Supplementary Material for

A large-scale Sr and Nd isotope baseline for archaeological provenance in Silk Road regions and its application to plant-ash glass

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1. Data used for establishing the baseline

Table S1: Bioavailable Sr isotope data used in this baseline study.

No.	material	location	$^{87}Sr/^{86}Sr$	source
Sr1	surface water	Caspian Sea	0.708183	(Clauer et al., 2000)
Sr2	surface water	southern rivers into the Caspian	0.708293	(Clauer et al., 2000)
Sr3	surface water	Aral Sea	0.70914	(Pokrovsky et al., 2017)
Sr4	plant	Syrian coast	0.708396(Q1)–0.708503(Q3) (n=5)	(Henderson et al., 2009)
Sr5	plant	Aleppo, Syria	0.708020(Q1)–0.708091(Q3) (n=7)	(Henderson et al., 2009)
Sr6	plant	eastern Syria (Euphrates Valley: Raqqa, Tell Brak, and Balikh Valley)	0.708090(Q1)–0.708339(Q3) (n=10)	(Henderson et al., 2009)
Sr7	plant	Damascus, Syria	0.707815(Q1)–0.707937(Q3) (n=6)	(Henderson et al., 2009)
Sr8	plant	Bestansur, Iraq (bordering Iran)	0.708031(Q1)–0.708152(Q3) (n=5)	(Elliott et al., 2015)
Sr9	plant (wood)	UAE and Oman	0.70854(Q1)–0.70871(Q3) (n=28)	(Kutterer and Uerpmann, 2017)
Sr10	ostrich egg shell	Nineveh, Iraq	0.708237(Q1)–0.708520(Q3) (n=6)	(Hodos et al., 2020)
Sr11	ostrich egg shell	Ur, Iraq	0.707992(Q1)–0.708221(Q3) (n=8)	(Hodos et al., 2020)
Sr12	faunal tooth enamel	Tepe Yahya, southeastern Iran	0.708132(Q1)–0.708301(Q3) (n=10)	(Gregoricka, 2013)

Sr13	faunal tooth enamel	Mashkan Shapir, Iraq	0.708 (n=3)	(Kenoyer et al., 2013)
Sr14	faunal tooth enamel	Aali Burial Mounds and Barbar, Bahrain	0.708168(Q1)–0.708320(Q3) (n=20)	(Gregoricka, 2013)
Sr15	faunal tooth enamel	UAE sites (Qidfa, Dibba, Shimal, al-Buhais 18, Tell Abraq, Umm an-Nar)	0.708660(Q1)–0.708843(Q3) (n=47)	(Gregoricka, 2013; Kutterer and Uerpmann, 2017)
Sr16	human tooth enamel	UAE sites (Qidfa, Dibba, Shimal, Unar 1, Mowaihat, al-Buhais 18, Umm al-Quwain 2, Tell Abraq, Umm an-Nar)	0.708733(Q1)–0.708881 (Q3) (n=181)	(Gregoricka, 2014, 2013; Kutterer and Uerpmann, 2017)
Sr17	human tooth enamel	Ur, Iraq	0.7080, 0.7081	(Kenoyer et al., 2013)
Sr18	human tooth enamel	modern Iranian cities	0.70809(Q1)–0.70840(Q3) (n=18)	(Posey, 2011)
Sr19	human tooth enamel	modern Afghanistan	0.70904	(Posey, 2011)
Sr20	river water	Tian Shan and northern Tarim (China)	0.7105±0.0007(1σ) (n = 25)	(Wang et al., 2018)
Sr21	river water	eastern Pamirs (China)	0.7110±0.0009(1σ) (n = 19)	(Wang et al., 2018)
Sr22	river water	Syr Darya, Kazakhstan (approx. [46.1N, 61.5E])	0.7094	(Pokrovsky et al., 2017)

Table S2: Detrital Nd isotope data used in this baseline study.

