}Ar/^{39}Ar$ (n = 15) and U–Pb (n = 2) (Thouret et al., 2016).

Thouret et al. (2016) also designated “Arma” pyroclastic density current (PDC) deposits, though these are not equivalent to the Arma Formation proposed by INGEMMET geologists. The Arma PDCs have limited exposure along the Arma River valley and are dated to ~8 Ma by $^{40}Ar/^{39}Ar$. Alca-4 obsidian sampled within 3 km of the dated Arma PDC is stratigraphically higher (Fig. 10A) and thus postdates 8 Ma.

Thouret et al. (2016) map the ignimbrites along the Quebrada Angostura tributary and within the Pucuncho Basin (designated as Arma Formation by INGEMMET geologists) as Upper Sencca Formation. Cerro Condorsayhua and areas along the plateau edge south and east of Condorsayhua are mapped as Alpabamba Formation, dated elsewhere to ~18–20 Ma. However, the presence of non-devitrified, high-quality Alca obsidian within these ignimbrites suggests a younger age, lending support to the INGEMMET mapping here. A more recent map by Thouret et al. (2017) designates Condorsayhua within the Las Lomas PDC, which they date elsewhere on the plateau to ~1.56–1.26 Ma.

While the naming, absolute dating, and correlation of various volcanic units in the study area has been in flux over the past several decades, there has been a progressive resolution of the local, complex volcanic and geomorphic history. The INGEMMET Arma Formation appears to correspond well to where our team has located and sampled Alca obsidian. Moreover, the INGEMMET scheme recognizes their Arma Formation as a stratigraphic equivalent with Upper Sencca Formation dated locally by Thouret et al. (2007, 2016, 2017) to ~2 Ma, Pleistocene age. A more recent age of formation is consistent with the presence of high-quality, non-devitrified obsidian in these ignimbrites.

Our obsidian samples suggest that the Arma Formation extends beyond INGEMMET mapping in some areas. On the other hand, the overall extent of Arma Formation on INGEMMET maps suggests there are few areas likely to contain obsidian that we have not sampled (Figs. 11, S1, and S2). These areas include the Angostura valley, east of the Pucuncho Basin toward Andagua, and east of Cerro Condorsayhua toward Cerro Mesani. Based on current information, Alca obsidian occurs in ignimbrites up to ~55 km from geochemically identical bedrock deposits. Pyroclastic flows may have extended beyond this distance, and distal ignimbrites may contain Alca obsidian, but the small size of obsidian clasts would likely preclude their use as raw material for stone tools.

In summary, Alca-1, Alca-2, and Alca-3 obsidian pyroclasts in ignimbrites in the Cotahausi valley, including samples characterized previously (Burger et al., 1998b; Jennings and Glascock, 2002), geochemically match obsidian at three distinct rhyolite domes at the plateau edge, Cerro Condorsayhua (Alca-1), Nevado Sapojahuana (Alca-2), and Cerro Aycano (Alca-3) (Fig. 2). Of these three sub-sources, only Alca-1 is found in more distant geologic settings as pyroclastic material, where it is accompanied by two other distinct sub-sources not present in the Cotahuasi valley, Alca-5 and Alca-7 (Figs. 3 and 11). The greatest distance from Cerro Condorsayhua that Alca-1 geologic obsidian has been documented is ~55 km in the Andagua valley, at 3450 masl (Wasilewski, 2011).

In the Pucuncho Basin Alca-1, Alca-5, and Alca-7 obsidian pyroclasts occur in ignimbrites eroded and reworked by glaciofluvial erosion throughout the Pleistocene (Figs. 3 and 11). Wasilewski (2011) also characterized geochemically identical pyroclastic obsidian from these three sub-sources between 4350 and 4550 masl on the plateau ~30 km northeast of the Pucuncho Basin.

The Alca-4 sub-source southwest of the Pucuncho Basin (Figs. 3 and 11) includes the largest fragments of obsidian aside from those at the Cerro Condorsayhua Alca-1 outcrop. Although the majority of the Alca-4 bedrock outcrop may be buried beneath younger volcanic material, it has been exposed by extensive erosion at the west edge of the plateau above the Arma River valley. No pyroclastic Alca-4 obsidian has yet been found.

