Compositional data supports decentralized model of production and circulation of artifacts in the pre-Columbian south-central Andes

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The circulation and exchange of goods and resources at various scales have long been considered central to the understanding of complex societies, and the Andes have provided a fertile ground for investigating this process. However, long-standing archaeological emphasis on typological analysis, although helpful to hypothesize the direction of contacts, has left important aspects of ancient exchange open to speculation. To improve understanding of ancient exchange practices and their potential role in structuring alliances, we examine material exchanges in northwest Argentina (part of the south-central Andes) during 400 BC to AD 1000 (part of the regional Formative Period), with a multianalytical approach (petrography, instrumental neutron activation analysis, laser ablation inductively coupled plasma mass spectrometry) to artifacts previously studied separately. We assess the standard centralized model of interaction vs. a decentralized model through the largest provenance database available to date in the region. The results show: (*i*) intervalley heterogeneity of clays and fabrics for ordinary wares; (*ii*) intervalley homogeneity of clays and fabrics for a wide range of decorated wares (e.g., painted Ciénaga); (*iii*) selective circulation of two distinct polychrome wares (Vaquerías and Condorhuasi); (*iv*) generalized access to obsidian from one major source and various minor sources; and (*v*) selective circulation of volcanic rock tools from a single source. These trends reflect the multiple and conflicting demands experienced by people in small-scale societies, which may be difficult to capitalize by aspiring elites. The study undermines centralized narratives of exchange for this period, offering a new platform for understanding ancient exchange based on actual material transfers, both in the Andes and beyond.

south-central Andes | archaeology | exchange | complexity | compositional

The long-distance exchange of goods and resources has long been central to the investigation of cultural complexity in human societies (1–4), with recent developments expanding our understanding of the deep roots of human networked sociality (5). The south-central Andean region of South America, with its long-term record of socio-material interactions across vast areas (6, 7), has provided a fertile ground for scholarly debates on the role of such practices in the emergence of socio-political hierarchies and statehood (7–15). We examine some of these practices in northwest Argentina (NWA), part of the south-central Andes, through a multianalytical approach incorporating petrography, compositional, and archaeological analysis of pottery and obsidian artifacts, previously studied separately. Our study examines the circulation of pottery and stone artifacts between 400 BC and AD 1000. This long segment in the region's prehistory is a part of the Formative Period (FP, approximately 1500 BC to AD 1000), characterized by the gradual unfolding of sedentary lifestyles, productive subsistence technologies, and new craft technologies (for a comprehensive critical synthesis of the FP and its internal phases, see ref. 16).

Earlier studies of long-distance mobility and exchange in NWA focused on reconstructing regional networks on the bases of typological similarities, hypothesizing the dominance of different centers through time (17–19). These approaches raised important questions on the degree of integration of the region within the wider south-central Andean context, while developing an important baseline to investigate the general direction of interregional contacts. However, the nature and scale of interaction has remained largely speculative until today, with discussions focusing on specific areas that are taken as exemplary (e.g., refs. 12 and 20), or on integrating disparate evidence generated through a variety of approaches and methodologies (e.g., refs. 21–24).

Significance

The exchange of goods is a key factor in the development of complex societies. The Andes have provided a fertile ground for investigating this process, yet the long-standing emphasis on qualitative assessments of artifact similarities has left important aspects of ancient exchange open to speculation. Through a multianalytical and multimaterial approach we examine regional connections in Formative Period northwest Argentina. The results unveil a far more multifaceted, decentralized network than previously thought, challenging standard approaches that have favored centralized patterns of regional interaction. The study opens avenues for investigating the dynamic interaction between local and regional networks in small-scale societies through actual material transfers, both in the Andes and beyond.

Author contributions: M.L. designed overall research; L.P.D. designed petrography strategy; M.C.S. and M.A.K. contributed to design of research; M.L., L.P.D., W.D.S., and M.D.G. performed research; W.D.S. contributed new reagents/analytic tools; M.L., L.P.D., W.D.S., M.C.S., M.A.K., and M.D.G. analyzed data; M.L., L.P.D., and W.D.S. wrote the paper; L.P.D. created and edited all figures, except the photograph in Fig. 2*A*; M.C.S. oversaw field strategy and sampling design in core study area; M.A.K. oversaw field strategy and sampling design in the Bolson valley; M.C.S. and M.A.K. conducted contextual analysis of archaeological data; M.L., L.P.D., W.D.S., M.C.S., and M.A.K. revised and edited several versions of the paper; and M.D.G. revised a final version of the paper.

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Data deposition: All elemental data can be accessed at the University of Missouri Research Reactor (MURR) Archaeometry Laboratory website archaeometry.missouri.edu/datasets/. The article and all supporting material, including the petrographic point counts dataset, will be deposited in the University of Exeter's repository: https://ore.exeter.ac.uk/repository/.

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Specific methodologies oriented to answering questions of intercommunity and interregional interaction have been implemented in the last 35 y in NWA and in the Andes more widely, with particular emphasis on the combination of petrography and compositional analysis (e.g., refs. 25–29), or through the incorporation of compositional analysis to the study of a variety of materials into broader studies in recent years (30–40). However, such studies have selectively focused on individual classes of archaeological evidence (i.e., either pottery or obsidian), unintentionally concealing the substantial complexity of ancient exchange practices. Although more expansive methodologies involving several analytical approaches to pottery, such as the one implemented in this study, are starting to be applied elsewhere (41), examples of multiartifactual studies are rare, both in the study area and beyond. Our methodology was designed to implement the phased integration of different materials into the same study following the conceptual underpinnings of our project, which focuses on understanding the diverse socio-material basis for the constitution of early village societies and their regional spaces of interaction. We follow Gosden's (42) early proposition of "social landscapes" as the effect of—and precondition for—the development of complex webs of interpersonal and intercommunity mutual obligations, understandings, and expectations. Embedded in this concept is an approach that, although not eschewing formal analysis, emphasizes networks as both powerful descriptors for regional social practices and as performative cultural models for how societies imagine and create their own regional worlds (43, 44). The present study considerably expands a successful preliminary study (45) by determining source areas for 542 ceramic samples, 74 obsidian artifacts, and 39 volcanic rock artifacts from 7 sectors in the semiarid valleys subarea of NWA (*Materials and Methods* and Fig. 1).

