Quaternary Science Reviews 329 (2024) 108543

Contents lists available at ScienceDirect

Quaternary Science Reviews

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

Diversity of obsidian sources in the northwest Anatolian site of Bahçelievler and the dynamics of Neolithisation

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ARTICLE INFO

Handling editor: Mira Matthews

Keywords:
Obsidian sourcing
pXRF
Bahçelievler
Anatolia
Holocene
Neolithic
Cappadocia
Galatia
Melos

ABSTRACT

Recent excavations at the site of Bahçelievler (in modern Bilecik, northwest Anatolia) revealed a Neolithic settlement that was established during the late 8th/early 7th millennium BCE and continuously occupied until ca. 6000 BCE. One of the earliest Neolithic villages known in the region, its obsidian assemblage offers a good opportunity to investigate regional networks and obtain a better understanding of the mechanisms behind the spread of farming to regions peripheral to the earliest Neolithic communities in southwest Asia. To this end, we present here the results of a portable X-ray fluorescence (pXRF) analysis conducted on obsidian artefacts representing the entire sequence in Bahçelievler. Results indicate that a wide variety of obsidian sources were utilised, ranging from outcrops in central and northwest Anatolia to the Aegean islands. Even though the majority of the obsidians originated in Nenezi Dağ in central Anatolia, some of the other obsidian artefacts in Bahçelievler are from sources known to be only rarely used in prehistory such as Acıgöl, Hasan Dağ, and Yağlar. Contextualisation of Bahçelievler results within analytically sourced obsidians from Neolithic sites in the region indicates that a coastal colonisation along the Mediterranean shore might not have played a major role in the Neolithisation of west Anatolia.

1. Introduction

The initial emergence of farming in southwest Asia is well known from various sites in central Anatolia and the Levant-Zagros arc (Ibáñez et al., 2018; Watkins, 2023). However, the mechanism by which the Neolithic way of life spread westward into the periphery of the Aegean Sea remains a debated subject (Düring, 2013; Leppard, 2022, pp. 242–245; Özdoğan, 2019; Reingruber, 2018). Recent excavations have pushed the establishment of earliest Neolithic communities back to the first half of 7th millennium BCE in both west Turkey (Çevik and Erdoğu, 2020; Duru and Umurtak, 2019; Erdoğu et al., 2021a; Gerritsen et al., 2013; Horejs et al., 2015) and Greece (Douka et al., 2017; Karamitrou-Mentessidi et al., 2015; Perlès et al., 2013). Yet, even though a variety of data, including (among others) lithic (Atakuman et al., 2022; Carter, 2019; Gatsov et al., 2017; Guilbeau and Perlès, 2019; Milić, 2019), ceramic (Brami and Heyd, 2011; Özdoğan, 2016), mortuary (Bacvarov, 2007; Lichter, 2017), architectural (Çilingiroğlu, 2019; Schoop, 2005), zooarchaeological (Arbuckle et al., 2014; Trantalidou, 2008), archaeobotanical (Colledge and Conolly, 2007; Kotzamani and Livarda, 2018), and chronological (Brami, 2015; Reingruber, 2015) evidence have been brought to bear on the issue, definitive conclusions about the Neolithisation of the Aegean remain elusive. The extent to which migration and/or acculturation contributed to this process still forms a focus of discussion. The discovery of hunter-gatherer groups inhabiting the Aegean islands (from the north Aegean and Sporades to the south Aegean and Crete) in the late Pleistocene and early Holocene (Carter, 2019; Efstratiou et al., 2014; Sampson, 2019), together with the presence of foragers in both mainland Greece (Galanidou, 2014; Galanidou and Perlès, 2003) and west Turkey (Atakuman et al., 2022; Çilingiroğlu et al., 2020; Gatsov and Özdoğan, 1994; Özbek and Erdoğu, 2014; Takaoğlu et al., 2014) highlight the possibility of a process that admitted significant contributions by local groups (Erdoğu et al., 2021b; Özdoğan, 2019, p. 146; Reingruber, 2017; Sérfériadès, 2007). On the other hand, the "inescapable hypothesis" as put forward by Perlès (2001, pp. 45–51) of a demic diffusion responsible for the introduction of farming to Greece, while leaving the door open for the contribution of

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https://doi.org/10.1016/j.quascirev.2024.108543
Received 14 January 2024; Received in revised form 8 February 2024; Accepted 8 February 2024
Available online 1 March 2024

possible Mesolithic groups to the spread of Neolithic in the mainland, did not detect a hunter-gatherer input to the development of farming communities. At the same time, even though possible colonisation trajectories have been offered (Horejs et al., 2015), isolating the source areas of distinct population movements has proved challenging (Kotsakis, 2001, p. 70; Özdoğan, 2019; Perlès, 2001, pp. 52–56). Recent advances in ancient DNA extraction have opened up a source of data that can offer more direct answers in this regard (Hofmanová et al., 2016; Kılınç et al., 2017; Marchi et al., 2022); but a representative picture so far has been precluded by the uneven distribution of available genetic profiles around the Aegean Sea, where it has not been possible to make direct comparisons with any pre-Neolithic population due to a lack of investigated material (Brami, 2023; Kazancı et al., 2021, pp. 362–363). The local and regional dynamics responsible for the emergence of farming on both sides of the Aegean Sea therefore still await clarification, and who exactly were the first farmers of the different parts of the Aegean (locals, migrants, or admixed groups) continues to be an open question.

A complementary avenue of research in this context is obsidian sourcing. Obsidian is a glassy rock that forms as a result of volcanic activity, occurring in various overlapping colours and textures in nature (Williams-Thorpe, 1995). It was widely used as a raw material by prehistoric communities in Anatolia and the surrounding regions (Cauvin and Chataigner, 1998; Ibáñez et al., 2016; Milić, 2014). The main utility of obsidian was the production of chipped stone implements, as the non-crystalline texture dominating its structure makes it possible to obtain very sharp edges upon its fracture (Buck, 1982; Dewbury and Russell, 2007), though its use extended to the production of beads, pendants, inlays, mirrors, and containers (Healey, 2021). Together with its physical properties, at least part of the demand for obsidian might have been caused by the small number of geological sources around southwest Asia that it can be quarried from (Frahm, 2023a, 2023c), which possibly elevated its status to a prestige good in regions without easy access to the unevenly spread outcrops of obsidian (Williams-Thorpe, 1995, Fig. 2). There are a variety of analytical techniques that also take advantage of the relative scarcity of this raw material to chemically distinguish these different obsidian sources (Gratuze, 1998). This in turn enables the characterisation of obsidian artefacts recovered from prehistoric sites, allowing the transmission of obsidian to be traced from geological outcrops to archaeological contexts.

The interpretive potential of obsidian sourcing thus described is readily apparent, as it presents itself as a powerful tool to inspect patterns of prehistoric connectivity over wide regions based on the diffusion of this raw material from different sources (Chataigner, 1998). It has been possible to ascertain, for example, that obsidians from Nenezi Dağ in Cappadocia had already been relayed to Öküzini in the late Pleistocene (Carter et al., 2011), exposing the early range of connections (whether directly through seasonal movements or indirectly via intermediary groups) established by hunter-gatherers along the southern shore of Anatolia (see Fig. 1 for the locations mentioned in the text). Similarly, a reliance on Melos and Giali obsidians identified in Aphrodisias (Blackman, 1986) and Çine-Tepecik (Kolankaya-Bostancı et al., 2020) attests to the Aegean contacts of these inland communities prior to the emergence of urban centres in southwest Anatolia. The origin of farming in southwest Asia and its spread to surrounding regions, falling chronologically between the aforementioned instances of Epipaleolithic foraging and Bronze Age urbanisation, is also a subject that can receive valuable insights from obsidian sourcing. Obsidian distribution patterns can reveal the directionality and scale of interaction between different groups that formed part of a complex, polycentric network within which the Neolithic transition took place in this region (Ibáñez et al., 2018). In fact, recent provenance analyses underpinned the identification of

Fig. 1. Location of Bahçelievler and the sites mentioned, together with known obsidian sources in the region. Sources represented in the Bahçelievler assemblage are underlined.

intensified contacts that might have facilitated the transmission of new ideas and practices related to farming in the Zagros, where assemblages in southwest Iran yielded obsidians from increasingly diverse sources in east Anatolia and the south Caucasus (Frahm and Carolus, 2022). Multi-site investigations of sourced material from the earliest sedentary cultivators of the Levant likewise made it possible to identify alternative networks and routes responsible for the arrival of obsidian from sources in central Anatolia (Carter et al., 2023a), while the integration of obsidian sourcing analyses with techno-typological evaluations enabled the elucidation of consumption and interaction spheres during the early stages of Neolithisation both in north Mesopotamia (Carter et al., 2013) and southeast Europe (Milić, 2016). Another novel output of obsidian sourcing relates to the detection of spatiotemporal trends that would otherwise remain invisible within multigenerational sites. For instance, it was revealed that the primary reliance on Göllüdağ obsidians in the earlier habitation levels of Neolithic Çatalhöyük in central Anatolia was reversed to the benefit of Nenezi Dağ obsidians in the later part of the sequence (Carter and Shackley, 2007), even though these two sources are at practically the same distance from the settlement. This was accompanied by a parallel shift to the pressure technique to reduce lithic raw materials (Carter and Milić, 2013), hinting at a more complex interaction between the organisation of raw material acquisition and lithic production in the site than expected.

The discovery of similar patterns and their elaboration in finer detail inevitably require more complete, assemblage-wide investigations. Portable X-ray fluorescence (pXRF) spectrometry, in this regard, is one of the more prominent non-destructive characterisation techniques used to provenance obsidian objects (Frahm, 2023b) that can conduct analyses on large sample sets with a more affordable rapidity (Campbell and Healey, 2016; Carter et al., 2023b, p. 9; Frahm and Carolus, 2022; Gemici et al., 2022). We present here such an obsidian sourcing analysis using pXRF on ca. 92% (n = 120) of the entire obsidian chipped stone assemblage excavated from Bahçelievler, a Neolithic settlement in northwest Anatolia (Fidan, 2020). Bahçelievler has a long history of occupation that spans the 7th millennium BCE (Fidan et al., 2022), making it well suited to contribute new insights to the debates revolving around the westward spread of farming in this time frame. Our aim is to disentangle the different networks responsible for the transmission of obsidian to Bahçelievler by combining source identifications with techno-typological observations and to compare the trends visible in contemporary sites in the region to offer a raw material perspective on the Neolithisation of Anatolia.

1.1. *Bahçelievler, a Neolithic settlement in northwest Anatolia*

The site of Bahçelievler is located in the urban centre of Bilecik in northwest Anatolia, falling within the eponymous district of the modern city. It was first discovered in 2013 during a survey project (Efe et al., 2015). Threatened by urban encroachment, rescue excavations took place between 2019 and 2021, uncovering ca. 1000 square metres of prehistoric habitation (Fidan, 2020; Fidan et al., 2022). These excavations revealed an open-air Neolithic settlement that was first inhabited around the turn of the 8th millennium, and was occupied continuously through the 7th millennium BCE. Radiocarbon dates obtained from the seven Neolithic occupation levels, summarised in Table 1, indicate that Bahçelievler is one of the earliest known villages west of the Konya Plain in south-central Anatolia (Fidan et al., 2022, Fig. 3). Iron Age remains in the uppermost level, meanwhile, date to the Archaic period.