Alca obsidian has been found over an area spanning 2000 km^2. Over the majority of this area obsidian-bearing ignimbrites are overlain by younger geologic formations, such as the Pleistocene Barroso andesite lava flows, the massive stratovolcanoes, and their extensive aprons. The exposure of the Alca obsidian source occurs at the margins of these younger formations and in erosional features where the plateau has been dissected, notably the 2-km erosion of the Cotahuasi valley, the Arma valley and its headwaters in the Pucuncho Basin, and the headwaters of the Andagua valley.

5.2. Human use of the Alca obsidian source

Although the volcanic plateau where the Alca source is located was glaciated episodically during the Pleistocene, glacial ice never covered the Alca source during or after the Last Glacial Maximum, ~20 ka. Current evidence suggests humans entered this area of the Andes after 12.5 ka. At this time glaciers were in retreat from their late-glacial positions and confined within alpine valleys, well above the elevation of the Pleistocene ignimbrites (Bromley et al., 2009, 2011). Glacial ice neither constituted a barrier to human dispersals nor obscured important resources such as obsidian outcrops at Alca and other Central Andean sources.

The earliest known use of Alca obsidian was ~12.3 ka at the site of Cuncaicha, located at 4480 masl within the Pucuncho Basin (Fig. S1) (Rademaker et al., 2014). The rockshelter, formed within Pleistocene Barroso andesite lavas, is perched 25 m above the Arma Formation ignimbrite containing nodules of Alca obsidian (Meinekat et al., 2021). From the beginning of residence and during subsequent occupations over the past 12 ky, local Alca obsidian was the most common raw material used to produce abundant stone tools at Cuncaicha. Alca obsidian tools were also found at a contemporary Terminal Pleistocene workshop site 7 km west of Cuncaicha, on Arma Formation ignimbrite (Fig. 10E) (Sandweiss and Rademaker, 2011).

Beyond local use, Alca-1 obsidian was transferred 145 km south from its source area to the contemporary Terminal Pleistocene site Quebrada Jaguay, located on the Pacific coast (Sandweiss et al., 1998) (Fig. 1). At Quebrada Jaguay the obsidian is in the form of small waste flakes (Tanner, 2001) and two broken bifacial tools. Obsidian from the Alca source continued to be transferred to the Pacific coast at Pampa Colorada, just west of Quebrada Jaguay. McInnis (2006) documented obsidian projectile points, other formal tools, and debitage at 17 sites. NAA was used to characterize 89 obsidian flakes at MURR. The majority of these (n = 71, 80%) were Alca-1. Fifteen flakes (17%) can now be assigned to the Alca-4 sub-source. Radiocarbon dates from these sites suggest repeated highland to coast obsidian transfers between ~11.5 and 5.5 ka.

By ~6.3 ka Alca-1 obsidian was carried or traded ~200 km across the Andes to the Cuzco area (Burger and Glascock, 2007). An increasing number of sites contained Alca obsidian by 4 ka. These include sites close to the Alca source, such as Wayñuna in the Cotahuasi valley (Rademaker, 2006), and possibly at Manachaqui Cave in the eastern Andes of northern Peru, some ~1000 km distant (Burger and Glascock, 2009) (Fig. 1).

Over 75 known archaeological sites with Alca obsidian date to within the past two millennia when complex civilizations rose and fell (see Fig. 1, summarized in Burger et al., 2000; Reid, 2020). The vast majority of Alca obsidian artifacts from these periods is from the Alca-1 sub-source (Glascock et al., 2007). By ~2 ka and the Early Horizon, Alca obsidian was transported 825 km to Chavín de Huántar in north-central Peru (Burger et al., 2000). Almost 40 sites with Alca obsidian date to the Middle Horizon (~1.4–1.0 ka) and occur within the interaction sphere of the Wari Empire (Reid and Ridge, 2018). Transfers to northern Peru exceeded 1000 km, including to Early Horizon site Kuntur Wasi and to the Middle Horizon sites Cerro Amaru, Huamachuco, and Marca Huamachuco. Transfers 300–400 km south and east are documented at Middle Horizon Cerro Baúl, Cerro Mejía, and Omo in the Moquegua valley (Williams et al., 2012) and at Quelcatani, Incatunuhuiri, and Taraco in the Titicaca Basin (Burger et al., 2000). The transfer of only the Alca-1 sub-source suggests emphasis on the large bedrock outcrops at Cerro Condorsayhua and organized systems of extraction and distribution, facilitated by pre-existing economic networks, llama caravans, and periodic state involvements (Burger et al., 2000; Tripcevich, 2010; Williams et al., 2012; Reid, 2020).