Exchange and Interaction in the South-Central Andes

Within the broader context of Andean exchange and ecological complementarity studies (46, 47), south-central Andean scholars have developed models that consider the region's specificity, particularly in connection to the role of llama caravans (7, 22–24, 48–50). Although large caravans were a late development in NWA, llama-assisted long-distance circulation of goods can be traced to the region's earliest human occupations (6, 51). Such practices have been seen as promoting societal integration through the development of symmetrical regional ties that, although long-lasting, became increasingly co-opted by aspiring elites (7, 50, 51). For example, the expansion of Tiwanaku, particularly in its peak phase (AD 500–1000), is often related to the extension of long-existing networks, which substantiated new interelite exchanges and facilitated the growth of regional centers in NWA and Chile (17, 19, 48, 52).

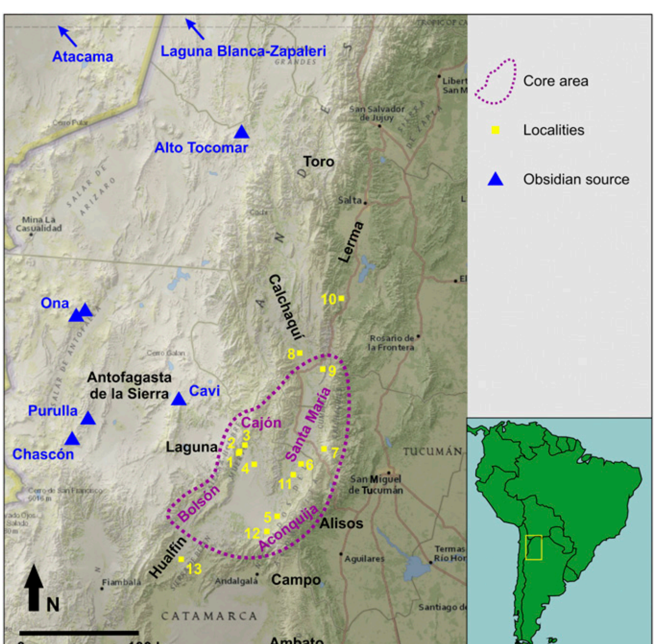

Fig. 1. Study area, with valleys, obsidian sources, and localities mentioned in the text. Clay sources: 1 and 2, Cardonal; 3, Yutopián; 4, Arcillas Verdes; 5, La Aspereza; 6, Quebrada de Jujuil; 7, Los Colorados; 8, Palo Pintado: 9, Las Conchas; 10, La Viña. Archeological sites: 11, Soria 2; 12, Ingenio del Arenal-Falda; 13, La Ciénaga. Full list of sites included in the study available in *SI Appendix*, Tables S1–S3.

Within this framework, and based on typological analysis, the spatial distribution of diagnostic artifacts and motifs has been used to propose internally homogeneous and mutually exclusive regional spaces of interaction (or "cultural areas") dominated by particular "head settlements" or nodes. For example, the Alamito culture within Campo del Pucará (approximately AD 100–500, "Campo" in this report), and the sites comprising the "Aguada complex" in the Ambato Valley (approximately AD 600–900, "Ambato" in this report) (Fig. 1), have been proposed by early researchers (17–19, 53, 54) as centers that controlled the regional dissemination of materials and ideas across NWA at different times in the region's prehistory. This emphasis on the central role of particular areas in regional networks has started to be revised recently, yet it continues to underlie studies of socio-political change (55–58). In particular, the alleged ceremonial centrality of these areas has been recently questioned within a broader discussion of the material basis for assessing ceremonial monumentality in the region (59). Similarly, the extent to which the so-called Aguada "phenomenon" or "cultural complex" reflects a hierarchical society, and the nature and scope of its regional influence continue to be debated (59, 60). Scattolin (61–63) in particular, has documented the sparsity of the characteristic Aguada ceramic styles and iconographic motifs in our core study area, which appears to indicate a very limited, if not altogether absent, Aguada influence. Although initially noted (64), this fact became largely obscured by models that treated the chronological sequence of the Hualfín Valley as the "master sequence" for most of NWA (17, 19, 52, 64). Scattolin's careful revision of stylistic data complements the observation that the distinct spatial layouts recorded at Alamito and Aguada heartlands, which stimulated much examination of their internal complexity and hierarchy, as well as their mutual relationship (56, 19), were actually one of the many architectural traditions within the varied settlement landscape of NWA's FP (63).

There is, therefore, much room for improvement in the definition of the nature and scale of the relationship between alleged central areas, as well as within these and peripheral archaeological areas of NWA, in ways that are sensitive to artifactual diversity across several axes of variation (technical, stylistic, spatial, temporal). Although interelite exchanges of high-value items cannot be ruled out (22, 51, 65), such exchanges and connections need to be contextualized in a broader set of practices of circulation involving a wide range of communities and materials at various spatial scales, before assumptions are made on the capacity of elites or charismatic individuals to build their authority on the bases of regional exchange. Here we build upon data acquired in recent years by members of this project and collaborators, which shows that FP communities had a more generalized, nonhierarchical access to materials, resources, and skills than previously allowed by elite-oriented models (63, 66, 67), to generate a new approach to regional interaction in the period. Central to our project of reexamining the nature of regional connections are the facts that: (*i*) pottery styles traditionally assumed to have mutually exclusive distributions in specific cultural areas often coexist in the same archaeological contexts (62, 68); (*ii*) traits long-assumed to be diagnostic of particular pottery styles were actually modified and recombined in various ways across the region (69); and (*iii*) obsidian circulation crossed over the distribution areas of a variety of pottery styles, thus connecting communities engaged in the use of very different material assemblages (70). This cumulative body of evidence calls for a concerted effort to revise the standard centralized, elite-driven model of long-distance interaction, which continues to be active as the basis for most operative assumptions when investigating the period's socio-political dynamics (55–58, 60), and dominates overall approaches to the region's cultural prehistory (see discussion in ref. 71). This is not only apparent in our study area, as broader reappraisals on the enduring power of typological approaches in archaeology have shown (e.g., refs. 2 and 72). However, unlike other critical reviews of such models (73), our study not only reexamines existing data under new theoretical light, it also provides a large-scale multianalytical dataset of both stone and ceramic artifacts. This dataset enables the careful tracking of concrete, material relations between places before assuming the importance, or lack thereof, of particular connections.