Notably, pottery is present in Bahçelievler from the start of the occupation in Level 8 (Fidan et al., 2022, p. 142). Cereals, albeit in small amounts, have also been recovered from Level 8; they increase in number and are accompanied with pulses from Level 7 onward (Balcı et al., 2022). The site can be interpreted in the framework of the Neolithic Fikirtepe culture of northwest Anatolia (Özdoğan, 2013) as the pottery in Bahçelievler starts to converge with Fikirtepe types (dark wares, polypod boxes, incised decoration) beginning with Level 6 (Fidan et al., 2022, pp. 142–143), though it is possible to trace in Bahçelievler the earlier, proto-Fikirtepe stage of this sequence (Fidan et al., 2022, Tab. 3). Architecture in Bahçelievler is characterised by circular forms through most of the sequence: rectangular buildings appear only in Level 2 (Fidan et al., 2022, p. 141). A number of flexed burials were also recovered within pits dug in areas between structures (Fidan et al., 2022, p. 141). Meanwhile, domestic animals among the Bahçelievler fauna include caprines and cattle (Fidan et al., 2022, p. 144).

Table 1
Stratigraphic levels of Bahçelievler and the corresponding radiocarbon dates. AMS results from Fidan et al. (2022, Tab. 1) were calibrated using OxCal v.4.4.4 (Bronk Ramsey, 2009) and IntCal20 (Reimer et al., 2020) and combined to obtain the chronological intervals.

	Approximate dates (cal. BCE)
Level 1	Iron Age
Level 2	6100-6000 BCE
Level 3	6200-6100 BCE
Level 4	6300-6200 BCE
Level 5	6400-6300 BCE
Level 6	6600-6400 BCE
Level 7	6800-6600 BCE
Level 8	7100/6900-6800 BCE

The chipped stone assemblage in Bahçelievler relied mainly on non-obsidian raw materials as only 7% of the collection is of obsidian, though obsidian artefacts have been found in all occupation levels. Knapping appears to have taken place in open spaces, and to a lesser extent within a few buildings (Kolankaya-Bostancı and Fidan, 2021, pp. 98–99). The industry was geared toward the production of blades and bladelets; significantly, bullet-shaped bladelet cores are present in the assemblage from the earliest Level 8, attesting to the use of the pressure technique at an early date (Kolankaya-Bostancı and Fidan, 2021, pp. 100–101). No obsidian cores were recovered, but the presence of manufacture by-products and debris hints that a small part of the core reduction might have taken place within the settlement. In addition, trapezoid cross-sections, parallel edges, and punctiform striking platforms without a prominent bulb of percussion indicate that the pressure technique was used to detach at least some of the obsidian bladelets (Kolankaya-Bostancı and Fidan, 2021, p. 100). Formal tools (none of them on obsidian) include sickle blades, projectiles, endscrapers, borers, notches, burins, and knives (Kolankaya-Bostancı and Fidan, 2021; Tab. 4). 120 of the 130 obsidian artefacts excavated from Bahçelievler were available for sourcing analysis, details of which are provided below.

2. Materials and methods

Analyses were conducted with a Hitachi X-MET8000 Expert Geo handheld (portable) energy-dispersive XRF spectrometer. It contains a

Table 2
Elemental averages (in ppm) of obsidian samples from Meydan Dağ.

	This study	Frahm (2023c)	*p* value
Rb	196 ± 18	198 ± 5	**0.67**
Sr	16 ± 2	20 ± 5	**0.07**
Y	50 ± 6	50 ± 6	**> 0.99**
Zr	263 ± 22	273 ± 21	**0.32**
Nb	39 ± 4	32 ± 3	< 0.01
K	43599 ± 3784	35991 ± 643	< 0.01
Ca	3317 ± 275	2852 ± 150	< 0.01
Ti	629 ± 255	480 ± 26	**0.06**
Mn	540 ± 51	497 ± 54	**0.09**
Fe	10806 ± 2109	9385 ± 644	0.01
Zn	69 ± 5	76 ± 9	**0.09**
Ba	80 ± 8	63 ± 20	**0.18**
Pb	34 ± 6	32 ± 1	**0.48**
Th	31 ± 3	23 ± 1	< 0.01
U	8 ± 2	8 ± 1	**> 0.99**

25 mm^2 silicon-drift detector (SDD) and a 4 W X-ray tube with a rhodium (Rh) target. Maximum voltage and current settings are, respectively, 50 kV and 200 μA. REE-FP (rare earth elements - fundamental parameters) mode was used in the analysis of obsidian objects, during which two beams, 50 kV-15 μA and 15 kV-20 μA, are alternatively generated to detect trace elements of interest. While its analyser window is an ellipse ca. 16 mm by 13 mm, the device excites a spot that measures 10.7 mm by 9.4 mm. A stand was used to mount the pXRF in an upright position for all analyses. Since earlier tests under similar operating conditions had determined it to be sufficient, 60 s were used as the standard measurement duration per sample (Gemici et al., 2022, p. 6).

Table 2 reports the analysis results of six geological obsidian samples from Meydan Dağ, an obsidian source in east Anatolia for which abundant comparative material is available (Frahm, 2023c, p. 18), as a basis to gauge the accuracy of results generated by the Hitachi X-MET8000. Flatter/less irregular and fresher/less corticated surfaces were selected, as much as possible, for the measurements. Next to these results in Table 2 are consensus mean values compiled by Frahm (2023c, Tab. S44) for Meydan Dağ, based on results from 20 different laboratories using 10 different analytical techniques (adding up to a total of 25 sets of data). Elements included in the table are those for which the pXRF device used in our study allows a detection limit below the consensus means. Three of the six Meydan Dağ analyses did not yield Ba values, likely because the limit of detection for Ba is around 50 ppm. It can be seen that the concentrations obtained using the factory calibrations of Hitachi X-MET8000 are for the most part comparable to the consensus values for eligible trace elements (*p* value for two-tailed Student's t-test > 0.05, in bold numerals in Table 2). Most important exception for the purposes of this study is Nb, a frequently used element for obsidian discrimination, which has a small but statistically significant difference (39 ± 4 vs. 32 ± 3) with the consolidated literature data for Meydan Dağ.

Unlike geological samples, though, it is not always possible to find flat and fresh surfaces on archaeological artefacts to be analysed. This is also the case with the Bahçelievler obsidian assemblage, which is mainly composed of very thin bladelet fragments (Fig. 2). Sample geometry is a relevant concern in this regard, as specimen size, thickness, surface regularity, and curvature are known to affect XRF results (Davis et al., 2011; Ferguson, 2012, Fig. 12.4; Forster et al., 2011, pp. 392–393; Frahm, 2013, p. 1082). Quantitative ratios of elements that are similarly affected by these factors, such as mid-Z elements (from Rb to Nb in the periodic table), have been offered as a successful means to overcome the systematic errors introduced to pXRF measurements during the analysis of small artefacts (Frahm, 2016), and various elemental ratios using mid-Z elements are routinely used to identify and make source assignments to obsidian outcrops in southwest Asia and around the Mediterranean Sea (Carter et al., 2020; Chataigner and Gratuze, 2014; De Francesco et al., 2008; Frahm and Carolus, 2022; Healey, 2022, pp. 13–14; Mouralis et al., 2018; Muntoni et al., 2022; Tykot, 2021).

Similarly, for the purposes of this study, priority is given to the relative concentrations of Rb–Sr–Zr and elemental ratios using mid-Z elements to identify the sources of the obsidian artefacts analysed. These are supplanted with other elements, such as Mn, Ba, and Pb, when necessary. In addition, to control for the effects that specimen size has on analysis results, three parameters for each sample were recorded: thickness (which refers to the average thickness available for X-ray penetration and is not necessarily the same with the technological thickness of the chipped stone artefact, as the former is primarily a function of how the object is placed on the analyser window of the pXRF device), weight, and approximate proportion of the analyser window covered. Source assignments are made based on comparisons with both primary data generated from geological samples as a part of this study and secondary data found in published literature, generated from geological and archaeological samples. Compilation strategy for the secondary data prioritises those publications that contain results from a large number of the geological sources of interest in this study, to ensure a comparable cross-section of data pertaining to different sources that were generated in the same laboratory within the same analytical framework. Different studies (often conducted by different researchers using different analytical techniques) are then culled according to the goodness of their agreement on the variables of interest (based on the above-mentioned elements) for the same geological sources, to ensure the validity of the comparative dataset. Even though only a subset of the variety of sources around southwest Asia is typically reported in any single publication, it is possible to cover a large range of sources though consecutive overlaps between different publications. Moreover, obsidians from certain sources (such as Göllüdağ East, Nenezi Dağ, and Acıgöl West) are very frequently analysed and reported, providing a widely applicable benchmark to gauge the compatibility of different datasets.

The archaeological assemblage analysed as a part of this article comprises 120 out of the 130 obsidians recovered from the prehistoric site of Bahçelievler. This corresponds to 92% of all obsidians through all stratigraphic levels, forming a robust sample to look into the use of obsidian in this Neolithic settlement. Two additional objects, originally recorded as obsidian, were revealed to be depleted in mid-Z elements (Rb + Sr + Y + Zr + Nb totals smaller than 30 ppm) and are very likely microcrystalline silica varieties. These are not included in the discussion below.

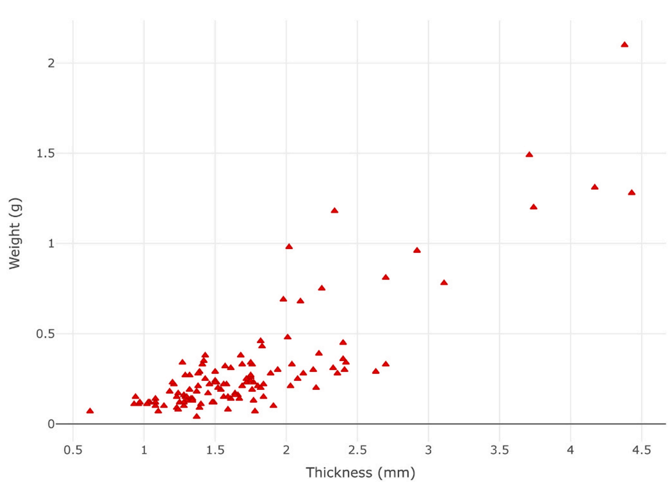

Fig. 2. Relationship between sample thickness and weight for the 120 obsidian artefacts from Bahçelievler analysed in this study.

3. Results

3.1. Obsidian sources represented in Bahçelievler

Relative concentrations of the trace elements Rb, Sr, and Zr indicate the presence of six different chemical groups among the Bahçelievler obsidians (Fig. 3 - left). A comparison with published data discloses overlaps with a number of Anatolian obsidian sources (Fig. 3 - right). Beside Anatolian obsidians, the presence of obsidian from the Aegean is also notable within the Bahçelievler assemblage. This is confirmed by a comparison with published results generated with the same Hitachi pXRF device used in this study under similar operating conditions, from archaeological obsidians that originated in the Dhemenegaki outcrop on the island of Melos (hereafter Melos D) in the Cyclades (Gemici et al., 2022). Meanwhile, even though several Anatolian obsidian sources are detected in Bahçelievler, the west Anatolian sources of Foça and Kütahya are not among them. These two sources remain obscure both in terms of research conducted on their outcrops and characteristics and also in terms of their prehistoric utilisation, as they have not been

[1] Applies to all instances in this paper where this data was used.

