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Geochemical and petrographic identification of stone quarries used for the construction of the Anahita Temple of Kangavar (West Iran)

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Abstract

The archaeological site of the Anahita Temple in Kangavar is one of the best-known stone monuments in western Iran and dates back to the Persian Empire period of Iranian history (about 550 BC to 650 AD). The Temple was constructed on a semi-artificial hill out of large stone blocks, many of which are cubic in shape, and short thick columns. In the Kangavar area (basin) there are various sites in which there is evidence of stone extraction. The aim of this paper is to characterize the stones used in the Anahita Temple of Kangavar and their correlations with the quarrying activities observed in the Kangavar regions. In fact, we tried to find out which of these quarries may have been the source of the stone blocks used in the construction of the Anahita Temple. To this end the stones used in the Temple have been characterized by conducting a multi-analytical study involving chemical, mineralogical and textural analyses including XRF, XRD and thin section petrography. The results show that although all the quarries could have provided the stone used in the construction of the Temple, the largest, most probable source was the Chel Maran quarry. It is due to the more similarity of stones used in the Anahita Temple and the samples from this quarry from geochemical point of view as well as the archaeological evidences present in this quarry. The results are also useful for conservators to select appropriate materials for reconstruction of the decayed parts of the Anahita Temple.

Keywords: Anahita Temple, Stone quarry, Geochemistry, Limestone, XRF, XRD, Petrography

Introduction

Stones were the main building material used in the construction of both large and small buildings in the Iranian highlands during the Persian Empire period (6th century BC to 7th century AD). These include many architectural complexes and archaeological sites such as Persepolis (Thakht-e Djamshid) and Pasargadae, which date from the Achaemenid era [1–4]; Sasanian buildings in the south of Iran such as the Palace of Ardeshir, Firuzabad, Bishapur and Qaleh Dokhtar; Takht-e Soleiman in northern Iran, and Taq-e Gara and Dias of Khosrow Palace in Qasr-e Shirin, etc. in the west of the country [5–10]. The extensive use of stone in the historical architecture of the

Iranian highlands was due to the availability of the raw materials (especially limestone and igneous rocks) in the Zagros Mountains, a long range of mountains that starts in northwestern Iran (Azerbaijan) and also covers significant areas of southeastern Turkey and northern Iraq. It then runs south along Iran's western border, until it reaches the coast of the Persian Gulf [11].

Scientific subjects such as stone mining activities and the investigation on provenance of stone raw materials used in ancient constructions have been widely studied around the world and are one of the most important subjects in multidisciplinary investigations in archaeological science [12–14]. Research is normally divided into two different parts. Firstly, the stones used in the construction of the buildings (masonry and large pieces) and secondly, decorative stones, stone tools and gemstones. With the development of advanced archaeological, geological, mineralogical and geochemical techniques for

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the analysis of ancient materials, archaeologists and archaeometrists from around the world started to carry out investigations on the sourcing areas of stones and raw materials used for ancient buildings, especially large, decorative stone blocks [e.g. 15–21]. These studies of the provenance of stone building materials, which have drawn the attention of experts from a range of different disciplines in recent decades, have three main purposes: sourcing stone for the conservation-restoration of ancient and historic buildings [e.g. 22–25], identification of the stones and quarries used in the construction of ancient buildings and monuments [e.g. 26–32] and the characterization of stone types, especially in decorative and gem stones, as a means of tracing trade and regional relations in the ancient world [33–35].

There have however been relatively few studies on ancient stone quarrying and stone working in the Iranian Plateau. These are limited to a few archaeological and archaeometric investigations of specific stone quarries related to important archaeological sites and monuments. These include, for instance, the studies on stone quarries and stone working in Persepolis and Pasargadae, two important Achaemenian world heritage sites in the Fars province (south-central Iran) [1, 3, 36, 37], preliminary studies of stone quarries in western Iran including Hegmataneh [38], Taq-e Bostan [39] and the Chel Maran quarry in Kangavar [40–42] and reviews about stone quarrying in Iran, such as the short review by D. Huff [43]. This shows that despite the fact that stone was the main building material in Iran's ancient monuments, insufficient research has so far been conducted on stone mining archaeology in different periods of Iranian history.

One of the best-known stone monuments in Iran is the Anahita Temple, which is located in the center of the modern city of Kangavar in western Iran (Fig. 1a, b). In this area there is widespread evidence of stone cutting and quarrying which have been linked to the construction of the Anahita Temple [44]. The aim of this paper is to perform analytical studies on the stones used in the construction of the Anahita Temple and different stone quarries in the Kangavar region, near the Anahita Temple, in order to discover which quarry was the main source of stone for the Temple. To this end the stones used in the Temple have been characterized by an analytical procedure which started with the sampling from the monument itself and from the different quarries, followed by microscopic and chemical analyses to characterize the ancient stone. Our results could also be useful in the selection of the most suitable stones for use in the conservation/restoration of the Anahita Temple in the future by using the main stone quarrying area as a

resource to select stone pieces for reconstructing decayed parts of the Anahita Temple of Kangavar.

The Anahita Temple of Kangavar

The Anahita Temple of Kangavar is one of the best-known archaeological and architectural heritage monuments in Iran and has been studied and excavated for many years. Archaeological excavations of the site were carried out by S. Kambakhshfard (1968–1975) and continued by M. Azarnoush (1977–1978) [10]. Further excavations together with conservation and restoration works were performed by A. Valinoori in 1986 and from 1988 to 2001 by A. Kabiri and M. Mehryar [45]. Archaeological studies in different layers of the excavations have uncovered a great deal of evidence from various periods in the history of Iran (Achaemenid, Parthian and Sasanian Empires up to the Early Islamic era). The findings were dated so confirming that the Temple complex had been used during these four historic periods [46]. It would seem that the complex was constructed in the Achaemenid period as a temple (4th or 5th century BC) and was used during the Parthian and Sasanian periods as either a temple or a palace. Nevertheless, some scholars believe the complex dates from a later era, arguing that it was built as a palace for the Sasanian kings (6th and 7th centuries AD) [43, 47, 48]. After the Muslims entered Iran (about 7th century AD), it fell into disuse, although there is some evidence from the Islamic period of small settlements on the ruins of the Temple [10]. The Anahita Temple also features in the accounts of various early Persian, Arab and western geographers and travelers, such as Ebn-e Khordadbeh, (ca. 870 AD), Estakhri (ca. 940 AD), Hamdollah Mostowfi (ca. 1360 AD) and Isidore of Charax (37 AD). These were followed in more modern times by western travelers such as Robert Ker Porter (1821 AD), Henry Rawlinson (1841 AD) and Marcel Dieulafoy (1884 AD), showing the importance of this complex even after it was dismantled and abandoned [10, 46]. The western geographers and historians described the complex as a Seleucid-Parthian temple, while Isidore of Charax suggested it might be the Temple of the Greek Goddess, Artemis, the equivalent to the Persian Goddess of Anahita in Ancient Persian culture. For their part, the Iranian/Islamic historians and geographers described it as a Sasanian palace for which they noted a range of names: Khosrow's Portico, Parviz's Palace, Qasr-e Shirin and Qasr-e Al-lasus (Al-luslus, Alsus) [10, 43, 45, 46, 49, 50]. Whatever its exact purpose, the fact that it was so often mentioned in ancient texts shows that the Anahita Temple of Kangavar was a very important place during the pre-Islamic Persian Empires from the 6th century BC to the 7th century AD [46].