No.	material	location	$^{143}Nd/^{144}Nd$	ε_{Nd}	source
Nd1	river sediment (silt)	Amu Darya, Uzbekistan [42.22N, 60.12E]	0.512168	-9.2	(Bayon et al., 2015)
Nd2	river sediment (silt)	Sefid Rud, Iran (river mouth) [37.47N, 49.94E]	0.512400	-4.6	(Bayon et al., 2015)
Nd3	sand dunes	Sharjah, UAE [25.18N,55.69E]	0.512365	-5.3	(Kumar et al., 2020)
Nd4	soil	Euphrates-Tigris floodplain, Kuwait [29.31N, 47.60E]	0.512379	-5.1	(Kumar et al., 2020)
Nd5	soil	Fars, south Iran [28.69N, 54.30E]	0.512259	-7.4	(Kumar et al., 2020)

Nd6	sand and sludge, fine sand	River Euphrates, north bank by Raqqa bridge [35.951N, 38.981E]	0.512559, 0.512506	-2.1	(Henderson et al., 2020)
Nd7	sands	semi-desert 20-70 km east of Raqqa	0.511967–0.512055 (n=3)	-12.3	(Henderson et al., 2020)
Nd8	top of sediment core	Strait of Hormuz	0.512286	-6.9	(Sirocko, 1995)
Nd9	top of sediment core	northern Gulf of Oman, off the Iranian coast (reflecting Zagros Mtns)	0.512331, NA	-6.0 or -6.4	(Cullen et al., 2000; Sirocko, 1995)
Nd10	soil (archaeological)	Tell Leilan/Abu Hgeira (northeast Syria)	NA	-4.9	(Cullen et al., 2000)
Nd11	sediment	Abadan, southwestern Iran (bordering Iraq)	0.5123216–0.5123376 (n=3)	-6.0	(Sharifi et al., 2018)
Nd12	sediment	Abu Zirig wetland, southern Iraq	0.5124104, 0.5124282	-4.3	(Sharifi et al., 2018)
Nd13	sands	Gurbantunggut Desert, northern Xinjiang, China	0.512432–0.512576 (n=4)	-4.0 to -1.2	(Chen et al., 2007)

2. Central Asia

The modern geopolitical definition of ‘Central Asia’ is the territories of the five former Soviet republics: Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, and Uzbekistan. Most of Central Asia sits tectonically at the southwest end of the Central Asian Orogenic Belt (CAOB), a massive accretionary collage spanning from western Kazakhstan to northeastern China. The CAOB contains abundant granitic rocks that are relatively juvenile (Jahn, 2004). Southern Central Asia extends into the Karakum Craton and the Afghan Blocks. Continental collision between India and Asia created extensive uplifts in Central Asia such as the Tian Shan and the Pamir Mountains. Two large rivers, the Syr Darya in the north and the Amu Darya in the south, originate from major mountain ranges and terminate at the Aral Sea. In geologic history, most of Central Asia had been part of the proto-Paratethys Sea and Paratethys Sea from the Cretaceous until the late Miocene with intermittent phases of transgressions and regressions (Bosboom et al., 2017; Kaya et al., 2019; Popov et al., 2004), leaving thick strata of marine-derived sediments. Precipitation in Central Asia is highly unbalanced, with the mountainous areas in the east receiving the vast majority of rainfall. The large area of flat, arid, unvegetated land in western Central Asia is particularly prone to dust storms.

The Tian Shan is an extensive system of mountain ranges that straddles Xinjiang in northwestern China and northeastern Central Asia. The northern and middle Tian Shan are predominantly reworked pre-Paleozoic crust (Kröner et al., 2014), and the southern Tian Shan is mainly composed of Precambrian and Paleozoic strata (Gao et al., 2009). Embraced by the Tian Shan, the fertile Fergana Valley is overlain by Cenozoic sediment consisting of accumulated eroded rocks. Southern Central Asia is towered by the Pamir Mountains, which for the most part consist of very old continental crust mainly of the Archean-Paleoproterozoic age (Petrov et al., 2021).