5.3. Use of minor Alca sub-sources

However, some recent projects employing analysis of larger artifact sets, many using pXRF, are revealing use of other Alca sub-sources. These cases contribute fine-grained behavioral information made possible by a complex obsidian source with geographically patterned geochemical variation that was used extensively throughout history.

Matsumoto et al. (2018) used pXRF to analyze 370 obsidian artifacts from the Early Horizon site of Campanayuq Rumi in the department of Ayacucho (Fig. 1). In an occupation dated to ~2.8 ka they identified three flakes of Alca-1 and two flakes of Alca-5 obsidian. A subsequent occupation phase contained 16 flakes of Alca-1 obsidian. These results indicate transfer of obsidian >200 km northwest from the Alca-5 and Alca-1 outcrops. Because the relatively rare Alca-5 sub-source was identified, the point of origin for the obsidian can be identified as the Pucuncho Basin. Plateau-based camelid pastoralists and caravanners and not valley farmers are therefore likely to have been involved in this obsidian procurement and transfer.

Using pXRF, Belisle et al. (2020) analyzed 463 obsidian artifacts from four sites in the department of Cuzco dating from ~2.6 to 0.4 ka. In all periods, Alca-1 obsidian is most prevalent (n = 428, 92.4%). In the Middle Horizon occupation of Minaspata (Fig. 1), Belisle et al. identified one flake of Alca-7. These results confirm Burger and Asaro (1977) conclusion that Alca was the most frequently used obsidian in the Cuzco valley. The resolution of provenance to sub-source level establishes a connection between the Cuzco valley sites and the Cerro Condorsayhua bedrock outcrop specifically, with Alca-7 providing further evidence that Alca obsidian was procured from the high-elevation plateau and not the lower-elevation Cotahuasi valley.

Hu and Shackley (2018) used ED-XRF to characterize 84 obsidian flakes from the Late Horizon site of Yanawilka in the department of Ayacucho (Fig. 1). Yanawilka was an agricultural colony in which the Inka resettled laborers from other areas of the empire. One flake was assigned to the Alca-3 sub-source, indicating a connection with Cerro Aycano above the Cotahuasi valley. Combining this provenance identification with ethnohistoric data, Hu and Shackley (2018) suggested the fascinating possibility that the obsidian was brought to Yanawilka by a member of the Conde ethnic group whose homeland was in the department of Arequipa, consistent with an origin in Cotahuasi. Three additional unassigned flakes were suggested to be Alca-2 or Quispisisa based on Mn concentrations. However, published Rb concentrations for the flakes indicate a match with the Alca-7 sub-source, Sr concentrations support assignment to Alca-5, and Zr concentrations are consistent with both sub-sources. Because outcrops of both Alca-5 and Alca-7 occur together in the Pucuncho Basin, the obsidian evidence at Yanawilka is even stronger for a connection to the Cotahuasi valley and adjacent plateau.

6. Conclusions

Due to the location of obsidian sources in remote, rugged, and relatively inaccessible areas of the Andean highlands, the development of obsidian provenance research in Peru began with obsidian artifacts contributed by archaeologists, and subsequently, investigation of geologic source areas became possible. As the source location of Alca obsidian came to light, a number of analyses of archaeological obsidian artifacts indicated a long and intensive utilization of Alca obsidian spanning more than 12,000 years of Peruvian history.

Insights from obsidian sources and the final destinations of artifacts made from those sources are both useful for understanding the evolution of past social and economic systems. However, in the Central Andes region systematic investigation of obsidian source areas has tended to lag behind provenance analyses of artifacts. This situation is being addressed through recent efforts at Chivay, Quispisisa, Alca, and other Andean obsidian sources.