It is therefore useful to carefully examine the expectations of both approaches to long-distance exchange and interaction. A centralized model would be compatible with the existence of a small number of production areas for key pottery styles, as well as with relatively few settlements controlling geographically scarce resources, such as obsidian, which redistributed these goods to sites in the network that lacked access to them. This pattern might be expressed as disproportionate densities of particular artifacts at sites according to rank, and with centralized production of lithic and pottery artifacts. Contrary to the centralized model, a decentralized model would expect the circulation of raw materials and finished goods in a variety of directions. This would result in the existence of multiple production areas for a variety of decorated pottery styles. In the cases of goods such as obsidian, which even in generally open regional exchange systems may be subjected to some level of selective or limited access (74), a decentralized model would imply a relatively even distribution of materials and a generally domestic production of artifacts across settlements of different standing in the network, given the absence of mechanisms and facilities for the organized control of production or distribution. The decentralized model would also be compatible with smaller, material-specific networks crisscrossing the larger circuits followed by other materials. These contrastive models encompass Nielsen's (75) classification of caravan network patterns: convergent or divergent (according to the degree of concentration in the flow of goods), and segmentary vs. continuous (according to the number of interconnected nodes), as well as Tripcevitch's

Fig. 2. (*A*) Obsidian artifacts from Cajón: Cavi source (top row and *A.1*); Purulla source (*A.2–A.4*), and Ona source (*A.5*); photograph courtesy of Sean Goddard. (*B*) Volcanic rock artifacts: from Hualfín (*B.1*) [no. 34010, artifact owned by Museo Etnográfico, University of Buenos Aires], Cajón (*B.2*) and Aconquija (*B.3*). (*C*) Ceramics: ordinary (*C.1*), polished gray incised (*C.2*), Condorhuasi (*C.3*) [UDM 6/R3, artifact owned by Museo de Antropología, University of Córdoba], Vaquerías (*C.4*), and Ciénaga Red on Buff (*C.5*) [no. 32180, artifact owned by Museo Etnográfico, University of Buenos Aires].

(40) extension of Nielsen's model to discuss diffuse and centralized networks for obsidian. Our study provides a multimaterial regional dataset to assess the occurrence of these patterns and their implications in terms of cultural complexity and socio-political hierarchization. Although some of the artifacts that circulated across the region were small components of the overall assemblages at particular sites (e.g., Vaquerías and Condorhuasi wares, obsidian) (*SI Appendix*), they provide a window to understand the backbone of this social landscape; that is, how the terrain was shaped through the material connections supporting mutual obligations, expectations, and demands experienced by the period's small-scale societies. These connections are raw material through which socio-political alliances are built or undermined; therefore, understanding their structure is of central importance when assessing the regional role played by particular locations. Although starting from a contrastive point can be a useful heuristic device, our approach aims at understanding the interaction between social processes of hierarchization and decentralization rather than fueling either/or discussions on the emergence and development of cultural complexity.

Materials and Methods

The study focuses on a 50- to 60-km-wide area in the semiarid valleys section of NWA, encompassing the southern Calchaquí valleys (Cajón, Santa María), the western hillside of the Aconquija Sierra (Aconquija), and El Bolsón Valley (Bolsón). This core study area provided the bulk of the samples analyzed, which were obtained directly through our primary research over the last three decades. The Santa María valley site of Soria 2 has been the focus of another research project (76), which has lent samples for this study. The study also included materials from relevant neighboring valleys and basins, such as Hualfín Valley (Hualfín), Campo del Pucará (Campo), Calchaquí Valley (Calchaquí), Laguna Blanca (Laguna), and Campo de los Alisos (Alisos), which were obtained through museum collections or provided by other research projects (see *Acknowledgments*). More distant areas (around 150–200 K_m) include Quebrada del Toro (Toro) and the Lerma Valley (Lerma) (Fig. 1 and *SI Appendix*, Table S1). The methodology combined petrography and instrumental neutron activation (NAA) for ordinary and decorated wares (n = 542) as well as for raw clay and experimental samples; X-ray fluorescence and NAA for obsidian and volcanic rock artifacts, and targeted laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) for two distinct polychrome wares (Condorhuasi and Vaquerías) (Fig. 2). The targeted approach to these two wares sought to assess earlier hypotheses concerning their nonlocal origin, which proposed that the Vaquerías style originated at Lerma and spread widely across NWA and Chile trough llama caravans, albeit in very low frequencies (77, 78; see recent discussion in ref. 79). Polychrome Condorhuasi style has been interpreted as originating either at Hualfín or Campo, and it has also been considered an indicator of long-distance llama caravan traffic, although its distribution seems to be limited to the southern sector of NWA (53, 80; see recent discussion in ref. 81). NAA also included clay samples from 10 known sources (Fig. 1), two samples of archaeological raw clays recovered at the site Soria 2 (Santa María), and two modern pottery samples manufactured with other local clays (*SI Appendix*). Petrographic analysis of 299 sherds (55% of the chemical sample) as well as clay and sand samples was conducted through point-counts, as well as qualitative analysis (*SI Appendix, Materials and Methods, Petrography Analysis*). Both ordinary (Fig. 2*C.1*) and decorated wares (Fig. 2 *C2–C5*) were sampled for each region when possible, attending to maximizing the representativeness of the ceramic variability of each area's assemblage (additional details on sampling in *SI Appendix, Materials and Methods, Sampling and Analysis Methods for Ceramic Materials*). Seventy-four obsidian samples were selected to monitor the range of different kinds of obsidian sources used at particular sites (Fig. 2*A*). The obsidian results contribute to previous studies conducted by members of this team as part of various projects in the last 23 y, resulting in a total sample of 210 sourced obsidian artifacts available for the study area (37, 39, 67, 82; for additional obsidian studies from this period in NWA, see ref. 83) (*SI Appendix*, Fig. S3 and Table S2). Thirty-nine volcanic rock artifacts (commonly referred locally as vulcanite) (84) from the "La Ciénaga basaltic industry," identified in the 1950's at Hualfín (85), were selected to assess whether this specific type of artifact was made at different locations with different varieties of this raw material (Fig. 2*B*).

To better monitor variations in the use and circulation of sources across the long period considered in this study, we divided our samples following stylistic and newly calibrated radiocarbon data (62, 86) in four phases or temporal groups: T1 (400 BC to AD 100); T2 (AD 100–450), T3 (AD 450–650), and T4 (AD 650–1000). Condorhuasi and Vaquerías have a temporal distribution limited to T1 and T2, whereas other motifs and decorative and manufacture techniques—including modeled, polished gray, or buff and incised decoration—continue across the sequence. Ciénaga wares vary considerably in time, with the variety red on buff being characteristic of T2 (*SI Appendix, Materials and Methods, Northwestern Argentina's Chronology and Temporal Groups Considered in this Study*). Statistical analysis showed that the observed spatial and temporal variation of pottery chemical group frequency is significant (*SI Appendix, Chi Square Analysis* and Fig. S1). All elemental data can be accessed at the University of Missouri Research Reactor (MURR) Archaeometry Laboratory website archaeometry.missouri.edu/datasets/. Petrographic data can be accessed at the University of Exeter's repository https://ore.exeter.ac.uk/repository/.