The large area between the Central Asian mountains and the Caspian Sea are mostly covered by Cenozoic and Mesozoic sediments (Persits et al., 1997). The Paratethys Sea began its retreat from Central Asia in the early Miocene (Popov et al., 2004). Aeolian deposition has been significant in this region during the Holocene. The involvement of weathered silicates likely elevates the bioavailable $^{87}Sr/^{86}Sr$ ratios from the range for marine-derived sediments. As a very general reference, the global majority of the predicted bioavailable Sr isotope ratios are close to 0.710, which has been interpreted as a convergence of marine and siliciclastic Sr contributions (Bataille et al., 2020).

Crucially, Central Asia is one of the regions with the most frequent dust storms. In general, it is believed that the Karakum, Kyzylkum, and Aralkum deserts (the last being the exposed floor of the dried-up Aral Sea), as well as the Caspian Depression (to the north of the Caspian), are the largest emitters of aeolian dust (Indoitu et al., 2012). Driven by mid-latitude westerlies and northwesterly winter monsoons, dust has been transported to the east and the south, resulting in an extensive accumulation of loess along almost the entire western and northern piedmonts of the Tian Shan and the Pamirs and in the Fergana Valley (Ding et al., 2002). This foothill loess belt considerably overlaps with historical and current areas of human settlement, forming the external environment that many Silk Road societies had interacted with (Owczarek et al., 2018). Aeolian deposition is a highly complex process depending not the least on wind conditions and local topography. The provenance of dust particles and loess contents, especially those formed in the past, is challenging. Some have suggested that proximal sources such as topsoil and river alluvium, rather than distal deserts, are more relevant to the generation of dust in the region (Li et al., 2019, 2018). For our aim of estimating isotopic patterns, it suffices to say that the prevailing aeolian processes in Central Asia have accelerated the break-down of exposed rocks, caused Sr isotopic fractionation with grain-size-dependent sorting by wind, and markedly shaped the distribution of surface materials. Small-grained particles that are characterized by higher $^{87}Sr/^{86}Sr$ ratios are more likely lifted and transported. As such, the $^{87}Sr/^{86}Sr$ for the loess deposit is likely elevated in comparison to the original sediments, whereas their ε_{Nd} values should not differ much.

The Syr Darya originates in the Tian Shan and meanders through the Fergana Valley and southern Kazakhstan, with much of its course situated in cultivated lands, shrublands, grasslands, and semi-deserts. The Amu Darya originates from the Pamirs and passes valleys and drylands for most of its length. Carbonates are present in both rivers' watersheds. The Amu Darya's flow, almost entirely supplied by mountain glaciers, is twice as large as that of the Syr Darya, and is likely able to transport considerable upstream silts downstream. The Amu Darya is also unique in that the fine particles in the final stretch contain 42% primary minerals, an unusually high level compared to other rivers (Bayon et al., 2021). It is thus expected that the upstream detrital material contributed by the Pamirs and the Hindu Kush could dominate the Amu Darya's isotopic composition.

3. Iran

Iran has a fragmentary highland landscape that was forged by two major orogens. During the Cimmerian orogeny, multiple Gondwana-derived micro-continents docked to the southern margin of Eurasia in the Late Triassic, leaving a suture along the Iranian plate's boundaries

(Shafaii Moghadam et al., 2015; Wilmsen et al., 2009). From the Late Cretaceous until the present, the subduction of the Arabian Plate beneath the Iranian Plateau created the Zagros Mountains in southern Iran, and shaped the Alborz and Kopet-Dagh Mountains which now define the northern boundary of the Iranian Plateau. The Zagros orogen stretches northwest–southeast from eastern Turkey, northern Iraq, western and southern Iran, to northern Oman, as part of the Alpine-Himalayan Orogenic Belt. Most of Iran is covered by some form of Mesozoic or Cenozoic sediments, dotted by volcanic outcrops and ophiolites.

Iran, especially central and eastern Iran, is dominated by arid and semi-arid climates, and hydraulic forces that facilitate long-distance sediment movement are limited. The mountainous areas in northern and western Iran have a more humid climate, where medium- and small-sized rivers are developed. Also, externally sourced dust should be reduced for Iran's highland landscape surrounded by mountains, except in a few areas on the outskirt such as the Khuzestan Plain, the Sistan Basin, and the Makran. This is confirmed by studies that identified the Al-Howizeh/Al-Azim marshes and Sistan Basin as the main sources in Iran for dust storms (Cao et al., 2015b). With these constraints on sediment transport, we presume that relatively local sources may control Iran's surficial isotopic patterns.

