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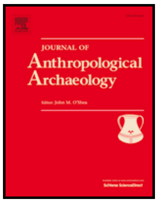

Residential patterns of Mexica human sacrifices at Mexico-Tenochtitlan and Mexico-Tlatelolco: Evidence from phosphate oxygen isotopes

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ABSTRACT

This is the first systematic study of residential patterns of Mexica human sacrifices, as determined from bone and enamel phosphate oxygen isotope data of individuals recovered at the Templo Mayor of Tenochtitlan (n = 36) and the Templo R of Tlatelolco (n = 24). We identify these individuals' geographic residences and compare these patterns with phosphate oxygen isotope data from a contemporary non-sacrificial group (Ecatepec; n = 24) from the Basin of Mexico. The sacrifices' residential patterns are evaluated to assess their group membership (i.e., as locals, long-term residents, or non-locals from other regions of Mesoamerica). The Tlatelolco subadult and adult sacrifices were either locals or long-term residents. The Templo Mayor subadult sacrifices offered at several ceremonies were non-locals and long-term residents, while the adult sacrifices were long-term residents (e.g., slaves living in Tenochtitlan > 10 yrs.) or non-locals (e.g., war captives, slaves, spoils-of-war sacrificed soon after arriving to the Basin). Our results demonstrate the Templo Mayor priests had broad access to long-term residents and non-locals with origins from Mesoamerican regions subjugated by the Mexica. This study illustrates the Mexica obtained individuals for sacrifice with a diverse range of physical, social, and geographic characteristics for their ritual ceremonies.

1. Introduction

In Mexica[1] society, human sacrifice was carefully planned and integrated into religious, social, and geopolitical practices (Carrasco 1999a; Conrad and Demarest 1984; López Luján and Olivier 2010; Matos Moctezuma 1995, 2010). There is evidence to suggest that human sacrifices were carefully chosen by the priestly elite based on their physical and social attributes as well as according to the type of ceremonies and specific deities to whom they were to be sacrificed (Graulich 2016; González Torres 1985; López Austin and López Luján 2008; López Luján 2018; López Luján et al. 2010; Román Berrelleza 2010). Nonetheless, who was chosen for Mexica sacrifice remains unclear, including their geographic origins and residence during their lifetime. In this paper, we investigate this question by assessing the residential patterns of human sacrifices recovered from two Mexica temples at the sister-cities of Mexico-Tlatelolco and Mexico-Tenochtitlan (hereafter referred as "Tlatelolco" and "Tenochtitlan") (Fig. 1), using phosphate oxygen isotope analysis. This paper provides the first systematic phosphate oxygen isotope analysis of a group of Mexica sacrifices to learn about their residential histories that, in turn unravel possible so-

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[1] The Mexica society refers to the people who lived in Tlatelolco and Tenochtitlan during the Late Postclassic period (1200–1521 CE). These people while commonly referred to as "Aztecs", named themselves "Mexica", and so we prefer to use the latter term. We use the term "Aztecs" to refer to the overall population living in the Basin of Mexico during the same time period for whom we do not specify particular ethnic or linguistic associations, including the San Cristóbal Ecatepec skeletal group in this study.

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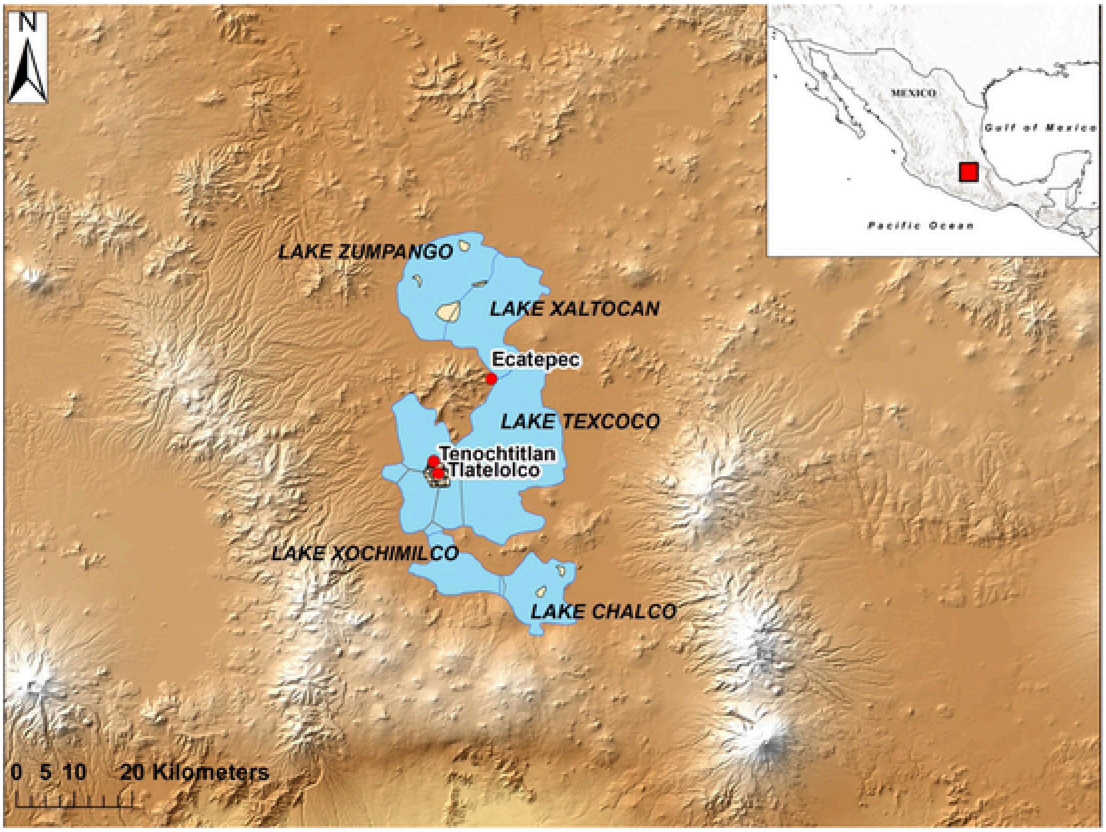

Fig. 1. Location of the Basin of Mexico (red square) within the central highlands of Mexico and the location of the three archaeological sites (red circles) in this study. Drawn by Amedeo Sghinolfi. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

cial identities prior to becoming a sacrificial victim for a ritual ceremony by the Mexica priesthood. Our study presents a more realistic portrayal about Mexica human sacrifice and highlights the diversity in the victims' social and geographic identities, all of which contribute to better understanding the diversity and complexity of Mexica sacrificial practices. As such, this bioarchaeological approach opens up a new window into the inner workings of Mexica sacrificial practices by gaining insight into the sacrificial victims themselves and the role they played within the Mexica's religious and geopolitical spheres in Postclassic Mesoamerica.

The human sacrifices in our study were recovered from the Templo R of Tlatelolco and the Templo Mayor of Tenochtitlan. These sister-cities were organized in neighborhoods (*calpulli*), large avenues or *calzadas*, and a sacred precinct (Guilliem Arroyo 1999; López Austin and López Luján 2016). Each Mexica city established their Templo Mayor in the center of the city, and in the case of Tenochtitlan, it became "a symbol of power embodying the hegemony of Mexico-Tenochtitlan" (López Austin and López Luján 2016:608). Each Templo Mayor was a dual pyramid with the southern side dedicated to the Mexica god of the sun and war, Huitzilopochtli, and the northern side dedicated to Tlaloc, god of rain and earth's fertility (Guilliem Arroyo 1999; López Luján 2019c). The sacred precinct at the sister-cities also included other important religious buildings such as pyramidal structures of various sizes (*teocalli*), priestly houses, temple schools for nobles (*calmecac*), and head/skull racks for display (*tzompantli*), among other buildings (López Austin and López Luján 2016; López Luján 2019a, b). The Templo R was a circular temple on the southeastern corner of the Tlatelolco sacred precinct dedicated to the god of wind, Ehecatl-Quetzalcoatl, where the Tlatelolcan priests carried out smaller scale ceremonies with somewhat humble offerings. The Templo Mayor of Tenochtitlan or *Huei Teocalli*, an imposing 45 m tall dual pyramid, was the most important religious building of the Mexica, where the most intricate large-scale ritual ceremonies were performed with the Tenochca priests offering the richest and most luxurious materials (including sacrificed human and exotic animal remains) to their deities (López Austin and López Luján 2016; López Luján 2019a).

2. Mexica human sacrifice

The surviving codices and Spanish accounts provide us with invaluable information about who the sacrificial individuals were, how they were obtained and managed by the Mexica, and how they were eventually chosen as offerings to the many Mexica deities as part of exceptional events—funerals, coronations, building consecration ceremonies, and times of crisis (e.g., famine)—and during regular festivals scheduled during each of their eighteen 20-day months (known as *veintenas* in Spanish) (Carrasco 1999a; Chávez Balderas 2014; Graulich 2016; González Torres 1985). Warriors captured in battle (*mamaltin*) were often chosen as sacrifices and Clendinnen (1991) argued that these warriors made up most of the foreign sacrifices in Tenochtitlan. However, there is wide diversity in the biological profile of the sacrificed individuals in our study. Thus, it is more likely that the Mexica obtained men, women, and children (*tlatlacotin* or slaves) through purchase in markets, gifting from other city-states, spoils-of-war, and tribute from provinces of the Aztec Empire[2].

Spanish chronicler friar Diego Durán (1984) mentions that slaves, either locals to the Basin of Mexico or foreigners, were a common source of sacrifices (Fig. 2). Some of the local slaves were identified by

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[2] Also known as *excan tlatoloya* in Nahuatl, refers to the territorial expansion by the Triple Alliance city-states of Tenochtitlan, Texcoco, and Tlacopan.

Fig. 2. Adult and child slaves in Mexica society wearing a wood collar depicted in the Florentine Codex (Sahagún 1953–1982: Book VII).

Durán (1984) to be convicted criminals, gamblers, and individuals (including subadults[3]) who were sold by their family due to hardship, famine, or disobedience (Berdan and Anawalt 1997; Clendinnen 1991). Friar Bernardino de Sahagún (1932) provides a detailed account describing when subadults were sold as sacrifices by their parents for the multiple *veintena* ceremonies associated with Tlaloc, god of rain and earth's fertility, and his little assistants (*tlaloque*)[4]. The group of foreign slaves included individuals either passing by an Aztec city-state, caught and sold into slavery, or who became slaves in their own communities and were sent to Tenochtitlan as tribute payments to the Mexica (Durán 1984; Graulich 2016). The slaves, including men, women and children, were sold by merchants (*tealtianime* or *tecoanime*) in specialized slave markets such as Azcapotzalco and Itzocan (Clendinnen 1991; Durán 1984; González Torres 1985; Graulich 2016). Other future sacrificial individuals that came from the local population included albinos, dwarfs, hunchbacks, virgins, volunteers, people considered "marked" with a particular physical trait, free citizens (when no slaves were available), and more rarely nobles and princesses (Graulich 2016). Thus, not all sacrifices were war captives: male and female individuals of different age groups (but mostly between 1 and 30 years of age), with particular physical traits, social attributes, and geographic origins/residences, were also sacrificed in Mexica ritual ceremonies. This study examines the residential patterns of people chosen for sacrifice at the Templo R of Tlatelolco and the Templo Mayor (*Huei Teocalli*) of Tenochtitlan through the phosphate oxygen isotope analysis of their skeletal remains.

3. Oxygen isotope systematics

Oxygen has three stable isotopes: ^{16}O, ^{17}O, and ^{18}O. When water undergoes evaporation, water molecules containing the lightest oxygen isotope (^{16}O) are preferentially evaporated, and so the air masses contain more ^{16}O while the condensate (i.e., rain, snow) that forms from water vapor and the liquid water remaining from evaporation become enriched in ^{18}O relative to that vapor (Coplen et al. 2000). The size of this fractionation in meteoric water is driven by temperature and influenced by environmental and geographic factors such as latitude, altitude, continental effect, precipitation amount, humidity, seasonal variation, and recycling (Bowen and Revenaugh 2003; Bowen et al. 2005; Coplen et al. 2000). Based on this process, meteoric water (mw) across the landscape has a specific ratio of ^{18}O to ^{16}O (normally presented in delta notation relative to Standard Mean Ocean Water – δ^{18}O), which becomes integrated into surface waters and groundwater (Bowen et al. 2005). The local meteoric water, with its corresponding $\delta^{18}O_{mw}$, is taken up by plants, which introduces it into the local food webs (Kirsanow and Tuross 2011). Humans also incorporate this isotopic signal into their body by ingesting the local meteoric water (iw = ingested water; $\delta^{18}O_{iw}$). This $\delta^{18}O_{iw}$ eventually becomes incorporated into a human's tissues, and in turn this signal can be related back to the $\delta^{18}O_{mw}$ of the region where that human resided during life (Bowen et al. 2005; Longinelli 1984; Luz et al. 1984).

The individual's $\delta^{18}O_{iw}$ is primarily controlled by the amount of water imbibed, the kinds of foods ingested and energy expenditure; as such $\delta^{18}O_{iw}$ is also influenced by an individual's travels to another location with a $\delta^{18}O_{mw}$ distinct from the original location (Bryant and Froelich 1995; Luz et al. 1984; Longinelli 1984; Luz and Kolodny 1985). While this process seems straightforward, there are several environmental, metabolic, and cultural factors that can influence an individual's $\delta^{18}O_{iw}$ (and the δ^{18}O in skeletal tissues), which pose uncertainties in association with tracking human geographic residential patterns (Lightfoot and O'Connell 2016). Environmental factors such as the altitude and latitude effects, seasonality, aridity, canopy cover, and evaporative fractionation may affect the isotopic composition of local waters. In these cases, a correction is necessary when using ancient bioapatite to obtain the δ^{18}O of local precipitation (Daux et al. 2008). Moreover, physiological and metabolic factors such as differing body size, percentage of water in the diet, regular exercise, nutritional stress, and disease (Bryant et al. 1996; Epstein and Zeiri 1988; Longinelli 1984; Reitsema and Crews 2011; Warinner and Tuross 2009) have been shown to influence tissue-diet isotope fractionations, affecting the oxygen isotope composition of human tissues, and thus, complicating the analysis and interpretation of their residential patterns. Feeding patterns, importation of foods and beverages, and culinary practices (e.g., brewing, meat cooking techniques, nixtamalization) (Brettell et al. 2012; Daux et al. 2008; Lightfoot and O'Connell 2016; Tuross et al. 2017; Warinner and Tuross 2009) can also affect a human's $\delta^{18}O_{iw}$, and in turn, the δ^{18}O in their calcified tissues. For instance, Brettel et al. (2012) found that brewing, boiling, and stewing all affected the δ^{18}O of the water due to the evaporative fractionation that took place in each case, which resulted in ^{18}O enrichments of various magnitudes depending on the specific cooking technique, time, and temperature. The multiple factors that can influence the δ^{18}O of human bioapatite must be taken into account when assessing the possible geographic origins and residences of archaeological human populations.