Results

Lithic Source Assignments. The analysis identified three sources that supplied most of the sites in the study area: Cueros de Purulla (Cueros), Ona-Las Cuevas (Ona), and Laguna Cavi (Cavi) (Fig. 2*A* and *SI Appendix*, Fig. S3 and Table S2). These results support the macroscopic identification of Ona obsidian, while highlighting that the same approach can be misleading when applied to opaque obsidian from either Cavi or Cueros. The results also strengthen previous observations regarding the preeminence and spatial reach of Ona. Cavi and Cueros obsidian were less frequently used and had geographically restricted distributions, with the former being relatively more frequent among the opaque sources. Toro continues to appear as a region with privileged access to obsidian, as identified in previous studies (39), including both the main northern source (Laguna Blanca-Zapaleri) and the principal southern source (Ona). Toro also had access to Alto Tocomar and an unidentified source in the Atacama region of Chile (Fig. 1). The minor sources Cavi and Cueros did not reach Toro. The overall pattern confirms a decentralized, diffuse network [in the sense discussed above (75)] of circulation of this material, particularly in connection with Ona. The results also show that areas, such as Cajón, Bolsón, Aconquija, and Santa María had access to all of the sources from the southern sector of NWA, although Cajón and Bolsón appear to have much larger frequencies of Cavi and Cueros compared with other areas.

The volcanic artifact samples analyzed mostly fell within type 1 (n = 26) and a few in type 2 (n = 7) (Fig. 2*B* and *SI Appendix*, Fig. S4 and Table S3). Three samples were considered outliers, and one sample was considered an extreme outlier. It is very significant that the type 1 includes La Ciénaga material collected at Hualfín in the 1950s (85), providing further support to the results obtained by the preliminary study mentioned earlier. Type 1 vulcanite connects Hualfín with Aconquija and Cajón (Fig. 1, see *Discussion*), whereas type 2 vulcanite circulated between Bolson and Aconquija, with a minimal presence at Santa María. Although the geological source remains unidentified, outcrops of the same geological formations located in both Hualfín and Cajón are likely sources for this material (87). These results show that the raw material used for making the highly formalized and very large side scrapers came largely from a single source, indicating the existence of a direction-specific, segmentary network in the sense discussed above (75), involving these artifacts during T2 and part of T3.

Pottery Results. The geology of our core study area makes it a difficult region to use petrographic and compositional analyses of pottery because most of the sediments suitable for pottery production form through weathering and run-off of similar parent materials in the mountains (87–89). Although mineralogical and chemical differences among the raw materials used to manufacture pottery appear across space within interior drainage basins, these differences tend to be very subtle because of the mixing of sediments. In this context, petrography analysis identified 16 fabric groups, which can be grouped in three large classes: coarse, intermediate, and fine fabrics (*SI Appendix*, Figs. S2 and S5*A*), but the classification in different petrographic groups was often dependent on minimal mineralogical variations (81).

Because of the difficulties of chemical sourcing in this region, we used a staged analysis for NAA involving firstly the

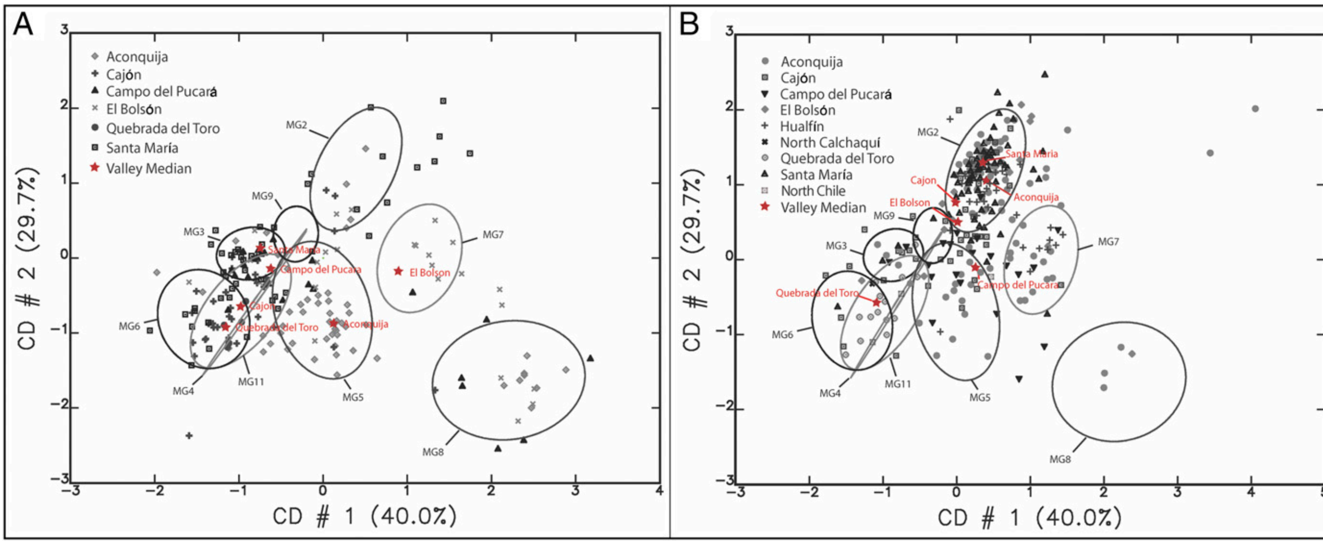

Fig. 3. Bulk NAA chemical data for (*A*) ordinary wares and (*B*) decorated wares, coded by valley where samples were collected. Axes are canonical discriminant functions #1 and #2. Ellipses represent 90% confidence intervals of membership within macrogroups. Data points represent chemical composition of individual samples. Red stars represent the median chemical composition for each valley. See *SI Appendix*, Fig. S6 for elements that are determinant of canonical discriminant factors 1 and 2.