The outlying mountain zones had been sedimentary basins or margins that later underwent fold-thrust orogenic dynamics. Lying across northern Iran, the Alborz consists of Mesozoic and Paleozoic platform-type successions, where limestone, dolomitic, and clastic rocks are found in the sedimentary strata (Eghbal et al., 2018). Large swaths of Tertiary volcanic rocks are featured in the western Alborz, while a small Precambrian and Devonian sedimentary section outcrops toward eastern Alborz (Pollastro et al., 1997). Massive, geologically recent volcanic cones, such as the Damavand, tower the central Alborz near Tehran. North of the eastern Alborz, the Kopet-Dagh Mountains at Iran's border with Turkmenistan are in nature a folded and uplifted continental margin of Eurasia, containing thick sedimentary sequences, including carbonate rocks, that were deposited during the Mesozoic (mainly Cretaceous) age (Lahijani and Tavakoli, 2012). Loess is present in northern Iran such as in the north foot-slopes of the Alborz, the Kopet-Dagh, and the Binaloud Mountain near Mashhad, and these aeolian deposits likely have relatively local origins (Eghbal et al., 2018; Wang et al., 2017). The small strips of Quaternary land on the southern Caspian littoral outside the Alborz had been part of the Paleo-Tethys Basin.

Central Iran is a geologically complex block comprising three individual crustal terranes, namely Lut, Tabas, and Yazd. These Central Iranian micro-continents (and the Alborz) are attributed as Cadomian fragments that rifted away from Gondwana and were accreted to Eurasia (Shafaii Moghadam et al., 2015). These blocks are believed to have a metamorphic basement of the Neoproterozoic age that was partially exhumed and eroded during the Cenozoic, while Mesozoic and Cenozoic sediments overlie much of the surface. Central Iran also has Quaternary salt deserts such as the Dasht-e Kavir and Dasht-e Lut, where dust emissions could increase. The Oligocene to Miocene carbonate-siliciclastic sedimentary sequences in the Esfahan-Sirjan Basin and Qom Basin contain environmental and fossil records that testify to the marine transgression of the Tethys Sea (Reuter et al., 2009). Toward the east, the area bordering Afghanistan is a mosaic of Cretaceous ophiolites, Late Cretaceous to Paleocene sedimentary deposits, and Cenozoic volcanic rocks (Pollastro et al., 1997; Shafaii Moghadam et al., 2015). Despite the protection of the Taftan Mountain, central-eastern Iran suffers from dust from the Sistan Basin. Hence, the isotopic landscape in Central Iran could be complex under the interplay of stratigraphic and atmospheric factors.

The terranes further south all follow a northwest–southeast direction, reflecting the continental collision that gave rise to the Zagros. The Urumieh-Dokhtar belt is a long and narrow magmatic belt of Tertiary intrusive and extrusive rocks. The Sanandaj-Sirjan Zone is characterized by metamorphosed marine and continental sediments, where few Tertiary formations are present (Shafaii Moghadam et al., 2015). The Zagros Fold-Thrust Belt displays Mesozoic and Cenozoic sedimentary sequences (notably Cretaceous marine strata) and limited Paleozoic outcrops (Khademi et al., 1997; Sepehr and Cosgrove, 2004). Specifically, the high Zagros in the north features more Cretaceous sedimentation, while the low folded zone in the south exhibits more Neogene and Quaternary deposits (Pollastro et al., 1997). Calcareous detrital sediments are prevalent in the Zagros, and karst features are often found due to exposed carbonate rocks and relatively intense erosion (Eghbal et al., 2018). The Khuzestan Plain in the southwestern tip of Iran is a natural extension of the Mesopotamian Plain and will be discussed together with Mesopotamia.