The spatial extent of Alca obsidian is 2000 km^2 indicated by our mapping and work by others (Burger et al., 1998b; Jennings and Glascock, 2002; Tripcevich, 2007; Wasilewski, 2011), an even larger area than previously suspected (Rademaker et al., 2013). Similar systematic investigations in Argentina and Chile (Stern, 2018; Barberena et al., 2019) and elsewhere in Peru (Nesbitt et al., 2021) reaffirm that archaeological provenance studies must consider the much larger extent of pyroclastic obsidian in ignimbrites surrounding effusive rhyolite domes, and in secondary fluvial and glaciofluvial deposits. Whether obsidian distant from primary bedrock outcrops occurs in clasts of suitable size and quality for stone toolmaking must be determined for each obsidian source.

Based on correspondence of our mapped obsidian samples with INGEMMET geologic mapping of the Arma Formation, and geochronologic data for the study area by Thouret et al. (2007, 2016, 2017), Alca obsidian crops out within ~2 ma Pleistocene ignimbrites. Our team's obsidian sampling shows minor extensions of the Arma Formation beyond INGEMMET mapping. Other nearby Peruvian obsidian sources, such as Anillo (Tripcevich, 2016) and Sayrosa (Burger et al., 2021), also occur in correlative Sencca and Barroso Pleistocene ignimbrites.

The new NAA work reported here confirms the six Alca sub-sources reported previously, and new pXRF analyses (n = 230) of Alca geologic samples verifies the efficacy of pXRF to differentiate the Alca sub-sources from each other and from other Central Andean obsidian sources. To the best of our knowledge, Alca is the most extensively mapped and geochemically characterized obsidian source in South America.

This source dataset is a foundation for additional, forthcoming analyses of archaeological artifacts by pXRF and other methods to resolve patterns in the use of Alca sub-sources through time. Questions that can be addressed include whether specific sub-sources were preferred based on greater accessibility, clast size or quality, or aesthetic or other cultural reasons, whether specific sub-sources were chosen for making specific tool types, whether patterns of local acquisition and use were similar to distant ones, or whether any of these phenomena changed or remained consistent over time (Eerkens and Rosenthal, 2004).

Analysis of large artifact sets likely is needed to identify the presence of rare obsidian sources and sub-sources, which may constitute <1% of an artifact sample (Belisle et al., 2020), especially in sites distant from source outcrops. Already some uses of the "minor" Alca sub-sources have been identified at Pampa Colorada (Alca-4), Campanayuq Rumi (Alca-5), Minaspata (Alca-7), and Yanawilka (Alca-3 and Alca 5/7). Alca-2 is the only sub-source that has not been identified yet in archaeological artifacts, perhaps due to its relatively poor quality, small clasts, and remote outcrops. Ongoing provenance analyses of obsidian artifacts throughout Peru will reveal how people engaged with the Alca source region over time. Equally important, future detailed study of Cerro Condorsayhua, the bedrock source of Alca-1 obsidian, will resolve questions on when and how Alca-1 became one of the most widely utilized and transported obsidians in the Americas.

Author contributions

Kurt Rademaker: Conceptualization, Investigation, Formal analysis, Data curation, Writing-Original draft preparation. Michael D. Glascock: Formal analysis, Data curation, Writing-Original draft preparation. David A. Reid: Investigation, Writing-Original draft preparation. Ermitaño Zuñiga: Investigation. Gordon R. M. Bromley: Investigation, Writing-Original draft preparation.

Data availability

Datasets related to this article can be found at https://doi.org/10.17632/pvz4y5xjwt.1, an open-source online data repository hosted at Mendeley Data (Rademaker et al., 2021).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We thank our generous colleagues for contributing geologic obsidian samples for analyses at MURR and MSU: Sarah Brooks, Richard Burger, Laure Dussubieux, Justin Jennings, Nicholas Tripcevich, Michal Wasilewski, and Patrick Ryan Williams. Bruce Kaiser provided calibration samples and guidance for pXRF analysis. Two anonymous reviewers provided helpful comments that improved the manuscript. Funding: Michigan State University.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.quaint.2021.11.029.

References

Barberena, R., Fernández, M.V., Rughini, A.A., Borrazzo, K., Garvey, R., Lucero, G., Della Negra, C., Romero Villanueva, G., Durán, V., Cortegoso, V., Giesso, M., Klesner, C., MacDonald, B.L., Glascock, M.D., 2019. Deconstructing a complex obsidian "source-scape:" A geoarchaeological and geochemical approach in northwestern Patagonia. Geoarchaeology 34 (1), 30–41. https://doi.org/10.1002/gea.21701.