construction of core reference groups, and secondly a canonical discriminant analysis on the core reference groups. We then used these discriminant functions to assign the remaining specimens to the best group, which served as bases for the creation of macrogroups (*SI Appendix*, *Materials and Methods*, *Analysis and Interpretation of Pottery Chemical Data*). NAA results show 12 core groups and 9 macrogroups obtained through canonical discriminant analysis, of which 8 are relevant to the sample discussed here: MG2, MG3, MG5, MG6, MG7, MG8, MG9, and MG11 (Fig. 3 and *SI Appendix*, Table S4). The core chemical groups that were the bases to construct the chemical macrogroups are described in *SI Appendix*. *SI Appendix*, Table S5 shows the distribution of ordinary and decorated wares in the assigned samples ($n = 417$). These assignments accord fairly well with the results of petrography analysis (*SI Appendix*, Fig. S5*A*; see also *SI Appendix*, Fig. S6 for canonical discriminant factor loadings for chemical macrogroups), but show clear differences between closely related or undistinguishable samples at the petrographic level. For example, most samples from petrographic groups A and A′, identified in ordinary wares local to the western and eastern slopes of the Aconquija Sierra, respectively, fall within the clearly distinct MG5 and MG8 (there is also some presence of each of the petrographic groups in both MGs, which will be addressed below). *SI Appendix*, Tables S7–S10 provide details of the uncertainty of values measured in ceramics, the detection limits, the mean and coefficient of variation for every macrogroup, and the discriminant factor loadings for the first four canonical discriminant factors. The results also accord well with the chemical group structure identified through previous analyses (45), although increasing sample sizes over time typically requires some restructuring (*SI Appendix*, *Materials and Methods*, *Pottery NAA: Irradiation and Gamma-Ray Spectroscopy* and Fig. S5*C*).

Some of the clay samples analyzed approximate certain chemical macrogroups: La Viña/Las Conchas to MG2, Jujuil to MG3, Los Colorados to MG6, and one Aconquija sample to MG8 (Fig. 1 and *SI Appendix*, Fig. S5*B*). However, these trends are not sufficiently strong to assert the membership of the clay samples into these groups. This is not surprising, as the location form where we took the sample may not have been where ancient potters collected their local clay for firing, whereas the addition or removal of aplastics may further complicate chemical matching between sample and raw clay. These associations are therefore best treated as hypothesis for further work. We discuss below the main trends in the pottery data:

Intervalley heterogeneity of clays and fabrics in ordinary wares within the core study area. Petrography analysis identified distinct coarse fabrics, with intentionally added sands (33–46%) of wide granulometric range at Aconquija, Cajón, Santa María, Campo, and Toro. Chemical results obtained for ordinary wares have assigned ordinary ware samples to five macrogroups (*SI Appendix*, Table S4) discussed below (*SI Appendix*, Fig. S10). The criterion of abundance, which states that the most common composition at any given site is likely of local production in societies that lack mass transportation technologies (90), is often used for determining source areas in compositional analysis. However, this principle should be applied alongside archaeological and petrographic observations, as an abundance of samples from particular areas may be signaling sampling biases due to availability, among other issues (29). Caution should also be exercised when interpreting the potential production areas and circulation routes of ordinary wares in basins, such as our core study area, given the geologic homogeneity mentioned above. With these considerations in mind, we advance the following source areas.

MG3 has a majority of ordinary samples from Santa María and Aconquija. Given the proximity of this group with the clay source Quebrada de Jujuil (Fig. 1 and *SI Appendix*, Fig. S5*B*), and the abundance of Santa María ordinary wares, it is possible to propose the southern Santa María as the source area for this group (source area MG3). The clay was also used to manufacture a few decorated wares from both areas as well as from Cajón, which appear to be local to the valleys where they were found, but petrography is inconclusive in this regard. MG5 has a majority of Aconquija ordinary wares, with samples from Campo and Cajón in second and third place, and a few specimens from Santa María, Bolsón, and Hualfín. The petrography of the Aconquija and Campo samples included in this macrogroup is very similar because of the similarity in the inclusions and the clay used on both sides weathering from the same parent material. Petrography analysis of a subset of the remaining samples in this group appears to indicate that these potsherds belonged to vessels made locally at each of the valleys where they were recovered, therefore cannot be considered imports. We therefore consider Aconquija as the source area for this group (source area MG5). MG6 contains a majority of samples from Cajón and Santa María, with three samples from Aconquija and one sample from Bolsón. As mentioned above, MG6 associates with the Los