3.1. Phosphate oxygen isotopes in human tissues

Oxygen is present as phosphate (PO_4^{3-}) and structural carbonate (CO_3^{2-}) in bioapatite (Tuross et al. 2008). The phosphate (p) ion has a δ^{18}O based on the human's ingested water that becomes incorporated into the human body as body water ($\delta^{18}O_{bw}$). Blood enzymes catalyze equilibrium oxygen isotope exchange between PO_4^{3-} and body water at a constant body temperature (37 °C), with bone and enamel being enriched in ^{18}O relative to body water (Bryant and Froelich 1995; Kohn and Cerling 2002; Longinelli 1984; Luz and Kolodny 1985). In sum, a human's bioapatite $\delta^{18}O_p$ reflects their $\delta^{18}O_{bw}$ at the time of tissue formation.

While $\delta^{18}O_{bw}$ is shaped in a matter of weeks within the body, $\delta^{18}O_p$ takes longer to be reflected in newly formed human tissues, depending on the period of mineralization of specific tissues (Kohn and

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[3] Refers to infants (birth–3 yrs. old) and children (4–14 yrs. old) in Mexica society.

[4] These were thought to be short, dwarf-like individuals in charge of helping Tlaloc bring the rain from the mountains (López Luján 1997, 2009, 2018; Román Berrelleza and Chávez Balderas 2006).

Cerling 2002; Luz et al. 1984). For enamel, $\delta^{18}O_p$ is obtained over several months based on the formation of particular teeth (Hillson 1996). Enamel does not remodel once it has mineralized; hence its $\delta^{18}O_p$ retains the signal of the period when the tooth mineralized during childhood (White et al. 2000, 2007). Bone, which constantly remodels, obtains its $\delta^{18}O_p$ more slowly than enamel and it represents an average of oxygen inputs encompassing several years. Bone turnover rates mainly depend on age, the type of bone and its composition (e.g., cortical vs. trabecular bone) (Hedges et al. 2007; Martin et al. 2015; Longinelli 1984). Infants and children have the highest bone turnover rates due to constant growth and development, while adults undergo much slower remodeling (Martin et al. 2015). This overall trend has been found in studies focused on turnover rates of bone collagen in humans (e.g., Hedges et al. 2007, Tsutaya and Yoneda 2013), and while this is the case for bone bioapatite, the remodelling process occurs at a slightly slower rate than the synthesis of the organic matrix of bone (Britton et al. 2015; Hedges et al. 2007, Tsutaya and Yoneda 2013). A cortical bone bulk $\delta^{18}O_p$ reflects an averaged signature of an individual's lifetime; $>$10 years in adults (based on the turnover estimate of 23.1 yrs.), $<$6 years in children, and much less time in infants (1–2 yrs.), depending on the individual (Hedges et al. 2007; Parfitt 1983; Tsutaya and Yoneda 2013: Table 1; White et al. 2007).

There is a linear correlation between $\delta^{18}O_{iw}$ and $\delta^{18}O_{mw}$, and so we can associate an individual's $\delta^{18}O_{iw}$ (imbibed during life) with the $\delta^{18}O_{mw}$ of the region where they lived (Luz and Kolodny 1985; Iacumin et al. 1996). In this way, it is sometimes possible to identify people who moved from one geographic location to another, assuming that their newly acquired $\delta^{18}O_p$, based on new water sources (and the corresponding $\delta^{18}O_{mw}$), is distinct from the original location's $\delta^{18}O_{mw}$ (Kohn and Cerling 2002; Longinelli 1984; Luz et al. 1984). While a ~3‰ human intra-population variability has been recently estimated by Lightfoot and O'Connell (2016) using data mostly from European archaeological contexts, the variability in Mesoamerica is ~2 ‰ based on control samples at several archaeological sites (White et al. 1998, 2000, 2004a and b, 2007), and so we expect to find a similar intra-population variability range for the Aztec-Mexica population.

In addition to the identification of human residence(s) and mobility in antiquity, oxygen isotope analysis can be used to identify the breastfeeding period in subadults and their transition to weaning (e.g., Britton et al. 2015; Roberts et al. 1988; White et al. 2004a and b; Wright and Schwarcz 1998). There is an ^{18}O-enrichment in human breast milk due to the fractionation associated with the lactating mother's metabolism. The mother's $\delta^{18}O_{bw}$ is higher than that of a non-lactating individual due to the preferential loss of the lightest oxygen isotope (^{16}O) as part of the metabolic processes driving oxygen fluxes inside the body (Bryant and Froelich 1995; Luz et al. 1984). Since breast milk is formed from the mother's ^{18}O-enriched body water pool, it has a significantly higher $\delta^{18}O$ compared to the local $\delta^{18}O_{mw}$ that the mother imbibed (Humphrey 2014; Wright and Schwarcz 1998, 1999). As such, infants consuming breast milk have higher $\delta^{18}O_p$ than those of their own mothers, other adults, and fully weaned children (Humphrey 2014; Tsutaya and Yoneda 2015; Wright and Schwarcz 1998). This nursing effect has been reported by several studies, such as those mentioned above; however, uncertainties surrounding this effect persist as we continue to learn more about the relationship between breastfeeding infants' skeletal tissues and their mother's milk $\delta^{18}O$.

Table 1
Three potential residential patterns by tissue and phosphate oxygen isotope result(s).

Residential Pattern	Tissue	
	Bone	Enamel
1. Local to the Basin of Mexico	Same as Basin of Mexico $\delta^{18}O$ range	Same as Basin of Mexico $\delta^{18}O$ range
2. Non-local to the Basin of Mexico	Outside of the Basin of Mexico $\delta^{18}O$ range	Outside of the Basin of Mexico $\delta^{18}O$ range
3. Long-term resident of the Basin of Mexico	Only tissue analyzed and same as Basin of Mexico $\delta^{18}O$ range	Outside of the Basin of Mexico $\delta^{18}O$ range

3.2. *Potable water sources in the Basin of Mexico*

The Basin of Mexico is located in the central highlands (Fig. 1). It is a large and hydro-geologically closed basin at a high elevation (2236–2250 m above sea level [masl]). The Basin of Mexico receives its water from mountain streams originating at high elevations (3000–5426 masl) that surround it to the east, west, and south and as precipitation during the rainy season from May to October (Edmunds et al. 2002; Durazo and Farvolden 1989). The Basin of Mexico originally featured five lakes, three of which contained non-potable, brackish water (Fig. 1) (Durazo and Farvolden 1989). This suggests that the Mexica had to use other water sources for consumption, aside from the freshwater lakes of Xochimilco and Chalco, which were primarily used for *chinampa*[5] agriculture (Carballal Staedtler and Flores Hernández 2006; Durazo and Farvolden 1989; Hassig 1985). Upon their arrival to Tenochtitlan in 1325 CE, the Mexica relied on the Chapultepec springs for potable water and after winning the war against the Tepanecs of Azcapotzalco (by 1430 CE) (López Austin and López Luján 2005), they took control of the Coyohuacan and Xochimilco springs in the southern part of the Basin (Durazo and Farvolden 1989). There is historical and archaeological evidence for the use of springs at Tenochtitlan. This evidence includes an illustration from the 16th century of an Indigenous individual at a spring in Tenochtitlan located north of the Templo Mayor (Durazo and Farvolden 1989; López Luján 2005). The springs are also mentioned in the *Florentine Codex* (Sahagún 1953–1982) and the *Mendoza Codex* (Berdan and Anawalt 1997). The Mexica built an intricate stone-and-mortar aqueduct system to carry the water from these springs and from the Chapultepec springs on the mainland, 5 km away from Tenochtitlan, across causeways known as *calzadas* (Berdan and Anawalt 1997). Water was also transported to all sectors of the city by canoe (Carballal Staedtler and Flores Hernández 2006; Durazo and Farvolden 1989; Hassig 1985).

3.3. *Meteoric water $\delta^{18}O$ interpolated isoscape of Mexico*

The climatic, continental, atmospheric, and altitudinal factors lead to a ~12 ‰ variability in $\delta^{18}O_{meteoric\ water}$ across Mexico (range = –14.5 to –2.3 ‰). Accordingly, there are distinguishable $\delta^{18}O_{mw}$ signals at Mesoamerican sites located in central Mexico, western Mexico, eastern/Gulf of Mexico, southern Mexico, and the Yucatán Peninsula. The $\delta^{18}O_{mw}$ of modern surface and shallow ground waters of several States in Mexico have been previously characterized (e.g., Edmunds et al. 2002; Ortega-Guerrero et al. 1997; Pérez-Quezadas et al. 2015; Portugal et al. 2005). Previous studies have also found that there is little seasonal variability in the surface water and shallow groundwater $\delta^{18}O$ across Mexico and that these isotope compositions directly reflect the source of the groundwater (IAEA 1992; Issar et al. 1984; Wassenaar et al. 2009). This observation is consistent with the $\delta^{18}O_{mw}$ data for the Basin of Mexico since the $\delta^{18}O$ mean (–10.1 ± 0.3 ‰) for shallow groundwater is similar to the mean $\delta^{18}O$ of surface precipitation (–9.6‰) (Issar et al. 1984; Jaimes-Palomera et al. 1989; Ortega-Guerrero et al. 1997; Vázquez-Sánchez et al. 1989). Thus, we can use both precipitation and shallow groundwater

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[5] Drained rectangular fields described as "floating gardens" on the lake beds of the Basin of Mexico where crops like maize, beans, squash, amaranth, fruits, and flowers were grown by the Mexica (Hassig 1985).

$\delta^{18}O$ data in our study as a reflection of the $\delta^{18}O_{mw}$ for the Basin and other regions across Mexico.

We compiled published modern $\delta^{18}O_{mw}$ data ($n = 287$) from surface water and shallow groundwater sampled and analyzed across Mexico between 1962 and 2010 (Moreiras Reynaga et al. in press) to create an oxygen isotope isoscape (interpolated map; Fig. 3) (Cortés and Farvolden 1989; Edmunds et al. 2002; IAEA 1992; Issar et al. 1984; Jaimes-Palomera et al. 1989; Ortega-Guerrero et al. 1997; Pérez-Quezadas et al. 2015; Portugal et al. 2005; Vázquez-Sánchez et al. 1989; Wassenaar et al. 2009). This isoscape provides a $\delta^{18}O_{mw}$ baseline for assessing geographic origins and residential patterns in our study. Some $\delta^{18}O$ patterns are visible. First, the least negative $\delta^{18}O_{mw}$ occurs in the Yucatán Peninsula (lowlands), ranging from –4 to –2 ‰. Second, both coasts have less negative $\delta^{18}O_{mw}$ (–4 to –3 ‰) than inland regions. The eastern coast of Mexico (Gulf of Mexico region) shows a more defined shift to more negative $\delta^{18}O_{mw}$ (–6 ‰) with a tight range (–6 to –3 ‰), which has been linked to shifts in elevation and temperature, rain-out effects, easterly circulation, and moisture transport (Morales et al. 2017; Wassenaar et al. 2009). Conversely, the western coast has $\delta^{18}O_{mw}$ of –5 to –4 ‰, which changes inland in western Mexico to $\delta^{18}O_{mw}$ as low as –12 ‰. This is a much wider range compared to the Gulf of Mexico region and underscores the different relationship with elevation, temperature, atmospheric circulation and moisture, and the rain shadow effect (Wassenaar et al. 2009). Third, the $\delta^{18}O_{mw}$ in southern Mexico (highlands) is mainly influenced by large-scale atmospheric circulation moving from the Pacific Ocean and the Gulf of Mexico (Hewitson and Crane 1992), such that the $\delta^{18}O_{mw}$ range lies between –9 and –6 ‰. The central Mexico region has low $\delta^{18}O_{mw}$, ranging from about –11 to –8 ‰, which follows the expected pattern based on the combined environmental and altitudinal effects that produce more negative $\delta^{18}O_{mw}$ compared to the eastern, western, and southern regions of Mexico.

3.4. Establishing baseline $\delta^{18}O_p$ zones in Mesoamerica

Earlier Mesoamerican oxygen isotope studies have analyzed human bone and enamel structural carbonate and phosphate from multiple archaeological sites located in present-day Mexico, Guatemala, Honduras, and Belize (Price et al. 2007, 2010; White et al. 1998, 2000, 2001, 2004a,b, 2007). Even though we still lack a systematic analysis of $\delta^{18}O$ data covering all areas of Mesoamerica, these values for human bioapatite $\delta^{18}O$ can be used to develop a baseline for Mesoamerica to aid interpretation of $\delta^{18}O$ data for humans of unknown geographic origins. The values of $\delta^{18}O_p$ follow the same overall environmental and geographic patterns as the $\delta^{18}O_{mw}$ data. Principally, regions located at lower elevations (lowlands) with hot/humid climate tend to have higher $\delta^{18}O_p$, while cooler, drier, and higher elevated regions (highlands) tend to have lower $\delta^{18}O_p$ (Price et al. 2007). Despite the fact that some Mesoamerican regions have overlapping $\delta^{18}O_p$ (e.g., the Gulf of Mexico and Petén regions), there are sufficient isotopic differences (as exemplified by the wide range of $\delta^{18}O_{mw}$ in Mexico) to divide the area into distinct $\delta^{18}O_p$ zones.