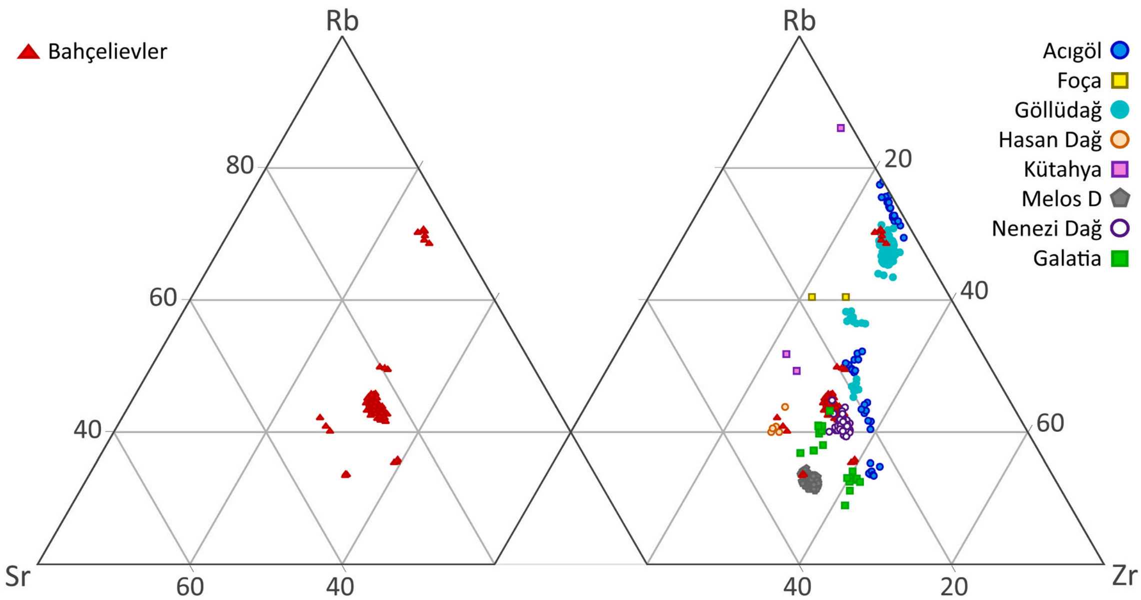

Fig. 3. Relative concentrations of Rb, Sr, and Zr of the Bahçelievler obsidians analysed in this study (left) and their relation to previously published samples from various obsidian sources (right). Literature data compiled from: Carter et al. (2006) (Acıgöl, Göllüdağ, Nenezi Dağ), Frahm (2023a) (consensus means[1]: Acıgöl, Foça, Galatia, Göllüdağ, Hasan Dağ, Kütahya, Nenezi Dağ), Gemici et al. (2022) (Melos), Gratuze (1999) (Acıgöl, Galatia, Göllüdağ, Hasan Dağ, Nenezi Dağ), Keller and Seifried (1990) (Acıgöl, Galatia, Göllüdağ, Hasan Dağ, Nenezi Dağ), Keller et al. (1996) (Galatia), Kobayashi and Mochizuki (2007) (Acıgöl, Göllüdağ, Nenezi Dağ), Oddone et al. (1997) (Acıgöl, Galatia, Göllüdağ, Nenezi Dağ), Poidevin (1998) (results of J.-L. Poidevin and N. Arnaud in Annex 2 without the pumice samples[1]: Göllüdağ, Nenezi Dağ), Poupeau et al. (2010) (ICP-MS and EDXRF results[1]: Acıgöl, Galatia, Göllüdağ, Nenezi Dağ).

discovered in any archaeological context. The latter, Kütahya, is the closest known obsidian source to Bahçelievler. Although recent surveys to record raw material sources in this region have not yet detected an obsidian outcrop (Fidan et al., 2023), it likely lies at a distance smaller than 100 km from Bahçelievler (Fig. 1) based on the description provided by Akkuş (1962) and the general area of recovery of the geological samples presented by Frahm (2023a). Furthermore, the known rhyolitic flows to the east of modern Kütahya are of Miocene age (Alan et al., 2018; Türkecan, 2015) and are compatible with the estimates of 16.1 and 25.1 Ma on two obsidian samples by Wagner and Weiner (1987). The lack of its use in Bahçelievler, one of the closer Neolithic settlements to the source region, imply that obsidians around Kütahya either went unnoticed or were avoided during this period.

In addition to these sources, a small number of obsidians from the peralkaline outcrops of east Anatolia are known to have reached central Anatolia in the 7th millennium BCE (Carter et al., 2008), but their very high Zr concentrations preclude a similar presence among the Bahçelievler artefacts (Frahm, 2023c, Tab. S29, S46-S51). Likewise, obsidians attributed to the Carpathian Mountains in central Europe, more than 1000 km from Bahçelievler, reached the northwest Aegean periphery and the Black Sea coast of modern Bulgaria (albeit in the 6th millennium BCE at the earliest in both cases) (Bonsall et al., 2017; Kilikoglou et al., 1996; Milić, 2014), but the C1 and C2 chemical groups in question have low Nb values relative to other mid-Z elements (and a low Sr concentration relative to Rb and Zr in comparison to Melos) that prevent any overlaps with Bahçelievler obsidians (Glascock et al., 2016; Hughes et al., 2018; Rózsa et al., 2006).

Elemental statistics of the six chemical groups identified in Bahçelievler are provided in Table 3. Three measurements from the same artefact are presented for chemical groups with a single assigned member. Recorded variation inside each group lies within the range that might be expected from an obsidian source (Frahm, 2013, pp. 1084–1085), especially considering their inflation due to the analysis of small and irregular specimens (Frahm, 2016, pp. 457–458). This is particularly notable in the Hasan Dağ group: two of the three artefacts included here are among the smallest in both thickness and mass among the Bahçelievler obsidians, while the third Hasan Dağ artefact is one of the heaviest and thickest in the assemblage, leading to higher relative standard deviation values than the other chemical groups. Further information on each analysed sample can be found in Appendix A. Source attributions are revisited and discussed in more detail in the following sections.

3.1.1. *Galatia*

The ternary graph of Rb, Sr, and Zr in Fig. 3 shows that a group of Bahçelievler artefacts plots close to Nenezi Dağ and Galatia obsidians, while another, smaller group plots close to a second cluster of Galatia obsidians and a subgroup of Acıgöl (EAPC: east Acıgöl post-caldera, i.e. Kocadağ/Hotamış Dağ). The Galatian group includes at least three obsidian occurrences that are responsible for the distinct clusters seen in Fig. 3: Orta, Sakaeli, and Yağlar; added to these is a scatter of archaeological material from Güdül that was determined to be originating from another, so far not located, source (Keller et al., 1996). Ages of various geological obsidians from the Galatian complex have previously been determined using fission-track dating. Wagner and Weiner (1987) provide a plateau age interval of ca. 24–29 Ma, while apparent ages of ca. 14–18 Ma and plateau ages of ca. 21–24 Ma (Bigazzi et al., 1993b; Ercan et al., 1990; Keller et al., 1996) have also been reported. The latter are compatible with what is known about the geology of the region, which hosted widespread Miocene volcanic activity (Fig. 4) that is bounded to the north by the North Anatolian Fault (Toprak et al., 1996), during which the dominantly calc-alkaline volcanism of the Early Miocene evolved into a basic/alkaline composition by the Late Miocene (Türkecan, 2015, pp. 35–37; Türkecan et al., 1991). Güdül artefacts have also been dated to the same time frame (with one, likely anomalous, exception that yielded a fission-track date of ca. 6 Ma) (Keller et al., 1996), indicating that its geological source should be sought in the same region, possibly in relation with one of the nine eruptive centres identified in the Galatian Volcanic Province by Toprak et al. (1996).

To resolve the potential overlaps of Bahçelievler artefacts and Galatia, Nenezi Dağ, and Acıgöl obsidians, six geological specimens from Galatia were analysed (Fig. 5). These correspond to three different obsidian occurrences, Berçinyayalar, Salur, and Sakaeli, named after the localities near which they were collected (Fig. 4). Two samples are

Table 3
Summary statistics of the obsidian groups identified in the Bahçelievler (BAHC) assemblage. Elemental concentrations in ppm.

BAHC group	Thickness	n	Rb	Sr	Y	Zr	Nb	Mn	Ba	Pb	
Acıgöl EAAC 2	All	1*	144.7	57.3	14.3	89.3	17.7	510.3	150.0	24.0	**MEAN**
			3.2	2.1	0.6	1.5	0.6	20.2	9.5	1.0	**ST.DEV.**
			2.2%	3.6%	4.0%	1.7%	3.3%	4.0%	6.4%	4.2%	**RSD**
Melos D	All	1*	128.3	125.3	19.0	129.0	12.0	612.3	201.0	24.0	**MEAN**
			11.6	11.2	1.0	12.1	1.0	53.5	16.4	9.5	**ST.DEV.**
			9.0%	9.0%	5.3%	9.4%	8.3%	8.7%	8.1%	39.7%	**RSD**
Hasan Dağ	All	3	106.7	82.7	8.0	71.7	17.0	397.7	136.7	21.0	**MEAN**
			31.5	25.5	4.2	24.4	6.4	71.0	87.2	4.3	**ST.DEV.**
			29.5%	30.8%	53.0%	34.1%	37.5%	17.9%	63.8%	20.6%	**RSD**
Galatia (Yağlar)	All	4	149.5	105.5	9.8	165.3	34.8	487.5	132.5	38.8	**MEAN**
			18.5	12.1	2.2	20.3	4.7	39.4	13.6	3.3	**ST.DEV.**
			12.3%	11.5%	22.2%	12.3%	13.6%	8.1%	10.3%	8.4%	**RSD**
Göllüdağ East	All	7	222.1	13.7	22.4	82.0	29.7	610.7	79.4	29.0	**MEAN**
			42.9	2.9	4.4	16.1	6.1	75.6	16.8	6.2	**ST.DEV.**
			19.3%	21.2%	19.6%	19.6%	20.6%	12.4%	21.2%	21.3%	**RSD**
Nenezi Dağ	All	104	176.3	96.4	19.3	132.1	23.7	628.4	216.0	30.0	**MEAN**
			36.5	20.9	4.8	30.2	5.5	100.5	72.4	6.4	**ST.DEV.**
			20.7%	21.6%	24.8%	22.8%	23.1%	16.0%	33.5%	21.4%	**RSD**
	>3 mm	6	194.2	106.5	23.3	155.5	29.2	641.0	367.0	32.3	**MEAN**
			15.2	6.9	1.1	9.0	2.0	42.1	17.4	3.0	**ST.DEV.**
			7.9%	6.5%	4.7%	5.8%	6.7%	6.6%	4.7%	9.4%	**RSD**

* *Average of three measurements.*

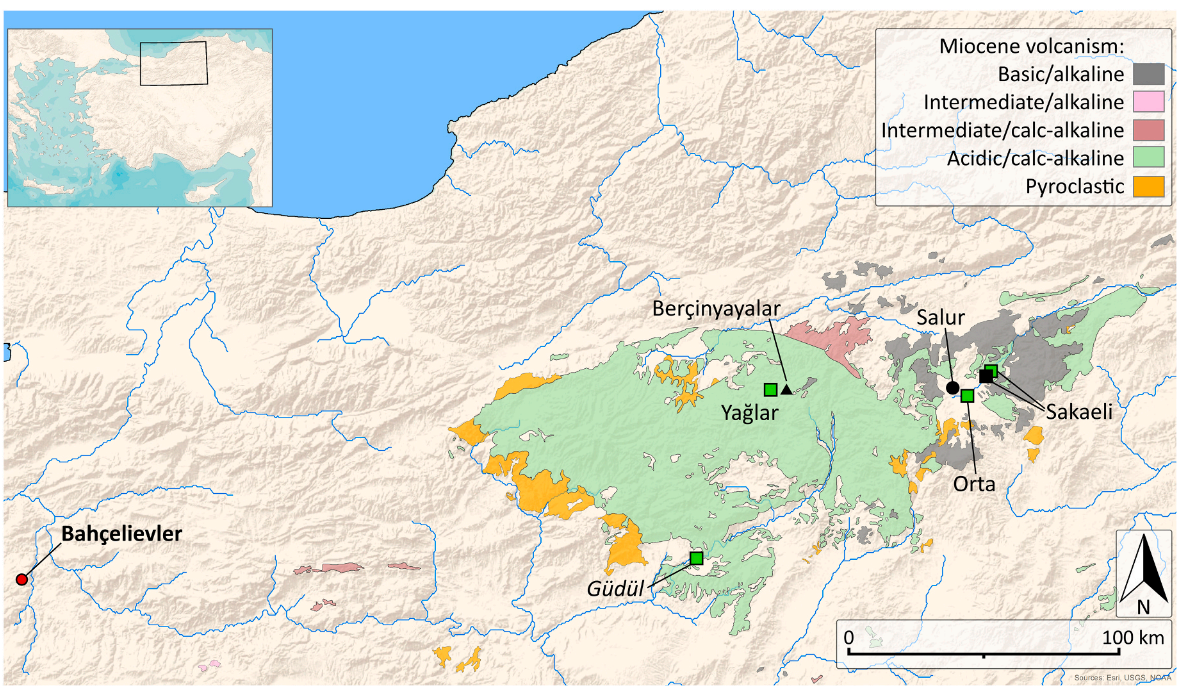

Fig. 4. Obsidian bearing localities related to the Galatian Volcanic Province in northwest Anatolia. Geology redrawn from Aksay et al. (2002); Uğuz et al. (2002) and revised according to Türkecan (2015).

available from each locality, all of them present as sub-angular, centimetric pebbles. All six are black in colour; they are dull and nearly opaque on weathered surfaces, while fresher breaks reveal a lustrous and translucent glass. Even though these specific specimens are too small to be knapped, bigger fragments would have been readily used in chipped stone production, as the samples contain no visible impurities. Elemental results of these six specimens are presented in Table 4, with two analyses from each sample. Fig. 5 shows that the relative concentrations of Rb, Sr, and Zr of the Galatian geological obsidians thus analysed are in broad agreement with published results from the comparative dataset.