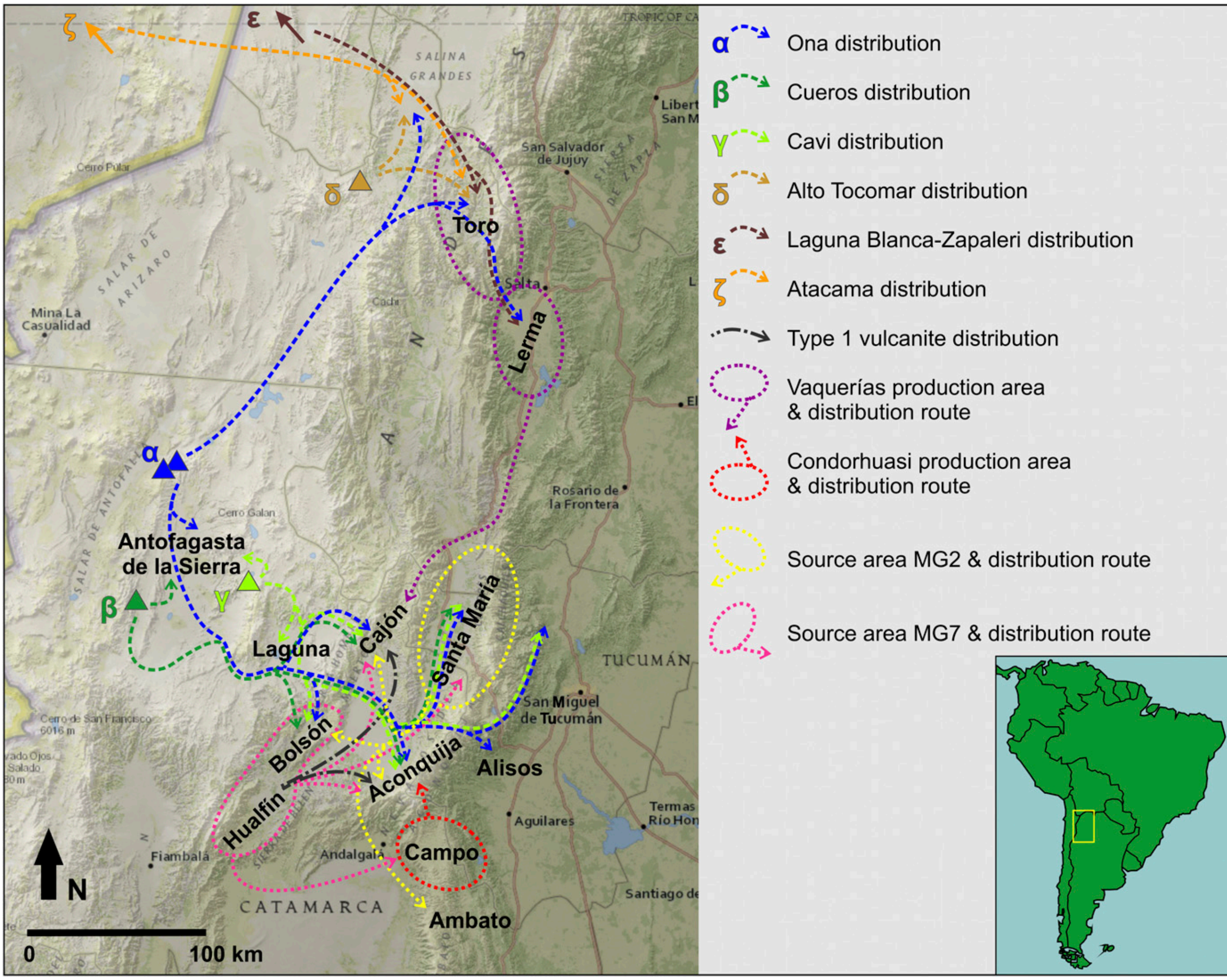

Fig. 4. Distribution routes for obsidian sources, decorated MG2 and MG7 pottery wares, Vaquerías and Condorhuasi wares, and type 1 vulcanite.

Colorados clay sample from Santa María (Fig. 1 and *SI Appendix*, Fig. S5*B*). Petrography analysis, however, shows that the samples in this macrogroup are local to the valleys from where they were recovered; therefore, we cannot assert whether Cajón or Santa María were the source areas for this group. MG8 has a majority of Aconquija ordinary wares, with Campo samples second in frequency, and it also contains a few ordinary samples from Bolsón and Cajón. This group presents a similar problem as MG5 in terms of source area allocation, with the difference that MG8 is closely associated to the clay source La Aspereza, in Aconquija (Fig. 1 and *SI Appendix*, Fig. S5*B*). This means that this clay was used on both sides of the Aconquija range to manufacture similar ordinary wares as indicated by petrography analysis. Although the majority of Aconquija samples could signal a sampling bias because of sample accessibility, the χ^2 test conducted shows that the distribution of macrogroup frequencies across valleys is not random (*SI Appendix*, *Chi Square Analysis*), therefore Aconquija could be considered the source area for this macrogroup (source area MG8). Samples from the Bolsón and Cajón included in this group could represent imports of the clay to these valleys, as their fabrics appear to be local, but petrography is inconclusive in this regard. MG11 includes most ordinary wares from Toro, and petrography clearly identifies the fabric as local (source area MG11). Two specimens from Cajón are also included in this group and they can be considered clear imports, as their petrography is also clearly similar to the samples from Toro as shown by their metamorphic content (fabric VC) (*SI Appendix*, *Materials and Methods*, *Petrography Analysis*).

Intervalley homogeneity of clays and fabrics for decorated wares within the core study area. Petrography analysis identified two major groups of fine fabrics, with either very low percentage of intentionally added very fine aplastics (fabric L) (10–30%) or absence of intentionally added aplastics (fabric M). These fabrics were used in the manufacture of a wide array of decorated wares found in most valleys and areas (*SI Appendix*, *Materials and Methods*). These results agree well with the results of NAA, which was able to distinguish two distinct chemical groups for decorated wares of fine and intermediate paste fabrics that were largely dominant in the manufacture of decorated wares in the core study region (*SI Appendix*, Fig. S11). MG2 includes 76% of the all assigned fine wares, and many of the unassigned specimens are also chemically similar to MG2. The samples come largely from Santa María and Aconquija, but also from Hualfín, Bolsón, and Cajón. We consider Santa María as a potential source area for this group (source area MG2) (Fig. 3). No samples from Campo or Toro were assigned to this group. MG7 mainly includes decorated wares from Hualfín, as well as decorated and ordinary wares from the Bolsón. No ordinary wares from Hualfín were available at the time of the study, but given this results and that both valleys belong to the same basin, it is possible to consider

Bolsón and Hualfín as a single source area (source area MG7) (Fig. 3).

The case of decorated style Ciénaga (red on buff painted variety), a characteristic style of the period (T1 and T2) thought to originate from Hualfín, (Fig. 2*C5*) is particularly interesting. Fragments of this style of pottery found at Aconquija sites were made with materials of the MG7 chemical group, whereas a few but similar Ciénaga specimens recovered at Hualfín sites were made with materials of the MG2 chemical group. MG2 could potentially be divided into two subgroups, MG2a and MGb, with predominance of Santa Maria/Aconquija and Hualfín specimens, respectively (*SI Appendix*, Fig. S5*C*). MG2b in particular includes a range of diagnostic styles traditionally associated with Hualfín, such as painted Ciénaga and incised Ciénaga, and painted Aguada wares. The manufacture, decorative techniques, and motifs are distinctive and the whole group clearly separates from the rest of MG2 wares. However, petrography analysis has not identified differences in the fabrics of potsherds belonging to both MG2 subgroups; therefore, this division cannot be explained because of the inclusion of different aplastics. If the current association MG2 with Santa María clay sources is confirmed in further studies, the pattern shows a complex scenario in which: (*i*) Hualfín potters were using a range of clays to manufacture Ciénaga, Aguada, and other characteristic pots, which then moved around the core study area (a network involving the movement of clay and/or skill initially, and then the pots themselves); or (*ii*) painted Ciénaga pots were made at different locations with different clays and then circulated between those areas (a network involving the relocation of potters who then exchanged pots of a particular style). These options should be evaluated alongside the possibility that MG2b is the result of the mixing of different clays; targeted analysis of the clay matrix of these wares was not available at the time of this study but it is planned for the next phase of analysis.

Selective circulation of two distinct polychrome wares: Vaquerías and Condorhuasi. The application of LA-ICP-MS to Condorhuasi, Vaquerías (Fig. 2 *C3* and *C4*), and ordinary wares found in the same archaeological contexts (n = 96), enabled the integration of the three different analysis (*SI Appendix*, Figs. S7–S9 and Table S6).