Fig. 4 illustrates the five $\delta^{18}O_p$ zones we have established across Mesoamerica, moving from lower to higher $\delta^{18}O_p$ ranges (Price et al. 2007, 2010; White et al. 1998, 2000, 2001, 2004a,b, 2007). The following equations were applied to the structural carbonate oxygen isotope data in order to develop ranges for each $\delta^{18}O_p$ zone: (1) $\delta^{18}O_{structural\ carbonate(VSMOW)} = (1.03091 \times \delta^{18}O_{structural\ carbonate(VPDB)}) + 30.91$ (Coplen et al. 1983), followed by (2) $\delta^{18}O_{phosphate(VSMOW)} = (0.973 \times \delta^{18}O_{structural\ carbonate(VSMOW)}) - 8.121$ (in Zazzo et al. 2004 from data in Bryant et al. 1996; Iacumin et al. 1996). Zone 1 comprises the regions of the Pacific coast and western Mexico (e.g., Michoacán), and the Valley of Oaxaca ($\delta^{18}O_p$ range = +12.1 to +13.9 ‰). Zone 2 ($\delta^{18}O_p$ range = +14.0 to +16.2 ‰) incorporates the central Mexican highlands, including the Basin of Mexico and the surrounding areas (e.g., States of Morelos, Mexico, Puebla, and Hidalgo). Zone 3 ($\delta^{18}O_p$ range = +15.6 to +17.7 ‰) overlaps slightly with Zone 2 and includes the southern highland regions in Mexico

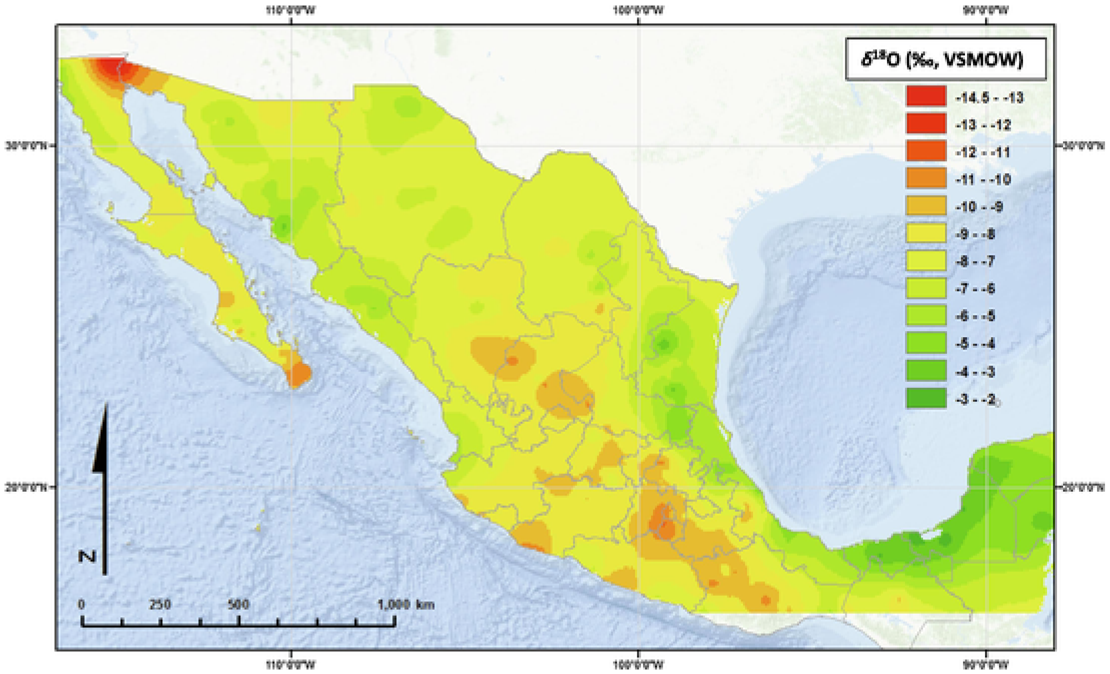

Fig. 3. Meteoric water oxygen isotope isoscape for Mexico. This interpolated isoscape was developed using the simple kriging method (default parameters) available in ArcGIS' (ArcMap 10.5) Geostatistical Analyst extension (ESRI 2017). The published data can be found in Moreiras Reyngaga et al. (in press) and were compiled from Cortés and Farvolden (1989), Edmunds et al. (2002), IAEA (1992), Issar et al. (1984), Jaimes-Palomera et al. (1989), Ortega-Guerrero et al. (1997), Pérez-Quezadas et al. (2015), Portugal et al. (2005), Vázquez-Sánchez et al. (1989), and Wassenaar et al. (2009).

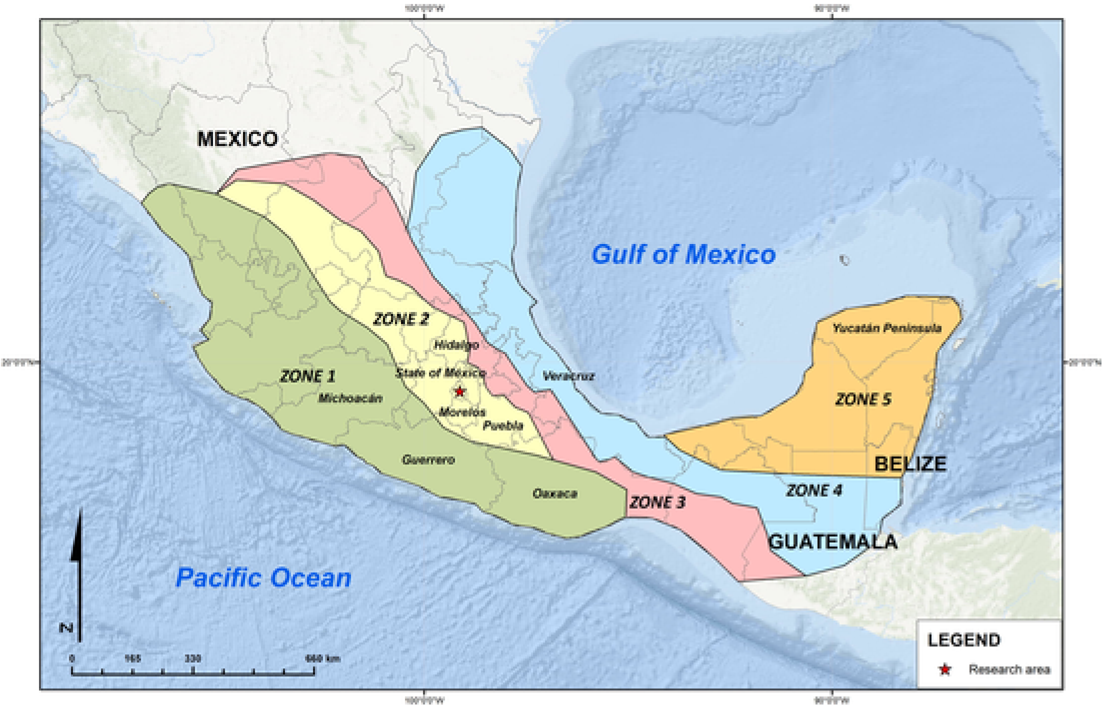

Fig. 4. Five estimated $\delta^{18}O_p$ zones across Mesoamerica using human bone and enamel oxygen isotope data in Price et al. (2007, 2010) and White et al. (1998, 2000, 2001, 2004a and b, 2007). Zone 1 = Pacific Coast, western Mexico, Oaxaca Valley ($\delta^{18}O_p$ = +12.1 to +13.9 ‰); Zone 2 = Central Mexican highlands ($\delta^{18}O_p$ = +14.0 to +16.2 ‰); Zone 3 = Southern Mexican highlands and northern Guatemala ($\delta^{18}O_p$ = +15.6 to +17.7 ‰); Zone 4 = Northern Chiapas, Petén region, Belize lowlands ($\delta^{18}O_p$ = +17.8 to +20.4 ‰); Zone 5 = Yucatán Peninsula ($\delta^{18}O_p$ = +20.7 to +24.9 ‰). Drawn by Amedeo Sghinolfi.

and northern Guatemala. Zone 4 comprises the Gulf of Mexico region (e.g., Veracruz, Tabasco), the southern lowlands such as northern Chiapas and the Petén region in Guatemala (e.g., Río Azul), and the lowland region in Belize (e.g., Altún Ha; $\delta^{18}O_p$ range = +17.8 to +20.4 ‰), and Zone 5 ($\delta^{18}O_p$ range = +20.7 to +24.9 ‰) is composed of the northern lowlands in the Yucatán Peninsula.

4. Research questions and expectations

Given the historical information presented above, we have used a bioarchaeological analysis to test the hypothesis that Mexica sacrifices were a diverse group of people. We investigate who was selected for sacrifice by the Mexica through the lens of geographic residence. To this end, we analyzed the subadult and adult sacrifices from multiple offering contexts at two Mexica temples spanning the latter part of the Late Postclassic period (1440–1521 CE). These sacrificial rituals took place after the establishment of the last Triple Alliance (*excan tlatoloyan*) by Tenochtitlan, Texcoco, and Tlacopan, and throughout the expansion and consolidation of the Aztec Empire (Chávez Balderas 2017; Guilliem Arroyo 1999; López Luján 1982, 2005, 2018; López Luján et al. 2010).

The phosphate oxygen isotope data for the sacrifices are interpreted alongside the phosphate oxygen isotope data for a non-sacrificial human collection at San Cristóbal Ecatepec (henceforth referred to as "Ecatepec"), a contemporary residential Basin of Mexico site (Fig. 1). The latter acts as a human isotopic baseline to determine locality to the Basin of Mexico. Previously published phosphate oxygen isotope data for people from various Mesoamerican sites (Price et al. 2007, 2010; White et al. 1998, 2001, 2004a and b, 2007) are used to establish "isotopic zones" to provide possible residences and/or homelands in our study. In addition, we incorporate the meteoric water oxygen isotope isoscape of Mexico (Fig. 3) to complement the phosphate oxygen isotope zones and guide our interpretations. Overall, we expected to find a degree of residential intra- and inter-group variability among the sacrifices, based on the information provided by the historic accounts, while little to no variability within the non-sacrificial group, based on the idea that these individuals were locals, i.e., they did not travel long distances or remained in foreign regions for long periods during their lifetime.

We expected to distinguish three types of residence among the sacrifices based on the tissue(s) analyzed for each individual: (1) locals to the Basin of Mexico (enamel and bone oxygen isotope compositions within the Basin of Mexico range), (2) non-locals to the Basin of Mexico (bone or enamel oxygen isotope compositions outside of the Basin of Mexico range), and (3) long-term residents of the Basin of Mexico (who have bone oxygen isotope compositions within the Basin of Mexico range but who could have an enamel oxygen isotope composition of non-local geographic origin) (Table 1). Except for three cases where we use tooth enamel to identify residential origins, the rest of the samples analyzed are bone fragments that provide information about the last years of life of the individuals.

We hypothesize that the infant sacrifices offered to the rain (Tlaloc) and wind (Ehecatl-Quetzalcoatl) deities were locals, as indicated by the historic accounts (Durán 1984; Sahagún 1932). Moreover, we evaluate whether children offered on either the Huitzilopochtli or Tlaloc shrines and during consecration ceremonies at the Templo Mayor of Tenochtitlan were non-locals or long-term residents of the Basin of Mexico. We hypothesize that the non-local subadults were likely slaves bought outside of Tenochtitlan, individuals caught during warfare (i.e., spoils-of-war), or individuals handed to the Mexica as tribute, while the local subadults were likely slaves from within the Basin of Mexico region or Mexica individuals from low socio-economic households whose parents sold them into slavery or directly as sacrifices for specific Mexica ritual ceremonies.

Based on the historic accounts on the Mexica (Benavente Motolinía [1967]; Durán [1964]; Mendieta [1971]; Sahagún [1953–1982]), the adult sacrifices could be obtained primarily through slavery, warfare, and spoils-of-war. According to these historic sources, slavery played a paramount role in Mexica sacrificial practices, yet this has been overshadowed in recent history by focusing on captured warriors as sacrifices since the accounts also describe their selection for several Mexica rituals (Cervera Obregón and Barrera Huerta 2017; Chávez Balderas 2019; Graulich 2016). As such, we can distinguish two main groups of sacrifices isotopically: (1) Warriors captured during warfare who were brought to the Basin of Mexico and sacrificed soon thereafter, and (2) Individuals who spent many years in the Basin of Mexico before becoming a sacrifice in a Mexica ritual, with slaves making up the majority of these sacrifices. We hypothesize that the majority of the non-locals could have been war captives and, to a lesser extent, slaves brought from other Mesoamerican regions, spoils-of-war, or given to the Mexica as tribute, who were sacrificed soon after their arrival to Tenochtitlan (Conrad and Demarest 1984; Durán 1984; López Austin and López Luján 2008). Conversely, we hypothesize that the majority of the individuals with a local isotopic signal were slaves and, to a lesser extent, spoils-of-war, or tributary individuals, who for some reason were assimilated by the Mexica society and sacrificed several years (>10 for adults, less for subadults) after their arrival to the Basin of Mexico (Cervera Obregón and Barrera Huerta 2017; Davies 1981; Durán 1984; González Torres 1985; Graulich 2016).

For the non-local adult and subadult sacrifices, we hypothesize that their possible residence/homelands can be connected temporally and geopolitically to the regions that were subjugated during each Tenochca Emperor's reign, as part of their imperial expansion and consolidation efforts across Mesoamerica. Finally, we hypothesize that substantial differences in adult and subadult residential patterns existed between the Templo R of Tlatelolco and the Templo Mayor of Tenochtitlan due to the nature of the rituals under study and/or due to the means of the Tlatelolcan and Tenochca priests involved in those sacrificial events.