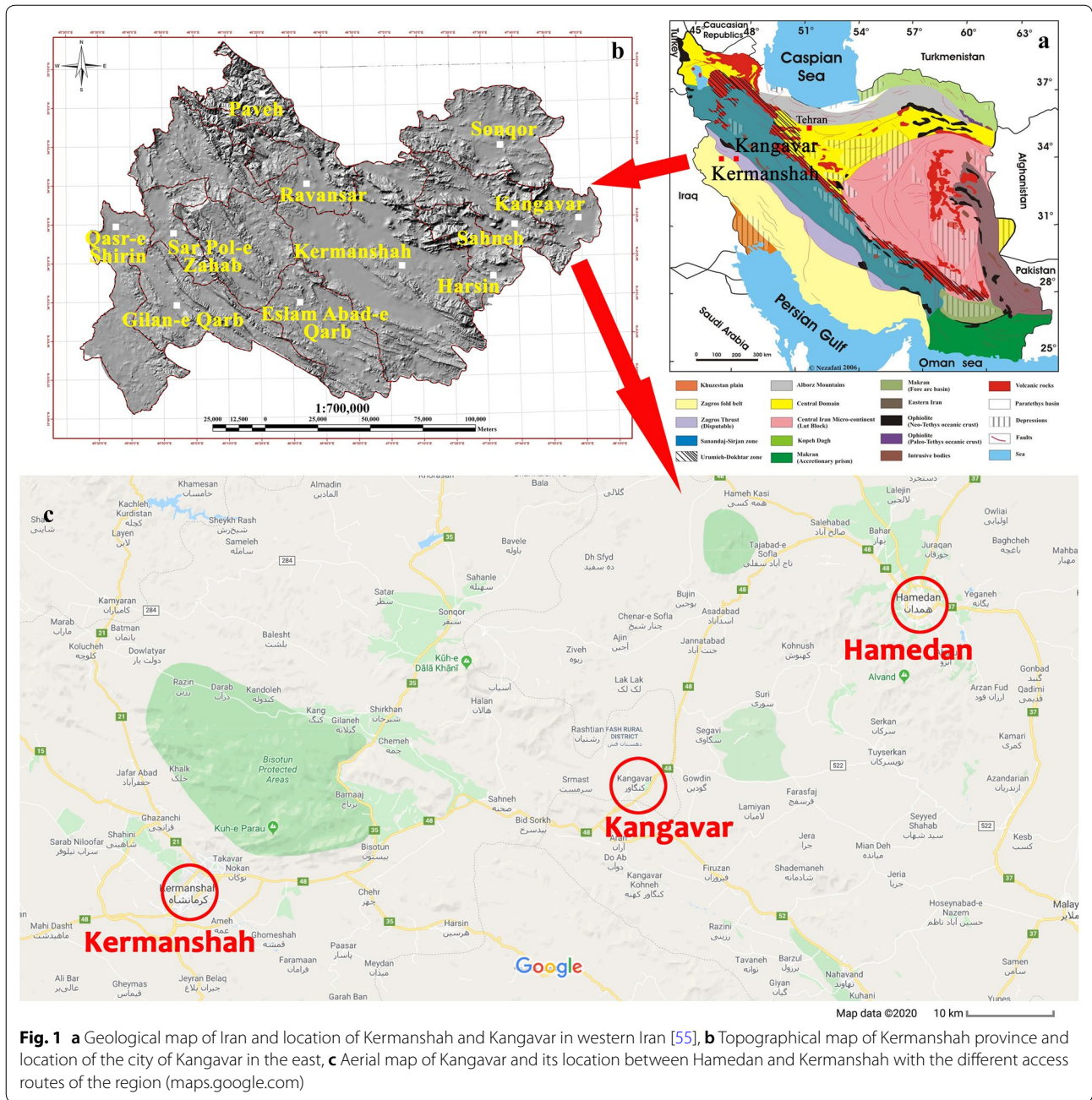


Fig. 1 a Geological map of Iran and location of Kermanshah and Kangavar in western Iran [55], b Topographical map of Kermanshah province and location of the city of Kangavar in the east, c Aerial map of Kangavar and its location between Hamedan and Kermanshah with the different access routes of the region (maps.google.com)

The city of Kangavar is in the center of the eastern county of Kermanshah province and lies west of Hamedan province and the northern part of the Zagros fold and thrust belt (Zagros FTB). Geological surveys indicate that Kermanshah province is located on two well-known geological formations in Iran, namely Sanandaj-Sirjan and Zagros FTB, which are bordered by the active seismic faults of Morvarid and Sahneh. The county and the city of Kangavar are located in the Sanandaj-Sirjan metamorphic belt of the Zagros Mountains (Fig. 1a) [51–54].

The Sanandaj-Sirjan zone was formed in the northern part of the Zagros orogeny and experienced both the Cimmerian and Late Cretaceous orogenies, as well as younger Alpine phases in some areas. Its northern part is composed of low-grade metamorphic rocks from the Mesozoic, which have been intruded by Jurassic to Mid-Tertiary intrusive bodies and granitoids [55]. The Kangavar basin is composed of unconsolidated terrestrial Quaternary sediments that cover Mesozoic and Cenozoic formations. In fact, most of the formations in this basin

include terrestrial deposits from flood plains composed of intermediate layers of sand and clay and lens-shaped layers of clay of different depths in the various parts of the basin. In some areas, the outcrops of the formations show both dark and light grey, recrystallized argillaceous limestones that are visible in thick-bedded structure. These outcrops are from the Cretaceous age [56, 57].

The Anahita Temple of Kangavar is located in the west of Kangavar city in western Iran, beside the road between Kermanshah and Hamadan (Fig. 1c). The geographical coordinates of this site are 47° 57' E and 34° 30' N respectively. The main construction of the archaeological complex is a massive building formed by a large square terrace measuring 209 m by 224 m, which was constructed around a low, natural rock (hill). The terrace was filled with raw stone pieces and gypsum mortar to create a large, semi-natural/semi-artificial hill—a natural hill that is shaped in rectangular form with stone pieces and gypsum mortar- which was then covered with large, carved stone blocks with smooth surfaces as a façade, above which two other floors were constructed (Fig. 2a, c–f). The stone blocks forming the surface of the building were joined together using iron clamps, a technique used by the Achaemenids [3, 46]. According to the virtual reconstructions by Kambakhshfard [10] and Mehryar

and Kabiri [45], the building had three floors or levels consisting of a main platform with two terraces built on top (Fig. 2a, b). In the southern part of the building, the remains of a staircase with opposing flights are visible parallel to the façade. A row of thick columns located on the first floor were also uncovered in excavation operations. These columns are short and thick, measuring 3.54 m in height and 1.44 m in diameter. Some of the columns are located in their original position on the north-west part of the largest terrace (Fig. 2d, f). Three of them have been restored in recent decades [45].

The construction and position of the two staircases in the Anahita Temple are reminiscent of the Achaemenid staircases in Persepolis and also of Sasanian staircases, such as the one at the Khosrow Palace in Qasr-e Shirin, western Iran [50, 58]. It is worth noting that the construction of the staircases and the stone walls around the large platform at the Anahita Temple of Kangavar is more rudimentary, less precise than that used in Persepolis and bears closer resemblance to the Khosrow Palace in Qasr-e Shirin [47, 50]. The idea of constructing the Kangavar staircase ramps in the Achaemenid manner is probably an Iranian tradition, although it may have a slight Hellenistic-Roman influence, given the details of the cornice and the pseudo-Roman colonnade [50]. The

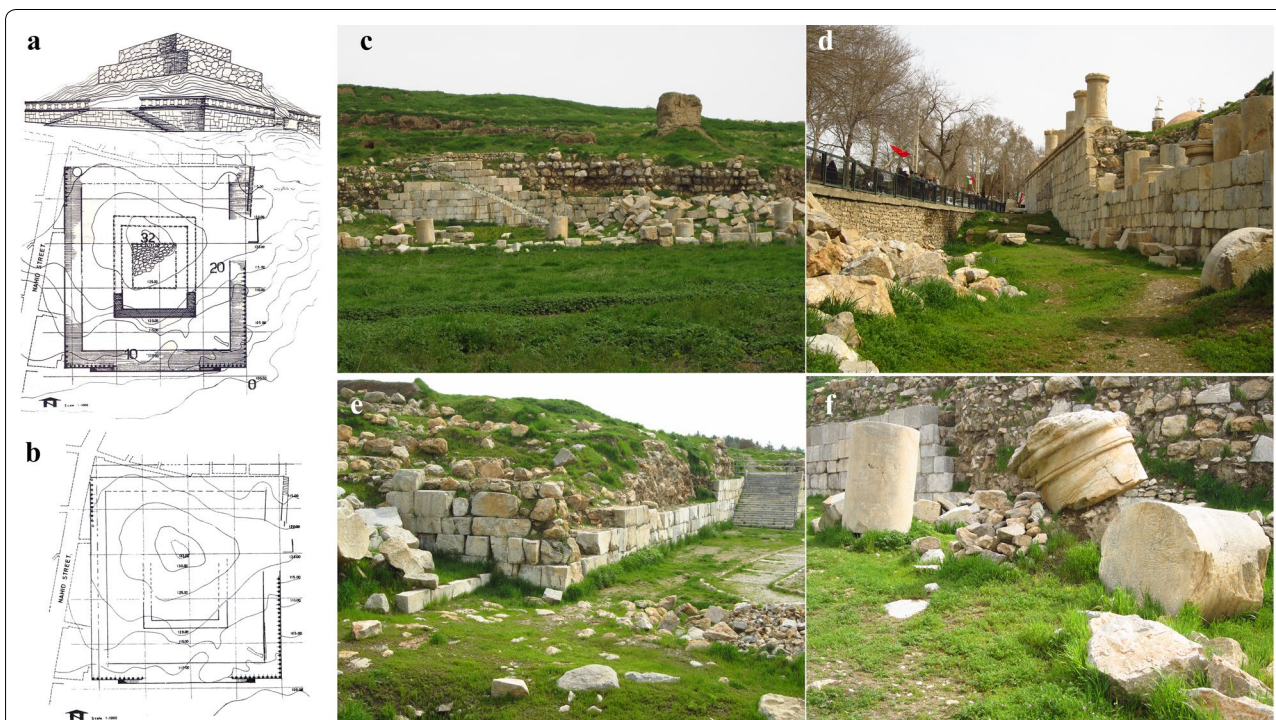


Fig. 2 a Reconstruction of the Anahita Temple of Kangavar [10], b plan of the excavated area of Anahita Temple [10], c view of the main terrace from the south showing the natural hill, the artificial stone and mortar mass and the carved stone blocks used to cover the structure, d western wall and remains of the huge columns over the wall, e southwestern corner of the main terrace and western part of the southern staircase, f broken pieces from the huge columns, remains of the western wall and of the large, artificial structure made of stone and mortar

exact function of the Anahita Temple of Kangavar is not yet clear, although archaeological excavations have been conducted at this site for many years. Archaeologists and historians disagree as to its possible function and date such that it has been variously described as an Achaemenid Palace, a Sasanian Palace and a Seleucid-Parthian temple. Despite this lack of consensus regarding its age and function, this huge building remains one of the most important examples of stone architecture from the Persian Empires of Iranian history.