Vaquerías. Petrography identified a distinctive intermediate fabric (Fabrics N, N′), which include metamorphic components that indicate that Toro and Lerma may have been the source areas. Fifty-two percent of the Vaquerías samples analyzed through petrography fall within NAA MG9, which showed their unique temper to be high in Sb. The clay fraction is also fairly homogenous. Eighty-seven percent of Vaquerías samples fall within ICP-group A (*SI Appendix*, Figs. S7 and S8). One Vaquerías sample from Cajón was found to have similar clay fraction to ICP-group B, but it is borderline and intermediate with the main ICP-group A. Additional studies would be needed to assess whether a second variety of Vaquerías was made locally in the southern sector of the study area with the same fabric but different clay. Additionally, the study showed that the potters who made Vaquerías style used different clay than the one they used for ordinary wares in Toro, which were made with ICP-group D clay. This does not necessarily mean that Vaquerías was foreign to Toro. The generalized use of metamorphic rocks as aplastics, both for Toro ordinary wares and Vaquerías, points at the Toro/Lerma basin as the source area for this ware. In the future, balancing the sample to include more specimens from Lerma (unavailable at the time of the study) could clarify the relationship between these two sectors of the same basin. The results strongly indicate the existence of a consistent technical mode and clay choice across the samples from various locations. It should be noted that among the Vaquerías samples, four could be considered local copies of this style made in Cajón, as shown by their petrographic pattern and their assignation to MG2 (these samples were not subjected to LA-ICP-MS).

Condorhuasi. Petrography analysis only identified very slight variations in the mineralogical composition of ordinary and Condorhuasi fabrics from Aconquija and Campo (fabrics A, D and A′, D′, respectively) (*SI Appendix*, Figs. S7 and S9). This result is not surprising given the closeness between these two areas. Additionally, NAA placed the samples in several groups with predominately ordinary wares: MG3 (n = 7), which is related to the southern sector of the Santa María Valley, and MG5 (n = 3) and MG8 (n = 1), related to the Aconquija. Two samples with intermediate fabrics fell within MG2. The combined petrography and NAA results emphasized the local nature of Condorhuasi in Aconquija and Campo, although it was not possible to distinguish clear production areas. Importantly, some of the samples recovered at Campo sites had aplastics that were closer to the geology of the Aconquija and vice versa, signaling a complex pattern of technical practices to manufacture this ware at these two locations. To clarify this pattern, LA-ICP-MS was applied and results show that 93% of the Condorhuasi samples recovered at sites in Aconquija and Campo were all made with ICP-group B clay, whereas 77% of Campo ordinary wares also fall in this group (as shown by the red lines in the diagram in *SI Appendix*, Fig. S9). These samples are chemically distinct from ordinary wares found at Aconquija sites, which all fall in ICP-group C (green lines in the diagram in *SI Appendix*, Fig. S9). At the same time, five ordinary samples from Campo were included in ICP-group E (black lines in the diagram in *SI Appendix*, Fig. S9), which is characterized by high Rb and Cs. This group is tentative and additional studies may suggest these samples are better considered to be outliers. However, it should be noted that these samples were all included in NAA MG8, which was also defined based on its extreme values of Cs and Rb. Petrography indicates the samples are similar to those in the Aconquija, but with slight textural variations indicating their local origin to Campo (petrography group A′; see *SI Appendix*); therefore, it is more likely that these samples are local to Campo, even though they might have used clay from Aconquija. The main results from the LA-ICP-MS support the hypothesis that Condorhuasi wares from these two areas were made at sites in Campo, or that people used the same clay to make this ware at a number of locations on both sides of the Aconquija range. More broadly, the results indicate that the circulation of Condorhuasi was part of a bidirectional movement of craft skills and materials between the communities on the western slope of the Aconquija Sierra and Campo, akin to what Gosselain (91) and others have described as "communities of practice"; small-to-medium scale networks involving the transmission of habitual learning practices through material and knowledge exchanges more than centralized and directed exchange of specialist-produced fine wares.

Discussion

The wide range of connections implied by these results can be partially visualized in Fig. 4, and in the pottery distribution maps in *SI Appendix*, Figs. S10 and S11. Although for the sake of clarity the circulation of type 2 vulcanite and of clays and ordinary wares was not represented in Fig. 4, these should be considered when assessing the overall significance of these connections. Importantly, Fig. 4 also leaves out other elements such as metals, salt, animals, produce, and organic materials (fibers, hides, shells) that may have circulated alongside, or in return for, the more durable ones considered here. The present section will draw the various strands of evidence generated by this study together.

Obsidian circulation, although low in volume (*SI Appendix*), provides a persistent signal of this wide range of connections across areas throughout the whole period. The main source, Ona, reached as far as the fringe of the humid lowlands on the eastern side of Aconquija (Alisos) among other areas in the eastern lowlands (Fig. 4 and *SI Appendix*, Table S2), and to the north as far as Toro. Many of the sites that shared access to this source had very different material culture assemblages, which shows that groups involved in different communities of practice and even different cultural identities were engaged in exchange (e.g., sites in Aconquija and Antofagasta de la Sierra) (Fig. 4) (67, 70). Through obsidian the region was connected farther afield, becoming a part of a long chain of sites (both in NWA and Chile) involved in the exploitation of the same sources. Whereas on the one hand obsidian acted as a mediator of a wide range of connections, at times even between disparate groups, the circulation of the very large side scrapers made on volcanic rocks was basically limited to Hualfín, Aconquija, and Cajón (Fig. 4), with a minor circulation of a secondary type of vulcanite between Bolsón, Aconquija, and Santa María. This shows that smaller and more directionally specific networks traversed the social spaces created by the larger networks, carrying particular sets of artifacts and the associated social and technical knowledge.

Ceramic results show a strong agreement among analytical techniques for ordinary and decorated wares. Petrography analysis indicates that "technical modes" of manufacture (81) for ordinary wares varied across valleys mostly qualitatively (in terms of type of aplastics) but not so much quantitatively (in terms of size and frequency of inclusions). In contrast, the technical modes of decorated wares did not vary so much across the study area, as a limited number were used for a great diversity of decorative styles (most decorated wares have fabrics with little or no aplastics; decorated wares with intermediate fabrics, such as Condorhuasi or Ciénaga Red on Buff and Vaquerías, have limited temporal distribution). NAA complements this picture by showing clear distinctions in the chemical fingerprint of ordinary wares across specific valleys and areas, and a limited number of clays used for decorated wares found across the region (MG2 and MG7) (Figs. 3 and 4). This pattern strongly suggests that there was a set of middle-range distance connections involving not only the circulation of raw materials and artifacts, but also the transmission of skills and concepts of manufacture and design that were not exclusionary. Some of these middle-range networks appear to have involved the associated circulation of particular styles and specific stone tools, as indicated by the circulation of vulcanite artifacts originated in the Hualfín valley and of Ciénaga wares between Santa María, Aconquija, and Cajón.

