Was Aztec and Mixtec Turquoise Mined in the American Southwest?

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Was Aztec and Mixtec turquoise mined in the American Southwest?

Allyson M. Thibodeau1*, Leonardo López Luján2, David J. Killick3, Frances F. Berdan4, Joaquin Ruiz5

Archaeologists have long suggested that pre-Hispanic states in Mesoamerica acquired turquoise through long-distance exchange with groups living in what is now the American Southwest and adjacent parts of northern Mexico. To test this hypothesis, we use lead and strontium isotopic ratios to investigate the geologic provenance of 43 Mesoamerican turquoise artifacts, including 38 mosaic tiles from offerings within the Sacred Precinct of Tenochtitlan (the Mexica or Aztec capital) and 5 tiles associated with Mixteca-style mosaics currently held by the Smithsonian’s National Museum of the American Indian. Most of these artifacts have isotopic signatures that differ from turquoise deposits in the American Southwest, but closely match copper deposits and crustal rocks in Mesoamerica. We thus conclude that turquoise used by the Aztecs and Mixtecs likely derives from Mesoamerican sources and was not acquired through long-distance exchange with the Southwest.

INTRODUCTION

For more than 150 years, scholars have argued that Mesoamerican societies imported turquoise from the American Southwest or adjacent parts of northwestern Mexico—a region that many archaeologists refer to as the Greater Southwest (1–7). Turquoise [CuAl6(PO4)4(OH)8·4H2O] was one of several blue-green minerals highly valued by pre-Hispanic societies across both regions, including the Aztec, Toltec, Maya, Mixtec, and Tarascan states in Mesoamerica, and the Hohokam, Mogollon, and Puebloan groups of the Greater Southwest (hereafter “Southwest”). Although turquoise artifacts are found in archaeological sites throughout these regions, major North American turquoise deposits and pre-Hispanic turquoise mines are largely confined to the U.S. states of Arizona, New Mexico, California, Colorado, and Nevada and to parts of northernmost Mexico (Fig. 1) ([6] and references therein).

The observation that there are numerous known examples of pre-Hispanic turquoise mines in the Southwest, but not in Mesoamerica, has, in part, formed the basis for claims that Mesoamerican groups imported turquoise from the north (7). The long-distance exchange of ideas and other items between Mesoamerican and Southwestern groups is well documented, especially after ~900 CE, when firm evidence for small quantities of Mesoamerican imports (for example, scarlet macaws, cacao, and copper bells) appears in Southwestern archaeological sites (9–11). Many archaeologists have suggested that turquoise was traded to Mesoamerica in exchange for these exotic goods. In addition, assertions about sources of Mesoamerican turquoise also derive from previous geochemical investigations. From the 1970s through the 1990s, there was a long-term program of chemical analysis by neutron activation of both Mesoamerican and Southwestern turquoise objects (2–5). These studies interpret the geologic provenance of various turquoise artifacts by comparing their trace and major element signatures with those of turquoise samples from pre-Hispanic mines. Although the resulting publications claim that turquoise artifacts from Mesoamerica derive from Southwestern mines (2–5), the underlying data were never published. Thus, their assertions that Mesoamerican societies acquired turquoise from the Southwest cannot be evaluated.

Here, we revisit the hypothesis that Mesoamerican turquoise derives from the Southwest by using lead (Pb) and strontium (Sr) isotopes as tools to investigate the geologic origin of turquoise objects associated with the Aztecs and Mixtecs. In the Basin of Mexico, Aztec (Mexica) elites were among the most prolific consumers of turquoise during the Aztec imperial years of the Late Postclassic (ca. 1430 to 1519 CE). Turquoise figures prominently in Aztec poetry, ritual, and cosmology (12–15) and was used to make a variety of mosaic objects (for example, ceremonial shields, handles on sacrificial knives, mirrors, diadems, pectorals, arm bands, necklaces, noseplugs, and earrings) that were worn or wielded by rulers, priests, or other high-status individuals in Aztec society (16–20) and even decorated wolves and other sacred animals (21). Our knowledge of xihuitl (or turquoise) in the Aztec empire primarily derives from 16th century documents and codices that contain textual and pictorial representations of the mineral (17–19, 22). According to the Codex Mendoza, an imperial tribute list, turquoise was sent to the Aztec imperial overlords from two provinces in the southern (Mixteca) area of the empire and from one province in the empire’s northeastern corner (Fig. 1) (22). Extant examples of Mesoamerican turquoise mosaics include about two dozen Mixteca- and Mixteca-style mosaics that reside in European and American museums and have no archaeological provenience (fig. S1) (16, 23–25). There are also a number of archaeologically recovered artifacts, including Mixtec turquoise mosaics directly excavated from Monte Albán’s Tomb 7 (26) and Mexica mosaics from buried offerings within the Sacred Precinct of Tenochtitlan (figs. S2 to S4 and table S1) (21, 27–29), which was the political and ceremonial center of the Aztec empire (Fig. 1) (27, 30).