Plotting Y/Nb against Rb/Sr offers a good separation between the sources in question (Fig. 6 - top). The smaller group of Bahçelievler obsidians that previously plotted close to both Galatia and Acıgöl EAPC now cluster with Berçinyayalar (i.e. Yağlar) samples, while the main group of Bahçelievler artefacts separate from the Galatian occurrences and instead plot together with Nenezi Dağ. The pattern is corroborated by a plot of Zr/Y against Sr/Nb, which produces the same results (Fig. 6 - bottom). This confirms the presence of Galatian obsidians among the assemblage: four Bahçelievler artefacts originated in Yağlar, the closest of the known Galatian outcrops (Fig. 4), whereas other Galatian sources still remain to be detected in the site.

3.1.2. *Central Anatolia*

Looking in more detail at the remaining obsidian artefacts, it can be seen that they plot closely with a number of obsidian sources in central Anatolia. A comparison of Zr and Sr values, normalised by Rb, emphasises the same overlap of the main group of Bahçelievler obsidians

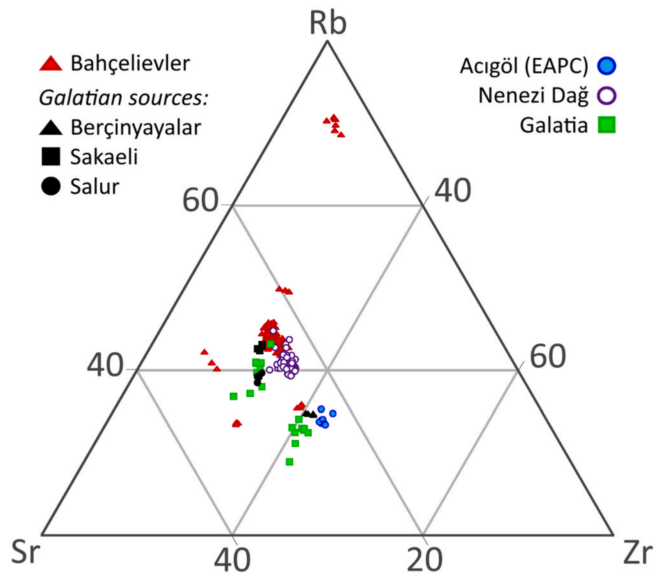

Fig. 5. Relative concentrations of Rb, Sr, and Zr of the geological samples analysed in this study from the Galatian outcrops. Literature data compiled from: Carter et al. (2006) (Nenezi Dağ), Frahm (2023a) (Acıgöl EAPC, Galatia, Nenezi Dağ), Gratuze (1999) (Galatia, Nenezi Dağ), Keller and Seifried (1990) (Acıgöl EAPC, Nenezi Dağ), Keller et al. (1996) (Galatia), Kobayashi and Mochizuki (2007) (Nenezi Dağ), Oddone et al. (1997) (Galatia, Nenezi Dağ), Poidevin (1998) (Nenezi Dağ), Poupeau et al. (2010) (Galatia, Nenezi Dağ).

(discussed in the previous Section 3.1.1) with Nenezi Dağ (Fig. 7). Furthermore, a smaller group of seven artefacts cluster with Göllüdağ East and three with Hasan Dağ. A last artefact, represented in Fig. 7 with three analyses, falls near the EAAC 2 (east Acıgöl ante-caldera 2) subgroup of Acıgöl obsidians. This chemical group, used here according to the definition provided by Gratuze (1999), includes the WTHD (White Tuffs Hotamış Dağ) and Taşkesiktepe outcrops as defined by Frahm (2023a). Göllüdağ East, likewise, is a volcanic complex with a collection of lava domes, and estimates for the number of chemically distinguishable obsidian groups range from three (Frahm, 2023a) to six (Binder et al., 2011). For the moment, we refrain from attempting to distinguish between the subgroups of the Göllüdağ East complex, pending more analyses and a comprehensive selection of geological specimens. Hasan Dağ as well, often treated as a single group, might contain more than one chemically distinguishable obsidian occurrence (Healey, 2022, Fig. 2; Mochizuki, 1999, p. 232).

Fig. 8 shows the distribution of two variables, Rb/(Rb + Sr + Y + Zr + Nb) and Zr/(Rb + Sr + Y + Zr + Nb), shorthanded to Rb and Zr indices, to verify the position of the Acıgöl EAAC 2 artefact in Bahçelievler. Similar indices, albeit with fewer elements, have previously been used by Kobayashi and Mochizuki (2007) to make source assignments among Anatolian obsidians. Fig. 8 also includes corresponding central Anatolian artefacts from Sofular Höyük previously analysed with the same pXRF device used in this study under similar operating conditions (Karakoç et al., 2023). The artefact from Bahçelievler, again represented with three analyses, clusters with the EAAC 2 subgroup of the Acıgöl complex. With the confirmation of Acıgöl, the number of central Anatolian sources represented in Bahçelievler rises to a total of four, all of which are a product of the Quaternary igneous activity within the Cappadocian Volcanic Province (Mouralis et al., 2019; Toprak, 1998).

3.1.3. *Aegean*

The presence of an obsidian from Melos D in Bahçelievler (Fig. 9), at a distance of more than 600 km, raises a new question: can other Aegean obsidians also be present in Bahçelievler? The main suspect here, as can be seen in Fig. 9, is the island of Giali in the Dodecanese. Even though obsidians from Giali have been detected in prehistoric sites in Anatolia (Gemici et al., 2022; Kolankaya-Bostancı et al., 2020; Schwall et al., 2020, p. 15) and the island is closer to Bahçelievler (and Anatolia) than Melos, Giali has apparently seen a more restricted use in prehistory (Carter et al., 2016, pp. 20–24; Georgiadis, 2008). Nevertheless, some of the Bahçelievler artefacts plot close to Giali obsidians in Fig. 9 and are worth further questioning.

Carter et al. (2016) previously defined two distinct occurrences of obsidian on this island: Giali A and Giali B. The two subgroups come from different localities and have different dates of formation, but they are almost identical in elemental composition (Carter et al., 2016, pp. 15–19; Frahm, 2023a, p. 14, Tab. S5). Giali B, in addition, is currently unknown from an archaeological context outside its island of origin (Carter et al., 2016, p. 20), though discussions pertaining to Giali artefacts in the literature typically does not differentiate between Giali A and Giali B. An inspection of the published data and consensus values indicates that both Giali A and Giali B obsidians have simultaneously higher Ba and lower Mn concentrations in comparison to Nenezi Dağ and Acıgöl EAAC 2 in central Anatolia (and other higher-Sr sources in Acıgöl and Göllüdağ) (Carter et al., 2016; Frahm, 2023a). This becomes visible on a plot of Mn against Ba using earlier results from

Table 4
Geological samples from the Galatian outcrops analysed in this study. Thicknesses (t) in mm, weights (w) in g, elemental concentrations in ppm.

Galatia group	ID	t	w	Rb	Sr	Y	Zr	Nb	Mn	Ba	Pb	
Berçinyayalar	GO-B1a	9.2	4.68	209	150	14	243	51	565	447	48	
(Yağlar)	GO-B1b	9.2	4.68	209	149	16	245	52	549	435	48	
	GO-B2a	8	4.24	201	141	14	240	52	485	453	50	
	GO-B2b	8	4.24	202	141	12	240	51	500	494	52	
				205.3	145.3	14.0	242.0	51.5	524.8	457.3	49.5	**MEAN**
				4.3	4.9	1.6	2.4	0.6	38.3	25.6	1.9	**ST.DEV.**
				2.1%	3.4%	11.7%	1.0%	1.1%	7.3%	5.6%	3.9%	**RSD**
Sakaeli	GO-SK1a	6.3	3.1	213	125	15	156	40	556	440	47	
	GO-SK1b	6.3	3.1	206	126	14	154	39	540	427	42	
	GO-SK2a	3.5	0.9	191	113	13	141	35	512	323	40	
	GO-SK2b	3.5	0.9	185	113	14	136	36	535	327	42	
				198.8	119.3	14.0	146.8	37.5	535.8	379.3	42.8	**MEAN**
				13.0	7.2	0.8	9.8	2.4	18.2	62.9	3.0	**ST.DEV.**
				6.5%	6.1%	5.8%	6.7%	6.3%	3.4%	16.6%	7.0%	**RSD**
Salur	GO-S1a	4.4	1.4	211	144	14	177	39	588	459	50	
(Orta)	GO-S1b	4.4	1.4	208	147	17	175	40	566	493	50	
	GO-S2a	5.7	1.0	233	170	19	202	46	603	593	57	
	GO-S2b	5.7	1.0	237	167	18	201	44	614	555	53	
				222.3	157.0	17.0	188.8	42.3	592.8	525.0	52.5	**MEAN**
				14.9	13.4	2.2	14.8	3.3	20.8	60.3	3.3	**ST.DEV.**
				6.7%	8.5%	12.7%	7.8%	7.8%	3.5%	11.5%	6.3%	**RSD**