Belisle, V., Quispe-Bustamante, H., Hardy, T.J., Davis, A.R., Antezana Condori, E., Delgado González, C., Gonzales Avendaño, J.V., Reid, D.A., Williams, P.R., 2020. Wari impact on regional trade networks: patterns of obsidian exchange in Cusco, Peru. J. Archaeol. Sci.: For. Rep. 32, 102439. https://doi.org/10.1016/j.jasrep.2020.102439.

Bromley, G.R.M., Schaefer, J.M., Winckler, G., Hall, B.L., Todd, C.E., Rademaker, K.M., 2009. Relative timing of last glacial maximum and late-glacial events in the central tropical Andes. Quat. Sci. Rev. 28, 2514–2526. https://doi.org/10.1016/j.quascirev.2009.05.012.

Bromley, G.R.M., Hall, B.L., Schaefer, J.M., Winckler, G., Todd, C.E., Rademaker, K.M., 2011. Glacier fluctuations in the southern Peruvian Andes during the late-glacial period, constrained with cosmogenic 3He. J. Quat. Sci. 26, 37–43. https://doi.org/10.1002/jqs.1424.

Brooks, S.O., Glascock, M.D., Giesso, M., 1997. Source of volcanic glass for ancient Andean tools. Nature 376, 449–450. https://doi.org/10.1038/386449a0.

Burger, R.L., Asaro, F., 1977. Trace Element Analysis of Obsidian Artifacts from the Andes: New Perspectives on Prehispanic Economic Interaction in Peru and Bolivia – LBL6343. Lawrence Berkeley Laboratory, Berkeley.

Burger, RL., Asaro, F., 1978. Obsidian distribution and provenience in the central highlands and coast of Peru during the Preceramic Period. Contrib. Univ. Calif. Archaeol. Res. Fac. 36, 61–83.

Burger, R.L., Asaro, F., 1979. Análisis de rasgos significativos en la obsidiana de los Andes centrales. Rev. Mus. Nac. 43, 281–325.

Burger, R.L., Glascock, M.D., 2000. Locating the Quispisisa obsidian source in the department of Ayacucho, Peru. Lat. Am. Antiq. 11 (3), 258–268. https://doi.org/10.2307/972177.

Burger, R.L., Glascock, M.D., 2001. The Puzolana obsidian source: locating the geologic source of Ayacucho Type obsidian. Andean Past. 6, 289–307.

Burger, R.L., Glascock, M.D., 2002. Tracking the source of Quispisisa Type obsidian from Huancavelica to Ayacucho. In: Isbell, W.H., Silverman, H. (Eds.), Andean Archaeology I: Variations in Sociopolitical Organization. Kluwer Academic Publishers, New York, pp. 341–368.

Burger, R.L., Glascock, M.D., 2007. The sourcing of Archaic obsidian from Kasapata, department of Cuzco. In: Bauer, B. (Ed.), Kasapata and the Archaic Period of the Cuzco Valley, 57. Cotsen Institute of Archaeology Monograph, pp. 118–121.

Burger, R.L., Glascock, M.D., 2009. Intercambio prehistórico de obsidiana a larga distancia en el norte peruano. Rev. Museo Arqueol. Antropol. Hist. 11, 17–50.

Burger, R.L., Asaro, F., Salas, G., Stross, F., 1998a. The Chivay obsidian source and the geological origin of Titicaca Basin Type obsidian artifacts. Andean Past. 5, 203–223.

Burger, R.L., Asaro, F., Trawick, P., Stross, F., 1998b. The Alca obsidian source: the origin of raw material for Cuzco Type artifacts. Andean Past. 5, 185–202.

Burger, R.L., Fajardo Rios, F.A., Glascock, M.D., 2006. Potreropampa and Lisahuacho obsidian sources: geological origins of Andahuaylas A and B type obsidians in the province of Aymaraes, department of Apurimac, Peru. Ñawpa Pacha 28, 109–127. https://doi.org/10.1179/naw.2006.28.1.007.