Background

Presently, there are Pb and Sr isotopic measurements of both geological and archaeological samples of turquoise from the Southwest that provide a baseline for evaluating whether Aztec or Mixtec artifacts have a Southwestern origin (8, 31–33). These measurements include Pb and Sr isotopic ratios on >150 geological samples of turquoise from 19 different mining districts across Arizona, New Mexico, Colorado, southeastern California, and southern Nevada in the United States, and in northern
Fig. 1. Map of locations discussed in the text. The Southwestern turquoise deposits shown here are discussed in the study of Thibodeau et al. (8) and have been previously characterized with Pb and Sr isotopic ratios (8, 31, 33). No isotopic data are available on turquoise deposits of the Concepción del Oro or Mazapil localities. Aztec tributary provinces are drawn based on the study of Berdan (18). Dotted red line indicates approximate boundary between the Aztec and Tarascan empires.
Sonora, Mexico (8, 31). Many of the geological samples derive from mining districts with known prehispanic mining activity.

Unlike the Southwest, where there are many documented prehispanic turquoise mines with associated isotopic data, little is known about possible turquoise deposits within the Aztec empire, including the Mixtec region, or in other bordering areas of Mesoamerica. In Mexico, the southernmost turquoise mines that have been documented in both the geological and archaeological literature are near the municipalities of Concepción del Oro and Mazapil in northern Zacatecas (2, 7, 34). Some of the older archaeological and ethnohistorical literature preserves secondhand reports of turquoise deposits in Jalisco and Puebla (18, 35, 36), but, to the best of our knowledge, no scholars have located or verified the existence of turquoise deposits in these areas. However, because turquoise mines are often small and shallow workings occurring near economically significant deposits of copper, they may be easily exhausted, altered, or destroyed by later mining practices. The destruction of ancient turquoise mines is known to have occurred in the American Southwest [for example, see discussion in the study of Thibodeau et al. (33)] and thus may have also occurred in Mexico as well.

Although we are not aware of any direct evidence for turquoise mineralization in Mesoamerica, Pb and Sr isotopes offer an indirect approach to evaluating the possibility that Mesoamerican turquoise artifacts derive from Mesoamerican sources. To understand how, it is useful to first consider Pb and Sr isotopic variation in Southwestern turquoise deposits. Turquoise is generally formed in the oxide zones of copper deposits and derives its elemental constituents from the weathering of the surrounding geologic formations. In the Southwest, the isotopic characteristics of turquoise deposits vary regionally and reflect broad-scale differences in the age, chemical composition, and sources of the associated rocks (8, 37). For example, in Arizona and New Mexico, many turquoise deposits have Pb isotopic signatures that broadly mirror those of their host copper porphyry deposits and associated felsic igneous complexes. In turn, these porphyry deposits have Pb isotopic characteristics that are consistent with the crustal province in which they are located, which is controlled by the age, initial Pb iso-

RESULTS AND DISCUSSION

The Pb and Sr isotopic ratios of the tesserae are given in Table 1. Of the 43 tesserae analyzed, we were able to collect both Pb and Sr isotopic data on 31 samples. For the other 12 samples, we obtained either Pb or Sr isotopic ratios. When both Pb and Sr isotopic data are considered, 29 of the 31 tesserae fall outside the distribution of ratios for turquoise deposits in the Southwest (Fig. 2) (47). Furthermore, most of the objects form a tight cluster in isotope space, and the tesserae excavated from Tenochtitlan’s Sacred Precinct have similar ratios to those associated with the Mixteca-style mosaics from NMAI (Fig. 2). For these reasons, we suggest that most of the turquoise mosaic tiles analyzed for this study derive from the same or geologically similar source(s).