5. Materials and methods

We selected bone ($n = 81$) and enamel ($n = 3$) samples from 83 individuals for phosphate oxygen isotope analysis from the Templo Mayor of Tenochtitlan offerings, the Templo R of Tlatelolco offerings, and the contemporary residential site of Ecatepec. Sample preparation and analytical procedures were carried out in the Laboratory for Isotope Science (LSIS) at The University of Western Ontario in London, Canada.

5.1. Templo Mayor of Tenochtitlan

Skull, mandible, enamel, or femoral fragments were sampled from adults ($n = 4$), children ($n = 29$), and infants ($n = 2$) from the Templo Mayor offerings (Fig. 1, Table 2). These collections have been associated with the Templo Mayor building construction phases IVa-1, IVb, VI, and VII, dating between 1440 and 1521 CE (López Austin and López Luján 2009). A permanent incisor and a premolar of two adults from offering 11 and a second permanent molar from the child recovered in offering 111 were also sampled. This child is the only individual for which we have multiple samples formed at different ages (i.e., enamel and bone). Offerings 11, 13, and 20 were located at the central axis of the building, offerings 64, 82, and 111 on the side of Huitzilopochtli, and offerings 22, 24, 48, and 88 on the side of Tlaloc (Fig. 5; Chávez Balderas 2017, 2019). As part of the post-sacrificial treatments, these cadavers were transformed into skull masks (e.g., of.[6] 11, 22, 24, 64), severed heads, skulls with basal perforation, and/or *tzompantli*[7] skulls (of. 20, 64, 82, and 88). The severed heads were used by the Tenochca priests for consecration ceremonies, while the skull masks, *tzompantli* skulls, and skulls with basal perforation were used as effigies that represented fleshless deities like Mictlantecuhtli and Cihuacoatl within the offerings (Chávez Balderas 2018; López Luján 2005; Robles Cortés et al. 2019). Offering 13 is a secondary burial, while offering 111 is a primary burial of a child *ixiptla* (image) of Huitzilopochtli who underwent heart extraction as part of the ritual (Chávez Balderas 2017; López Luján et al. 2010). Some sacrificial individuals had experienced first- and second-degree caries, dental calculus, and porotic hyperostosis. For the subadults from the Templo Mayor offering 48, second- and third-degree caries, severe tooth abscesses and enamel hypoplasias, as well as cribra orbitalia and porotic hyperostosis were present, which together indicate that these individuals experienced periods of nutritional stress and/or health deficiencies (Román Berrelleza 1990). Additionally, the individuals from offerings 22, 24, and 111 show evidence of dental fluorosis (Chávez Balderas 2017; López Luján et al. 2010).

5.2. Templo R of Tlatelolco

Samples include ribs from sacrificial adults ($n = 8$), children ($n = 8$), and infants ($n = 8$) from the Templo R of Tlatelolco (Fig. 1, Table 2). This group, particularly the subadults, suffered from multiple pathologies such as tooth decay, porotic hyperostosis, and cribra orbitalia (Román Berrelleza 1991). Ancient DNA analysis of these individuals indicates that most were males (De la Cruz et al. 2008). This group of human offerings was associated with a one-time sacrificial ceremony in connection with a major drought, between 1454 and 1457 CE, during the reign of Motecuhzoma I. Those sacrifices were offered to one of the main Mexica deities for the maintenance of successful agricultural cycles (Guilliem Arroyo 1999; Román Berrelleza 2010).

5.3. San Cristóbal Ecatepec

Rib and femoral fragments were sampled from adults ($n = 11$), children ($n = 3$), and infants ($n = 10$) from the Postclassic (900–1521 CE) residential site of Ecatepec (Fig. 1, Table 2). These burials were found below a house floor, located next to two *temazcales* (pre-Hispanic sweat lodges) (Moreiras Reynaga et al. 2020; Trejo Rangel 2014). Six adults were identified as males and five as females. This group serves as a baseline for the Basin of Mexico $\delta^{18}O_p$ signal, facilitating our assessment of the $\delta^{18}O_p$ of the sacrifices at Tenochtitlan and Tlatelolco.

5.4. Sample preparation and stable isotope analysis

Prior to the phosphate procedure, the offering 48 group (except for DM 10–12, 15, and 21) from the Templo Mayor underwent a 42 h acetone treatment to remove consolidants (polyvinyl acetate and acrylic resin) that were applied upon their recovery from the field in the early 1980 s (Moreiras Reynaga 2019). All samples of bone and enamel bioapatite were processed for phosphate oxygen isotope analysis, following methods adapted from Firsching (1961), Crowson et al. (1991), and Stuart-Williams and Schwarcz (1995). Approximately 35 mg of bone or enamel powder were dissolved in 3.0 M acetic acid for 24 or 48 h, respectively. To isolate and precipitate the silver orthophosphate (Ag_3PO_4), samples were volatilized in 10 mL of an ammoniacal silver solution followed by heating at 55 °C for 6 h (Firsching 1961). The Ag_3PO_4 crystals were filtered and washed three times with MQ water followed by drying at 60 °C. Approximately 0.2 mg per sample was weighed into silver capsules for oxygen isotope analysis.

The samples and standards were placed in a zero blank autosampler. They were then introduced into a Thermo Scientific™ High Temperature Conversion Elemental Analyzer (TCEA) where they were reacted at 1350 °C with a glassy carbon tube for a few seconds. The re-

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[6] Refers to "offering(s)" in the text, tables, and figures.

[7] The Mexica priests prepared human heads by opening two circular orifices on the temporal bones so that these could be placed on wooden posts and displayed on a head rack (*tzompantli*) next to their temples.

Table 2
Summary of oxygen isotope and FTIR parameter results by skeletal collection.

Sample/Offering	Age (yr.)	Sex	Sample Type	Ag_3PO_4 Yield	$\delta^{18}O_p$ (‰, VSMOW)	$\delta^{18}O_p$ converted to $\delta^{18}O_{iw}$ (‰, VSMOW)[a]	FTIR Parameters		
							CI	CO_3:PO_4	BPI
Templo Mayor of Mexico-Tenochtitlan									
DM1/of. 48	4 ± 12 mo.		Femoral fragment	1.3	+15.2[b]	−10.3	*3.0*	*0.2*	*0.5*
DM2/of. 48	7 ± 24 mo.		Femoral fragment	1.4	+13.2[b]	−13.4	*2.7*	*0.4*	*0.6*
DM3/of. 48	2 ± 8 mo.		Femoral fragment	1.0	+12.5*[c]	−14.5	*2.8*	*0.3*	*0.7*
DM4/of. 48	3 ± 12 mo.		Femoral fragment	1.1	+15.6[b]	−9.7	*2.8*	*0.4*	*0.7*
DM5/of. 48	5 ± 16 mo.		Femoral fragment	0.7	+14.8[b]	−10.9	*2.6*	*0.6*	*0.8*
DM6/of. 48	5 ± 16 mo.		Femoral fragment	1.3	+14.5[b]	−11.3	*2.7*	*0.4*	*0.6*
DM7/of. 48	5 ± 16 mo.		Femoral fragment	1.1	+13.9[b]	−12.3	*3.3*	*0.3*	*0.7*
DM8/of. 48	5 ± 16 mo.		Femoral fragment	1.3	+12.5[b]	−14.5	*2.8*	*0.3*	*0.6*
DM9/of. 48	4 ± 12 mo.		Femoral fragment	1.0	+13.8[b]	−12.4	*2.7*	*0.4*	*0.5*
DM10/of. 48	4 ± 12 mo.		Femoral fragment	1.2	+15.3[b]	−10.2	2.9	0.4	0.8
DM11/of. 48	6 ± 24 mo.		Femoral fragment	1.1	+12.9[b]	−13.9	3.0	0.2	0.5
DM12/of. 48	4 ± 12 mo.		Femoral fragment	1.4	+13.3[b]	−13.3	2.9	0.3	0.6
DM13/of. 48	6 ± 24 mo.		Femoral fragment	1.3	+13.5[b]	−12.9	*3.2*	*0.2*	*0.5*
DM14/of. 48	5 ± 16 mo.		Femoral fragment	0.8	+14.5[b]	−11.5	*3.3*	*0.2*	*0.4*
DM15/of. 48	6 ± 24 mo.		Femoral fragment	1.4	+15.1[b]	−10.4	3.1	0.3	0.6
DM16/of. 48	4 ± 12 mo.		Femoral fragment	1.3	+14.9[b]	−10.8	*2.9*	*0.6*	*2.1*
DM17/of. 48	4 ± 12 mo.		Femoral fragment	0.6	+13.5[b]	−13.0	*3.1*	*0.2*	*0.5*
DM18/of. 48	6 ± 24 mo.		Femoral fragment	1.0	+15.5[b]	−9.9	*3.0*	*0.2*	*0.5*
DM19/of. 48	6 ± 24 mo.		Femoral fragment	0.7	+14.5[b]	−11.4	*3.1*	*0.2*	*0.4*
DM20/of. 48	4 ± 12 mo.		Femoral fragment	1.3	+13.6[b]	−12.7	*3.1*	*0.1*	*0.2*
DM21/of. 48	5 ± 16 mo.		Femoral fragment	1.5	+15.3[b]	−10.2	3.3	0.2	0.4
DM22/of. 48	6 ± 24 mo		Femoral fragment	1.4	+17.0[b]	−7.5	*3.2*	*0.2*	*0.5*
DM23/of. 48	5 ± 16 mo.		Femoral fragment	1.3	+14.3[b]	−11.7	*3.4*	*0.2*	*0.5*
DM24/of. 48	5 ± 16 mo.		Femoral fragment	1.4	+12.2[b]	−15.0	*3.1*	*0.2*	*0.4*
DM108/of. 111	~5	M?	LM^2	1.6	+16.4[b]	−8.5	3.1	0.3	0.6
DM109/of. 111	~5	M?	Skull, vertebrae, sternum fragments	1.2	+14.3[b]	−11.7	2.6	0.5	0.7
DM110/of. 11	7–8		Skull fragments	1.2	+13.2*	−13.5	2.6	0.6	1.0
DM111/of. 11	20–30	F	LI_1	1.8	+13.7[c]	−12.5	3.6	0.2	0.4
DM112/of. 11	20–30	M	LP^3	1.2	+19.6[b]	−3.6	3.6	0.1	0.3
DM113/of. 20	6–7		Mandibular fragment	1.4	+13.8[b]	−12.5	2.6	0.5	0.7
DM114/of. 13	5–7		Skull fragments	1.4	+14.1[b]	−12.1	2.8	0.5	0.8
DM116/of. 24	4–5		Skull fragments	1.5	+13.0[b]	−13.8	2.5	0.5	0.7
DM118/of. 64	10–11		Skull fragments	1.3	+14.8	−10.9	2.6	0.5	0.7
DM120/of. 22	~6		Skull fragments	1.1	+15.4[b]	−10.0	2.5	0.9	1.5
DM121/of. 82	20–30	M	Skull fragments	1.3	+14.1	−12.1	2.6	0.6	0.9
DM122/of. 88	20–30	M	Skull fragments	1.5	+12.8	−14.1	2.6	0.6	0.9
Templo R of Mexico-Tlatelolco									
DM40/of. 2-B16	~6	M	Rib fragment	0.7	+15.4[b]	−10.0	2.6	0.5	0.7
DM42/of. 2-B25	2 ± 8 mo.		Rib fragment	0.8	+15.8[c]	−9.4	2.6	0.5	0.7
D44/of. 3-B15	5 ± 16 mo.	M	Rib fragment	1.0	+16.1[b]	−8.9	2.5	0.5	0.7
DM46/of. 4-B1	2 ± 8 mo.	M?	Rib fragment	0.9	+15.6[c]	−9.7	2.5	0.9	1.5
DM47/of. 5-B11	~1	M?	Rib fragment	1.4	+16.2[c]	−8.7	2.6	0.6	0.9
DM48/of. 5-B22	2 ± 8 mo.		Rib fragment	1.0	+15.0[c]	−10.6	2.5	0.5	1.0
DM49/of. 7-B2	1.5 ± 6 mo.	M?	Rib fragment	0.9	+15.9[c]	−9.3	2.6	0.9	1.1
DM50/of. 8-B3	8 ± 30 mo.	M	Rib fragment	0.8	+15.3	−10.1	2.8	0.4	0.8
DM51/of. 8-B28	6 ± 24 mo.	M	Rib fragment	1.1	+16.1[b]	−8.9	2.6	0.8	0.9
DM52/of. 9-B4	11 ± 30 mo.	M	Rib fragment	1.0	+14.8	−10.9	2.5	0.8	1.2
DM53/of. 9-B7	15 ± 36 mo.		Rib fragment	0.7	+15.9	−9.2	2.6	0.9	1.0
DM56/of. 9-B5	6 ± 24 mo.	M	Rib fragment	1.5	+15.3[b]	−10.2	2.4	1.0	0.8
DM62/of. 17-B19	4 ± 12 mo.	M	Rib fragment	1.4	+15.1[b]	−10.5	2.7	0.6	0.8
DM63/of. 20-B32	2 ± 8 mo.	M?	Rib fragment	1.3	+14.8[c]	−11.0	2.7	0.6	0.8
DM64/of. 23-B36	2 ± 8 mo.	M?	Rib fragment	1.2	+15.1[c]	−10.5	2.6	0.8	1.2
DM66/of. 27-B30	4 ± 12 mo.	M	Rib fragment	1.1	+14.9[b]	−10.8	2.6	0.8	0.9
DM68/of. 27-B37	~1.5		Rib fragment	1.4	+15.1[c]	−10.4	2.7	0.4	0.9
DM60/of. 11-B18	20–25	M	Rib fragment	1.1	+14.3	−11.6	2.6	0.7	0.9

(*continued on next page*)

Table 2 (*continued*)