Although, there are different hypotheses about the archaeology, history and construction of the Anahita Temple of Kangavar [10, 45–48, 50], information about the sources of the raw materials, the carving and preparation of the stones in quarries and the finishing processes are limited to a number of descriptive reports on the stone quarries in this area [41, 44]. Other archaeological and conservation reports have identified one particular area as the stone quarry from which the masonry for the Temple was extracted.

Ancient stone quarries

Archaeological surveys and in-field documentation indicate that there are various quarries in the Kangavar region from which stone was extracted and worked in ancient times. After extraction the stones were cut and carved into blocks. Unfinished stone blocks can still be seen today. These ancient stone quarries are situated in or around the modern city of Kangavar and include Chel Maran mountain (Chehel Maran, Chelmaran or Shel Maran), Baq-e Melli (National Garden), Allah Daneh, Qureh Jil mountain, Rostam Abad, Sarab-e Dehlor, Helale Ahmar area (Red Crescent area), and the area to the south of the Anahita Temple itself (Fig. 3a, b) [10, 41, 44, 45].

In-field observations suggest that the very limited evidence of stone cutting in the Helale Ahmar quarry and south of the Temple itself mean that it is unlikely that these stone quarries were used for the Anahita Temple [44]. The nearest stone quarry to the archaeological complex is the Baq-e Melli stone quarry. The most widespread evidence of stone extraction, including some unfinished carved blocks, is in the quarry dug out of the Chel Maran mountain. This stone quarry is located about 3 km west of the Anahita Temple of Kangavar on the western slope of the Chel Maran mountain. The method used to extract the stone and prepare the blocks in this quarry (and other stone quarries in the Kangavar area) is similar to the method for working the stone used in Achaemenian stone quarries in Fars (southern Iran) [3, 43]. Although there are many areas with evidence of stone quarrying in the Kangavar area, large-scale stone working and cutting is only visible at certain sites such as Chel Maran,

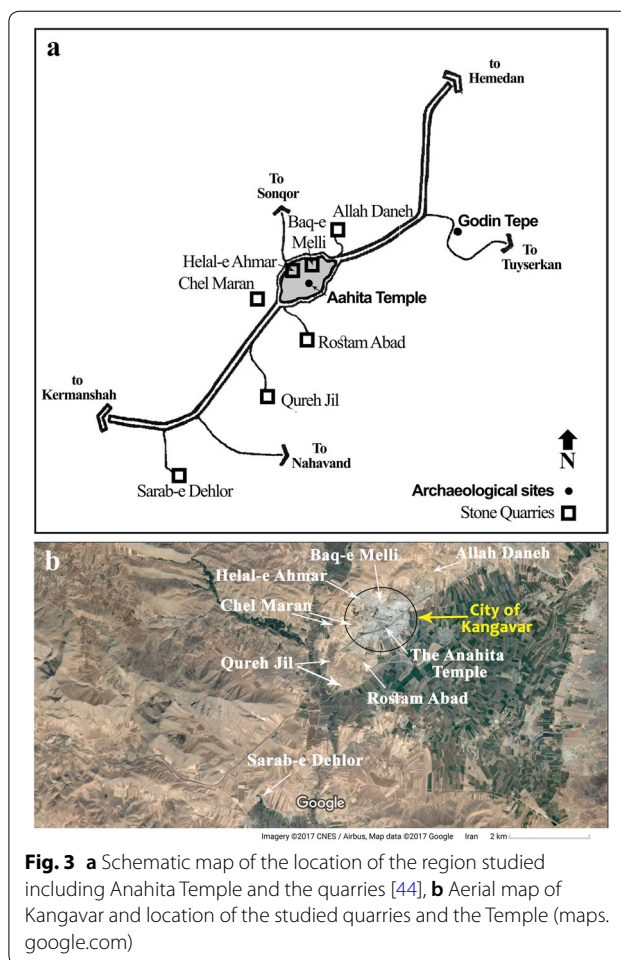


Fig. 3 a Schematic map of the location of the region studied including Anahita Temple and the quarries [44], b Aerial map of Kangavar and location of the studied quarries and the Temple (maps.google.com)

Baq-e Melli and Allah Daneh (Fig. 4). It is therefore very important to find out which stone quarries were used as the main source for the construction of the monument. This was done by conducting a range of different analytical studies as well as by comparing the results of analyses with the archaeological surveys and evidence.

Materials and methods

Sampling

An analytical study was planned and undertaken to investigate the correlation between the stones used at the Anahita Temple and the stone quarries in the Kangavar region. The process was started by collecting stone samples from the Temple and the quarries. These included five samples from stone blocks at the Temple and eight samples from the quarries and stone cutting areas. The stone samples from the Anahita Temple were collected from the stone blocks scattered around the main structure (samples KN-1, KN-2 and KN-3) and from two stone columns from the main building (KN-7 and KN-8). In total, six quarries were sampled and studied in this

research. The quarry samples were selected from the layers in which stone working and extraction were performed in ancient times (Fig. 4d–h). Given that in most of the quarries the limestone outcrop used for stone extraction and working was quite small, it was decided to take just one sample from each quarry. In two of the quarries, Chel Maran and Qureh Jil, there was wider evidence of stone working and quarrying and larger exposed

outcrops, so two samples were selected from each. On this basis the following samples were taken: two samples from the eastern and western hills of the Chel Maran mountain (CM-1 and CM-2, respectively), two samples from the Qureh Jil mountain (QJ-1 and QJ-2), and one sample each from the Allah Daneh (AD-1), Baq-e Melli (BM-1), Rostam Abad (RA-1) and Sarab-e Dehlor (SD-1) stone cutting areas. The characteristics of the samples are



Fig. 4 The stone quarries in the Kangavar region, **a** view of the Chel Maran mountain from north showing both western and eastern hills, **b** an unfinished column in the western hill of the Chel Maran quarry, **c** carved and unfinished stone blocks in the upper part of the Chel Maran quarry, **d** an overall view from the Baq-e Melli mountain and the surface stone quarry, **e** large extractions of stone blocks from the surface of the Baq-e Melli quarry, **f** another unfinished column left on the top of the western part of Chel Maran quarry, **g** a wide view from the Qureh Jil Mount that its surface is used as a small stone quarry, **h** view of Sarab-e Dehlor mount, **i** some small evidences of stone extraction in Helal-e Ahmar area located in the central part of the city, **j** view of Rostam Abad stone quarry and mountain from the top of the Anahita Temple, **k** remains of stone cutting activities in the Rostam Abad quarry including an unfinished column, **l** another extracted rock in Rostam Abad quarry showing surface quarrying

presented in Table 1. All samples from the archaeological site and the quarries were used to prepare thin sections and milled to powder for chemical and mineralogical studies.

Analytical studies

In order to identify the source of the stone used at the Anahita Temple of Kangavar, we decided to use an analytical approach that included microscopic, geochemical-mineralogical and petrographic analyses.

Petrographic characterization was performed on thin sections of the Temple and the quarries using a Primo-tech model Zeiss transmitted-reflected light microscope. Thin sections were observed under crossed polarized light illumination (XPL). In order to characterize the probable presence of dolomite in the structure of the stone samples, the Alizarin Red S test was performed, after which the thin sections were observed again using the XPL microscope [59].

The X-ray fluorescence technique was used to identify the chemical composition of the samples from the Temple and the quarries. The aim was to characterize the probable relation between the stones from the monument and those from the quarries from a chemical point of view and also provide significant data about the composition of the stone samples. For this purpose, four grams of each powdered sample were pressed into pellet form using boric acid powder as a binder for analysis by X-ray fluorescence (XRF) [60]. XRF analysis of the samples was undertaken to characterize their chemical composition (major, minor and trace constituents). This analysis was performed by a PANalytical PERL'X3 X-ray fluorescence analyser.