Although the tesserae have signatures that do not match those of any of the known turquoise deposits, their isotopic ratios provide constraints on their provenance. Notably, the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of most tesserae are substantially lower than the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios measured in Southwestern turquoise deposits (Figs. 2 and 3). For example, the lowest $^{87}\text{Sr}/^{86}\text{Sr}$ ratio measured on a sample of turquoise from the Southwest is 0.70624 (8). However, 30 of the 39 Mesoamerican samples for which we have data possess $^{87}\text{Sr}/^{86}\text{Sr}$ ratios that are lower (range, 0.70492 to 0.70622). One interpretation of these lower $^{87}\text{Sr}/^{86}\text{Sr}$ ratios is that these samples derive from deposits within Mesoamerica and possibly
Table 1. Isotopic ratios of Aztec and Mixtec turquoise artifacts. N.D., not determined.

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<th>Sample ID</th>
<th>Offering</th>
<th>$^{87}$Sr/$^{86}$Sr</th>
<th>% SE</th>
<th>$^{207}$Pb/$^{206}$Pb</th>
<th>$^{208}$Pb/$^{206}$Pb</th>
<th>$^{206}$Pb/$^{204}$Pb</th>
<th>$^{207}$Pb/$^{204}$Pb</th>
<th>$^{208}$Pb/$^{204}$Pb</th>
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<td>Aztec mosaic tiles from the Sacred Precinct of Tenochtitlan</td>
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<td>125</td>
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<td>22.866</td>
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continued on next page
within western Mexico. In Mexico, the felsic rocks of the Sierra Madre Occidental, Sierra Madre del Sur, and Trans-Mexican Volcanic Belt host a number of copper deposits (48). In particular, copper porphyry mineralization extends southward from Arizona along the length of western Mexico to the state of Guerrero (39). Prior studies of felsic igneous rocks associated with these porphyry copper deposits have demonstrated that their initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios decrease along a north-south trend (39, 41). These different initial ratios account, in part, for regional variations in their present-day $^{87}\text{Sr}/^{86}\text{Sr}$ ratios. For example, in southeastern Arizona, most felsic rocks associated with copper porphyry deposits have modern $^{87}\text{Sr}/^{86}\text{Sr}$ ratios greater than ~0.708 (49), while similar rocks in western Mexico (for example, Sinaloa, Jalisco, Michoacán, or Guerrero) frequently have values as low as 0.704 or 0.705 (39, 40, 50, 51). Because there are regional differences in the Sr isotope geochemistry of felsic magmatic rocks that host copper deposits, we would also expect there to be comparable differences in the Sr isotopic composition of any associated turquoise mineralization. Thus, we suggest that the lower $^{87}\text{Sr}/^{86}\text{Sr}$ ratios measured on most tesserae (compared to Southwestern turquoise deposits) indicate they derive from Mesoamerican and not Southwestern sources.

Pb isotope ratios provide a second, independent line of evidence that these objects may derive from a source or sources within Mesoamerica. Although the Pb isotopic signatures of the tesserae overlap with Southwestern turquoise deposits (fig. S5A), they cluster in a region of Pb isotope space where they are collectively a poor match for any single deposit or group of deposits (fig. S5B). Notably, there is no overlap between the Pb isotopic composition of the tesserae and the turquoise...
Note that samples TM-10 and TM-37, which have $^{87}\text{Sr}/^{86}\text{Sr}$ ratios that are similar to compositions measured in Mexican mineral deposits (Thibodeau (42)), in contrast, the tesserae fall well within the range of Pb isotopic compositions measured in Mexican mineral deposits (42–45). Note that samples TM-10 and TM-37, which have $^{87}\text{Sr}/^{86}\text{Sr}$ ratios that are much higher than those of the other tesserae (see Fig. 2), have Pb isotope ratios that are similar to that of the other samples. Because of this similarity, we suggest that even the few samples with relatively high $^{87}\text{Sr}/^{86}\text{Sr}$ ratios may derive from the Mesoamerican and not the Southwestern mines.