Sample/Offering	Age (yr.)	Sex	Sample Type	Ag_3PO_4 Yield	$\delta^{18}O_p$ (‰, VSMOW)	$\delta^{18}O_p$ converted to $\delta^{18}O_{iw}$ (‰, VSMOW)[a]	FTIR Parameters		
							CI	CO_3:PO_4	BPI
DM57/of. 9-B6	15 ± 36 mo.	M	Rib fragment	0.9	+15.2	−10.2	2.5	0.6	0.9
DM55/of. 9-B20	15 ± 36 mo.	M	Rib fragment	1.3	+14.9	−10.8	2.8	0.4	0.6
DM58/of. 9-B8	~18	M	Rib fragment	0.9	+14.0	−12.1	2.6	0.7	0.9
DM59/of. 9-B9	~20	M	Rib fragment	0.9	+14.6	−11.2	2.6	0.7	1.0
DM61/of. 12-B14	20–25	M	Rib fragment	1.2	+14.7	−11.1	2.5	0.8	0.9
DM67/of. 27-B31	20–25	M	Rib fragment	1.2	+16.7	−8.0	2.5	0.9	1.1
San Cristóbal Ecatepec									
DM72	~23	M	Rib fragment	1.3	+15.2	−10.3	2.8	0.3	0.6
DM74	~4		Rib fragment	1.1	+15.4[b]	−10.1	2.9	0.7	1.4
DM76	~1.5		Rib fragment	1.0	+15.4[c]	−10.0	2.8	0.5	1.0
DM77	~47	F	Rib fragment	1.1	+15.4	−10.0	2.9	0.5	1.0
DM78	~1.5		Rib fragment	1.1	+16.3[c]	−8.6	2.8	0.5	0.9
DM80	~3		Rib fragment	1.0	+15.4[c]	−10.0	2.8	0.6	1.0
DM81	~2		Rib fragment	0.9	+14.4[c]	−11.5	2.8	0.5	0.9
DM82	~2		Rib fragment	1.3	+15.2[c]	−10.3	3.0	0.3	0.7
DM83	~1.5		Rib fragment	1.3	+13.8[c]	−12.4	3.1	0.3	0.7
DM84	~33	M	Rib fragment	1.1	+14.3	−11.7	3.1	0.5	1.1
DM85	~32	F	Femoral fragment	1.3	+15.3	−10.1	3.0	0.4	0.9
DM86	~1		Rib fragment	1.5	+16.0[c]	−9.1	3.1	0.3	0.7
DM88	~32	M	Rib fragment	1.8	+15.9	−9.3	3.1	0.4	0.8
DM89	~36	F	Femoral fragment	1.7	+15.1	−10.5	3.2	0.3	0.8
DM90	~4		Rib fragment	1.1	+16.4[b]	−8.4	3.0	0.5	1.0
DM91	~1		Rib fragment	1.3	+15.7*[c]	−9.6	2.8	0.6	1.1
DM92	~43	M	Rib fragment	1.4	+16.2	−8.8	3.1	0.4	0.9
DM94	~36	F	Rib fragment	1.1	+16.1	−9.0	2.8	0.5	1.0
DM96	~41	F	Rib fragment	1.1	+15.6	−9.7	2.9	0.5	1.0
DM98	~3		Rib fragment	1.0	+14.3[c]	−11.7	3.0	0.5	0.9
DM100	~45	M	Rib fragment	1.3	+15.7	−9.5	2.9	0.5	0.9
DM102	~30	M	Rib fragment	1.2	+14.6	−11.3	2.9	0.5	1.0
DM105	~2.5		Rib fragment	1.2	+16.2[c]	−8.8	3.4	0.3	0.7
DM106	~11	M	Rib fragment	0.9	+16.0	−9.1	3.0	0.4	1.1

The italicized FTIR results for the Templo Mayor offering 48 illustrate values after an acetone treatment for 42 h to remove consolidants (Moreiras Reynaga 2019).

* = Average of two/three analyses.

a = $\delta^{18}O_{iw}$ stands for the calculated oxygen isotope composition of ingested water using the Daux et al. (2008) equation.

b = Child value corrected by −0.35 ‰ (White et al. 2000, 2004b)

c = Infant value corrected by −0.7 ‰ (White et al. 2000, 2004b)

sulting carbon monoxide (CO) gas was passed through a heated (120 °C), custom GC column packed with a 0.5 nm molecular sieve to eliminate impurities (e.g., water). The CO gas was then swept using He gas in continuous-flow (CF) mode to a Thermo Scientific™ DELTA^{plus} XL® isotope ratio mass spectrometer (IRMS), where sample and standard oxygen isotope compositions were measured. At least 10% of samples were analyzed in duplicate during each analytical session.

Samples were calibrated to VSMOW using Aldrich Silver Phosphate – 98%, Batch 03610EH (accepted $\delta^{18}O$ = +11.2 ‰; Webb et al. 2014) and IAEA-CH-6 (ANU-sucrose, accepted $\delta^{18}O$ = +36.4 ‰; Zöckler et al. 2006). International and internal standard reference materials were analyzed in all analytical sessions to monitor analytical accuracy and precision. Reproducibility of Aldrich Silver Phosphate was $\delta^{18}O$ = ± 0.3 ‰ (1σ) (n = 52) and for IAEA-CH-6, ± 0.4 ‰ (1σ) (n = 18). To check accuracy and reproducibility NBS120c was analyzed and the value of $\delta^{18}O$ = +21.9 ± 0.6 ‰ (1σ) (n = 13) obtained compares well with the accepted value ($\delta^{18}O$ = +21.7 ‰; LSIS running value and Lécuyer et al. 2004). The absolute mean difference in $\delta^{18}O_p$ between 7 duplicate pairs was 0.3 ‰. Method duplicates (i.e., bioapatite isolation, preparation of silver phosphate and isotopic analysis of a different tissue fragment of the same sample) had a mean reproducibility of ± 0.4 ‰ (n = 14) for $\delta^{18}O_p$. The mean Ag_3PO_4 yield was 1.2 ± 0.2 mg (range = 0.6–1.8 mg). This overall high yield indicates that the samples were precipitated successfully (White et al. 2004b).

5.5. *Sample preservation and data treatment*

We assessed bone and enamel bioapatite preservation for all samples using a Bruker™ Vector 22® Fourier Transform Infrared (FTIR) spectrometer to obtain absorbance spectra between the wavenumbers of 400 to 4,000 cm^{-1} (resolution of 4 cm^{-1}). About 2 mg of powdered sample (< 63 μm) was mixed with 200 mg of fully dried IR spectroscopic-grade potassium bromide (KBr) powder and compressed in a hydraulic press at 10 tons for 10 min to produce a 12 mm pellet for analysis. The principal FTIR parameters used to evaluate sample preservation include the Crystallinity Index (CI), the CO_3/PO_4 ratio, and the B-carbonate to Phosphate Index (BPI). The CI indicates the degree of recrystallization of bioapatite, which can lead to isotopic exchange (Shemesh 1990). Increases beyond the normal range of CI for unaltered human bone (2.9–3.3) indicate high probability of recrystallization (Dal Sasso et al. 2018; Webb et al. 2014; Wright and Schwarcz 1996). The CO_3/PO_4 ratio is used to identify the incorporation of exogenous carbonate in association with bioapatite as well as the loss of carbonate from the sample (Smith et al 2007; Wright and Schwarcz 1996). Modern bone has a ratio ~0.5 and modern enamel ~0.2 (Smith et al 2007; Webb et al. 2014). The BPI deter-

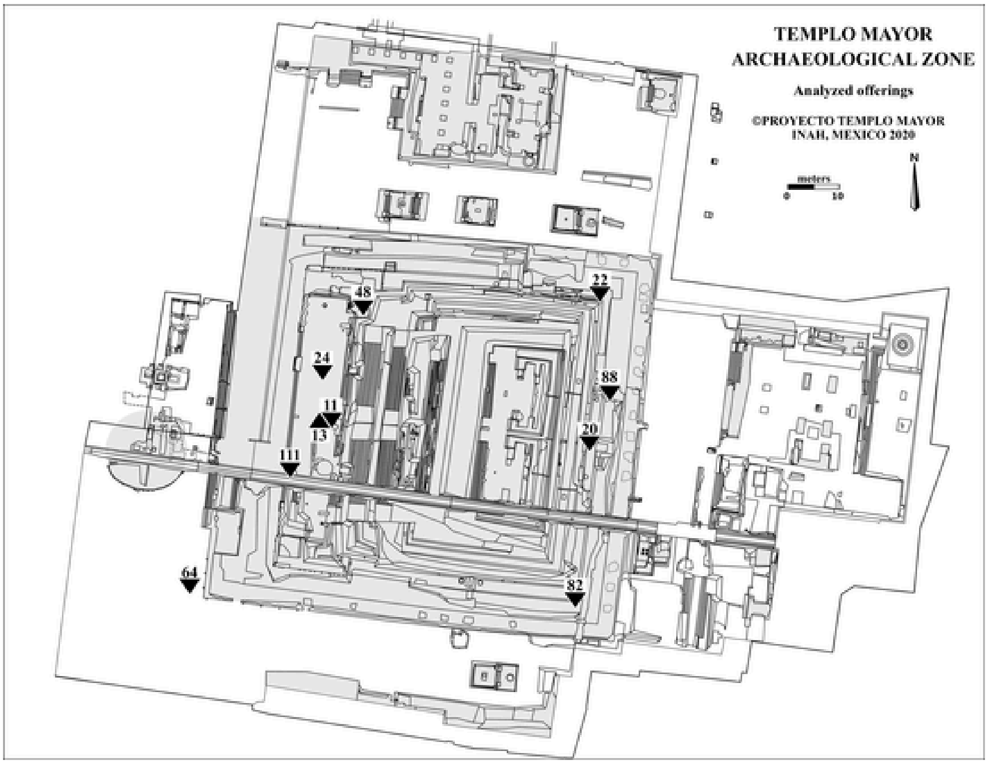

Fig. 5. Templo Mayor of Tenochtitlan diagram. The black triangles show the location of the offerings in this study. Courtesy of the Templo Mayor Project ©.

mines the amount of B-type carbonate to phosphate in bioapatite. Well-preserved bone and enamel bioapatite have been reported to have a BPI of about 0.7 ± 0.1 and 0.6 ± 0.1, respectively (Webb et al. 2014). Inspection for characteristic peaks of calcite (Wright and Schwarcz 1996), the peak at 866 cm^{-1} associated with amorphous carbonate content (Metcalfe et al. 2009), and francolite (F-apatite) (Shemesh 1990), all of which indicate alteration, was also performed.

The isotopic and FTIR data for all samples are normally distributed. Hence, the statistical techniques used throughout this paper include the Pearson's R correlation and linear regression between a dependent and an independent variable (R^2 from 0.0 to 0.3 = weak, 0.3–0.6 = moderate, 0.7–1.0 = strong). The software package IBM SPSS Statistics (V25) was used to compute all statistical analyses.

Following White et al.'s (2000, 2004b) breastfeeding and weaning assessments of other Mesoamerican populations, we have corrected the infant (birth–3.9 yrs. old) $\delta^{18}O_p$ data (bone as well as first permanent molars and incisors) by lowering these values by 0.7 ‰ and the children (4.0–7.0 yrs. old) bone as well as permanent premolars and second molars by 0.35 ‰ (Table 2). These corrections are approximations and subject to change as we learn more about the influence of subadult bioapatite $\delta^{18}O$ during breastfeeding and weaning across Mesoamerica (and elsewhere). These corrections serve to make the subadult $\delta^{18}O_p$ comparable to the adult $\delta^{18}O_p$ when assessing residential patterns in ancient human populations. The corrected $\delta^{18}O_p$ data are used throughout the paper.

5.6. Calculation of ingested water $\delta^{18}O$ from phosphate $\delta^{18}O$

Researchers have proposed several regression equations for the calculation of $\delta^{18}O_{iw}$ from $\delta^{18}O_p$ for mammals (including humans), based on the premise that this is a linear relationship (Daux et al. 2008; Iacumin et al. 1996; Longinelli 1984; Luz et al. 1984; Levinson et al. 1987). The value of $\delta^{18}O_{iw}$, in turn, largely reflects the $\delta^{18}O_{mw}$ consumed by such individuals throughout their lifetime. There are exceptions, for example, in cases where most of the water ingested had undergone evaporative ^{18}O-enrichment relative to precipitation (e.g., lake water or water modified during cooking).

Daux and colleagues compared their own equation with those of Longinelli (1984), Luz et al. (1984), and Levinson et al. (1987) and found that none of these models differed significantly at the $\alpha = 0.01$ significance level, and thus, they combined all of the data ($n = 42$) to develop an overall relationship (Daux et al. 2008: Equation 6). We applied this overall equation to our local adult $\delta^{18}O_p$ data ($n = 11$) from Ecatepec (Table 2):

$$\delta^{18}O_{iw} = 1.54(\pm 0.09) * \delta^{18}O_p - 33.72(\pm 1.51) \quad (1)$$

The results reflect the Basin of Mexico $\delta^{18}O_{mw}$ mean (–10.1 ± 0.3 ‰) quite closely, with a $\delta^{18}O_{iw}$ mean of –10.0 ± 0.9 ‰ (range = –11.7 to –8.8 ‰). The $\delta^{18}O_{iw}$ results for two individuals (DM 84 and 102) lie outside the Basin $\delta^{18}O_{mw}$ range (–11.7 ‰ and –11.3 ‰, respectively; Table 2), but remain within the standard error associated with this equation (SE = ± 1.6 ‰). Based on these results, we calculated the $\delta^{18}O_{iw}$ for the rest of the individuals in our study (Tables 2 and 3). We recognize that the standard error associated with this equation remains high; hence, we use these values as estimates only and in tandem with the baseline $\delta^{18}O_p$ data to guide our interpretations.