Finally, the X-ray diffraction (XRD) method also was used on all samples from the Temple and the quarries

to identify the phase composition and the mineralogy of the powdered samples. This method was also used to compare the stone samples from a mineralogical point of view. XRD data were collected on a Philips PW1070 X-ray diffractometer, using a CuK α X-ray source ($\lambda = 1.54 \text{ \AA}$) with an angular range of between 5° and 60° (2θ) and 2 h counting time.

Results and discussion

The petrographic studies showed that the five samples from the Temple are mainly composed of calcite and have very similar fabric. The microstructure of the samples shows a multi-layered texture including different grain sizes from micrite to sparite (Fig. 5). There are many veins that are filled with secondary calcite with different grain sizes. At higher magnifications, sparitic calcite in xenotopic and hypidiotopic crystal fabric are visible within the micritic layers (Fig. 5). In some parts, peaked low amplitude stylolites along a bedding plane separated laminated fine-grained micrite from sparite. Moreover, there are veins crossed by microstylolites in dark colour, which probably have an accumulation of clay minerals or secondary iron compounds and/or organic matter [59]. The porosity of the samples is very low; some secondary pores are visible due to the removal of the dark phase from the veins, especially in KN-2, KN-7 and KN-8 (Fig. 5). The presence of crosscutting veins and stylolites are signs of chemical compaction and differential chemical turbulences beside pressure solution by load or tectonic stress during diagenesis in which sediment was transformed into rocks. In fact, these crosscutting veins and fractures may have been formed due to the presence of clay (dark parts) within the calcite during diagenesis, when the stone was subject to high pressure [61]. One important difference between KN-1 and KN-2 and the

Table 1 Characteristics of the stone samples analyzed in this study

	Sample code	Type of sample	Place of sampling
Temple	KN-1	Anahita Temple	Stone block around the main structure
	KN-2	Anahita Temple	Stone block around the main structure
	KN-3	Anahita Temple	Stone block around the main structure
	KN-7	Anahita Temple	Stone Column
	KN-8	Anahita Temple	Stone Column
Quarries	RA-1	Rostam Abad Quarry	From the stone cutting area
	QJ-1	Qureh Jil Quarry	From the stone cutting area
	QJ-2	Qureh Jil Quarry	From the stone cutting area
	CM-1	Chel Maran Quarry	From the stone cutting area
	CM-2	Chel Maran Quarry	From the stone cutting area
	AD-1	Allah Daneh Quarry	From the stone cutting area
	BM-1	Baq-e Malli Quarry	From the stone cutting area
	SD-1	Sarab-e Dehlor Quarry	From the stone cutting area

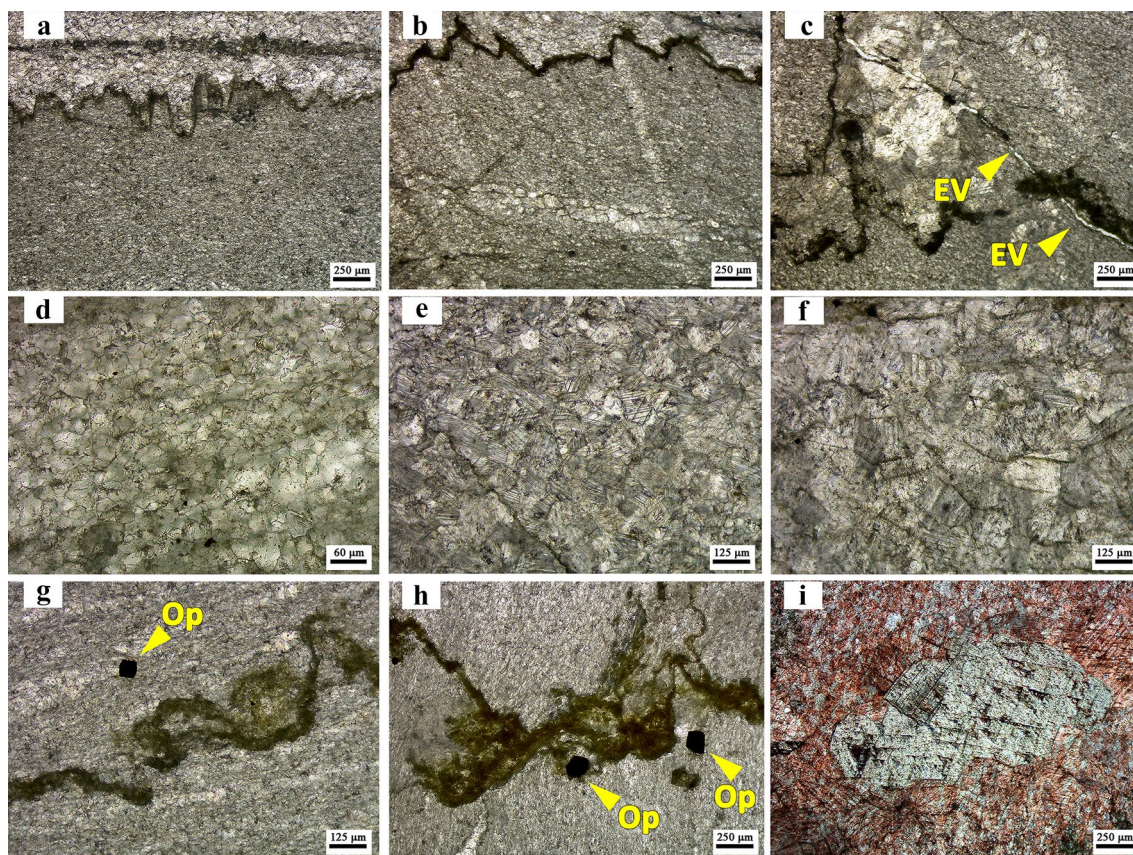


Fig. 5 Petrographic images of samples from the Temple: **a** multi-layer fabric of sample KN-1 including micrite to sparite; **b** multi-layer fabric of KN-7 in which the crosscutting veins are brighter in the micrite matrix; **c** crosscutting veins and stylolite in sample KN-8. Yellow arrows show an empty vein (secondary porosity); **d** detail of hypidiotopic calcite crystals from KN-8; **e** detail of micro-sparite texture from KN-3, which shows the hypidiotopic calcite crystals; **f** detail of hypidiotopic sparite from KN-2; **g** detail of stylolite and cubic opaque crystals from KN-2 (yellow arrow); **h** arrows show the opaque cubic crystals in the fabric of KN-1; **i** Alizarin Red S staining test indicates idiotopic rhombohedral crystals of dolomite in the fabric of KN-1

other samples from the Temple is that they include cubic crystals which are black in transmitted light (Fig. 5) and opaque in reflected light that is probably hematite (iron oxide) or other iron compounds such as pyrite (iron sulphide). Furthermore, the Alizarin Red S staining test revealed the presence of idiotopic crystals of dolomite within the micritic texture in one sample (KN-1) (Fig. 5i), while sporadic dolomite crystals were observed around the sparite veins and stylolites in KN-3 and KN-8.

The microstructures of the samples from the quarries vary in terms of fabric, although they have similar constituents, including micritic to sparitic calcite grains. Other features include veins of varying size filled with sparitic secondary calcite and some stylolites, probably filled with dark phases of clay and secondary Fe-rich phases (Fig. 6). All samples have very low porosity, although some holes and pores have appeared due to the disappearance of clays and iron phases from the veins and pores leading to an increase

in the secondary porosity (e.g. samples CM-1, AD-1 or QJ-2). Nevertheless, we were able to rule out some of the possible quarries due to differences in the morphology and size ranges: for example, the size of the secondary veins filled with calcite and clay varies from large to very small in samples RA-1, BM-1, QJ-2 and AD-1, which indicated a different fabric (Fig. 6). Another different feature in some samples, in particular QJ-1, was the presence of microfissures filled with dark phases due to high pressure during diagenesis beside rhombohedral dolomite crystals in the fabric of the stone. The most important difference was the presence of bioclots in QJ-1, SD-1 and CM-1 (Fig. 6b–d). The stone sample from Sarab-e Dehlor (SD-1) had another characteristic distinguishing feature, namely microfossils in significant amounts. These can be categorized as bio-micrite fabric, which suggests that SD-1 is quite different from the other samples. The Alizarin Red S test showed that dolomite is widespread in the calcitic matrix of all the