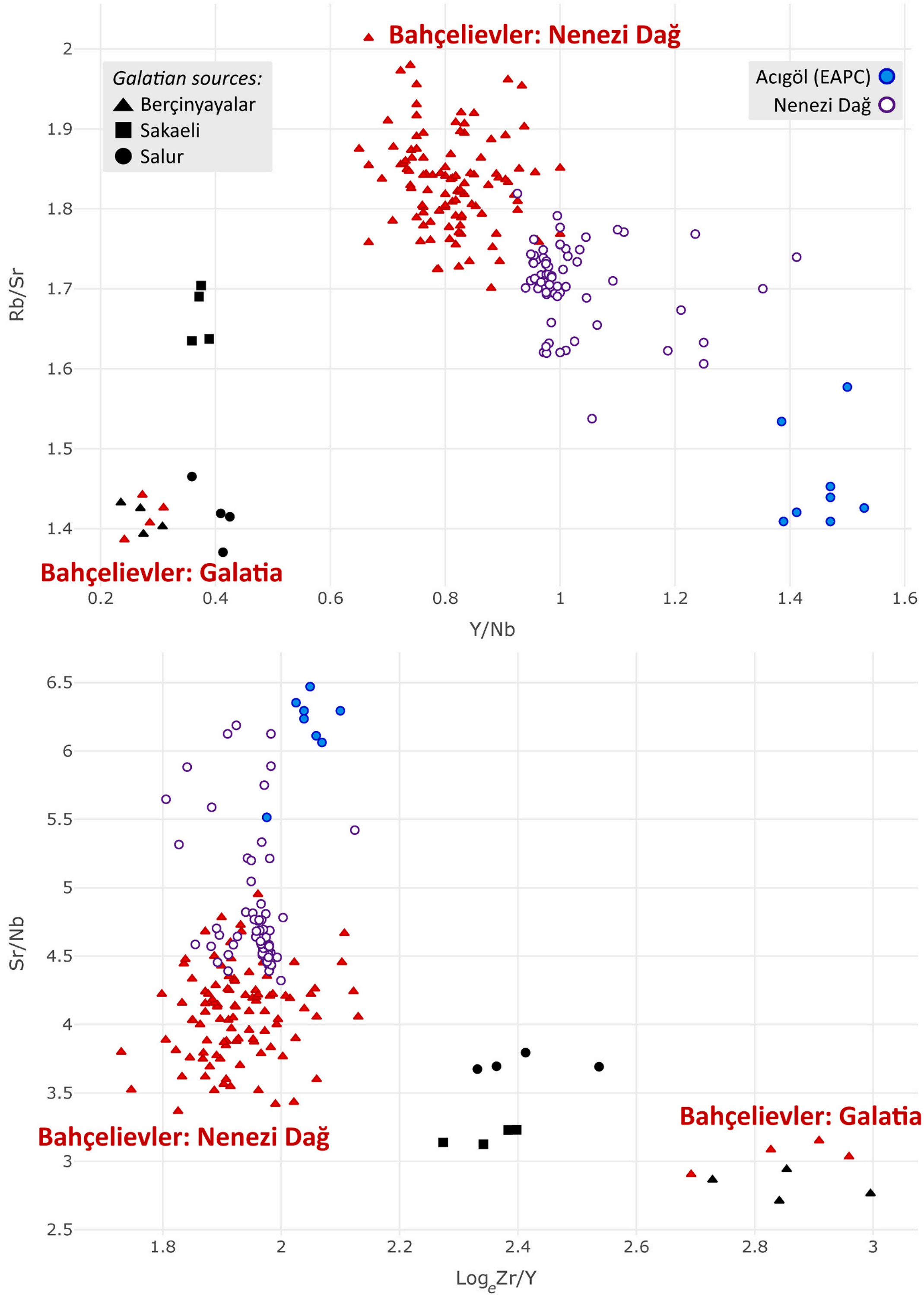

Fig. 6. Y/Nb plotted against Rb/Sr (top) and Zr/Y plotted against Sr/Nb (bottom) for previously published Acıgöl and Nenezi Dağ obsidians (the applicable subset of data from Fig. 5) together with geological samples from Galatia analysed in this study and the corresponding groups identified among the Bahçelievler assemblage.

archaeological Giali obsidians from Bozburun (Fig. 10), obtained by the same Hitachi X-MET8000 device in this study under similar operating conditions (Gemici et al., 2022) except regular energy calibrations and software updates over the years. The Bozburun obsidians in question were assigned to the Giali A subgroup, but the distinction is also applicable to Giali B due to the compositional similarity between Giali A and Giali B obsidians. The distribution in Fig. 10 thus separates Bahçelievler artefacts from Giali and confirms that Melos was not accompanied by Giali obsidians on its way to Bahçelievler.

A similar pattern is present for Antiparos, another island in the southern Aegean Sea that hosts obsidian outcrops. Antiparos obsidians are characterised simultaneously by low Ba and high Pb concentrations, in addition to elevated Rb levels (Acquafredda et al., 2019; Carter and Contreras, 2012; Frahm, 2023a). This presents a contrary profile to the Bahçelievler obsidians that plot close to Antiparos in Fig. 9, assigned instead to Göllüdağ East (Section 3.1.2).

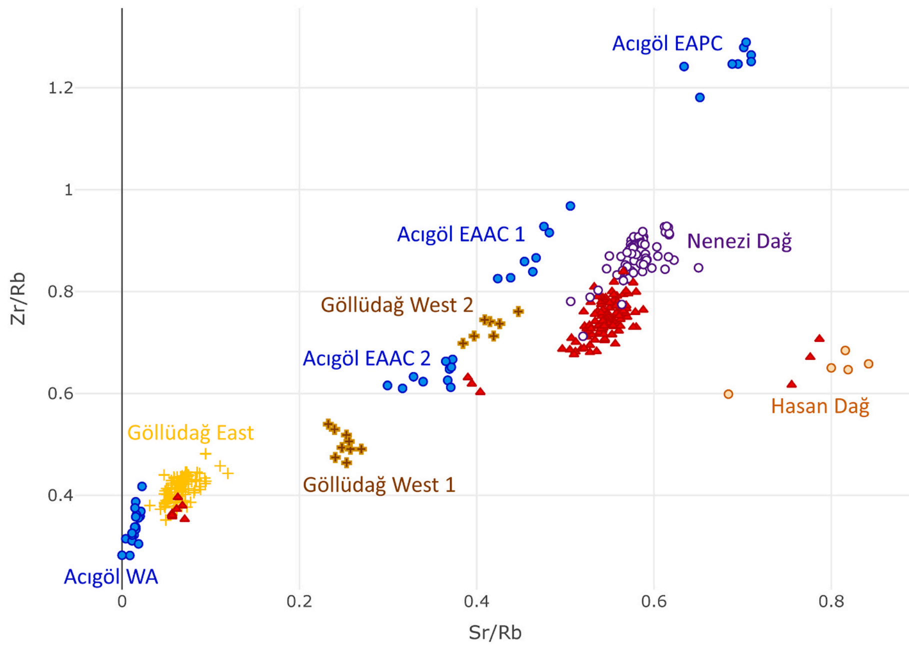

Fig. 7. Sr/Rb plotted against Zr/Rb for previously published central Anatolian obsidians and the corresponding Bahçelievler samples analysed in this study (red triangles). Literature data compiled from (the applicable subset of data used in Fig. 3): Carter et al. (2006) (Acıgöl WA, Göllüdağ East, Nenezi Dağ), Frahm (2023a) (Acıgöl EAAC 1, 2, EAPC, WA, Göllüdağ East, West 1, 2, Hasan Dağ, Nenezi Dağ), Gratuze (1999) (Acıgöl EAAC 1, 2, WA, Göllüdağ East, West 1, 2, Hasan Dağ, Nenezi Dağ), Keller and Seifried (1990) (Acıgöl EAAC 1, 2, EAPC, WA, Göllüdağ East, West 1, 2, Hasan Dağ, Nenezi Dağ), Kobayashi and Mochizuki (2007) (Acıgöl EAAC 2, WA, Göllüdağ East, West 2, Nenezi Dağ), Oddone et al. (1997) (Acıgöl EAAC 1, WA, Göllüdağ East, West 1, Nenezi Dağ), Poidevin (1998) (Göllüdağ East, West 1, 2, Nenezi Dağ), Poupeau et al. (2010) (Acıgöl WA, Göllüdağ East, Nenezi Dağ).

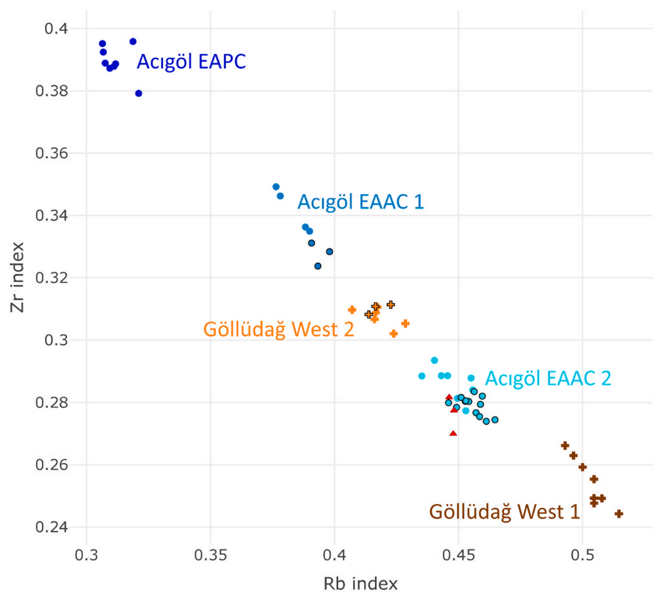

Fig. 8. Scatter plot of Rb and Zr indices for previously published Acıgöl (EAAC, EAPC) and Göllüdağ (West) obsidians (the applicable subset of data from Fig. 7 with the addition of corresponding Sofular Höyük obsidians, outlined in black, from Karakoç et al., 2023) and the corresponding Bahçelievler group identified in this study (red triangles).

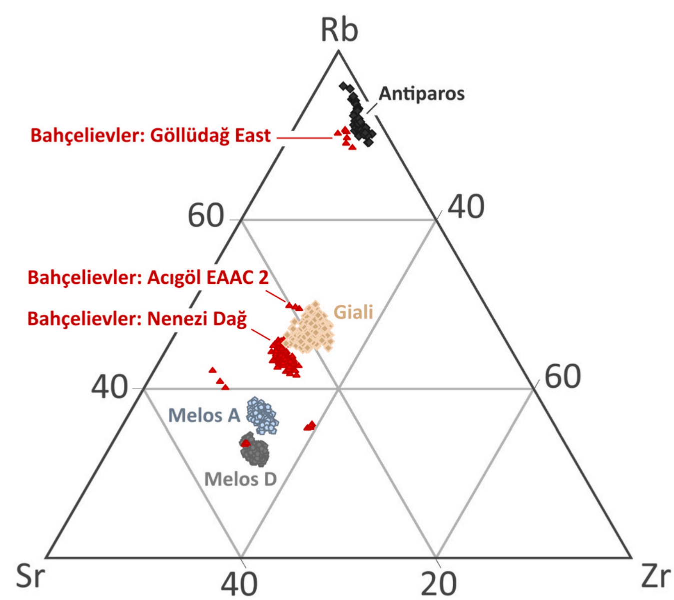

Fig. 9. Relative concentrations of Rb, Sr, and Zr of previously published Aegean obsidians and the Bahçelievler artefacts analysed in this study. Literature data compiled from: Acquafredda et al. (2019) (Antiparos), Carter and Contreras (2012) (Antiparos), Frahm (2023a) (Antiparos), Gemici et al. (2022) (Giali, Melos), Milić (2014) (Antiparos).

Table 5 summarises the results of the pXRF investigations described above. Of the 120 obsidian artefacts analysed from Bahçelievler, 115 originated in the Cappadocian sources of central Anatolia. Among these, the biggest contribution was made by Nenezi Dağ with 104 samples (ca. 87%), while Göllüdağ East, Hasan Dağ (Fig. 11), and Acıgöl EAAC 2 were represented by much smaller numbers. Galatian source of Yağlar, even though at a much shorter distance than Cappadocia (ca. 220 vs. 440 km), could only be detected in 4 artefacts (Fig. 11). Lastly, an obsidian piece from the island of Melos, in the southern Aegean Sea, travelled more than 600 km to reach its context of discard in the Neolithic settlement of Bahçelievler.

