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Review of the Sayh al Uhaymir (SaU) 005, Plus Pairings, Martian Meteorite from Al Wusta, Oman

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ABSTRACT: Al Wusta is a desert area in the Sultanate of Oman which is famous due to the discovery of a number of Martian and Lunar meteorites since the start of the present millennium. According to the Meteoritical Bulletin database, 137 approved Martian meteorites have been found worldwide, including 17 from Oman (4 from Zufar, 13 from Al Wusta region). Interestingly 11 finds in the last 15 years have been of Sayh al Uhaymir (SaU) 005 and its pairings. These finds (estimated mass = 11.2 kg) are linked to 10 search expeditions carried out between November 26, 1999 and March 2, 2014 by the Swiss group from the University of Bern and several anonymous meteorite hunters. The bulk of these meteorites (~97%) is in the possession of anonymous collectors, negatively affecting Oman’s natural heritage and denying further research opportunities, given their associated scientific value.

SaU 005 and its pairings belong to the shergottite group of the Shergotty-Nakhla-Chassigny (SNC) meteorites, originating from various depths within the Martian mantle. We discuss the recently published oxygen isotope data of bulk and mineral fractions of SaU 008 recovered during the very first expedition in 1999 in the context of other shergottites found in Oman. The bulk oxygen isotope data of SaU 008 and Dhofar 019, another Martian meteorite from Oman, show a narrow range in $\delta^{18}O$ values. Their $\Delta^{17}O$ values are remarkably close to identical and fall linearly on a Martian fractionation line above the terrestrial fractionation line (TFL) by + 0.32‰, suggesting that Mars’ mantle is homogeneous in oxygen isotopes.

Petrographic and mineralogical data of SaU 005 and other pairings published in the Meteoritical Bulletin are compiled, and it is noted that all the meteorites are identical and are likely paired. The story behind these rare extra-terrestrial specimens demands a local meteorite museum and preliminary testing laboratory at Sultan Qaboos University (SQU) to protect this treasure trove of Omani heritage.

Keywords: Mars; Oxygen isotopes; SNC meteorites; Oman.

مراجعة لنيازك سيح الأحيمر 005 المريخية وقريناتها، المنطقة الوسطى، سلطنة عمان

أرشاد علي، صبحي نصير، عفت جابيين و أحمد الرواس

الملخص: تشتهر منطقة سيح الأحيمر بالمنطقة الوسطى الصحراوية في سلطنة عمان باكتشاف عدد من النيازك المريخية والقمرية منذ مطلع القرن الحالي. وطبقا الى بيانات نشرة النيازك فقد تم العثور على 137 نيزك مريخي في العالم تتضمن 17 نيزك من عمان (4 من ظفار، 13 من المنطقة الوسطى). ومن المثير ان 11 نيزكا تم العثور عليها في سيح الأحيمر خلال الخمس عشر سنة الماضية. عثر على هذه الموجودات خلال 10 رحلات استكشافية من قبل مجموعة جامعة بيرن السويسرية وكذلك صيادو النيازك خلال الفترة من 26 نوفمبر 1999 الى 2 مارس 2014. من المحتمل ان تعود جميع هذه النيازك (11.2 كلغم) الى نفس النيزك الأصلي الذي وقع في الصحراء. تقع معظم نيازك سيح الأحيمر المريخية (97%) في أيادي مجهولين، وهذا يؤثر على التراث العماني الطبيعي وقيمته العلمية. تتبع نيازك سيح الأحيمر005 ورديفاتها الى مجموعة الشيروجيت ضمن نيازك الشيروجيت -نخلا- شاسجني ذات الأصل المريخي من اعماق مختلفة. نناقش في هذا البحث بيانات نظائر الاوكسيجين المنشورة لمعادن وتركيب نيزك سيح الاحيمر 008 وهو من اول النيازك التي عثر عليها خلال عام 1999مقارنة مع النيازك المريخية الاخرى من عمان. تظهر بيانات نظائر الاكسيجين 18 لنيزك ظفار 019 وسيح الاحيمر 008 نطاق ضيق من قيم الاكسيجين 18. هذه البيانات متشابهة في قيم الاكسيجين 17 وتقع على خط تمايز المريخ وفوق خط تمايز الصخور القارية بقيمة +0،32% مما يدل على تجانس نظائر الاكسيجين في المريخ. تم تجميع ومناقشة البيانات المعدنية والمجهرية المنشورة حول النيازك المريخية من سيح الأحيمر005 ورديفاتها. يتطلب تواجد نيازك سيح الاحيمر وتوزعها عمل متحف خاص بالنيازك ومختبر متخصص لها في الجامعة لحماية التراث العماني.