Burger, R.L., Mohr Chávez, K.L., Chávez, S.J., 2000. Through the glass darkly: prehispanic obsidian procurement and exchange in southern Peru and northern Bolivia. J. World Prehist. 14 (3), 267–362.

Burger, R.L., Schreiber, K.J., Glascock, M.D., Ccencho, J., 1998c. The Jampatilla obsidian source: identifying the geological source of Pampas Type obsidian artifacts from southern Peru. Andean Past. 5, 225–239.

Burger, R.L., Tsurumi, E., Boulanger, M., Rademaker, K., Belisle, V., Glascock, M.D., 2021. Sayrosa, a minor obsidian source in the puna of Arequipa. Ñawpa Pacha (in press).

Cann, J.R., 1983. Petrology of obsidian artefacts. In: Kempe, D.R.C., Harvey, A.C. (Eds.), The Petrology of Archaeological Artefacts. Clarendon Press, Oxford, pp. 227–255.

Craig, N., Speakman, R.J., Popelka-Filcoff, R.S., Aldenderfer, M., Flores Blanco, L., Brown Vega, M., Glascock, M.D., Stanish, C., 2010. Macusani obsidian from southern Peru: a characterization of its elemental composition with a demonstration of its ancient use. J. Archaeol. Sci. 37, 569–576. https://doi.org/10.1016/j.jas.2009.10.021.

Eerkens, J.W., Rosenthal, J.S., 2004. Are obsidian subsources meaningful units of analysis?: temporal and spatial patterning of subsources in the Coso volcanic field, southeastern California. J. Archaeol. Sci. 31, 21–29. https://doi.org/10.1016/S0305-4403(03)00081-5.

Frye, K.L., Aldenderfer, M., Glascock, M.D., 1998. The Aconcahua Obsidian Source and its Relation to South Central Andean Exchange Systems. Paper presented at the 38th annual meeting. Institute for Andean Studies, Berkeley, California.

Giesso, M., Nami, H.G., Yataco Capcha, J., Glascock, M.D., MacDonald, B.L., 2020. XRF obsidian analysis from Ayacucho Basin in Huamanga province, south-eastern Peru. Archaeometry 62 (2), 215–231. https://doi.org/10.1111/arcm.12529.

Glascock, M.D., 2020. A systematic approach to geochemical sourcing of obsidian artifacts. Sci. Cult. 6 (2), 35–46.

Glascock, M.D., Ferguson, J.R., 2012. Report on the Analysis of Obsidian Source Samples by Multiple Analytical Methods. Archaeometry Lab, University of Missouri Research Reactor, p. 18.

Glascock, M.D., Braswell, G.E., Cobean, R.H., 1998. A systematic approach to obsidian source characterization. In: Shackley, M.S. (Ed.), Archaeological Obsidian Studies: Method and Theory. Plenum Press, New York and London, pp. 15–69.

Glascock, M.D., Speakman, R.J., Burger, R.L., 2007. Sources of archaeological obsidian in Peru: descriptions and geochemistry. In: Glascock, M.D., Speakman, R.J., Popelka-Filcoff, R.S. (Eds.), Archaeological Chemistry: Analytical Techniques and Archaeological Interpretation. American Chemical Society Symposium Series No. 968. Washington, D.C., pp. 522–552.

Gregory-Wodzicki, K.M., 2000. Uplift history of the central and northern Andes: a review. Geol. Soc. Am. Bull. 112, 1091–1105. https://doi.org/10.1130/0016-7606(2000)112<C1091:UHOTCA>2.0.CO;2.

Hu, Di, Shackley, M.S., 2018. ED-XRF analysis of obsidian artifacts from Yanawilka, a settlement of transplanted laborers (*mitmaqkuna*), and implications for Inca imperialism. J. Archaeol. Sci.: Rep. 18, 213–221. https://doi.org/10.1016/j.jasrep.2018.01.018.

Jennings, J., 2002. Prehistoric Imperialism and Cultural Development in the Cotahuasi Valley, Peru. Unpublished Ph.D. thesis. University of California, Santa Barbara.

Jennings, J., Glascock, M.D., 2002. Description and method of exploitation of the Alca obsidian source, Peru. Lat. Am. Antiq. 13 (1), 107–118. https://doi.org/10.2307/971743.