6. Results

6.1. Sample preservation

The results for CI (mean = 2.8 ± 0.3), the CO_3/PO_4 ratio (mean = 0.5 ± 0.2), and the BPI (mean = 0.8 ± 0.3), as well as lack of correlation between $\delta^{18}O_p$ and CI ($R^2 = 0.010$, $n = 84$, p = 0.371), CO_3/PO_4 ratio ($R^2 = 0.016$, $n = 84$, p = 0.253), and BPI ($R^2 = 0.032$, $n = 84$, p = 0.103) suggest that this sample set ($N = 84$) has preserved original oxygen isotope compositions. To evaluate whether isotopic fractionation occurred in the laboratory during silver phosphate (Ag_3PO_4) precipitation, the relationship between $\delta^{18}O_p$ and Ag_3PO_4

yields was tested via linear regression (Webb et al. 2014; White et al. 2004a and b). No correlation was found (R^2 = 0.007, n = 84, p = 0.457), which suggests the absence of any preferential precipitation of either ^{16}O or ^{18}O. Collectively, these tests demonstrate that the $\delta^{18}O_p$ data reliably reflect original isotope compositions of the bone and enamel samples.

Table 3
Summary of calculated $\delta^{18}O_{iw}$ (mean, SD, and range) by skeletal collection and age group[a].

Skeletal Collection	n (samples)	Age group (s)	Mean $\delta^{18}O_{iw}$ (‰, VSMOW)[b]	SD	Range $\delta^{18}O_{iw}$ (‰, VSMOW)
Ecatepec	14	Children and adults	−9.8	0.9	−11.7 to −8.4
	10	Infants	−10.2	1.3	−12.4 to −8.6
Templo R of Tlatelolco	8	Adults	−10.5	1.4	−12.1 to −8.0
	8	Infants	−10.0	0.8	−11.0 to −8.7
	8	Children	−10.0	0.8	−10.9 to −8.9
Templo Mayor of Tenochtitlan	4	Adults	−10.6	4.7	−14.1 to −3.6
	32	Subadults	−11.7	1.8	−15.0 to −7.5

[a] The Basin of Mexico region has a mean $\delta^{18}O_{mw}$ of **− 10.1 ± 0.3‰** and an estimated overall range of **− 11 to − 8‰**. Both precipitation and shallow groundwater $\delta^{18}O$ provide a good estimate of $\delta^{18}O_{mw}$ for the Basin and other regions across Mexico that is minimally affected by seasonal variations; see text.

[b] $\delta^{18}O_{iw}$ stands for the calculated oxygen isotope composition of ingested water using the Daux et al. (2008) equation.

6.2. General phosphate oxygen isotope trends

Fig. 6b shows that the Ecatepec children and adult $\delta^{18}O_p$ mean is +15.4 ± 0.6 ‰ (n = 14), ranging from +14.3 to +16.2 ‰ (Table 2). The infants (n = 10) in this group have a very similar $\delta^{18}O_p$ mean (+15.3 ± 0.9 ‰) and range (+13.8 to +16.4 ‰) to the rest of the group (Fig. 6b and 7, Table 2). All Ecatepec $\delta^{18}O_p$ data compare well with the $\delta^{18}O_p$ (+15.0 ‰) reported by Levinson et al. (1987) and the range of +14.0 to +16.0 ‰ reported by White and colleagues (2002, 2004a and b, 2007) for the Basin of Mexico. As with other Mesoamerican populations (White et al. 2002, 2004a and b, 2007), the range of intra-population variability is estimated to be ~2 ‰. Hence, this group serves as an excellent $\delta^{18}O_p$ baseline for assessing locality to the Basin of Mexico. The combined Ecatepec phosphate oxygen isotope range for subadults and adults is labelled as the local range in the remainder of this paper.

The Templo R subadults and adults have a $\delta^{18}O_p$ mean of +15.3 ± 0.6 ‰ (n = 24) and the values range from +14.0 to +16.7 ‰ (Fig. 6b and 7, Table 2). The $\delta^{18}O_p$ mean is close to the Ecatepec group, but the range is slightly wider because of one individual with a higher value (+16.7 ‰; Fig. 6b). As a result, all Templo R individuals, except for DM 67, have $\delta^{18}O_p$ consistent with the local $\delta^{18}O_p$ range.

The Templo Mayor adults and subadults have a $\delta^{18}O_p$ mean of +14.3 ± 1.4 ‰ (n = 35; Fig. 6b and 7), ranging from +12.2 to +19.6 ‰ (Table 2). This $\delta^{18}O_p$ mean is lower by 1.0 ‰ compared to the Ecatepec $\delta^{18}O_p$ mean and this group shows the widest $\delta^{18}O_p$ range. These results strongly suggest that while some of the individuals in this sacrificial group, subadults and adults alike, can be considered either locals or long-term residents of the Basin of Mexico, others have non-local residential origins.

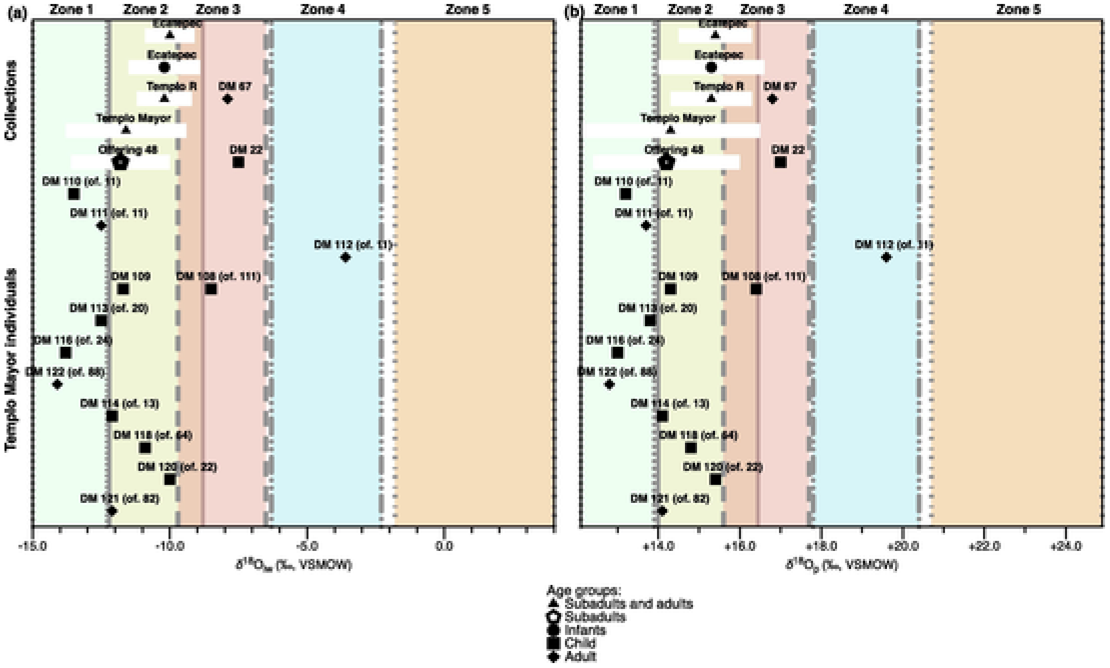

Fig. 6. Five zones across Mesoamerica shown with (a) $\delta^{18}O$ ingested water and (b) $\delta^{18}O_p$ (‰, VSMOW) ranges for the Ecatepec, Templo R, and Templo Mayor skeletal collections (white bar graph = SD) by age and for individuals mentioned in the text (triangle = subadults and adults; pentagon = subadults; circle = infants; square = child; diamond = adult). "DM" = sample ID and "of." = offering. Zone 1 (green; tiny circle dotted line) = Pacific Coast, western Mexico, Oaxaca Valley; Zone 2 (yellow; solid line) = Central Mexican highlands; Zone 3 (red; long dotted lines) = Southern Mexican highlands and northern Guatemala; Zone 4 (blue; two dots and one line) = Northern Chiapas, Petén region, Belize lowlands; Zone 5 (orange; tiny squared dotted line) = Yucatán Peninsula. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

6.3. Phosphate oxygen isotope patterns by age

Given that the sacrificial groups include individuals of different ages, we also examined our results by age subgroup: infants (birth–3 yrs. old), children (4–14 yrs. old), and adults (15+ yrs. old). The development of these age subgroups is guided by the physiological, chronological, and socio-cultural conceptions of childhood (Sofaer 2006) and adulthood in Mexica society (Chávez Balderas 2010b; Joyce 2000; Román Berrelleza and Chávez Balderas 2006).

After correction for the breastfeeding isotopic effect, all the Templo R infants have $\delta^{18}O_p$ that fit within the local $\delta^{18}O_p$ range (Fig. 7). This suggests that these infants were likely born in this region. Similarly, after any necessary breastfeeding correction, the Templo R children have $\delta^{18}O_p$ within the local range (Fig. 7), indicating long-term residence in the Basin of Mexico.

Eighteen children from the Templo Mayor group (DM 1, 4–7, 10, 14–16, 18–19, 21, and 23 [of. 48], DM 113 [of. 20], DM 114 [of. 13], DM 118 [of. 64], and DM 120 [of. 22]) have $\delta^{18}O_p$ that are considered local (Fig. 6b, Table 2). Hence, they were long-term residents of the Basin, but we do not know if they were born in this region. The children in offerings 11 and 24 (DM 110 and 116) have lower $\delta^{18}O_p$ (+13.4 ‰ and +13.0 ‰, respectively; Fig. 6b, Table 2) compared to the local $\delta^{18}O_p$ range. Two infants (DM 2–3) and eight children (DM 8–9, 11–13, 17, 20, and 24) from offering 48 also have a lower $\delta^{18}O_p$ (range = +12.2 to +13.8 ‰), and one child (DM 22) has a higher $\delta^{18}O_p$ (+17.0 ‰) compared to the local range (Fig. 6b, Table 2). The results suggest that these Templo Mayor infants and children lived in other Mesoamerican regions before they moved to the Basin of Mexico, where they were sacrificed. The 5-year-old child from offering 111 (DM 109) has a bone $\delta^{18}O_p$ of +14.3 ‰ (Fig. 6b and 8, Table 2), which agrees with the local $\delta^{18}O_p$ range. This child's (DM 108) second permanent molar $\delta^{18}O_p$ (+16.4 ‰; Fig. 8), however, is elevated by 2.1 ‰, indicating that s/he came from another Mesoamerican region and remained in the Basin of Mexico for sufficient time to acquire the local $\delta^{18}O_p$ signal.

All of the Templo R adults, except for DM 67, have $\delta^{18}O_p$ indicating that they were long-term residents of the Basin region (Fig. 7). The adult DM 67 has a higher $\delta^{18}O_p$ (+16.7 ‰; Fig. 6b, Table 2) and was likely a non-local. A Templo Mayor adult male (DM 121 [of. 82]) has a bone $\delta^{18}O_p$ (+14.1 ‰; Fig. 6b, Table 2) close to the local $\delta^{18}O_p$ range, suggesting he was a long-term resident of the Basin. The Templo Mayor adult female (DM 111 [of. 11]) has a lower enamel $\delta^{18}O_p$ (+13.7 ‰; Fig. 6b and 8, Table 2), indicating that she was born outside of the Basin of Mexico and moved to Tenochtitlan later in life. Likewise, two Templo Mayor adult males (DM 112 [of. 11] and DM 122 [of. 88]) have $\delta^{18}O_p$ (+19.6 ‰ and + 12.8 ‰, respectively) outside the local $\delta^{18}O_p$ range (Fig. 6b, Table 2).

6.4. Phosphate oxygen isotope results converted to $\delta^{18}O_{iw}$

The Ecatepec children and adults have an overall $\delta^{18}O_{iw}$ mean of −9.8 ± 0.9 ‰ (range = −11.7 to −8.4 ‰), which agrees well with the surface and groundwater $\delta^{18}O_{mw}$ data for the Basin of Mexico region (Fig. 6a, Table 3). The infants have a similar $\delta^{18}O_{iw}$ mean (−10.2 ± 1.3 ‰), but their range is slightly wider (−12.4 to −8.6 ‰; Fig. 6a, Table 3). This small change may be due to slight differences in the water sources accessed by their mothers during lactation (Lightfoot and O'Connell 2016), differences in breastfeeding and weaning patterns across the age range (Reynard and Tuross 2015), and/or the use of the $\delta^{18}O_p$ breastfeeding corrections (White et al. 2000, 2004b). Accordingly, we consider the Ecatepec adult $\delta^{18}O_{iw}$ dataset to be the most reliable baseline for establishing locality or long-term residence in the Basin of Mexico.

The Templo R infants, children, and adults have similar $\delta^{18}O_{iw}$ means and ranges to the Ecatepec baseline $\delta^{18}O_{iw}$ (Fig. 6a, Table 3), indicating that these individuals, except for one adult, were long-term residents of the Basin of Mexico. The adult male (DM 67) outlier has a less negative $\delta^{18}O_{iw}$ (−8.0 ‰) and could have come from either the central highland region surrounding the Basin (especially northeast; $\delta^{18}O_{mw}$ = − 9 to −7 ‰) or the southern highlands ($\delta^{18}O_{mw}$ = −9 to −6 ‰; Figs. 3 and 6a).