الكلمات المفتاحية: المريخ، نظائر الأكسجين ، نيازك شيروجيت- نخليت -شاسجنيت (ش ن ش).

1. Introduction

Meteorites are extra-terrestrial objects that land on Earth after extensive travel in space. Our Earth is constantly showered by chunks of meteorites from the asteroid belt and neighboring planets. These alien rocks heat up when they enter the Earth's atmosphere due to friction and give them a dark and shiny surface called a fusion crust. This unique visual characteristic helps in tracking down meteorites particularly in flat, light-colored deserts due to the color contrast [1]. The Sultanate of Oman has been the hub of meteorite search since the start of this millennium. In the early years, private collectors took advantage of the free trafficking of meteorites across Oman's borders, leaving the country deprived of its national treasure [1]. Fortunately, Oman has recently regulated the export of meteorites for the protection of future meteorite finds; however, damage has already been done to some precious samples including Sayh al Uhaymir (SaU) 005 and most of its pairings. Al Wusta is the desert area in Oman where several Martian and Lunar meteorites have most commonly been spotted by the commercial meteorite dealers and international scientific teams. Until recently (April 2016), Meteoritical Bulletin has reported 137 approved Martian meteorites including 17 from the Sultanate of Oman (Table 1).

Table 1. Martian meteorite finds from the Sultanate of Oman.

Approved Name	Classification	Find Location	Year	Mass (g)
Dhofar 019	Shergottite-basaltic (ol phyric)	Zufar	2000	1056
Dhofar 378	Shergottite-basaltic	Zufar	2000	15
Dhofar 1668	Shergottite	Zufar	2011	6.1
Dhofar 1674	Shergottite	Zufar	2010	49.2
Jiddat al Harasis 479	Shergottite	Al Wusta	2008	553
Jiddat al Harasis 910	Shergottite	Al Wusta	2011	27
SaU 005	Shergottite-basaltic (ol phyric)	Al Wusta	1999	1344
SaU 008	Shergottite-basaltic (ol phyric)	Al Wusta	1999	8579
SaU 051	Shergottite-basaltic (ol phyric)	Al Wusta	2000	436
SaU 060	Shergottite-basaltic (ol phyric)	Al Wusta	2001	42.3
SaU 090	Shergottite-basaltic (ol phyric)	Al Wusta	2002	94.8
SaU 094	Shergottite-basaltic (ol phyric)	Al Wusta	2001	223
SaU 120	Shergottite-basaltic (ol phyric)	Al Wusta	2002	75
SaU 125	Shergottite-basaltic (ol phyric)	Al Wusta	2003	31.7
SaU 130	Shergottite-basaltic (ol phyric)	Al Wusta	2004	279
SaU 150	Shergottite-basaltic (ol phyric)	Al Wusta	2002	107.7
SaU 587	Shergottite (ol phyric)	Al Wusta	2014	4.7

Since the year 2000, the rate of meteorite finds has been rapid, triggering a delay in the reporting and classification of an exponentially increasing number of new samples [1]. For classification of a new meteorite, a submission is made to the Meteoritical Bulletin in the form of a template filled with some basic details such as find/fall location, date of recovery, latitude and longitude and mass, along with some visual observations of the sample at the time of recovery. Quite often, further petrographic, mineralogical, geochemical and isotopic data is also included for classification of the meteorite. These unique samples may represent tiny pieces from the core or mantle of other planets; providing us with the opportunity to learn more about the Earth's interior, given that the Earth is inaccessible at such depths. In order to learn about the origin of extraterrestrial materials in space, multiple stable isotope ratios of oxygen are commonly utilized. Oxygen is the most abundant element in the Earth's crust and mantle and the third most abundant, after hydrogen and helium, in the Solar System [2]. It has three isotopes; ^{16}O, ^{17}O and ^{18}O, differing in their masses and abundances in nature. The lightest isotope (^{16}O) comprises > 99% of the oxygen abundance in nature. Oxygen isotope ratios are conventionally expressed using the delta (δ) notation as:

$$\delta^{18}O = (^{18}R_{sample} - {}^{18}R_{VSMOW})/{}^{18}R_{VSMOW} \quad \text{where } {}^{18}R = {}^{18}O/{}^{16}O$$

and

$$\delta^{17}O = (^{17}R_{sample} - {}^{17}R_{VSMOW})/{}^{17}R_{VSMOW} \quad \text{where } {}^{17}R = {}^{17}O/{}^{16}O$$

Delta values are commonly expressed as permil (i.e., ‰). When oxygen isotope compositions of terrestrial silicate rocks and minerals are plotted on a three-isotope diagram of $\delta^{18}O$ and $\delta^{17}O$ values, the resultant straight line of slope-1/2 [3, 4] is commonly referred to as the terrestrial fractionation line (TFL). The TFL serves as a reference line to evaluate the provenance of meteorites. Offsets in oxygen isotope ratios relative to the TFL are used to characterize meteorite groups (Figure 1). A meteorite sample is mostly made up of silicate minerals and in order to liberate all the oxygen from it, the laser-fluorination technique is used. This method has been used globally at various laboratories for precise $\delta^{17}O$ and $\delta^{18}O$ measurements of terrestrial rocks [5-13] and meteorites [14-19] since the 1990s. The significance of triple oxygen isotopes is unprecedented in the realm of geochemistry and cosmochemistry, and the study of their relationship has found widespread and diverse applications in various fields including meteoritics. This system provides key information about the origin of rocks and the processes they underwent in the past. Oxygen isotope data of samples formed from any terrestrial chemical or physical process (e.g., melting-crystallization or evaporation-condensation) fit on the TFL having a slope of ~0.52 [4]. Conventionally, the offsets (i.e., $\Delta^{17}O$; negative or positive) from the TFL are calculated ($\Delta^{17}O = \delta^{17}O - 0.52\ \delta^{18}O$; [20]) to study the unique oxygen isotope signatures of meteorites. However, Miller [21] proposed the use of prime notation ($\delta'^{17}O$, $\delta'^{18}O$), which takes into account the linear function relationship between $\delta^{17}O$ and $\delta^{18}O$ for a sample measured with respect to a reference, instead of the conventional approximation of a power law function. Construction of the TFL, based on various types of terrestrial materials, is a pre-requisite to conduct geochemical and cosmochemical studies in a stable isotope laboratory.

Over half a century ago, [22] started reporting oxygen isotope data of various types of meteorites using the conventional method of oxygen extraction by fluorination (e.g., F_2, HF, BrF_5, ClF_3) of samples at 500-700ºC in Ni-tubes. More recent studies have employed affordable and reliable laser systems (e.g., CO_2 & Nd:YAG lasers) for heating the samples in a fluorinating atmosphere [5, 19, 23-25]. Compared to conventional fluorination methods, the laser fluorination technique is advantageous owing to its significant sample size reduction (1000-1500%) and improved reaction efficiency (e.g., 300%) without compromising the precision and accuracy of the data. It also has the considerable benefit of operating at high temperatures in order to react refractory mineral phases such as olivine and some oxides. In addition, oxygen produced by conventional methods typically involves conversion to CO_2 gas by reacting with hot graphite rods prior to analysis on a mass spectrometer. This requires further C-isotope corrections than if using oxygen gas as an analyte. As a result, the laser-fluorination technique is a preferred method to extract oxygen and measure triple oxygen isotopes online or offline.

We include the Sayh al Uhaymir (SaU) 005 meteorite and its pairings in this review to assess their oxygen isotope data of bulk materials and separated fractions, along with published data of other Martian meteorites from Oman. In addition, an account of the collection history and petrographical/mineralogical details of SaU 005, plus pairings, are compiled and discussed.