Lajo Soto, A., Díaz Rodríguez, J., Barreda De La Cruz, M.A., 2001a. Mapa Geológico del Cuadrángulo de Cotahuasi, Escala 1: 100,000. Instituto Geológico Minero y Metalúrgico, Lima.

Lajo Soto, A., Díaz Rodríguez, J., Umpire, Ll L., 2001b. Mapa Geológico del Cuadrángulo de Orcopampa, Escala 1: 100,000. Instituto Geológico Minero y Metalúrgico, Lima.

Matsumoto, Y., Nesbitt, J., Glascock, M.D., Cavero Palomino, Y.I., Burger, R.L., 2018. Interregional obsidian exchange during the late Initial Period and Early Horizon: new perspectives from Campanayuq Rumi. Lat. Am. Antiq. 29 (1), 44–63. https://doi.org/10.1017/laq.2017.64.

McInnis, H.E., 2006. Middle Holocene Culture and Climate on the South Coast of Peru: Archaeological Investigation of the Pampa Colorada. Unpublished Ph.D. thesis. University of Oregon, Eugene.

Meinekat, S.A., Miller, C.E., Rademaker, K., 2021. A site formation model for Cuncaicha rock shelter: depositional and post-depositional processes at the high-altitude keysite in the Peruvian Andes. Geoarchaeology. https://doi.org/10.1002/gea.21889.

Nesbitt, J., Matsumoto, Y., Burger, R.L., Cavero Palomino, Y., Johnson, R., Mendoza, E., Glascock, M.D., 2021. New observations on the Puzolana obsidian source and its exploitation in the south-central highlands of Peru. Archaeometry (in press).

Olchauski, E., Davila, D., 1994. Geología de los Cuadrángulos de Chuquibamba y Cotahuasi. Boletín No. 50, Serie A: Carta Geológica Nacional. Instituto Geológico Minero y Metalúrgico, Lima.

Rademaker, K., 2006. Geoarchaeological Investigations of the Wayñuna Site and the Alca Obsidian Source, Peru. Unpublished MS thesis. University of Maine, Orono.

Rademaker, K., Glascock, M.D., Kaiser, B., Gibson, D., Lux, D.R., Yates, M.G., 2013. Multi-technique geochemical characterization of the Alca obsidian source, Peruvian Andes. Geol. 41 (7), 779–782. https://doi.org/10.1130/G34313.1.

Rademaker, K., Glascock, M.D., Reid, D.A., Zuñiga, E., Bromley, G.R.M., 2021. Comprehensive Mapping and Compositional Analysis of the Alca Obsidian Source, Peru: Datasets and Supplementary Materials. Mendeley Data. https://doi.org/10.17632/pvz4y5xjwt.1 v1.

Rademaker, K., Hodgins, G., Moore, K., Zarrillo, S., Miller, C., Bromley, G.R.M., Leach, P., Reid, D.A., Yépez Álvarez, W., Sandweiss, D.H., 2014. Paleoindian settlement of the high-altitude Peruvian Andes. Science (Wash. D C) 346, 466–469. https://doi.org/10.1126/science.1258260.

Reid, D.A., 2020. Networks of Empire: the Role of Infrastructure in Wari State Expansion in Arequipa, Peru (AD 600-1000). Unpublished Ph.D. thesis. University of Illinois at Chicago.

Reid, D.A., Ridge, W.P., 2018. Obsidian Procurement and Exchange in Peru: A Social Network Analysis (SNA). Poster presented at the 83rd Annual Meeting of the Society for American Archaeology, Washington, D.C.

Salas, A.G., Lajo, S.A., Chávez, V.A., Díaz, R.J., Aguilar, V.E., Umpire, Ll A., Chávez, B.E., Barreda, M., 2003. Memoria Descriptiva de la Revisión y Actualización de los Cuadrángulos de Chulca (30-q), Cayarani (30-r), Cotahuasi (31-q) y Orcopampa (31-r). Instituto Geológico Minero y Metalúrgico, Lima.

Sandweiss, D.H., Rademaker, K., 2011. El poblamiento del sur peruano: costa y sierra. Bol. Arqueol. PUCP 15, 275–293.