Condorhuasi and Vaquerías clearly stand out from the rest of the pottery styles, as the networks involved in their production, circulation, and use were temporally limited and geographically selective (Fig. 4). LA-ICP-MS results for Condorhuasi appear to strongly support the hypothesis that this ware was produced at Campo sites; however, this should not lead to the conclusion that Campo had a central or exclusive role in its production. Published records show low frequency of this ware in Campo assemblages (53), and our own excavations have shown that it is actually more abundant at some sites in Aconquija (at the site Ingenio Arenal-Falda) (Figs. 1 and 4). Although Campo had a strong connection with Aconquija, its role in regional exchange may have been more nuanced than the one assumed by earlier studies (e.g., ref. 54), which argued, as discussed earlier, that Campo sites controlled emergent caravan networks and developed an important regional ceremonial role as a consequence of that purported control. The circulation of Condorhuasi wares between Campo and Aconquija has to be seen as part of one of the many movements of artifacts, skills, and possibly clays that took place across the Aconquija sierra. This approach agrees with the expectation of the decentralized model regarding the existence of artifact-specific networks criss-crossing the circuits followed by other types of artifacts that circulated larger distances and more frequently. Future work should focus on assessing the significance of Condorhuasi presence in other areas, such as the funerary assemblages at Hualfín and Laguna (80), and the domestic assemblages at Cajón and Bolsón (66, 68) (Fig. 1).

The integrated analysis of Vaquerías samples showed that there was a technical mode of making Vaquerías—with aplastics, including metamorphic rocks, quartz, sandstone, and crushed pots—that was characteristic of the Toro/Lerma basin. Most of the samples found outside Toro/Lerma are clear imports, and only four can be considered local imitations. The results clearly show that Cajón was the only place in the core study area with substantial presence of Vaquerías style (as well as a small presence of MG11 ordinary wares from Toro), which reveals the role of this traditionally "peripheral" valley in connecting the core study area with the Toro/Lerma basin, and indirectly to the northern sector of NWA and Chile. Here it should be noted that lithic assemblages from Cajón have a relatively higher frequency of the minor obsidian sources (Cavi, Cueros) compared with contemporary sites, whereas Toro had access to a wide range of obsidian sources, including one in Chile (Fig. 4).

One of the major outcomes of this study is the absence of Ambato Valley compositions (8) among our samples. Not only were the characteristic Ambato engraved gray-black wares absent from our study area, but also the clay used by Ambato Valley potters for these wares was not used to make any of our samples. Together with the observed low frequency of painted Aguada varieties in our core study area (most of which are local versions of the style), the results of the geochemical analysis support a reconsideration of the purported central role of this valley. Recent analysis done by Giesso et al. (92) at MURR suggest that some of the Ambato valley Aguada wares were manufactured with MG2 clay, thus opening new avenues to rethink the relationship between our study area and the Ambato valley outside the traditional centralized models that have dominated regional discussions.

Although the core study area can be considered to have been highly integrated through the circulation of materials and skills, this integration was not seamless. Resource circulation shows that rather than single, bounded cultural areas, the circulation of different materials and the enactment of various communities of practices created various regional spaces of participation and exchange, as shown by the shared modes of manufacture of ordinary wares in some cases (e.g., Campo and Aconquija), and the technical and chemical homogeneity observed among decorated wares in others (e.g., Aconquija, Santa María-Cajón-Hualfín, Bolsón). Collectively, the results demonstrate that a wide range of complex, intersecting networks were active simultaneously, without clear dominance of any particular node in time. Although it is possible that some wares may have been produced at the same time in different areas, the hypothesis that clays, aplastics, and potters circulated across the region should be considered. These scenarios have been amply documented among present-day potters in the Andes (25, 93, 94) and our study contributes to improving the modeling of these practices in the past. This finding shows that ancient material circulation networks may have involved multiple mechanisms—including but not reducible to—camelid-assisted transport (24, 67). It also shows that different types of networks [i.e., segmentary, continuous, divergent, convergent, diffuse or centralized (40, 75)] are not necessarily associated with specific types of socio-political organization, but rather they are part of the wide repertoire of strategies that communities drew upon to build regional worlds of belonging through socio-material connections.

Early sedentary communities in NWA were embedded in a widespread range of transactions, projecting their daily activities onto a complex and ever-widening network of associations and mutual dependencies. These exchanges, although primarily integrative, were not devoid of competition and conflict, contrary to what earlier interpretations emphasized (e.g., refs. 7 and 51). Mutual obligations among members of small-scale societies are fraught with stress over the possibility of their breaking down (95). This decentralized social landscape, a web of places connected through mutual obligations over the long term (42), certainly reflects the multiple and conflictive demands experienced by these societies. The importance of these demands for increasing social complexity cannot be minimized, as they can stimulate technological innovation, economic specialization, and social control. However, the diverse connections identified in this study show that communities did not need centralized organization to maintain flourishing networks. Intercommunity exchanges deployed a wealth of material and immaterial resources, which if used strategically, could limit the efforts of aspiring elites seeking to capitalize upon long-distance links. The results preclude simplistic interpretations of the role of exchange in the emergence and transformation of early sedentary societies, both in the Andes and elsewhere. Artifactual homogeneity across space can result from other types of interaction different from those proposed by centralized models, as communities may have participated in several scales or transactions: from the habitual learning networks that result in specific pottery manufacturer's modes (which may include both decorated and ordinary wares, such as, Campo and Aconquija wares, including Condorhuasi) to the movements of raw materials and decorated vessels as part of the exchange of a wide (but not homogeneously distributed) range of materials (e.g., Vaquerías; various obsidian types); and even the movement of specific decorated types and formalized tools, involving perhaps the relocation of people across specific valleys (e.g., Ciénaga). Focusing on close intercommunity links rooted on common craft practices rather than solely on stylistic reconstructions is a more fruitful avenue to explore the ancient circulation of goods, skills, and people without assuming the capacity of early elites to manipulate and capitalize on such networks.

The recognition that small-scale, early sedentary pre-Columbian societies may have been able to manipulate exchange networks and reduce the capacity of aspiring elites to capitalize upon them for their own projects, challenges conventional wisdom of the nature of power and social interaction in small-scale societies. Our findings not only contribute to this debate, but also demonstrate how ancient, long-enduring practices of circulation and exchange—with their cumulative effects on land modification through routes and other infrastructure, as well as on the uses and cultural understandings of resources—have shaped past and present landscapes.

Although our conclusions are based on interpretations of the multitechnique and multiartifactual analysis undertaken here, and we recognize that additional sampling will serve to refine our reconstruction in the future, our study shows that evidence-based, theoretically informed research can substantially enrich our interpretations of ancient connectivity practices, both in the study area and more widely.

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