2. Analytical Description

A comprehensive study has recently been carried out to analyze various samples from the Shergotty-Nakhla-Chassignite (SNC) group, including meteorites found in Oman (e.g., SaU 008 and Dhofar 019), for precise triple oxygen isotope measurements using the laser fluorination technique coupled with the mass spectrometer [19]. For bulk analysis, this study utilized a minimum of 50-100 mg of sample aliquot of both SaU 008 and Dhofar 019 meteorites to make powder. A small portion of the powdered material was pre-treated with 6M HCl at 70 °C for 2-3 minutes in order to remove the potential terrestrial weathering products, and so to obtain the actual isotope data of each meteorite. Acid-treated and untreated bulk materials (1-2 mg) were loaded on the sample holder and placed in the sample chamber. After complete evacuation of the vacuum line, a reaction was performed by heating the sample with a 25W CO_2 laser (10.6 µm wavelength; Merchantek, Bozeman, MT, USA; Model MIR10-25) in a BrF_5 atmosphere to extract oxygen gas. Similarly, separated fractions such as pyroxene and olivine for SaU 008 and maskelynite for Dhofar 019 were also irradiated with the laser to produce oxygen gas from the mineral framework. Later, oxygen gas was purified using cryogenic metal traps and a heated KCl salt trap, giving yields of better than 95%. The triple oxygen isotope measurements were performed using a Delta V Plus mass spectrometer in dual inlet mode integrated with Isodat3.0 software for system controls and data acquisition. Data were reported as delta notation (δ) referenced to the Vienna Standard Mean Ocean Water (VSMOW). A detailed analytical methodology is described in [19].