Sandweiss, D.H., McInnis, H., Burger, R.L., Cano, A., Ojeda, B., Paredes, R., del Carmen Sandweiss, M., Glascock, M.D., 1998. Quebrada Jaguay: early maritime adaptations in South America. Science (Wash. D C) 281, 1830–1832. https://doi.org/10.1126/science.281.5384.1830.

Schreiber, K.J., 1992. Wari Imperialism in Middle Horizon Peru. Anthropological Papers 87. University of Michigan, Ann Arbor.

Speakman, R.J., 2012. Evaluation of Bruker's Tracer Family Factory Obsidian Calibration for Handheld Portable XRF Studies of Obsidian. University of Georgia Center for Applied Isotope Studies, Athens.

Stern, C.R., 2018. Obsidian sources and distribution in Patagonia, southernmost South America. Quat. Int. 468 https://doi.org/10.1016/j.quaint.2017.07.030, 190-2015.

Tanner, B.R., 2001. Lithic Analysis of Chipped Stone Artifacts Recovered from Quebrada Jaguay, Peru. Unpublished MS thesis. University of Maine, Orono.

Thouret, J.-C., Gunnell, Y., Jicha, B.R., Paquette, J.-L., Braucher, R., 2017. Canyon incision chronology based on ignimbrite stratigraphy and cut-and fill sediment sequences in SW Peru documents intermittent uplift of the western central Andes. Geomorphology 298, 1–19. https://doi.org/10.1016/j.geomorph.2017.09.013.

Thouret, J.-C., Jicha, B.R., Paquette, J.-L., Cubukcu, E.H., 2016. A 25 myr chronostratigraphy of ignimbrites in south Peru: implications for the volcanic history of the central Andes. J. Geol. Soc. 173, 734–756. https://doi.org/10.1144/jgs2015-162.

Thouret, J.-C., Wörner, G., Gunnell, Y., Singer, B.S., Zhang, X., Souriot, T., 2007. Geochronologic and stratigraphic constraints on canyon incision and Miocene uplift of the central Andes of Peru. Earth Planet Sci. Lett. 263, 151–166. https://doi.org/10.1016/j.epsl.2007.07.023.

Tripcevich, N., 2007. Quarries, Caravans, and Routes to Complexity: Prehispanic Obsidian in the South-Central Andes. Unpublished Ph.D. thesis. University of California, Santa Barbara.

Tripcevich, N., 2010. Exotic goods, Chivay obsidian, and sociopolitical change in the south-central Andes. In: Dillan, C.D., White, C.L. (Eds.), Trade and Exchange: Archaeological Studies from History and Prehistory. Springer, New York, pp. 59–73.

Tripcevich, N., 2016. The ethnoarchaeology of a Cotahuasi salt caravan: exploring Andean pastoralist movement. In: Capriles, J.M., Tripcevich, N. (Eds.), The Archaeology of Andean Pastoralism. University of New Mexico Press, Albuquerque, pp. 211–229.

Tripcevich, N., Contreras, D.A., 2011. Quarrying evidence at the Quispisisa obsidian source, Ayacucho, Peru. Lat. Am. Antiq. 22 (1), 121–136. https://doi.org/10.7183/1045-6635.22.1.121.
Tripcevich, N., Contreras, D.A., 2013. Archaeological approaches to obsidian quarries: investigations at the Quispisisa source. In: Tripcevich, N., Vaughn, K.J. (Eds.), Mining and Quarrying in the Ancient Andes: Sociopolitical, Economic, and Symbolic Dimensions. Springer, New York, pp. 23–44.
Tripcevich, N., Mackay, A., 2011. Procurement at the Chivay obsidian source, Arequipa, Peru. World Archaeol. 43 (2), 271–297. https://doi.org/10.1080/00438243.2011.581447.
Wasilewski, M., 2011. Obsidians in the Valley of the Volcanoes, Peru: A Geoarchaeological Analysis. British Archaeological Reports International Series 2223, (Oxford).
Williams, P.R., Dussubieux, L., Nash, D., 2012. Provenance of Peruvian Wari obsidian: comparing INAA, LA-ICP-MS, and portable XRF. In: Liritzis, I., Stevenson, C. (Eds.), Obsidian and Ancient Manufactured Glasses. University of New Mexico Press, Albuquerque, pp. 75–96.