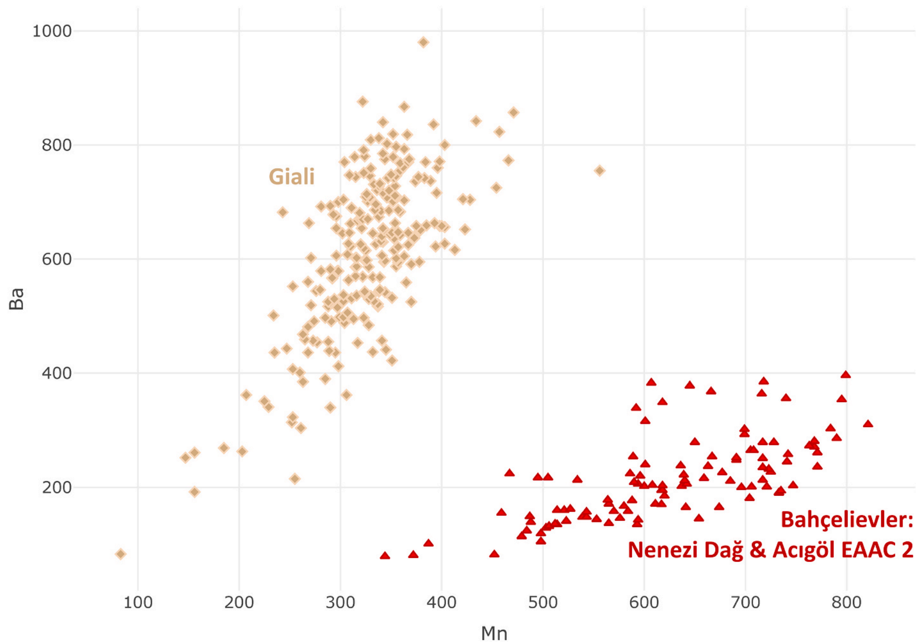

Fig. 10. Mn plotted against Ba (in ppm) for Giali obsidians from Bozburun (Gemici et al., 2022) and the Acıgöl EAAC 2 and Nenezi Dağ group of obsidians from Bahçelievler identified in this study.

Table 5
Sources identified in Bahçelievler and their proportions in the obsidian assemblage.

Obsidian source	Region	n (Bahçelievler)	Proportion
Nenezi Dağ	Cappadocia	104	86.7%
Göllüdağ East	Cappadocia	7	5.8%
Yağlar	Galatia	4	3.3%
Hasan Dağ	Cappadocia	3	2.5%
Acıgöl EAAC 2	Cappadocia	1	0.8%
Melos D	Cyclades	1	0.8%

3.2. *A diachronic look at obsidian procurement*

The Bahçelievler sequence allows the pursuit of procurement trends through the ca. 1000 years of continuous occupation in the site. Most noticeable among these is the consistent use of obsidian. Even though it is a minority component of the chipped stone assemblage, this raw material is present in all the occupation levels (Fig. 12) in spite of the 435 km of distance to the preferred outcrop, Nenezi Dağ. In fact, starting from the earliest Level 8 (ca. 7000 BCE), Nenezi Dağ was the main source that the inhabitants of Bahçelievler relied upon, and remained that way until the abandonment of the settlement. Proportion of Nenezi Dağ obsidians never falls below 60% in any phase, and except Level 5 it is always higher than 80%. A comparable threshold is exceeded only by Göllüdağ East in levels 5, 7, and 8 with ca. 20%, and by Galatia and Hasan Dağ in Level 5 with ca. 10%. Göllüdağ East was also represented in the assemblage since the first occupation, but its flow into the site appears to be interrupted at intervals. In terms of raw numbers, there is a sharp increase (fivefold) in Level 6 (ca. 6500 BCE). However, this increase did not coincide with a parallel diversification of sources: the number of sources present in Level 6 remains the same as Level 7, even though an Acıgöl obsidian made an appearance in Bahçelievler for the first (and the last) time in Level 6. The main diversification appears to have taken place in Level 5, when both Galatia and Hasan Dağ obsidians were first introduced to the settlement (6400-6300 BCE). Galatian source of Yağlar remained in use except a hiatus in Level 3, when the overall number of obsidians is at its lowest. Level 2, the last occupation phase of the Neolithic settlement, saw another sharp increase (fourfold) in numbers (6100-6000 BCE). Like its predecessor, this proliferation also brought a new obsidian source, this time Melos, to Bahçelievler.

No obsidian cores were recovered, but a few reduction by-products (plunging and crested bladelets) of Nenezi Dağ, Galatia (Yağlar), and Hasan Dağ suggest that some knapping might have taken place in the settlement (Table 6). Such by-products are higher in proportion for Galatia (25%) and Hasan Dağ (%33) (compared to 1% for Nenezi Dağ), and the distances involved (220 and 430 km, respectively) do not rule out direct procurement by the inhabitants of the settlement, at least for the former source. Melos and Acıgöl are both represented by a single bladelet, and the only proposition this meagre evidence allows is that they more likely arrived as finished products. One consideration to keep in perspective in this regard is the small size of the obsidian assemblage. 120 obsidians analysed in this study (92% of the entire obsidian assemblage of Bahçelievler) correspond to a mere 37 g of raw material. Bladelets are the dominant product (89%), and this might have been encouraged by a desire to conserve as much obsidian as possible.

4. Discussion

4.1. *Bahçelievler obsidians in regional context*

These results from Bahçelievler significantly expand the number of known Galatian obsidians in the archaeological literature. Previously, only three artefacts from a securely stratified context (Ilıpınar IX and X, ca. 6000 BCE) were assigned to the Galatian sources using instrumental neutron activation analysis (INAA) and fission-track dating (Bigazzi et al., 1995). A cluster analysis based on Ce, Nb, Hf, and Ba as discriminant factors indicated a cluster with Galatia, but a more specific attribution was not possible as Sakaeli was the only reference material available (Bigazzi et al., 2007). Two artefacts from Pendik were also associated with Galatian outcrops based on fission-track dates (Bigazzi et al., 1993a). Fission-track parameters have later been used to suggest specific source assignments for these two obsidian pieces from Pendik (as Yağlar and Güdül/Galatia-X) and also one of the above-mentioned artefacts from Ilıpınar (as Sakaeli) (Keller et al., 1996), but the age brackets are broad and overlapping, and do not permit a conclusive attribution to any one of the Galatian sub-sources. Further complicating the matter is the presence of similarly aged obsidian near Kütahya

Fig. 11. Hasan Dağ (top row) and Galatia (bottom row) obsidians identified in Bahçelievler (photographs: excavation archive).

(Wagner and Weiner, 1987), discussed in Section 3.1. In addition, the stratigraphic position and dates of the Pendik artefacts thus sourced are not clear, so is whether they were excavated or were collected from the surface of the site (Özdoğan, 1983). It must also be noted here that three further artefacts from Pendik were previously attributed to sources in east Anatolia based on INAA results (Bigazzi et al., 2007). It is likely that these artefacts belong to the same group of ca. 50 pieces (would amount to ca. 25% of the entire assemblage) that Milić (2016, p. 144) came across in a bag in the Pendik collection, and analysed to identify as belonging to an east Anatolian source. She discarded these results as she (reasonably) suspected that the objects originally did not belong to Pendik. Such an east Anatolian presence in Pendik is also deemed to be "unlikely both geographically and archaeologically" by Bigazzi et al. (1994, p. 29).

Beside Ilıpınar and Pendik, surface scatters of worked obsidians have previously been noted near source areas in Yağlar and Sakaeli (Keller and Seifried, 1990, pp. 82–83). Possible Galatian obsidians have also been reported during surveys near the Black Sea coast to the northwest of the sources (Kartal et al., 2016, p. 402), but analyses remain unpublished. Three artefacts from another survey near the coast, to the north of the sources, have been assigned to Orta-Sakaeli and Yağlar based on laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) analyses (Düring and Gratuze, 2013).

Another significant result that emerges from this study concerns the use of Hasan Dağ obsidians in central Anatolia. Chipped stone scatters have recently been detected around obsidian outcrops in Hasan Dağ (Yaman and Yıldız, 2020). However, the only long-distance transmission of Hasan Dağ obsidians prior to the results from Bahçelievler had been recorded in the northwestern part of modern Iran: Mahdavi and Bovington (1972) assigned three obsidians from two survey sites (Chalcolithic and Iron Age) south of Lake Urmia to Hasan Dağ based on Na and Mn contents as determined by neutron activation analysis (NAA). A failure to distinguish between Acıgöl and Göllüdağ, on the other hand, has led Chataigner (1998, p. 292) to suspect the validity of their results. Lastly, one obsidian from Neolithic-Chalcolithic Hoca Çeşme in northwest Turkey was previously assigned to Hasan Dağ based on fission-track dates (Oddone et al., 2003). This object, stratigraphic context of which was not provided, has yielded an apparent age of ca. 0.35 Ma and a plateau age of ca. 0.44 Ma. But comparable estimates have also been reported for Acıgöl at ca. 0.34 Ma (Wagner and Weiner, 1987, p. 27), and for Göllüdağ at ca. 0.44 Ma (Türkecan, 2015, p. 124), necessitating a compositional analysis to determine to source of this artefact more securely.

The remaining sources were more frequently transported and used in prehistoric settlements. Table 7 provides a summarised overview of obsidian use in the regions surrounding Bahçelievler during the Neolithic period. Percentages of different outcrops in the table are based on analytically sourced obsidians. Recent (post-1990) results, if present, have been taken into account to the exclusion of older analyses (see Frahm, 2023a, pp. 3–4 for related concerns). Fission-track dating source assignments are also ignored except the few attributions to the Miocene complex of Galatia (from Pendik, discussed above). This is because Quaternary volcanism in Anatolia and the Aegean have overlapping ranges for different obsidian sources (Frahm, 2023a, Tab. 2; Frahm, 2023c, Tab. 2), and also because archaeological interferences can affect the fission-track dates obtained (Bellot-Gurlet et al., 1999; Yeğingil et al., 2020, pp. 7–8), both complicating a straightforward interpretation of most results. Distance of the site in question to different obsidian sources, sources identified in nearby sites, and macroscopic interpretations of researchers that worked on the material are used to evaluate which obsidian sources might be predominant when analytical data is lacking or unavailable. Data pertaining to layers that postdate the

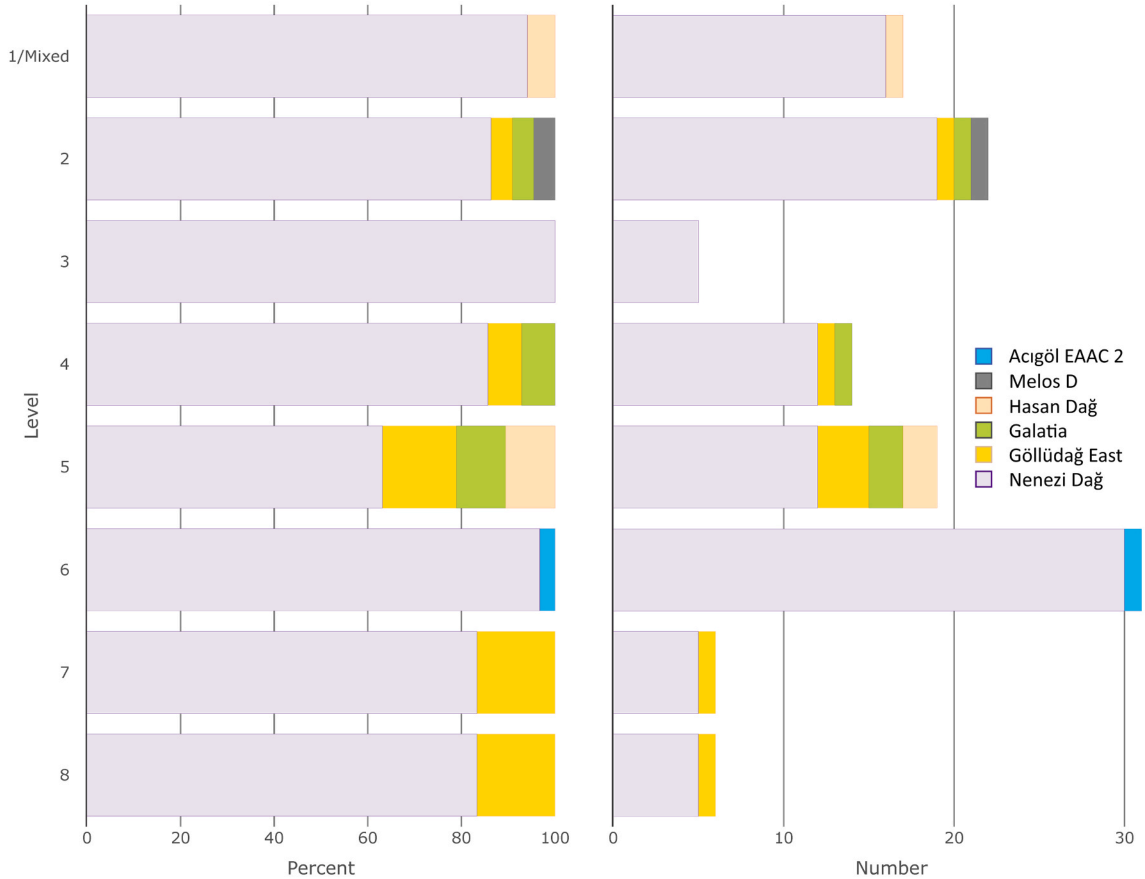

Fig. 12. Shifts in obsidian sources used through the Bahçelievler sequence.