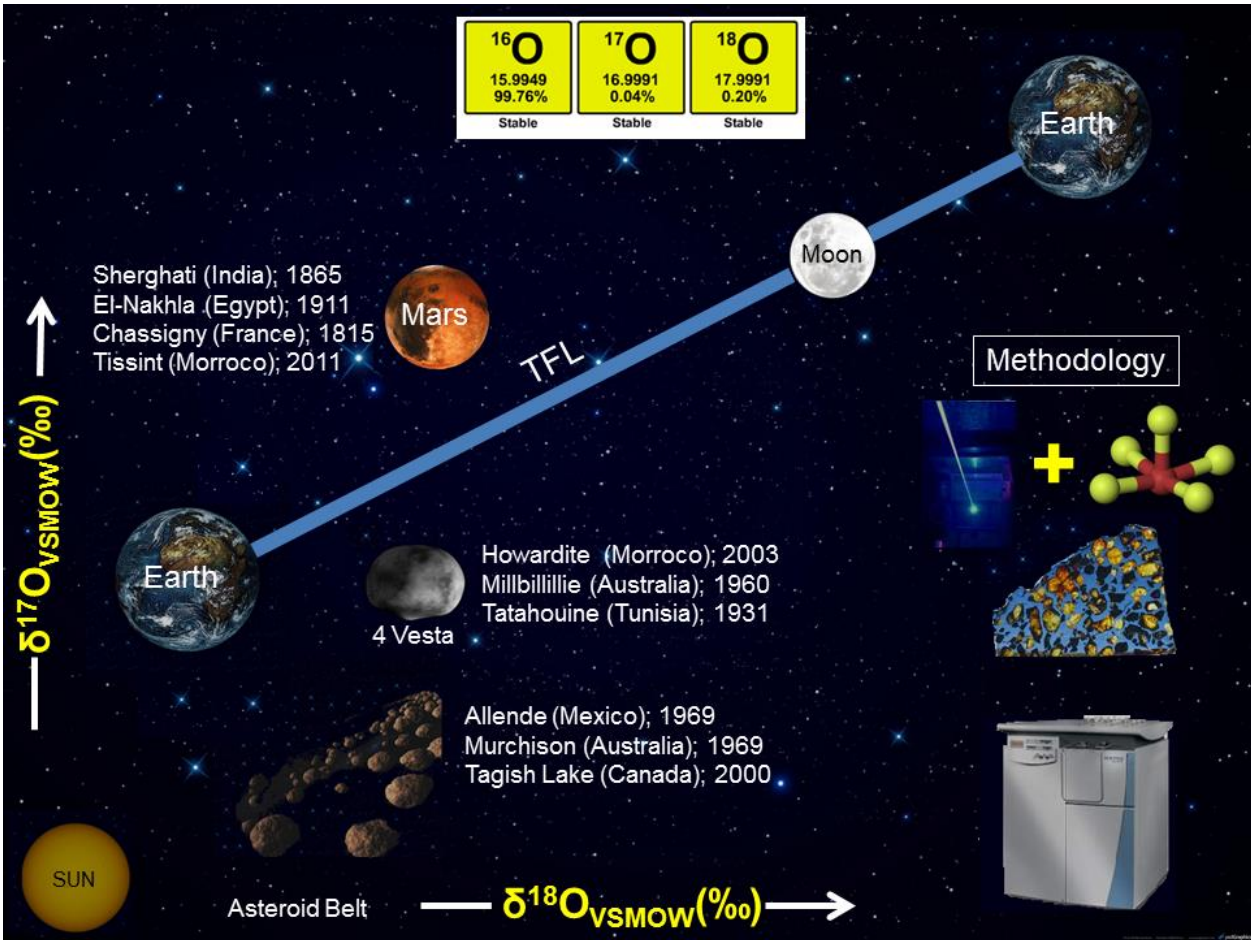


Figure 1. Pictorial illustration of the triple oxygen isotope diagram. Slope-1/2 line is referred to as the Terrestrial Fractionation Line (TFL); triple oxygen isotope data from planet Earth, moon and Enstatite Chondrites fall on the TFL; however, data from other extra-terrestrial bodies either fall above or below the TFL. Some meteorites (with their place and year of fall) are shown for comparison. Right bottom of the illustration (methodology) displays an image of a laser and BrF_5 (Br attached to 5 fluorine atoms) for extracting oxygen gas from the crystal framework (e.g., olivine) of a meteorite (image: pallasite) followed by isotopic measurements using a mass spectrometer. Individual images are taken from the Internet. This illustration is not to scale.

3. Discussion

Sample preparation and pre-treatment

After extensive space travel, meteorites encounter terrestrial conditions for long periods of time, of thousands of years and more. Terrestrial weathering will result in shifts in $\Delta^{17}O$ of a meteorite towards the TFL compared to its actual value, due to the formation of secondary carbonate and oxide minerals. For example, meteorite data below the TFL, will move upwards, as in the case of pallasites, and that above will move downwards, as with SNC meteorites, due to terrestrial weathering, so there is a two directional shift around the TFL depending on what type of meteorite is under investigation. If weathering is non-terrestrial, e.g., having occurred on the surface of Mars, the trend will be different as evidenced by [26] from the Lafayette meteorite. They reported heavier $\delta^{18}O$ and higher $\Delta^{17}O$ values for Low-T mineral (e.g., Iddingsite) formed on the surface of Mars. Antarctica has a large population of meteorites which have remained preserved under the ice cover for extended periods of time. A recent study [18] has reported contrasting weathering trends in Antarctic and non-Antarctic meteorite finds. A reasonable interpretation of this paradigm is that whenever there is terrestrial weathering in a non-Antarctic environment, the data will go up due to secondary carbonate and oxide minerals, whilst in an Antarctic environment, the data of weathered meteorites will go down possibly due to Antarctic snow which is extremely low in $\delta^{18}O$ compositions [e.g., Longhovde area has -30‰; 27], that could become incorporated into the weathering products.