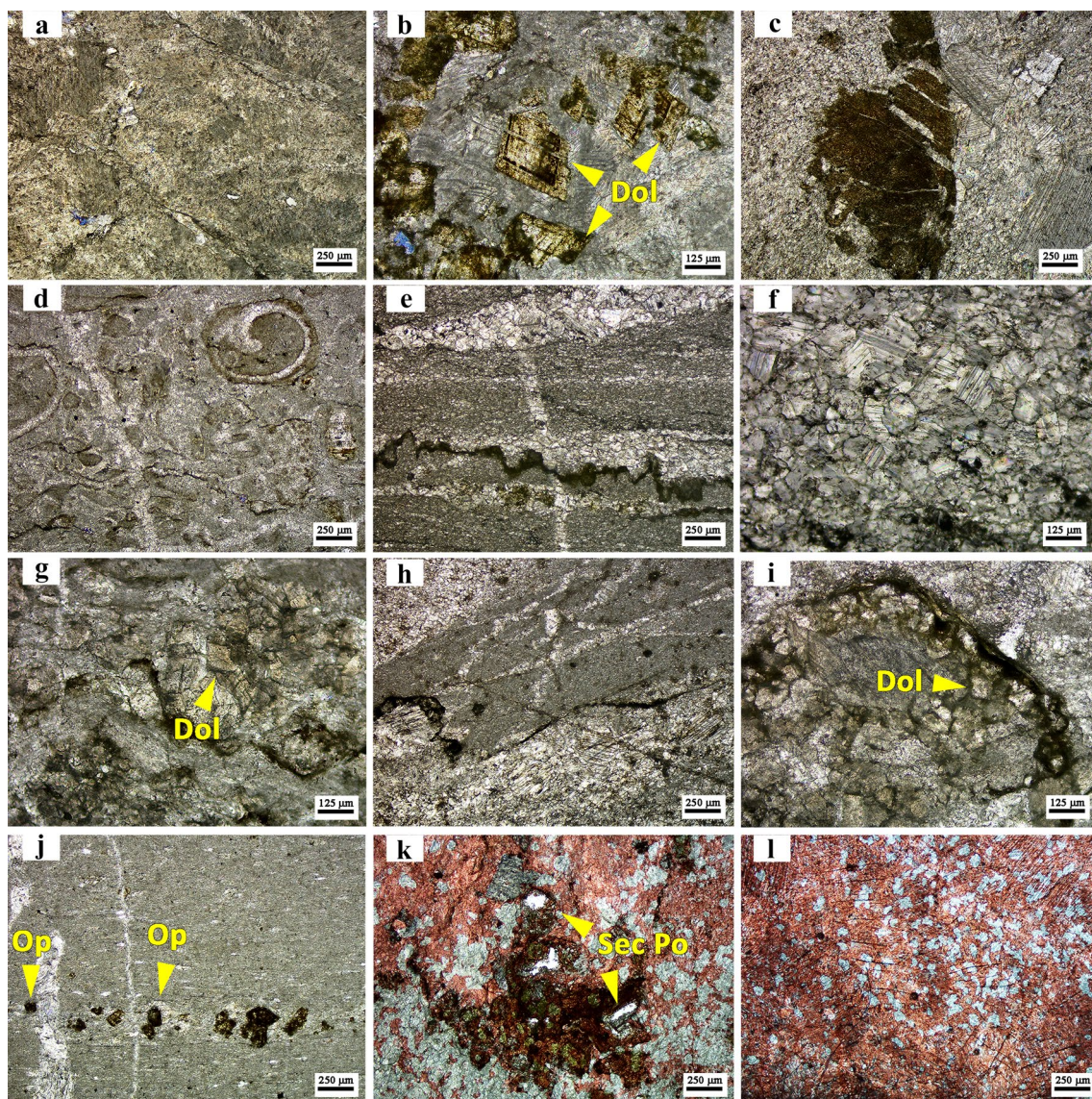


Fig. 6 Petrographic images of the samples from the quarries, **a** micrite to sparite fabric of sample RA-1 that shows a microfissure and fine stylolite due to diagnosis pressure; **b** sparite fabric from QJ-1 including rhombohedral crystals of dolomite (marked with arrows); **c** sparite crystals from CM-1 including bioclast filled with secondary phase (clay or iron component); **d** bioclast fabric of SD-1; **e** multi-layer fabric from micrite to sparite from CM-1 including stylolites; **f** detail of hypidiotopic sparite crystals from CM-1; **g** yellow arrow indicates rhombohedral crystals of dolomite from BM-1 scattered within the micrite to sparite fabric; **h** crosscutting of veins filled with sparitic calcite beside stylolites in sample AD-1; **i** detail of AD-1 fabric indicates rhombohedral dolomite crystals beside the vein (yellow arrow); **j** dark crystals within the micrite fabric of QJ-2, yellow arrow indicates two probable opaque cubic crystals; **k** Alizarin Red S staining of CM-1 indicates the wide presence of dolomite crystals, arrows indicate secondary porosities; **l** widespread dolomite crystals within the fabric of RA-1 after Alizarin Red S staining

samples from the quarries, except for CM-2 and AD-1, which include sporadic dolomite crystals, although the amount and the size of the dolomite grains vary greatly from one sample to the next (Fig. 6k–l). We also noticed the presence of cubic-shaped opaque crystals in just one sample QJ-2, which shows a correlation with the KN-1 and KN-2 samples from the Temple.

The petrographic study of thin sections of stones from the Anahita Temple showed a layered fabric of micrite to sparite in all samples. There were many veins of secondary calcite in the texture of the samples. Furthermore, some compact dark veins, presumably composed of clays, were visible in the microstructure. The Alizarin Red S test indicated some sporadic dolomite crystals in

the texture of the stone samples. The petrographic study comparing the microstructure of the stones from the Temple and the quarries shows that the Qureh Jil (QJ-1), Sarab-e Dehlor and Baq-e Melli have fewer similarities with the fabric of the stones used in the Temple. The sample with least similarities is the one from the Sarab-e Dehlor quarry. The stone texture of samples QJ-2, RA-1, AD-1 and CM-1 is closer to that of the Temple stones, although they have a higher quantity of dolomite. In fact, QJ-2 has a similar fabric to the samples from the Temple because of the micritic matrix, the sparitic veins and the cubic opaque crystals, which are probably filled with iron compounds such as pyrite. However, the greatest similarity between the fabric of the samples from the quarries and those from the Temple was in CM-2, due to the small amount of dolomite, the layered micrite to hypidiotopic sparite and the similar morphology of the stytolites and the veins filled with secondary calcite and clay minerals probably such as illite or muscovite.

XRD analysis of the stone from the Anahita Temple also showed that calcite (CaCO_3) is the main phase detected in all the samples (Table 2, Fig. 7). Quartz (SiO_2) was detected as the minor phase in all five samples of the Temple, while dolomite ($\text{CaMg}(\text{CO}_3)_2$) was detected in sample KN-1 and gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) was detected in samples KN-7 and KN-8. The analysis of the stone samples from the quarries revealed that, like the samples from the Temple, calcite is the major phase in the composition of almost all the stones (Table 2, Fig. 7). The exception was BM-1 in which dolomite was identified as a major phase alongside calcite. Quartz was identified as a minor phase in the stone from all the quarries, although it is detected in samples QJ-1

and BM-1 in significant content. Also, dolomite and illite/muscovite were detected as minor phases in three samples. In general, the phase composition of the samples from the Temple resembles those from quarries such as Rostam Abad (RA-1), Qureh Jil (QJ-1 and QJ-2) Chel Maran (CM-2) and Sarab-e Dehlor (sample SD-1).

Table 3 shows the results of XRF analysis of major and minor elements in the stone samples. The results revealed that the main component of all the samples (Temple and quarries) is CaO, whose content varies from 39.23 to 54.95 wt%. The second most important component was SiO_2 . The amount of SiO_2 has been measured 7.5 and 10.76 wt% in samples QJ-1 and BM-1, respectively. It shows that why quartz is detected as minor phase with significant content in the composition of both samples. Instead, MgO was an important constituent of just two samples (AD-1 and BM-1) and the Al_2O_3 content of the sample from the Sarab-e Dehlor quarry was more than one percent. Other constituents with less than 1% content were considered minor components. The results of XRF analysis show that the stone samples from the Temple and the quarries are carbonate stones (calcareous) due to their high CaO content [62, 63]. Perhaps the most important differences between the stones we analyzed is the presence of significant amounts of MgO and SiO_2 in some of the samples. Figure 8 shows the ternary diagram for CaO– SiO_2 –MgO in the composition of the analyzed stones. This diagram shows that all the stones are rich in CaO and that the composition of the samples from quarries such as Rostam Abad (RA-1) and Chel Maran (CM-2) was very similar to that of the samples from the Temple. The samples from Qureh Jil (QJ-1) and Sarab-e Dehlor have less in common with the samples from the Temple in terms of their main composition.