While the Templo Mayor adults have a similar $\delta^{18}O_{iw}$ mean (−10.6 ± 4.7 ‰) to the Ecatepec baseline $\delta^{18}O_{iw}$ mean (Fig. 6a, Table 3), there are clear cases of individuals with $\delta^{18}O_{iw}$ outside the local range. One non-local adult male (DM 112 [of. 11]) was born either in the southeastern coastal region of the Gulf of Mexico (e.g., Veracruz)

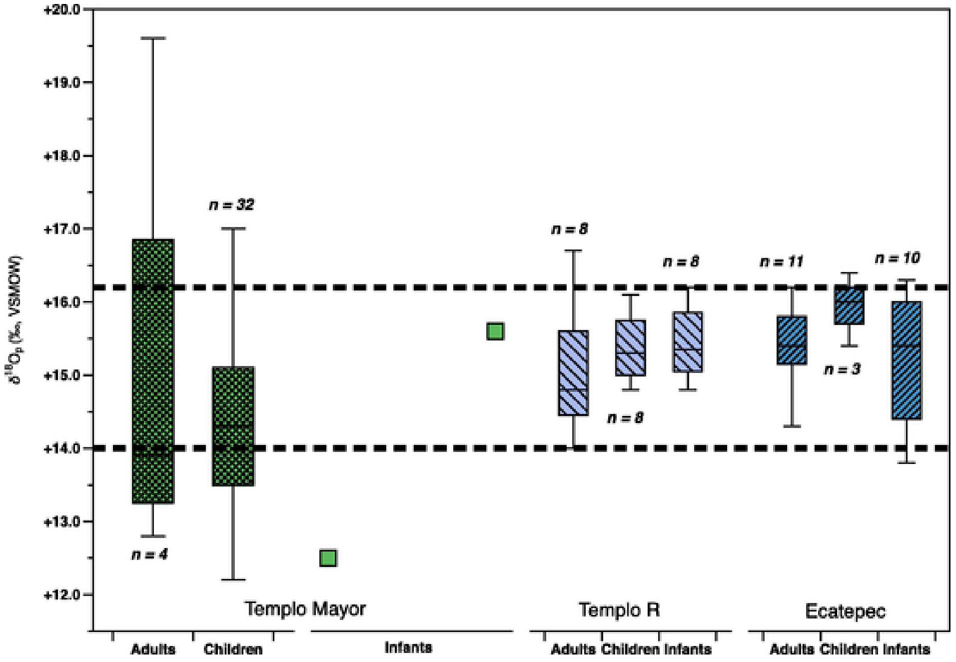

Fig. 7. $\delta^{18}O_p$ by age group and skeletal collection. Green = Templo Mayor; green square = Templo Mayor infant; light blue = Templo R; ocean blue = Ecatepec. The dotted horizontal lines encompass the $\delta^{18}O_p$ range (+14.0 ‰ to +16.2 ‰) for the Basin of Mexico based on the Ecatepec bone sample data in this study. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

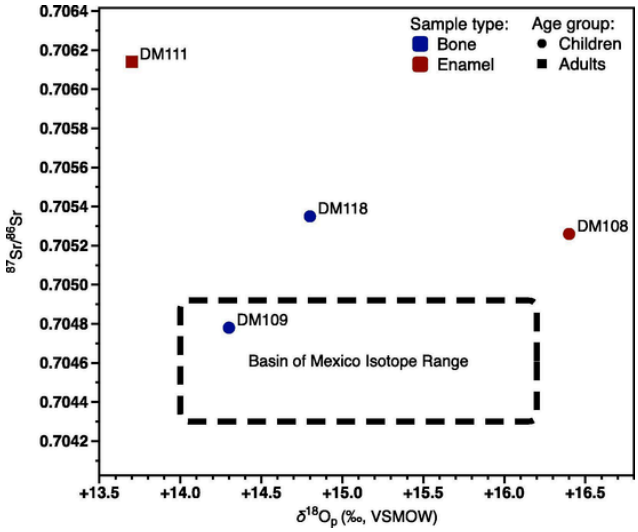

Fig. 8. Phosphate oxygen vs. strontium isotope ratios scatterplot of three Templo Mayor individuals. Circle = children; square = adults. Red = enamel sample; blue = bone sample. DM108 and DM109 are enamel and bone samples, respectively, from the same child (of. 111). The dotted rectangle represents the Basin of Mexico isotope range based on $\delta^{18}O_p$ (this study) and $^{87}Sr/^{86}Sr$ ratios (0.7043 to 0.7049; Barrera Huerta 2014). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

or somewhere in the southern lowlands (e.g., Petén region), given his elevated $\delta^{18}O_{iw}$ of −3.6 ‰ (Figs. 3 and 6a, Table 2). Another non-local adult male (DM 122 [of. 88]) and the adult female (DM 111 [of. 11]) could have come from the western Mexico highlands or the Valley of Oaxaca based on their very negative $\delta^{18}O_{iw}$ of −14.1 ‰ and −12.5 ‰, respectively (Figs. 3 and 6a, Table 2).

The Templo Mayor subadults have a more negative $\delta^{18}O_{iw}$ mean (−11.7 ± 1.8 ‰) compared to the local $\delta^{18}O_{iw}$ mean with values ranging from −15.0 to −7.5 ‰ (Table 3). This result indicates that while some infants and children were locals or long-term residents of the Basin of Mexico, others were non-locals. Two infants and eleven children from offerings 11, 20, 24, and 48 have more negative $\delta^{18}O_{iw}$ (range = −15.0 to −12.4 ‰), suggesting a geographic origin from western Mexico or the Oaxaca Valley (Figs. 3 and 6a, Table 2). Two children (DM 22 [of. 48] and DM 108 [of. 111]) have less negative $\delta^{18}O_{iw}$ (−7.5 ‰ and −8.5 ‰, respectively; Fig. 6a, Table 2), suggesting that these individuals resided either in the central Mexican highlands or the southern highlands of Mexico and Guatemala.

7. Discussion

7.1. Residency of the Templo R and Templo Mayor sacrifices

At Templo R, the infants and children (n = 16) and the adults (n = 7) chosen for sacrifice to Ehecatl-Quetzalcoatl came from the Basin of Mexico region (except for DM 67). Some were possibly long-term residents who came from elsewhere, while others were likely born and raised in this region, especially the infants. The Tlatelolcan priests, therefore, seem to have chosen to sacrifice locals, that is, Aztecs living within the Basin of Mexico communities (but not necessarily Tlatelolcas or Tenochcas), rather than foreigners for this one-time sacrificial ritual. Some of these adults and children could have been purchased from the specialized slave markets. Durán (1984) narrates that slave men, women, and children were purchased at these markets for a range of sacrificial rituals and that these slaves were not strangers, foreigners, or war captives, but people from the local communities. Sahagún (1932) mentions that the infants and children could have been purchased from their mothers. According to friar Toribio de Benavente (1995) these children were not slaves, but sons and daughters of dignitaries, while Juan Bautista Pomar (1941:18) alludes to the fact that the sacrificed children were "…those [voluntarily] provided by lords or the wealthy to be offered in such occasions". As a result, the sacrificed individuals at the Templo R seem to exemplify the use of locals—bought or willingly given by their families—for a Mexica sacrificial ritual, thus corroborating historical accounts on this matter.

In contrast, about half of the Templo Mayor of Tenochtitlan sacrificial subadults (n = 16) were long-term residents of the Basin of Mexico, while the other half (n = 15) came from elsewhere in Mesoamerica. Likewise, an adult male sacrifice (DM 121 [of. 82]) was a long-term resident while two adult males (DM 112 [of. 11] and DM 122 [of. 88]) were non-locals (Fig. 6). The adult female (DM 111 [of. 11]) had a residential origin outside of the Basin of Mexico. While some of the adults and subadults may have been obtained in the slave market, these results also hint at other ways through which the Tenochca priests obtained men, women, children, and infants for sacrificial rituals at the Templo Mayor—aside from adult male war captives. Durán (1964: Chapter XXV) narrates that "Provinces who lacked foodstuffs and clothes paid [tribute] in maidens, girls and boys, who were divided among the lords—all slaves". The same chronicler mentions that these slaves were sent every eighty days to Tenochtitlan. Similarly, in the Anales de Cuauhtitlán (1945) the Huaxtec had to provide 20 slaves as part of their tribute contributions to the Mexica. These accounts support the idea that non-local men, women, and subadults were commonly taken to Tenochtitlan through the Triple Alliance's tributary system. These non-local individuals could have also been captured during warfare. When the Triple Alliance attacked Oztoma, during the reign of Ahuitzotl, it is narrated by Alvarado Tezozómoc (1944:343-345) that about half of the men as well as all the boys and girls of this town were taken to Tenochtitlan. In addition, according to Muñoz de Camargo (1998), individuals, men and women, captured in this manner were sold. These individuals were likely free citizens who became spoils-of-war and eventually sacrificial victims. Moreover, Durán mentions that Motecuhzoma II received prisoners as a gift from the sister-city of Tlatelolco (in Davies 1981). The gifting of prisoners may have included men, women, children, and infants and they could be locals to the Basin of Mexico (from neighboring city-states like Azcapotzalco, Coyohuacan, Chalco, etc.) as well as non-locals (i.e., from the Triple Alliance's tributary provinces). These results demonstrate that the Tenochca priests chose to offer individuals from a range of geographic locations, who were likely obtained in various ways, to their deities as part of a wide range of ritual ceremonies.

7.2. Combined phosphate oxygen and strontium isotope ratios

Strontium ($^{87}Sr/^{86}Sr$) isotope ratios can also be obtained from enamel and bone tissues to assess residence to a geographic region. While phosphate oxygen isotopes are introduced into the human body mostly by drinking water, strontium isotopes are incorporated into human tissues based on the foods consumed. Soils, plants, and animals obtain their strontium isotope ratios based on the geological composition of the continental crust (Bentley 2006; Faure and Powell 1972). Since there are differences in the strontium isotope signatures across geographic regions based on their respective geological compositions, we can use such data to identify geographic regions where individuals may have lived. The variation in strontium isotope composition of the central Mexico region has been previously characterized by several scholars and deemed appropriate for use in the reconstruction of geographic residential patterns in pre-Columbian times (Pacheco-Forés et al. 2020, 2021; Price et al. 2008). It can be especially informative to pair the $\delta^{18}O_p$ and $^{87}Sr/^{86}Sr$ ratios of particular individuals to better assess their place(s) of residence.

Fig. 8 illustrates this study's $\delta^{18}O_p$ and the $^{87}Sr/^{86}Sr$ ratios obtained by Barrera Huerta (2014) for three sacrificed individuals (of. 11, 64, and 111) from the Templo Mayor and Table 4 presents the ^{87}Sr/^{86}Sr ratios of several archaeological sites by $\delta^{18}O_p$ Zone. The offering 111 child (DM 108–109) shows a local bone signal for both $\delta^{18}O_p$ and ^{87}Sr/^{86}Sr, which confirms that s/he resided in the Basin for a period long enough to acquire the local isotopic signatures. This child's tooth enamel isotopic signals are clearly outside the local $\delta^{18}O_p$ and ^{87}Sr/^{86}Sr ranges and suggest a residential origin either in Zones 2 or 3 (central or southern highlands). The child (DM 118) from offering 64 shows a local $\delta^{18}O_p$ but a non-local ^{87}Sr/^{86}Sr ratio. This could be due to either faster equilibration of $\delta^{18}O_p$ to the local range compared to ^{87}Sr/^{86}Sr or a location outside of the Basin of Mexico that shares the same $\delta^{18}O_p$ but different ^{87}Sr/^{86}Sr signals. Based on the latter, this child could have resided somewhere in the central highlands (Zone 2) prior to their sacrifice. The adult female (DM 111) from offering 11 was a non-local to the Basin of Mexico; however, it is difficult to determine a location that agrees with both her $\delta^{18}O_p$ and ^{87}Sr/^{86}Sr signals, based on the available isotope baseline data. Her ^{87}Sr/^{86}Sr ratio suggests a location in the central highlands (Zone 2), while her $\delta^{18}O_p$ suggests a location in the Oaxaca or western Mexico regions (Zone 1). This discrepancy could also be due to having two different teeth sampled for ^{87}Sr/^{86}Sr and $\delta^{18}O_p$ (1st permanent molar vs. permanent incisor), which may be reflecting signals at different points in this woman's infancy.

7.3. On the subadult sacrifices

The offerings at the two Mexica temples considered in this study illustrate that Mexica priests mainly sacrificed subadults for three types of rituals: (1) to the gods of rain, wind, and earth's fertility, (2) for the consecration of the Templo Mayor's enlargements, and (3) to the god of war, Huitzilopochtli (Chávez Balderas 2010a; López Luján 2005; López Luján et al. 2010). Historical, archaeological, and bioarchaeological evidence has shown that these individuals were selected based on particular physical traits, health conditions, age and sex, and were handled differently by the priests based on the deity and type of ceremony (e.g., sacrifice method, post-sacrificial treatment) (Chávez Balderas 2010a, 2017, 2019; De la Cruz et al. 2008; González Torres 1985; López Austin 1988; López Luján 2018; López Luján et al. 2010; Román Berrelleza and Chávez Balderas 2006). Our phosphate oxygen isotope results exemplify three residential patterns for these sacrifices: (1) the infants dedicated to Ehecatl-Quetzalcoatl were of local origin; (2) the infants and children sacrificed to or in association with the Tlaloc shrine (Templo Mayor of. 22, 24, and 48), Ehecatl-Quetzalcoatl (Templo R), and in consecration ceremonies (Templo Mayor of. 11, 13, 20, and 64) could be non-locals or long-term residents of the Basin of Mexico, and (3) the child sacrificed to Huitzilopochtli (Templo Mayor of. 111) was of non-local origin, but had been a long-term resident of the Basin of Mexico (~2 yrs.) at the time of sacrifice.

Table 4
^{87}Sr/^{86}Sr isotope ratios of several archaeological sites arranged by the five $\delta^{18}O_p$ Zones in Mesoamerica.

$\delta^{18}O_p$ Zones in Mesoamerica		Archaeological Sites	^{87}Sr/^{86}Sr Isotope Ratios[a]
Zone 1	Western Mexico	Tzintzuntzán	0.7042
	Oaxaca Valley	Monte Albán	0.7079
		Tehuacán	0.7074
	Pacific Coast	La Zanja	0.7095
Zone 2	Basin of Mexico	Chapultepec	0.7047
		Teotihuacan	0.7046
		Tlapacoya	0.7048
	Central Highlands	Tula	0.7065
		Chingú	0.7060
		Tlaxcala	0.7052
		Cholula	0.7067
Zone 3	Southern Highlands	Toniná and Palenque	0.7079
		Kaminaljuyú	0.7052
		Atitlán	0.7042
Zone 4	Gulf of Mexico	Maltrata	0.7062
		Tres Zapotes	0.7042
	Petén	Tikal and Piedras Negras	0.7080
		El Mirador	0.7079
	Belize Lowlands	Buenavista	0.7084
		Colhá	0.7082
Zone 5	Northern Lowlands/Yucatán Peninsula	Calakmul	0.7077
		Campeche	0.7082
		Chichen Itzá	0.7087

[a] Published data reported in Price et al. (2010).