Table 6
Techno-typological distribution of the analysed obsidians from Bahçelievler.

	Nenezi Dağ	Göllüdağ East	Galatia	Hasan Dağ	Melos D	Acıgöl EAAC 2	TOTAL
Blade	3	0	0	0	0	0	3
Bladelet	96	5	3	1	1	1	107
Plunging bladelet	0	0	1	1	0	0	2
Crested bladelet	1	0	0	0	0	0	1
Flake	1	0	0	0	0	0	1
Debris	3	2	0	1	0	0	6
TOTAL	104	7	4	3	1	1	120

7th millennium BCE were omitted from percentages whenever published information permitted it, and major shifts in resource procurement, if identified, have been noted.

Obsidian was clearly a desired raw material in the Neolithic period: most sites in Table 7 are hundreds of kilometres away from the closest source, yet it was nevertheless procured in some amount. It can be seen that Nenezi Dağ and Göllüdağ East obsidians circulated far and wide, while Acıgöl is almost always a minority raw material in the rare cases that it is represented. Obsidians from both outcrops on the island of Melos (Melos A and D) mainly appear in the assemblages near the Aegean coast and do so at an early date, ca. 6800 BCE, and possibly at an earlier date in the Bozburun Peninsula in southwest Anatolia (Atakuman et al., 2022; Gemici et al., 2022). Unfortunately, sites in the nearby Lakes Region are terra incognita with regard to obsidian sourcing: the only information comes from Hacılar, where Melos obsidians might have reached, but source attributions have been contested (Gale, 1981; Renfrew et al., 1966).

4.2. *Obsidian transmission and the frontiers of Neolithisation*

The pattern that emerges in northwest Anatolia resonates with the findings from Bahçelievler. Sites near the eastern shore of the Marmara Sea relied heavily on Nenezi Dağ as an obsidian source (Fig. 13, Table 7). The only exception here is Ilıpınar, which yielded only Göllüdağ and Galatia obsidians at the end of the 7th millennium BCE. Meanwhile, Bahçelievler is the earliest Neolithic site and the earliest user of both Göllüdağ and Nenezi Dağ obsidians in the region. The site is suited, chronologically and also geographically as it is very close to the Sakarya River, to be an entrance point through which Cappadocian obsidian dispersed in the region. An overwhelming reliance on Nenezi Dağ, however, contrasts with the visible pattern in central Anatolia. It is clear that aceramic/pre-pottery Neolithic (PPN) groups around the Konya plain had a marked preference for Göllüdağ obsidians. This preference continued in the early sequence of Çatalhöyük, and appears to be disrupted only ca. 6500 BCE when Nenezi Dağ became the more popular obsidian source in the site (Table 7). More critically, the reliance on Göllüdağ was not limited to central Anatolia: PPN (and later) communities in the Levant, Euphrates, and Cyprus were engaged in exchange

Table 7
Obsidian utilisation in the regions surrounding Bahçelievler in the 7th millennium BCE. Also included are earlier sites near the obsidian sources in Cappadocia. Melos A: Adhamas/Sta Nychia, Melos D: Dhemenegaki.

No.	Site	Obsidian	Notes	References
1	Pınarbaşı	Present	Not sourced (likely Cappadocia)	Baird (2012)
2	Aşıklı Höyük	Göllüdağ East (79%) Nenezi Dağ (21%)	Proportions are based on the analysis of 24 samples (< 1%)	Gratuze et al. (1993) Yıldırım-Balcı (2007)
3	Balıklı	Present	Not sourced (likely Cappadocia)	Kayacan et al. (2022)
4	Boncuklu	Göllüdağ and Nenezi Dağ	Sourcing analysis not fully published	Muller et al. (2018), p. 724
5	Sofular	Göllüdağ East (76%) Acıgöl (22%) Göllüdağ West (2%)	Based on 63 samples (1% of the obsidian assemblage)	Karakoç et al. (2023)
6	Sırçalıtepe	Göllüdağ East (58%) Nenezi Dağ (25%?) Acıgöl (17%?)	Based on 12 samples (< 1%). Results not finalised	Balcı et al. (2022)
7	Kömürcü-Kaletepe	Göllüdağ East	Procurement site on outcrop	Balkan-Atlı and Binder (2012)
8	Musular	Present	Not sourced/published (likely Cappadocia)	Kayacan and Özbaşaran (2007)
9	Can Hasan III	Göllüdağ (75%) Nenezi Dağ (25%)	Based on 20 samples (< 1%). Sourcing analysis not fully published	Ataman (1988)
10	Tepecik Çiftlik	Present	Not sourced (likely Cappadocia)	Vinet and Guilbeau (2018), pp. 2–3
11	Çatalhöyük	Early: Göllüdağ East (69%) Nenezi Dağ (30%) Acıgöl (1%) Late: Nenezi Dağ (76%) Göllüdağ East (24%)	Based on 272 samples (< 1%). Later analyses increased the sample size, but the overall pattern remains the same (Carter and Milić, 2013).	Carter and Shackley (2007)
12	Köşk Höyük	Present	Not sourced (likely Cappadocia)	Öztan (2012)
13	Can Hasan I	Present	Not sourced (likely Cappadocia)	French (2010)
14	Erbaba	Present	Not sourced (possibly Cappadocia)	Bordaz and Bordaz (1982)
15	Yumuktepe	Göllüdağ East (73%) Nenezi Dağ (20%) Acıgöl (7%)	7th mil. BCE occupation. Based on 15 samples (2%). Sourcing analysis not fully published	Altınbilek-Algül (2011)
16	Bahçelievler	Nenezi Dağ (87%) Göllüdağ East (6%) Galatia (3%) Hasan Dağ (2%) Acıgöl (1%) Melos D (1%)	Based on 120 samples (92%)	This study
17	Barcın Höyük	Nenezi Dağ (64%) Göllüdağ East (29%) Melos A (3.5%) unknown (3.5%)	Based on 28 samples (ca. 14%)	Milić (2016)
18	Aktopraklık	Present	Not sourced	Balcı (2011)
19	Fikirtepe	Nenezi Dağ (60%) Melos A (30%) Göllüdağ East (10%)	Based on 10 samples (ca. 24%)	Milić (2016)
20	Pendik	Melos (34%; A: 21%, D: 13%) Nenezi Dağ (32%) Göllüdağ East (29%) Galatia (5%)	Based on 38 samples (ca. 19%)	Milić (2016) Bigazzi et al. (1993a)
21	Menteşe	Present	Not sourced	Gatsov (2009)
22	Ilıpınar	Galatia (50%) Göllüdağ East (50%)	Based on 6 samples (6%)	Bigazzi et al. (1995) Gatsov (2008)
23	Hoca Çeşme	Melos (56%; A: 33%, D: 22%) Göllüdağ East (33%) Acıgöl (11%)	Based on 9 samples (ca. 64%)	Milić (2016) Oddone et al. (2003)
24	Uğurlu Höyük	Initial Neolithic: Melos (100%) (later) Neolithic: Melos A (51%) Melos D (33%) Göllüdağ East (12%) Nenezi Dağ (4%)	Based on 55 samples (> 61%). Latter analysis not fully published	Milić (2016) Dirican et al. (2018)
25	Coşkuntepe	Melos A (67%) Melos D (33%)	Not excavated, but likely 7th mil. BCE. Based on 3 samples (3%)	Perlès et al. (2011)
26	Ulucak Höyük	Initial Neolithic: Melos (100%) (later) Neolithic: Melos D (55%) Melos A (43%) unknown (1%) Göllüdağ East (< 1%)	Based on 302 samples (> 11%)	Milić (2016)

(*continued on next page*)

Table 7 (*continued*)

No.	Site	Obsidian	Notes	References
27	Çukuriçi	Initial Neolithic: Melos (100%) (later) Neolithic: Melos (ample) Nenezi Dağ (few), Giali (few) Göllüdağ (very rare)	Sourcing analysis not fully published	Schwall et al. (2020), pp. 14–15
28	Yeşilova	Melos D (63%) Melos A (33%) Nenezi Dağ (4%)	Based on 85 samples (ca. 9%). Melos specimens might include Chalcolithic contexts	Milić (2016)
29	Ege Gübre	Melos A (56%) Melos D (43%) Göllüdağ East (1%)	Based on 68 samples (ca. 34%)	Milić (2016)
30	Dedecik-Heybelitepe	Melos D (50%) Melos A (40%) Nenezi Dağ (10%)	Based on 10 samples (3%)	Herling et al. (2008)
31	Ekşi Höyük	Present	Not sourced	Dedeoğlu et al. (2023)
32	Girmeler	Cappadocia and Melos	Pottery Neolithic occupation. Sourcing analysis not fully published	Takaoğlu and Korkut (2019), p. 492
33	Öküzini	Göllüdağ East (50%) Nenezi Dağ (50%)	Based on 14 samples (100%). Some might be residual from earlier layers	Carter et al. (2011)
34	Karain	Present	Not sourced	Kartal (2018), p. 3
35	Bademağacı	Present	Not sourced	Duru and Umurtak (2019)
36	Hacılar	Acıgöl or Melos	Based on 4 samples (ca. 1%)	Gale (1981) Mellaart (1970) Renfrew et al. (1966)
37	Höyücek	Present	Not sourced	Duru and Umurtak (2005)
38	Kuruçay	Present	Not sourced	Duru (1994)

networks that predominantly conveyed Göllüdağ obsidians to their settlements, whereas Nenezi Dağ obsidians were only rarely encountered in these regions (Campbell and Healey, 2018; Carter et al., 2023a; Cauvin and Chataigner, 1998; Chataigner, 1998; Ibáñez et al., 2016; Moutsiou, 2019). It is likely that production workshops such as that in PPN Kaletepe on Göllüdağ played an important role in the maintenance of this Göllüdağ diffusion. Such exchange networks might have been inherited by the people in Yumuktepe, a Neolithic settlement established ca. 7000 BCE on the southern coast, which yielded predominantly Göllüdağ obsidians in the 7th millennium BCE (Table 7). However,