Although Pb isotopes provide strong evidence that the tesserae derive from Mesoamerican mines, we cannot isolate their exact source(s) because of the substantial overlap among the Pb isotopic signatures of copper deposits throughout western and central Mexico (42–45, 53). We do note, however, that the Pb isotopic ratios of the tesserae are especially good match for copper mineralization from the state Michoacán (Fig. 4), an area to the west of the Aztec capital (Fig. 1) where copper mining and melting may have begun as early as the 650 CE (53) and where at least one Late Postclassic copper-smelting site has been identified (54). Although this area was controlled by the Tarascans in the Late Postclassic (Fig. 1), Mesoamerican merchants from virtually all polities operated within and beyond their political boundaries (19). Thus, if turquoise was available from mines in the Tarascan region, then it is plausible the material entered the Aztec realm along with other commodities.

It is also possible that the Aztecs and Mixtecs acquired turquoise from other parts of western or central Mexico. The Codex Mendoza indicates that the Aztec received turquoise tribute from three provinces (Fig. 1) (22). The two southern (Mixteca) tributary provinces were Quiauhtetepan, which was located in what is today eastern Guerrero and possibly adjoining parts of Puebla, and Yoaltepec, which was located in present-day western Oaxaca. The northeastern province Tochpan was located in what is today northern Veracruz (Fig. 1). The Pb isotopic compositions of the tesserae partially overlap with the signatures of copper deposits in Veracruz [for example, compare to the study of Hosler and Macfarlane (43)], and may also overlap with the signatures of copper mineralization in Guerrero or Jalisco [see Hosler (53) and references therein] and with deposits in central Mexico [for example, compare to Potra and Macfarlane (44)]. Thus, the isotopic evidence also allows for the possibility that the inhabitants of these tributary provinces (including the Mixtecs) acquired turquoise from local sources or imported it from other parts western or central Mexico.

Unless direct evidence of ancient Mesoamerican turquoise mines comes to light, the specific source(s) of turquoise used by the Aztecs and Mixtecs cannot be identified. This is because neither the Pb nor Sr isotopic data are able to pinpoint the precise origin for these artifacts within Mesoamerica. However, the isotopic data provide strong evidence that none of the Aztecs or Mixtec turquoise artifacts analyzed for this study derive from the Southwest. Our data primarily pertain to turquoise objects associated with the Late Postclassic Aztec Empire and do not provide evidence about the source(s) of Mesoamerican turquoise artifacts from other regions or time periods. However, based on these findings, we suggest that turquoise may not have been an important component of long-distance trade between the Southwest and Mesoamerica.

**METHODS AND MATERIALS**

To ensure that all tesserae were turquoise (and not other blue-green minerals), we used nondestructive x-ray diffraction and scanning electron microscopy to examine their mineralogical and elemental compositions. Turquoise tesserae were prepared and analyzed for Pb and Sr isotopic ratios in the Department of Geosciences at the University of Arizona according to methods published elsewhere (8), but repeated here.

To remove any superficial contaminants or residue of adhesive material, the edges and faces of all tesserae were carefully sanded with a silicon carbide sandpaper and then inspected under a binocular microscope. After sanding, all samples were ultrasonicated in Milli-Q water (18.2 megohm), rinsed four to five times, and set to dry. Once dry, they were crushed with an alumina mortar and pestle. Between each sample, the mortar and pestle set was cleaned by grinding a slurry of silica sand and 200 proof ethanol and rinsing several times with ethanol and Milli-Q water.

All sample preparation procedures were conducted using ultrapure twice-distilled acids. After crushing, samples were weighed into acid-cleaned Savillex vials. Samples were then capped and refluxed in concentrated hydrochloric acid on a hotplate overnight at ~125°C. The next day, solutions were cooled and then, if necessary, centrifuged to remove any undigested material. The supernatant was dried down and redissolved in...
8 M nitric acid. Pb and Sr were separated using Sr Spec resin (Eichrom Industries).