Table 4 shows the trace elements identified in the composition of stone samples from the Temple and the quarries (measured in ppm). Sr, Zr, Cr, Ba and Pb were all detected in significant amounts while other trace elements had much lower content. Also it is worth noting that the composition of the samples is very similar based on many of REE elements. The analysis of the correlation between the trace elements and the minor constituents in the composition of carbonate stones is a useful way of studying the provenance of these type of stones [64, 65]. Figure 9a–c shows scatter plots for Fe_2O_3 , Al_2O_3 and Na_2O versus Sr in the composition of the stone samples. The diagrams show that the stone samples from the Temple have a very close correlation with two samples from the Chel Maran (especially CM-2) and Qureh Jil (QJ-1 and QJ-2 samples) quarries. Some samples from Allah Daneh and Sarab-e Dehlor also have considerable correlation with samples from the Temple. The scatter plot for Fe_2O_3 , Al_2O_3 and Na_2O versus Zr in the composition of the stone samples can be seen in Fig. 9d–f. It is clear from these scatter plots that the

Table 2 Results of XRD analysis of the stone samples from the Anahita Temple and the stone quarries

	Sample	Major phase	Minor phase
Temple	KN-1	Calcite	Quartz; dolomite
	KN-2	Calcite	Quartz
	KN-3	Calcite	Quartz
	KN-7	Calcite	Quartz; gypsum
	KN-8	Calcite	Quartz; gypsum
Quarries	RA-1	Calcite	Quartz
	QJ-1	Calcite	Quartz
	QJ-2	Calcite	Quartz
	CM-1	Calcite	Quartz; dolomite; Illite (muscovite)
	CM-2	Calcite	Quartz
	AD-1	Calcite	Quartz; dolomite; Illite (muscovite)
	BM-1	Calcite; dolomite	Quartz; Illite (muscovite)
	SD-1	Calcite	Quartz; dolomite

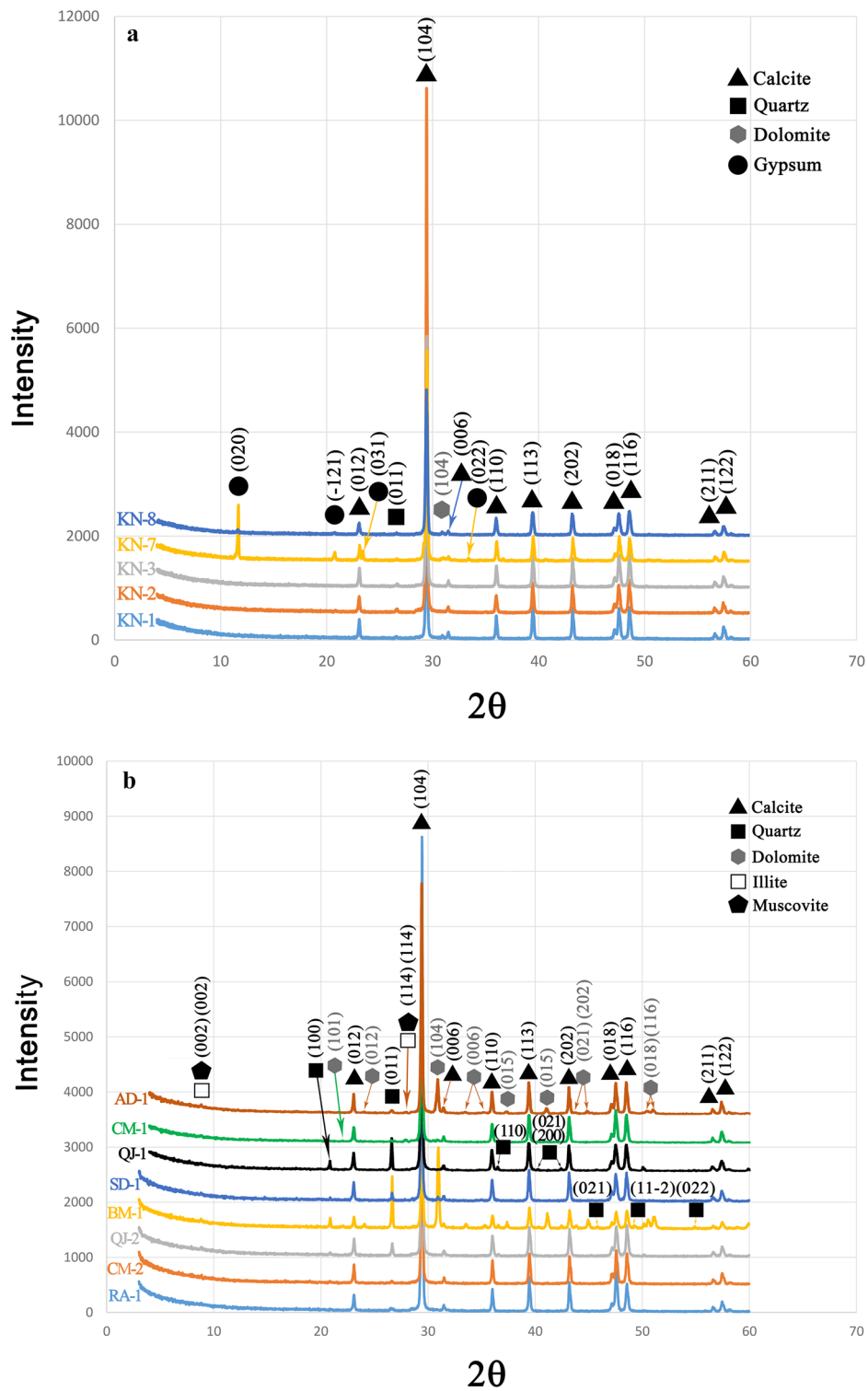
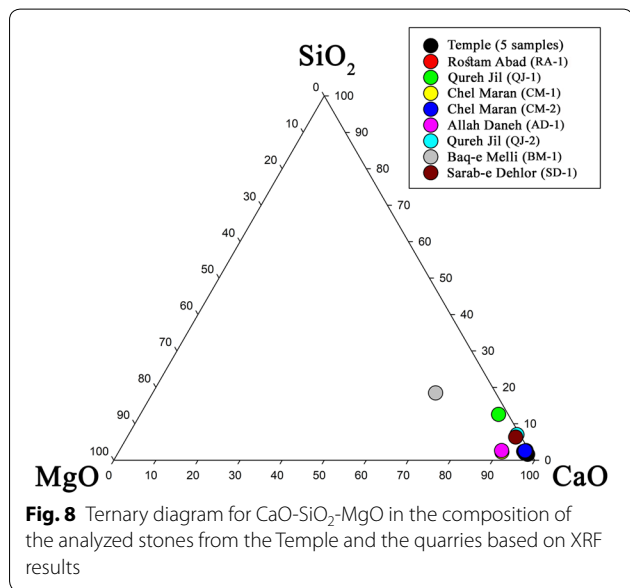


Fig. 7 a X-ray diffractogram of five stone samples from the Anahita Temple. Calcite is the main phase, while the minor phases are quartz and dolomite. Gypsum is the minor phase in two samples (KN-7 and KN-8). **b** X-ray diffractogram of eight samples from the stone quarries. Calcite is detected as the main phase in all the samples. In sample BM-1 dolomite is also an important phase. Quartz is detected in two samples in significant content. Quartz, dolomite and illite/muscovite are the minor phases in other samples

Table 3 Results of XRF analysis of the major and minor constituents (oxides, wt %) of the stone samples from the Anahita Temple and the quarries

	Sample	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MnO	MgO	CaO	Na ₂ O	K ₂ O	TiO ₂	P ₂ O ₅	LOI	Sum
Temple	KN-1	1.07	0.59	0.17	0.01	0.77	54.49	0.06	0.11	—	0.02	42.45	99.74
	KN-2	1.47	0.62	0.21	0.01	0.41	54.22	0.04	0.1	—	0.02	42.72	99.82
	KN-3	0.89	0.17	0.11	0.01	0.49	54.95	0.05	0.03	—	0.02	43.12	99.84
	KN-7	1.37	0.62	0.18	0.01	0.8	54.91	0.19	0.09	0.02	0.03	41.12	99.34
	KN-8	1.31	0.49	0.18	0.01	0.74	53.56	0.07	0.09	0.02	0.02	42.74	99.23
Quarries	RA-1	1.38	0.66	0.31	0.01	0.45	53.87	0.14	0.15	—	0.03	42.85	99.85
	QJ-1	7.5	0.42	0.4	0.02	0.49	50.85	0.02	0.11	—	0.03	40.03	99.87
	QJ-2	3.97	0.76	0.43	0.02	0.41	52.47	0.05	0.17	—	0.01	41.59	99.88
	CM-1	1.33	0.57	0.14	0.01	0.72	54.09	0.11	0.09	—	0.02	42.78	99.86
	CM-2	1.43	0.41	0.14	0.01	0.56	54.39	0.03	0.08	—	0.01	42.85	99.91
	AD-1	1.45	0.69	0.32	0.05	3.64	50.47	0.01	0.17	—	0.02	43.06	99.88
	BM-1	10.76	0.83	0.54	0.03	8.34	39.23	—	0.18	0.01	0.06	39.64	99.62
	SD-1	3.53	1.35	0.59	0.04	0.76	51.61	0.07	0.28	0.04	0.02	41.48	99.77



samples from the Temple are closely correlated with those from the Chel Maran (especially sample CM-2), Qureh Jil (samples QJ-1 and QJ-2), Allah Daneh (sample AD-1) and Rostam Abad (RA-1) quarries, respectively.