4. Mesopotamia (and environs)

Tectonically, Mesopotamia is located in the northern part of the Arabian plate, which subducts into the Anatolian Plate in the north and the Iranian plate in the east. Therefore, Mesopotamia can be described as a transition zone between the stable Arabian Platform and the Zagros orogen. Mesopotamia was once part of the Tethyan Seaway that connected the Mediterranean Sea to the Indian Ocean, which was closed during the Miocene as part of the Zagros orogenic event (Bialik et al., 2019; Harzhauser et al., 2007). Two mighty rivers, the Euphrates in the west and the Tigris in the east, originate in the mountains created by tectonic movement and empty into the Persian Gulf. Due to the arid climate and flat terrain, Mesopotamia is vulnerable to aeolian dust.

Northeastern Iraq is naturally contiguous with the mountain ranges in Turkey (the Southeastern Taurus) and Iran (the Zagros). This area comprises a small thrust zone, a high-folded zone, and a low-folded zone, all following the same northwest–southeast trend as the Iranian Zagros. Mesozoic and Cenozoic sediments, similar to the Zagros, cover this area, with Mesozoic (mostly Cretaceous) outcrops found in the high-folded zone, while the low-folded zone features outcrops not older than Neogene (Aqrawi, 1998; Pollastro et al., 1999).

The Mesopotamian Plain encompasses most of the inhabited areas in Iraq and also extends to Iran’s Khuzestan Plain and Kuwait. Many have classified this flat area as the unstable shelf of the Arabian Platform, as the subsurface folds reflect the ongoing effects of the Zagros Orogen (Fouad, 2010). Mesozoic and Cenozoic sedimentation created alternating layers of carbonates, evaporites, and shales, which are covered by Quaternary clasts (Fouad, 2010). With an even surface landscape, this area should yield relatively homogeneous isotopic signatures from the fluvial deposits related to the Euphrates and Tigris rivers, but could also be affected by aeolian deposition (see below).

Deserts dominate western Iraq, which is situated on the stable part of the Shelf. On this stony plateau, outcrops of Miocene and Paleogene sediments exist (Aqrawi, 1998). In particular, the Rutbah Uplift in the westernmost part of Iraq is structurally a large basement-cored dome, which displays a thick, mostly Paleozoic cover and Triassic to Cretaceous sedimentary outcrops (Al-Saad et al., 1992; Pollastro et al., 1999).

Most of eastern Syria is covered by Cenozoic sediments, consisting of Paleogene and Lower Neogene marine deposits of carbonates and evaporites as well as mostly terrigenous deposits since the Upper Miocene (Sawaf et al., 1993). Both the Abd el Aziz uplift and the Palmyride Mountain received deposits of limestone and calcareous marl during the Late Cretaceous. Late Cretaceous rocks are exposed in part of the Abd el Aziz uplift (and the Sinjar uplift in northern Iraq), with rocks as old as the Carboniferous cropping out (Sawaf et al., 1993). The Palmyrides is an elongated range whose northeastern blocks extend to the west of the Euphrates, which also feature Upper Cretaceous outcrops (Brew et al., 2001). In addition, a few volcanic outcrops of the Quaternary and Tertiary periods are scattered in eastern Syria (Pollastro et al., 1999).

Flat drylands are hotbeds for the emission and invasion of dust. The entire Tigris-Euphrates Plain is one of the most important dust source areas in the Middle East due to natural and anthropogenic (e.g., degradation of agricultural land) factors (Ginoux et al., 2012). The areas with the most dust storms include three clusters: (1) eastern Syria (such as the farmland near Raqqa) and northwestern Iraq, (2) central Iraq and Iraq's south border with Kuwait and Saudi Arabia, and (3) the southern boundary area between Iraq and Iran (Cao et al., 2015a; Ginoux et al., 2012). Dust transport in this region is controlled by the northwesterly Shamal wind (as well as prefrontal troughs). For Mesopotamia, most dust storms follow paths that originate from the west or the north, advance into eastern Syria and western/central Iraq, and branch off to arrive at the southern borders between Iraq/Saudi Arabia and between Iraq/Iran (Cao et al., 2015a). The main dust receptors are the countries around the Persian Gulf and southwest of Iran (Nabavi et al., 2016). We note that the paths of dust cross with several geologically old sources of sand, such as the Palmyrides, the Rutbah Uplift, and northern Saudi Arabia (near the northern edge of the Arabian Shield, a Precambrian structure), although the exact suppliers of dust are still a contended issue. The dust storms have the potential to disperse geologically old sand, for example, in eastern Syria.