Strontium samples were loaded onto degassed tantalum filaments with phosphoric acid and tantalum gel to enhance ionization. Strontium isotope ratios were measured on a VG Sector 54 thermal ionization mass spectrometer in dynamic collection mode at the University of Arizona. Fractionation was corrected using a \(^{88}\text{Sr}/^{86}\text{Sr}\) ratio of 0.1194. The National Institute of Standards and Technology (NIST)-987 standard was run before, during, and after samples during each analytical session. The average value of the NIST-987 standard over all analytical sessions was 0.710266 ± 0.000014 (2 SD, n = 19).

Lead isotope measurements were made on a GV-Instruments Isoprobe multi-collector inductively coupled plasma mass spectrometer. To correct for fractionation, samples were spiked with TI to achieve a Pb/TI ratio of approximately 10. Samples were Hg-correction and empirically normalized to TI after methods used by (55). All samples were then normalized to the values of Galer and Abouchami (56) for the NIST-981 standard. The NIST-981 standard was run before, between, and after the samples, and sample standard concentrations were matched within 20%. The errors on the Pb isotope ratios were calculated from the reproducibility of the NIST-981 standard over the course of each measurement session. Errors associated with each sample are given in table S2.

**SUPPLEMENTARY MATERIALS**

Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/4/6/eaas9370/DC1

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27. L. López Luñán, The Offerings of the Templo Mayor of Tenochtitlan (University of New Mexico Press, 2005).
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37. Turquoise is usually found within ~30 m of the surface in the form of veins, nodules, and other open-space fillings. In the American Southwest, turquoise is usually associated with, or contained within, the near-surface portions of copper porphyry deposits, their related felsic igneous rocks, and their hosts [see Thibodeau et al. (8) and references therein]. Because the major elemental constituents of turquoise derive from the weathering of preexisting minerals, trace amounts of Pb and Sr contained within turquoise (or its matrix) are scavenged from rock formations though which the copper-bearing fluids passed. As neither Pb nor Sr isotopes undergo significant isotopic fractionation during weathering, turquoise deposits are expected to inherit their Pb and Sr isotopic signatures (8).
These variations in Sr isotopic composition are interpreted to reflect variations in the age and type of basement lithologies that underlie these areas (39). In American Southwest and Northern Mexico, igneous complexes associated with copper porphyries intruded through Proterozoic (>1 Ga) crystalline basement rocks with more radiogenic strontium isotopic signatures. South of Sonora, most of Mexico underlain by younger accreted terranes with more primitive Sr isotopic signatures (see Damon et al. (39) and references therein).

Materials. Additional data are available from the authors upon request.

Data and materials availability: All data needed to evaluate the conclusions in the paper are present in the paper and/or the Supplementary Materials. Additional data are available from the authors upon request.

Acknowledgments: We thank P. Meehan at Mexico’s Instituto Nacional de Antropología e Historia for assistance with the selection of samples from Tenochtitlan. We also thank G. Chiari of the Getty Conservation Institute for conducting nondestructive x-ray diffraction on some of the analyzed artifacts from Tenochtitlan. We are indebted to J. Ciarrocca at Dickinson College for assistance with the making of Fig. 1. We thank J. Ciarrocca at Dickinson College for assistance with the making of Fig. 1. The initial stages of this research were supported by the Florence C. and Robert H. Lister fellowship to A.M.T. Author contributions: All authors jointly conceived of and designed the research. L.L.L. and his team excavated and recorded the turquoise artifacts from Tenochtitlan and selected the Aztec samples for this project. F.F.B. and A.M.T. selected the Mixtec samples from NMAI and obtained permission for their analysis. A.M.T. prepared the samples, measured the isotope ratios, and processed the data in the laboratory of J.R. A.M.T. interpreted the data with input from all the other authors. A.M.T. and D.J.K. wrote the manuscript with significant contributions from all the other authors. Competing interests: The authors declare that they have no competing interests. Data and materials availability: All data needed to evaluate the conclusions in the paper are present in the paper and/or the Supplementary Materials. Additional data are available from the authors upon request.

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Sci Adv 4 (6), eaas9370.
DOI: 10.1126/sciadv.aas9370