Nevertheless, on the basis of chemical and phase analyses, all the samples from the Temple and the quarries can be categorized as either limestone or dolomitic limestone. There are different methods for classifying carbonate stones which can be used to identify a particular type of limestone in petrological studies. Cox et al. [66] suggested a classification method for carbonate stones based on the percentage of CaO in their chemical composition. According to this classification, carbonate stones with

more than 55.2% CaO content contain more than 98.5% of CaCO₃ and can therefore be considered as “very high purity” limestone (method I). The next level of purity is “high purity”, for stones with a CaO content of between 54.3 and 55.2%, in which the amount of CaCO₃ will be between 97 and 98.5%. Another method is based on the MgO content of carbonate stones (method II) [67]. Some early publications about the composition of carbonate stones classified them according to their CaO/MgO ratio (method III) [63, 68, 69]. Previous researchers have also proposed different classifications based on the quantity of calcite, dolomite and other insoluble constituents (quartz, clay minerals, etc.) present in the composition of carbonate stones (method IV) [62, 70, 71]. In our case, the XRD analysis showed that minerals such as quartz, dolomite, illite/muscovite and gypsum are present in the composition of samples as impurities.

Based on the analytical results for the stone samples from the Anahita Temple and the quarries, we used the four classification methods described above (methods I, II, III and IV respectively) to identify the different types of carbonate stones analysed. The results are set out in Table 5. According to Classification Method I, the stones used in the Temple can be classified as high-purity and medium-purity limestones. In particular, the sample from Chel Maran 2 (CM-2) is high purity, the samples from Chel Maran 1 (CM-1) and Qureh Jil 2 (QJ-2) are medium purity, Qureh Jil 1, Allah Daneh and Sarab-e Dehlor are low purity and the sample from Baq-e Melli is classified as impure limestone. According to Classification Method II all the analyzed samples can be categorized as dolomitic limestone except for those from Allah Daneh (AD-1) and Baq-e Melli (BM-1). These are classified as slightly dolomitic limestones and

Table 4 Results of XRF analysis of trace elements (ppm) in the stone samples from the Anahita Temple and the quarries

	Sample	V	Cr	Co	Ni	Cu	Zn	Ga	Ba	As	Cd	Mo	Nb	Pb	Rb	Sb	Sr	Th	U	Y	Zr
Temple	KN-1	—	10.8	—	3.6	1.7	16.4	1.8	34.2	2.5	1.6	1.1	2.1	1.7	5.4	—	147.2	—	—	1.5	18.8
	KN-2	2.2	8.5	—	5.6	7.2	15.9	2.8	38.2	2.7	1.7	1	2.5	3.5	5.6	—	177.8	—	—	2.7	19.1
	KN-3	—	8.5	—	3.4	0.6	13.7	1.5	31	2.4	1.7	0.8	2.1	2.1	2.6	—	159	—	—	1.2	15.8
	KN-7	—	—	—	—	—	—	—	—	—	—	—	—	16	15	—	249	—	—	12	11.3
	KN-8	—	1	—	—	—	—	—	—	—	—	—	—	18	7	—	212	—	—	11	14.2
Quarries	RA-1	—	9.7	—	5.5	2.3	21.1	1.8	58.9	4.7	1.7	1.2	4.8	2.8	5.8	—	477.6	—	—	2.7	9.7
	QJ-1	—	14.3	—	10.1	2.6	21.4	1.8	35.4	10.2	1.6	1.3	3.4	18.1	4.9	—	246.4	—	—	4.4	17.6
	CM-1	—	8.7	—	4.3	3.3	12.1	1.8	37.2	2	1.7	0.5	3.4	2.4	4.3	—	360.9	—	—	0.9	12.3
	CM-2	—	7	—	4.9	2.8	15.3	1.6	31.9	1.2	1.7	0.9	1.8	4.3	4.7	—	140.3	—	—	0.4	18.3
	AD-1	16.2	9.5	—	6.4	0.9	17.1	1.8	39.7	4.4	1.5	1.1	2.4	3.7	6.0	0.2	214.9	0.1	2.1	2.7	18.5
	QJ-2	7	9.5	—	5.2	3.1	13.1	2.5	37.4	4.6	1.6	1.2	2.9	2.8	6.6	—	177.8	—	—	5.5	21.2
	BM-1	2.5	14.5	—	8.3	—	38.3	1.6	38.3	3.5	1	1.2	2.2	5.9	6.5	—	91	0.5	0.4	6.5	32.5
	SD-1	6.5	9.8	—	5.8	2.7	106.2	1.9	62.9	9.7	1.7	1.6	1.9	10.9	7.5	0.4	97	0.1	0.3	1.1	29.7

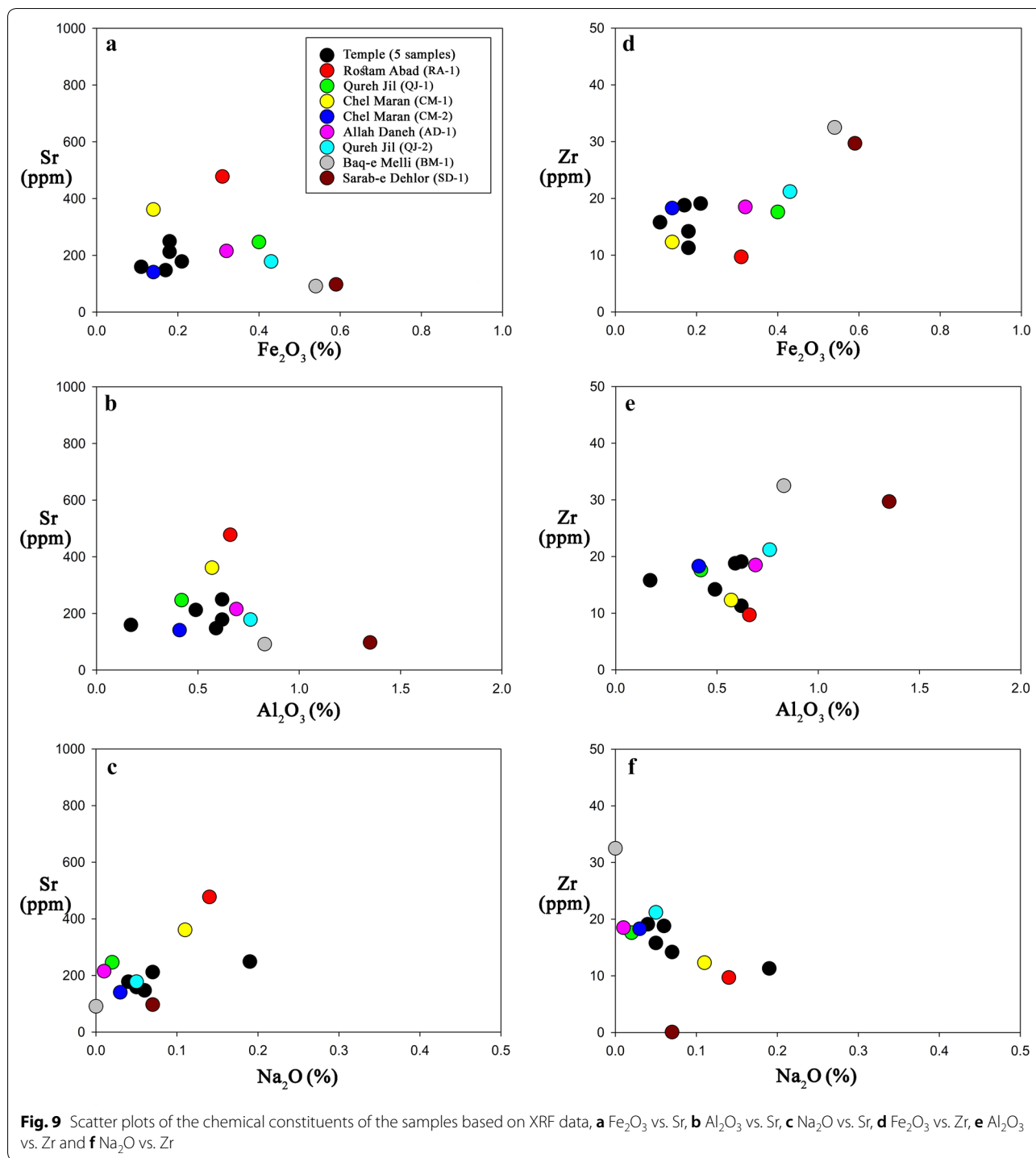
dolomitic limestones *sensu stricto*, respectively. This is due to the high concentration of MgO in the stone from these two quarries. According to Classification Method III, all the samples are limestone, although samples AD-1 and BM-1 are slightly dolomitic limestone and dolomitic limestone respectively. Finally, Method IV classifies all the samples from the Temple and the quarries as limestone, except for AD-1 and BM-1, which are classified as dolomitic limestone and impure dolomitic limestone respectively. In general, these comparisons show that the stones used in the Temple are very similar, while the samples from the quarries can vary in terms of composition. In fact, some of the stones from the quarries show low purity based on CaCO₃ content (QJ-1, AD-1 and BM-1). Nevertheless, according to Classification Methods II, III and IV the samples from the Temple and the quarries have very similar compositions, while the stones from Allah Daneh and Baq-e Melli are slightly different.