The Tigris and Euphrates Rivers have a major influence on the regional landscape and history. Both rivers originate in the mountainous areas in eastern Turkey and run roughly parallel to the southwest. They join each other in southern Iraq to form the Shatt al-Arab before discharging into the Persian Gulf. The two rivers bring fluvial deposits along their courses and have created a large fertile alluvial plain that is heavily populated and cultivated. The Euphrates has most of its upper course in the Southeastern Taurus Mountain, and flows through deserts for a considerable length of its middle reach. The Tigris receives a substantial volume of water from several tributaries originating in the Zagros. Its river flow is twice as large as that of the Euphrates and is likely capable of sending more sediments downstream, which also makes it prone to flooding. Moreover, the tributaries joining the Shatt al-Arab after the Euphrates-Tigris confluence also flow out of the Zagros. Consequently, the bioavailable Sr and detrital Nd isotopic signatures of the Mesopotamian floodplain in southern Iraq should mainly exhibit values characteristic of the Tigris, which itself is likely close to the Zagros Mountains.

5. A summary of isotopic groups in three other studies

Here, we summarize the isotopic groups identified in three previous studies to provide an intuitive reference for the often complex relations between isotopic compositions and lithologies. Isotopic compositional data for each lithology group are listed straightforwardly. We directly adopt the designated lithologies and have not accounted for possibly different strategies/criteria that may exist in the original publications. We note that although the patterns of Sr and Nd isotopes under similar geo-environmental controls should follow similar principles, specific isotopic ranges are not expected to be the same due to distinct and varied conditions for each location.

Table S3: Bioavailable $^{87}Sr/^{86}Sr$ groups for France (Willmes et al., 2018) and the Maya region (Hodell et al., 2004).

main lithology	$^{87}Sr/^{86}Sr$ (French group)	$^{87}Sr/^{86}Sr$ (±1σ) (Maya group)
volcanic rocks	0.7033–0.7059	0.70415±0.00023
carbonaceous sediments	0.7072–0.7115	0.70888±0.00066 (northern) 0.70770±0.00052 (southern)
siliciclastic sediments	0.7076–0.7170	
plutonic rocks	0.7084–0.7252	0.71327±0.00167
metamorphic rocks	0.7155–0.7213	0.70743±0.00572 (incl. ultrabasic rocks)

Table S4: ε_{Nd} values of sediments from certain rivers with medium or small watershed sizes (Bayon et al., 2015) and the main geology of their watersheds (from *CGMW Bedrock and Structural Geology*). The ε_{Nd} data are for clay and have been normalized with $(^{143}Nd/^{144}Nd)_{CHUR}=0.512638$.

River	ε_{Nd}	Sedimentary rocks	Endogenous rocks (plutonic and/or metamorphic)	Extrusive volcanic rocks	Ophiolitic complex
Fly	-4.0	Cenozoic, Mesozoic		Cenozoic	
Guadiana	-9.6	Upper Paleozoic, Lower Paleozoic, Cenozoic	Lower Paleozoic to Neoproterozoic		
Chubut	-0.5	Cenozoic, Mesozoic		Cenozoic	
Mae Klong	-13.9	Upper Paleozoic, Cenozoic	Mesozoic		
Sefid Rud	-4.8	Cenozoic, Mesozoic	Proterozoic	Cenozoic	Meso-Cenozoic
Narva	-16.9	Lower Paleozoic, Upper Paleozoic, Neoproterozoic			
Elorn	-11.0		Upper Paleozoic, Neoproterozoic		
Waikato	0.2	Cenozoic, Mesozoic		Cenozoic	

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