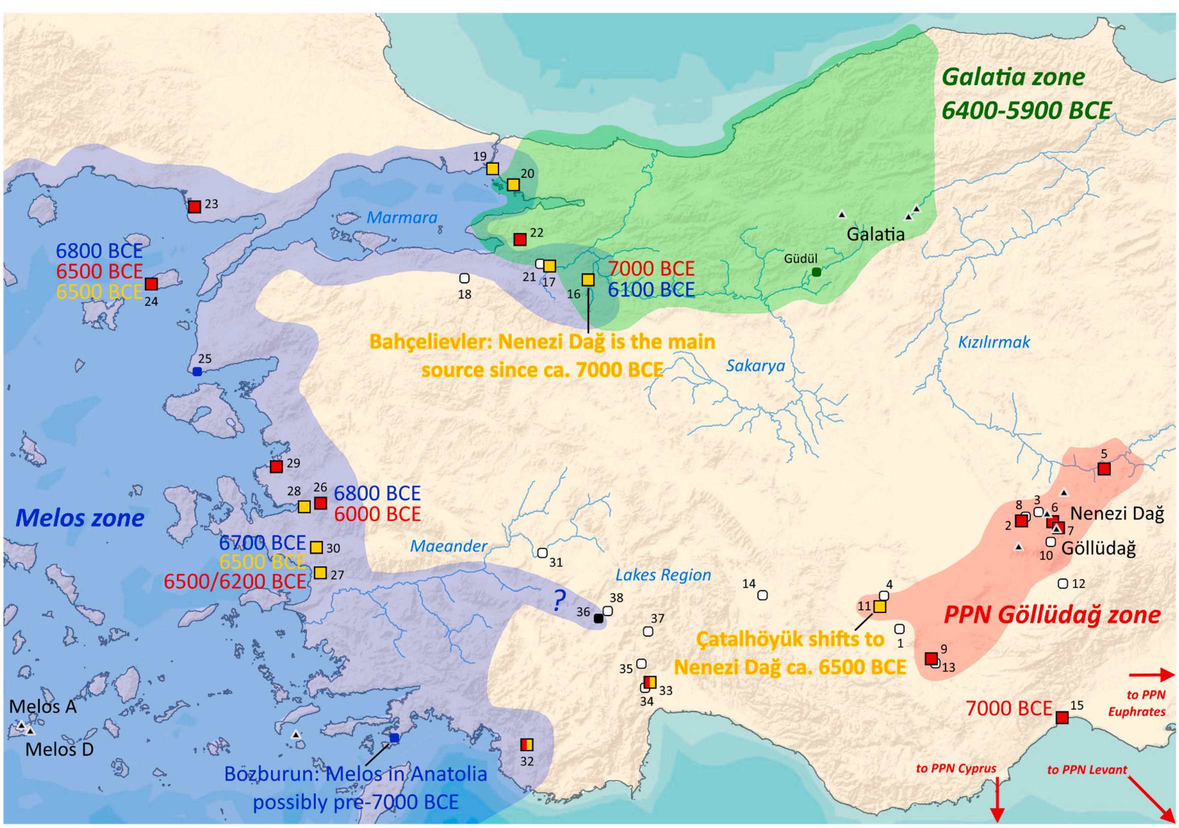

Fig. 13. Distribution of Galatia (green), Göllüdağ (red), Nenezi Dağ (yellow), and Melos (blue) obsidians. Colours of the large squares indicate which Cappadocian obsidian is more abundant in the site. White squares: obsidians unsourced, black square: source identification uncertain. Table 7 contains site-specific details.

detected Göllüdağ obsidians remain strikingly rare in the 7th millennium BCE assemblages of west Anatolian Neolithic sites (single piece each in Ege Gübre, Ulucak Höyük, and Çukuriçi; none in Yeşilova and Dedecik-Heybelitepe) (Herling et al., 2008; Milić, 2016; Schwall et al., 2020). In addition, the arrival of Göllüdağ obsidians seems to postdate the establishment of these villages by a large margin: earliest levels of Ulucak Höyük and Çukuriçi, both founded 6800/6700 BCE, yielded obsidians exclusively from Melos instead (Table 7). This poses an obstacle for the interpretation of these pioneer farming sites as colonisers with links to the PPN sphere that arrived through an east Mediterranean maritime route (Horejs et al., 2015). Arrival of Cappadocian obsidian in west Anatolia might instead be a reflection of the shifts in obsidian procurement that took place in Çatalhöyük ca. 6500 BCE, which in turn might have been a reflection of various transformations in the social landscape (Düring, 2007; Marciniak and Czerniak, 2007).

Events unfolded in a parallel manner in Uğurlu Höyük (Table 7), a similarly early village (founded ca. 6800 BCE) on the island of Gökçeada (Imbros) in northeastern Aegean. Melos obsidian is present in the earliest occupation level, whereas Göllüdağ and Nenezi Dağ obsidians appear to have joined the assemblage only ca. 6500 BCE. Given the early presence of these sources in Bahçelievler, it seems more likely that Anatolian obsidians reached the northern Aegean through a northern route that followed the east-west axis of the Marmara Sea. The same route is almost certainly responsible for the transmission of Melos obsidians to sites in northwest Anatolia. While the ca. 6100 BCE procurement in Bahçelievler presents a solid *terminus ante quem*, the first arrival of Melos obsidians to the wider region remains uncertain. Settlements further west probably procured Melos obsidians at an earlier date; unfortunately, the data extracted from these sites so far lack the stratigraphic resolution to offer a more tangible date.

The dominance of Nenezi Dağ in Bahçelievler since its establishment ca. 7000 BCE suggests a few possibilities with regard to the nature of its distribution. There is currently no known site in central Anatolia that relied mainly on Nenezi Dağ obsidians at a comparable date, from which Bahçelievler might have inherited its pattern of procurement. One possibility is that a similar pattern is present in an assemblage that has not been chemically profiled yet: Musular is one such candidate where it has been argued that Nenezi Dağ obsidians eventually superseded Göllüdağ obsidians in number (Kayacan and Özbaşaran, 2007), but the claim relied on macroscopic observations that regrettably have not been confirmed by compositional analyses from the assemblage. Another, and not mutually exclusive, possibility is that Bahçelievler was able to engage neighbouring regions in a way that allowed a more selective dispersion of goods and concepts, whether the Bahçelievler community had demographic roots in the earlier foragers of the Marmara Region or not. This engagement allowed the transfer of various domesticates but not Göllüdağ obsidians. Habits around the use of baked clay containers were shared but not those around intramural burials, a component of the mortuary domain in central Anatolia (Somel et al., 2023) but not in Bahçelievler. Nenezi Dağ obsidians and lithic pressure technique could be diffused but not rectangular architecture, which was an established cultural element in central Anatolia for almost a thousand years before the establishment of Bahçelievler (Duru et al., 2021), but did not appear in Bahçelievler until the end of the 7th millennium BCE. The early presence of the pressure technique in Bahçelievler and also in the possibly earlier assemblages of the Marmara Region (Gatsov and Nedelcheva, 2019, pp. 266–267) compared to west and central Anatolia (in the latter, after a hiatus between an early appearance in the PPN period and reoccurrence around the middle of the 7th millennium BCE) (Carter and Milić, 2013; Guilbeau et al., 2019; Milić and Horejs, 2017) implies that any such engagement was not necessarily unidirectional.

The last sphere of interaction that crystallises after the findings from Bahçelievler is related to the distribution of Galatian obsidians in north/northwest Anatolia. Dates gauged from Bahçelievler and Ilıpınar indicate an interval between 6400 and 5900 BCE for the transmission of obsidians from the three known outcrops, Yağlar, Orta, and Sakaeli, to sites in northwest Anatolia. The problem is a lack of excavated sites closer to source areas that exchange can in some way be associated with (Düring, 2008). An obvious inference is that some northwest Anatolian groups (currently either from Bahçelievler, Ilıpınar, or Pendik) obtained these obsidians through direct visits to the outcrops and were also responsible for their dispersion to other communities in the region. This scenario remains feasible, but we are also aware of possible early Holocene groups, maybe mobile hunter-gatherers, near the Black Sea coast that utilised the same sources (Düring and Gratuze, 2013). Perhaps it is some of these latter, so far mostly undetected, communities that were responsible for the westward dispersion of Galatian obsidians.

A final note concerns the current status of obsidian sourcing in Neolithic Anatolia. Only 20 of the 38 Neolithic sites surveyed for this study were associated with analytical data that could be used to obtain percentages of the obsidian sources used, and only 9 of these 20 datasets were generated through a sample size that accounts for more than 10% of the obsidians uncovered in the site. Related sampling issues might be behind the rarity of Acıgöl obsidians that have been confirmed so far: in Sofular, Çatalhöyük, Yumuktepe, Bahçelievler, and Hoca Çeşme, a distribution that is hard to explain. Visual categorisations, meanwhile, typically shoehorn most obsidians into two groups as either Göllüdağ (East) and Nenezi Dağ and disregard other possibilities. The risk here is a negative cycle that discovers less Acıgöl obsidians and results in less researchers looking for Acıgöl obsidians. Uncertainties inherent in macroscopic source assignments further amplify the potential for errors (Frahm and Carolus, 2022, pp. SI3–SI4). Such shortcomings will presumably be rectified as the number of assemblages and obsidians that are subjected to sourcing analyses increase.

5. Conclusion

Obsidian is a raw material that permits a uniquely close look at prehistoric interaction patterns, thanks in large part to a physical structure that permits chemical fingerprinting and relatively few sources scattered over a wide geography. Obsidian sourcing analysis presented in this paper dealt with the ca. 1000 years long assemblage from the 7th millennium BCE settlement of Bahçelievler, one of the earliest farming villages in northwest Anatolia. Results reveal a Neolithic community that relied on a chain of proximate obsidian sources in central Anatolia since its establishment. Even though the principal supplier (Nenezi Dağ) did not change through the sequence, the Bahçelievler community diversified its resource base at least two times: once around the middle of the 7th millennium BCE to include a scarcely explored source in northwest Anatolia (Galatia-Yağlar), and a second time at the end of the 7th millennium BCE to participate for the first time in the exchange of Melos obsidian that pervaded the Aegean.

An interrogation of previous sourcing studies conducted in the surrounding region, while capable of yielding interesting answers like how colonisation through coastal routes seems unlikely for Neolithic west Anatolia based on an obsidian distribution perspective, also indicates that a priority of research should be the confirmation of results that are based on very low percentages of samples. Sites at some distance from the outcrops typically yield manageable obsidian assemblages, rarely above a couple of hundred artefacts. XRF analysis is one way to mass source such assemblages in a rapid and low-cost manner, possibly identifying sources that were previously missed, and allowing a higher-resolution and a more time-sensitive picture of procurement patterns to be drawn. This is crucial, together with tighter stratigraphic controls, for more accurate interpretations of possibly generation-scale events and trends that affected various obsidian using communities that were also the first farmers around the Aegean.

CRediT authorship contribution statement

Hasan Can Gemici: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing – original draft, Writing – review

& editing, Visualization. **Çiğdem Atakuman:** Conceptualization, Writing – review & editing, Supervision. **Neyir Kolankaya-Bostancı:** Formal analysis, Writing – review & editing, Supervision. **Erkan Fidan:** Writing – review & editing, Supervision, Project administration.

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.

Data availability

The data supporting the findings of this study are available within the article and its supplement.

Acknowledgements

This research was supported by the European Research Council (ERC) project ''NEOGENE: Archaeogenomic Analysis of Genetic and Cultural Interactions in Neolithic Anatolian Societies'' (grant number 772390). Surveys in Eskişehir and Kütahya were supported by the Scientific Research Projects Coordination Unit of Bilecik Şeyh Edebali University (project number 2023-01.BŞEÜ.36-01). These funding sources had no involvement in the study beyond financial support. Geological samples were provided by İsmail Baykara (Meydan Dağ) and Rana Özbal (Berçinyayalar, Salur, and Sakaeli), for which we are very grateful. We would also like to thank Tristan Carter and Ellery Frahm for their constructive criticism and comments.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.quascirev.2024.108543.

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