7.4. The Non-Local Sacrifices' origins by Tenochca imperial reign

Given that some sacrificed individuals correspond to non-locals, we analyzed the possible geographic origins of these individuals with reference to the Triple Alliance expansion. The Tenochca began expanding their empire from the time they defeated Azcapotzalco (1428–1430 CE) up to the arrival of the Spaniards in 1519 CE. Following Pedro Carrasco's (1999b) organization of the empire into three main Mesoamerican territorial sectors, it extended northwest, south, and northeast of the Basin of Mexico . Here we discuss the extent of the imperial expansion across the three sectors during the reigns of Motecuhzoma I (1440–1469 CE) and his successor, Axayacatl (1469–1481 CE; Table 5). This approach provides insights into the geographic origins of the identified non-local sacrificial individuals at the two temples based on their phosphate and calculated ingested water oxygen isotope compositions.

Building on the military prowess of Itzcoatl (1427–1440 CE), Motecuhzoma I and his army, alongside the Triple Alliance city-states, consolidated their dominance at the core of the Aztec Empire (the communities and tributary provinces surrounding the Basin of Mexico) by extending their conquests across the three imperial sectors (Table 5). In the Northwestern sector, tributary provinces were established in what are today the present States of Mexico and Hidalgo (; Table 5; Carrasco 1999b). Conquests in the Southern sector included the kingdoms of Chalco in the southeastern part of the Basin of Mexico as well as tributary provinces located in the States of Morelos, Puebla, Guerrero, northern Oaxaca, and Veracruz (Carrasco 1999b; González Torres 1985). To the northeast, the provinces located in the present-day States of Puebla, Hidalgo, and Veracruz, were subjugated with the aid of Texcoco's king Nezahualcoyotl (Carrasco 1999b).

The Templo R adult's (DM 67) possible geographic origins (Zone 3; Figs. 4 and 6, Table 5) agree well with the regions covered by Motecuhzoma I's imperial expeditions, particularly in the Northeastern and Southern sectors. The regions northeast of the Basin, in the States of Hidalgo, San Luis Potosí, and Veracruz, as well as further southeast into the Veracruz highlands, have a less negative $\delta^{18}O_{mw}$ range (−8.0 to −7.0 ‰) compared to the Basin of Mexico (Figs. 3 and 4). The child (DM 108–109 [of. 111]) sacrificed to Huitzilopochtli presents itself as an illustration of the richness in the diversity of the sacrificial victims (i.e., not all sacrifices were adult male war captives). This child, who became the *ixiptla* of Huitzilopochtli as part of this ceremony, was buried in a unique ritual context (López Luján et al. 2010). The child's enamel $\delta^{18}O_p$ (+16.4 ‰) is 2.1 ‰ higher than the bone $\delta^{18}O_p$ (+14.3 ‰; Figs. 6b and 8), suggesting that s/he was a non-local who arrived at Tenochtitlan after the age of three. This child's severe dental fluorosis[8] (López Luján et al. 2010), tooth enamel strontium isotope ratio (Fig. 8; Barrera Huerta 2014), bone mitochondrial *a*DNA (Bustos Ríos 2012), and this study's oxygen isotope results (Fig. 6, Table 2), all

Table 5
Summary of possible geographic origins of the non-local sacrificial individuals by Tenochca Emperor and reign period.

Tenochca Emperor/ Reign Period	Military Campaigns/Tributary Provinces[a]	Temple and Offering	Ceremony Type/Deity Associated	Non-local Individual (s)	Age group	Possible Residence (s) Based on $\delta^{18}O_p$ Zones
Motecuhzoma I 1440–1469 CE	**Northwestern sector:** Cuauhtitlán, Axocopan, Atotonilco de Tula, and Hueypochtlán (Tepanec Kingdom), Tollan, Xilotépec, Itzcuincuitlapilco, as well as Atotonilco el Grande to the east (States of Mexico and Hidalgo). **Southern sector**: Chalco, Tepeyacac, Tlachco, Tlalcozauhtitlan, Quiauhteopan, Yoaltepec, Tepecuacuilco, Coaixtlahuacan, Tochtepec, located in the States of Morelos, Puebla, Guerrero, Northern Oaxaca, and Veracruz. **Northeastern sector:** Tlapacoyan, Tlatlauhquitepec, Tochpan, Tamapachco, and Tziuhcoac (States of Puebla, Veracruz, and Hidalgo).	Templo R, of. 27	Ehecatl-Quetzalcoatl	DM 67	Adult (Male)	**Zone 2 or 3**
		Templo Mayor, of. 111	Huitzilopochtli	DM 108 and 109	Child	**Zones 2 and 3**
		Templo Mayor, of. 48	Tlaloc	DM 2, 3, 8, 9, 11–13, 17, 20, 24	Child	**Zone 1**
				DM 22	Child	**Zone 3**
Axayacatl 1469–1481 CE	**Northwest sector:** Cuahuacán, Tolocan (Toluca), Matlatzinco, Ocuillan, Malinalco (States of Mexico and Guerrero), Tenancingo, Xiquipilco, Xocotitlán, Xilotépec, Malacatepec, Amatepec, Cimatepec (beyond Valley of Toluca, adjacent to the Tarascan kingdom in Michoacán). **Southern sector:** Tepecuacuilco (Guerrero), Toltepec (frontier with Michoacán). **Northeastern sector:** Atlan (Tecapotitlán)-Huaxtec region (States of Puebla and Veracruz).	Templo Mayor, of. 11	Consecration	DM 110	Child	**Zone 1**
				DM 111	Adult (Female)	**Zone 1**
				DM 112	Adult (Male)	**Zone 4**
		Templo Mayor, of. 20		DM 113	Child	**Zone 1**
		Templo Mayor, of. 24	Tlaloc (offerings found on this deity's shrine)	DM 116	Child	**Zone 1**
		Templo Mayor, of. 88		DM 122	Adult (Male)	**Zone 1**

[a] Based on Durán (1964), Carrasco (1999b), López Austin and López Luján (2008), and González Torres (1985).

suggest that this child's homeland was somewhere in the north-central region of Mexico or the Mexican Plateau (Northeastern imperial sector; Zone 3; Fig. 4).

All but one of the non-local child sacrifices to Tlaloc (Templo Mayor of. 48) could have come from either western Mexico or the Oaxaca Valley (Zone 1; Figs. 4 and 6). The exception is a child (DM 22) who came from the southern Mesoamerican highlands (Zone 3; Figs. 4 and 6), an area beyond the extent of the Triple Alliance at that time. We know that the merchants used to travel beyond the frontier of the Triple Alliance's imperial sectors to obtain luxury materials (Hassig 1985; Carrasco 1999b), and so it is possible that slaves were also obtained during these journeys.

By the time Axayacatl was selected as the next *huei tlatoani*, a large part of Mesoamerica was already under the Triple Alliance's power. During his reign, the Mexica focused on conquering western provinces, which consolidated the Northwestern imperial sector in the States of Toluca, Mexico, northern Guerrero, and the region beyond the Toluca Valley near the Tarascan Kingdom (present-day State of Michoacán; Table 5). The Southern sector included a re-conquest of Tepequacuilco (Guerrero), control of Toltepec on the border with the Tarascan, and continued dominance in southern Veracruz. The Northeastern sector incorporated towns in the Huaxtec region in the States of Puebla and Veracruz (Carrasco 1999b). Also, even though Tlatelolco was a dependent of Tenochtitlan, they rebelled during this period (1473 CE), but the outcome was unsuccessful for the Tlatelolcans; Axayacatl took full control making this city even more dependent than it was before the uprising (Carrasco 1999b; López Austin and López Luján 2008; López Luján 2005).

The Templo Mayor adult male from offering 88 (DM 122), the child (DM 110) and adult female (DM 111) from offering 11, and the children from offerings 20 and 24 (DM 113 and DM 116, respectively), could have come from either western Mexico or the Oaxaca Valley (Zone 1; Figs. 4 and 6). Based on the fact that the Triple Alliance did not expand far into the Oaxaca Valley until years later during the full imperial expansion (with Ahuitzotl) and consolidation (with Motecuhzoma II) periods, and that Axayacatl focused on the North and Southwestern sectors of Mesoamerica (Table 5), there is a strong probability that the majority of these sacrifices were taken from provinces in western Mexico that were subjugated by the Triple Alliance during this time. The Templo Mayor adult male from offering 11 (DM 112), who originated from either the Gulf of Mexico or the southern Mesoamerican lowlands (Zone 4; Figs. 4 and 6), is the only non-local sacrifice from Zone 4 in our dataset. During this period (1469–1481 CE), parts of the southern coast of Veracruz were already part of the empire but Axayacatl spent further efforts consolidating this region (Carrasco 1999b). Thus, this adult may have been either a war captive from one of Axay-

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[8] This condition arises from drinking water rich in fluorine. The F-rich potable water sources in Mexico are located in the north-central region including the States of San Luis Potosí, Hidalgo, Coahuila, Zacatecas, Guanajuato, and Jalisco) (Barrera Huerta 2014; Grimaldo et al. 1995; Juárez-López et al. 2003).

acatl's expeditions or a slave sent to Tenochtitlan as part of these subjugated provinces' tribute contributions.

7.5. *Templo R versus Templo Mayor sacrificial individuals*

The data presented above show substantial differences in the residential pattern of sacrificial victims at the Templo R of Tlatelolco and at the Templo Mayor of Tenochtitlan. All but one individual at the Templo R have a local oxygen isotope signal while the victims from the multiple Templo Mayor offerings showed much more residential variability. We hypothesize that this difference could be due to either the nature of the rituals under study, the means of the Tlatelolcan and Tenochca priests involved in those sacrificial events, or a combination of these two possibilities. The nature of the rituals could be central to understanding the residential pattern of the sacrificial victims. Indeed, the Templo R sacrifices were part of a one-time ceremony for which the Tlatelolcan priests may have deemed that locals and long-term residents were the best-suited subjects of sacrifice. Conversely, the Templo Mayor sacrifices encompass multiple sacrificial ceremonies, at different points in time, each of which may have required sacrificial victims with specific characteristics, some related to their geographic residence(s). Nevertheless, it is also possible that the Tlatelolcan and Tenochca priests may have had differential access to future sacrificial victims due to their relative positions in the Mexica geopolitical landscape (Broda et al. 1987; López Austin and López Luján 2009; Smith 2008). Being responsible for the most sacred temple of the empire, the Tenochca priests would have had easy access to sacrificial victims (including locals, long-term residents, and non-locals) to offer to Tlaloc, Huitzilopochtli, and for building consecration ceremonies associated with the installment of successive Tenochca rulers, building enlargements, and funerary rituals. While different residential patterns are evident in our dataset, comparison between these two Mexica temples is complex due to their differing socio-cultural and religious contexts. Further research that analyzes the bioapatite oxygen and strontium isotope compositions of a larger human dataset from multiple Mexica temples and ritual contexts is needed to test the proposed hypotheses.

8. Conclusions

This is the first Aztec-Mexica sample set to be analyzed using phosphate oxygen isotopes to determine their geographic origins and residence during the last years of life. This study has brought to light the residential patterns of individuals chosen as sacrifices by the Mexica. The results suggest that most of the Templo R individuals (except for one adult) were long-term residents of the Basin of Mexico. The infant sacrifices from Templo R corroborate the historical accounts that these were likely local infants purchased from their mothers or voluntarily provided by nobles that were to be offered to the wind, rain, and earth's fertility deities. The Templo R subadults could be an example of locals—Aztecs living within the Basin of Mexico communities—who could have been slaves purchased for sacrifice, as mentioned in historic sources. At the Templo Mayor, however, the infants and children offered to Tlaloc, Huitzilopochtli, and those used in consecration ceremonies include both non-locals and long-term residents (with a possible foreign geographic origin as exemplified by DM 108–109 [of. 111]) of the Basin of Mexico. These results indicate that there was a wide diversity in the residences of subadults selected by Tenochca priests for a range of Templo Mayor ceremonies.

The adult sacrifices analyzed thus far provide valuable insights into the residential variability among this group. All but one of the Templo R adults and one Templo Mayor adult were long-term residents at the time of their sacrifice. These individuals could have been either purchased slaves, tribute payments, gifts, or spoils-of-war who resided for a period longer than 10 years before becoming sacrifices in a Mexica ceremony. Conversely, two Templo Mayor adult males and one female as well as one Templo R adult male were distinctly non-locals. These individuals could have been war captives, purchased slaves, tribute payments, gifts, or spoils-of-war sacrificed soon after their arrival to the Basin of Mexico. Our results suggest that the difference in geographic residential patterns between the Templo R of Tlatelolco and the Templo Mayor of Tenochtitlan may be due to the nature of the rituals under study and/or due to the means of the Tlatelolcan and Tenochca priests involved in those sacrificial events. This study demonstrates that the Tenochca priests had broad access to long-term residents of Tenochtitlan and to non-local subadults and adults. Moreover, our results indicate that the non-local sacrifices had geographic origins that fall in line with the Mesoamerican regions that became subjugated during multiple Tenochca imperial reigns. Thus, the Mexica obtained individuals for sacrifice from the subjugated provinces with a diverse range of physical and social identities for the many ritual ceremonies carried out at their *Huei Teocalli*.

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Author contributions

DKMR, JM, XCB, JARB, LLL, and FJL, designed the research; XCB, JARB, and LLL excavated and studied the collections; XRB, JARB, DKMR, and FJL sampled the collections for analysis; DKMR performed isotopic research; DKMR, JM, and FJL interpreted the data; DKMR wrote the initial manuscript with input from JM, XCB, JARB, LLL, and FJL.

Uncited references

López Austin (1988), López Luján (2019b).

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.

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