The analytical studies proved that the stone blocks from the Anahita Temple were made out of calcareous stone with some dolomite content as well as very small amounts of impurities such as quartz and clay minerals.

The next stage was to compare the petrographic micrographs for the samples from the Anahita Temple and the quarries. These reveal that the samples from Chel Maran are very similar from a textural point of view, and in particular sample CM-2, which comes from the western part of the Chel Maran mountain, where widespread evidence of quarrying and stone extraction is visible. Based on the classification of the carbonate stones set out in Table 5, it would seem that the stone used in this monument was either limestone or dolomitic limestone. This type of limestone has a fine texture from micritic to sparitic microstructure in which veins of different thickness filled

by secondary calcite are visible. A lot of fine veins of iron compounds and clay minerals can also be observed in the fabric of the stones from the Anahita Temple. The results of the analysis of the stone samples from different areas in the Kangavar region in which there was evidence of ancient stone quarrying suggest that some of these quarries were used extensively as a source of raw materials for the construction of the Temple. These materials can be identified as calcareous stones with different impurities. In fact, the stones from the quarries can be classified as either limestone or dolomitic limestone with different impurities (Rostam Abad, Qureh Jil, Chel Maran and Sarab-e Dehlor), with small amounts of dolomite (Baq-e Melli) and as dolomitic and impure dolomitic limestone with large amounts of dolomite (Allah Daneh). Quartz and clay minerals are also present in the composition and texture of the stones from the quarries. It is worth noting that the stone samples from Chel Maran, Qureh Jil and Rostam Abad show a significant correlation with the stones from the Anahita Temple, while the stones from Allah Daneh, Baq-e Melli and Sarab-e Dehlor are less closely related. Nevertheless, it is important to note that from a petrological point of view the latter quarries have a lot in common with the others (except for Sarab-e Dehlor), and that where they differ is in terms of composition, with high MgO and SiO₂ contents as well as different amounts of trace elements. In fact, all the quarries consist of calcareous stone (limestone) with varying major constituents and amounts of impurities (minor/trace constituents).

The analytical studies showed that the stones used in the construction of the Anahita Temple were from local sources. In fact, all the stone quarries and the stone cutting area around the Temple may have been used over the course of time to produce different types of stone



blocks used in the building. Nevertheless, some of the stone quarries, such as the western hill of the Chel Maran mountain and the Qureh Jil and Rostam Abad quarries may have been used more extensively. In addition, the survey of the local stone quarries in the Kangavar region shows that these three stone quarries were used more

than the other areas [44]. This is clear to see from the remains of archaeological mining and quarrying in these three quarries. This indicates that the analytical data for the stone quarries matches much of the archaeological evidence uncovered in this region. Furthermore, evidence shows that building stone was extracted and cut to

Table 5 Characterization of the analyzed stone samples from the Anahita Temple and the quarries based on four methods for the classification of calcareous stones

	Classification method I			Classification method II		Classification method III		Classification method IV	
	CaO (%)	CaCO ₃ (%)	Type	MgO (%)	Type	CaO/MgO	Type	CaCO ₃ (%)	Type
KN-1	54.49	96.79	High purity	0.77	Dolomitic limestones	70.77	Limestone	96.79	Limestone
KN-2	54.22	96.31	Medium purity	0.41	Dolomitic limestones	132.24	Limestone	96.31	Limestone
KN-3	54.95	97.60	High purity	0.49	Dolomitic limestones	112.14	Limestone	97.60	Limestone
KN-7	54.91	97.53	High purity	0.8	Dolomitic limestones	68.64	Limestone	97.53	Limestone
KN-8	53.56	95.13	Medium purity	0.74	Dolomitic limestones	72.38	Limestone	95.13	Limestone
RA-1	53.87	95.68	Medium purity	0.45	Dolomitic limestones	119.71	Limestone	95.68	Limestone
QJ-1	50.85	90.32	Low purity	0.49	Dolomitic limestones	103.78	Limestone	90.32	Limestone
QJ-2	52.47	93.20	Medium purity	0.41	Dolomitic limestones	127.98	Limestone	93.20	Limestone
CM-1	54.09	96.07	Medium purity	0.72	Dolomitic limestones	75.13	Limestone	96.07	Limestone
CM-2	54.39	96.61	High purity	0.56	Dolomitic limestones	97.13	Limestone	96.61	Limestone
AD-1	50.47	89.64	Low purity	3.64	Slightly dolomitic limestones	13.87	Slightly dolomitic limestone	89.64	Dolomitic limestone
BM-1	39.23	69.68	Impure	8.34	Dolomitic limestones sensu stricto	4.70	Dolomitic limestone	69.68	Impure dolomitic limestone
SD-1	51.61	91.67	Low purity	0.76	Dolomitic limestones	67.91	Limestone	91.67	Limestone

Classification Method I [66]; Classification Method II [67]; Classification Method III [63, 68, 69] and Classification Method IV [62, 70, 71]

size at these three quarries. Unfinished stone blocks similar to the finished blocks used in the Temple have also been discovered. This supports the hypothesis that these were the main stone quarries used in the construction of the Anahita Temple. The results of the analytical studies also matched the results of the archaeological studies very well.

It is also very interesting to note that the stone quarrying activities observed in Chel Maran and other quarries are very similar to those observed in the stone quarries near the Achaemenian sites including Persepolis and Pasargadae. These include cutting and carving the block into shape in the quarry and moving the unfinished blocks to the building for final preparations. Other clues include possible “signatures” of the stone workers on the surface of the blocks [3, 41]. Nevertheless, the quality of the stone working and the design in the Achaemenian sites was much better than that used in the Anahita Temple, which suggests that they date from different eras with less important rulers. It is clear that a lot more archaeological and scientific research is required on the Anahita Temple of Kangavar to find out

more about the history of this site. Comparative studies on the architectural and technological aspects of this huge building could also be carried out in the future. This study shows that the application of scientific experimental studies is very useful for characterizing the technological and archaeological features of ancient buildings, in this case the Anahita Temple, especially in the field of ancient mining and for identifying the source of the raw materials used in stone constructions.

Conclusion

Archaeological and field studies conducted over the last decades in the Kangavar region of western Iran, have uncovered evidence of ancient stone quarries that may have been used as a source of materials for the largest and most famous ancient stone construction in this region, the Anahita Temple of Kangavar. An analytical study of the stone from the Anahita Temple and from nearby ancient stone quarries was performed to identify the different types of stone in a bid to ascertain the provenance of the many stone blocks used in the construction of this

important archaeological complex. Results of mineralogical observations and chemical analyses showed that most of the stones used in the construction of the Temple are limestone with minor amounts of impurities such as Mg and Si. Other stones can be considered as dolomitic limestone because they have a slightly higher Mg content. Calcite is the main mineral in the composition of the stone samples from the Temple and dolomite and silicate phases (quartz and clay minerals) were detected as minor phases or impurities. The study of the samples from the stone quarries showed various similarities between the stones from the Temple and the stones from the quarries from the chemical and mineralogical points of view. Nevertheless, the Chel Maran, Qureh Jil and Rostam Abad quarries, and in particular the western hill of Chel Maran mountain (sample CM-2) were probably the main sources of the stone blocks used in the Anahita Temple, although it is likely that limited amounts of stone were also obtained from the other quarries.

Abbreviations

XRD: X-ray diffraction; XRF: X-ray fluorescence.

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Authors' contributions

AS studied the thin section of the stone samples by microscopy methods, contributed to the preparing the draft of paper and also read the text, OO prepared the samples, contributed in the analytical works and interpretation of the analytical data as well as preparing the draft of the paper, GC contributed to the chemical analyses and read and corrected the final paper, and MA collected the samples from quarries, provided photos of site and quarries and contributed to prepare samples for analyses. All authors read and approved the final manuscript.

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Availability of data and materials

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

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