Oxygen isotope data of SNC meteorites from the Sultanate of Oman

The published oxygen isotope compositions of SNC meteorites from the Sultanate of Oman are compiled in Table 2 and plotted in Figure 2. The few data points showing a scatter in $\Delta^{17}O$ values (Figure 2) are likely to be associated with either terrestrial weathering (assuming that samples were analyzed without acid-treatment given the absence of such details reported in the literature) or due to analytical artifacts in $\delta^{17}O$ measurements (^{17}O abundance = 0.04%; see Figure 1). However, recently researchers [19] have analyzed SNC meteorites and they have found no significant variation in $\Delta^{17}O$ values between the untreated and acid-treated samples. Their data did not support the idea of scatter in $\Delta^{17}O$ due to a weathering phenomenon. However, it is noted that the data of acid-treated samples are skewed towards lower values. They argued that the discrepancy is caused by the elimination of carbon dioxide gas from the carbonates (i.e., originated on Mars surface) after acid treatment. Carbonates are typically heavy in oxygen isotopes [28-31]. A recent work [19] also commented on the most common interferences (m/z = 33) on $\delta^{17}O$ values. Traces of fluorination by-products such as NF_3 and CF_4 are caused by inefficient removal of these species when they are trapped with extracted oxygen gas on adsorbing media (i.e., molecular sieves 13X and 5Å) at liquid-N_2 temperature. These analytical artifacts directly affect $\Delta^{17}O$ data.

Table 2. Triple oxygen isotope compositions of bulk and separated fractions of SNC meteorites from the Sultanate of Oman.

Sample	Type	$\delta^{17}O_{VSMOW}$ (‰)	$\delta^{18}O_{VSMOW}$ (‰)	$\Delta^{17}O$ (‰)	N	Reference
Dhofar 019	bulk	2.299±0.102 (SE)	3.826±0.189 (SE)	0.310±0.006 (SE)	3	[19]
Dhofar 019	bulk	2.569	4.474	0.216	–	[32]
Dhofar 019	bulk*	2.890	4.937	0.325	2	[19]
Dhofar 019	bulk	2.99	5.4	0.18	–	[33]
Dhofar 019	mask	2.918	4.985	0.328	2	[19]
Dhofar 378	bulk@	2.52	4.46	–	–	[34]
JaH 479	bulk§	2.951	5.070	0.315	–	[35]
SaU 008	bulk*	2.696	4.544	0.335	2	[19]
SaU 008	bulk	2.212	3.677	0.300	2	[19]
SaU 008	px	2.673	4.533	0.318	2	[19]
SaU 008	ol	2.518	4.223	0.324	2	[19]
SaU 094	bulk§	2.51	4.25	0.28	–	[36]
SaU 0150	bulk§§	2.78	4.74	–	–	[37]

ol = olivine. px = pyroxene. mask = maskelynite. JaH = Jiddat al Harasis. SaU = Sayh al Uhaymir. SE = standard error.
SE calculated by dividing the SD (standard deviation) with the square root of N. N = number of individual runs.
Samples marked with asterisk (*) were analyzed without acid treatment.
@oxygen isotope data were obtained by T. K. Mayeda and R. N. Clayton (University of Chicago, USA).
§oxygen isotope data were obtained by I. Franchi (Open University, UK).
§§oxygen isotope data were obtained by R. N. Clayton (University of Chicago, USA).

Sayh al Uhaymir (SaU) 005 Recovery Site

Sayh al Uhaymir (SaU) 005 and pairing meteorite finds are associated with several years of searches in the desert of Al Wusta, Oman. The latitude and longitude values, number of pieces, total mass recovered during each search and details of the finder are given in Table 3. The greatest part of the total mass of SaU 005 and pairings was recovered in the early years (1999-2000) and the tiniest mass of all (4.7 g) was found in the latest search carried out in 2014 (Figure 3). The heaviest pieces of all the finds were scattered in the middle of the find locations spanning an area of 2 km wide and 4 km long (Figure 4). It seems plausible that SaU 005 suffered shattering twice: first in the Earth's atmosphere due to heat generated by friction, and then by break-down due to impact on the ground causing heavily cracked pieces to fall apart within the vicinity of the larger stones (e.g., SaU 005 and SaU 008). For example, a lone piece of SaU 120 (75 g) has a well preserved fusion crust [37] which could have broken down from the original rock at a certain height in Earth's atmosphere. Consequently, the stone would have had sufficient time to react with the ambient air due to frictional heat, and as a result, developed a thick fusion crust. However, SaU 150 [37] shows relatively thinner fusion crust supporting the idea that this meteorite did not have sufficient interaction time to develop a thick fusion crust, as generally observed in other pieces (e.g., SaU 150). Moreover, SaU 587 [38] is characterized by the presence of partial fusion crust, owing to its possible break down after impact with the ground.

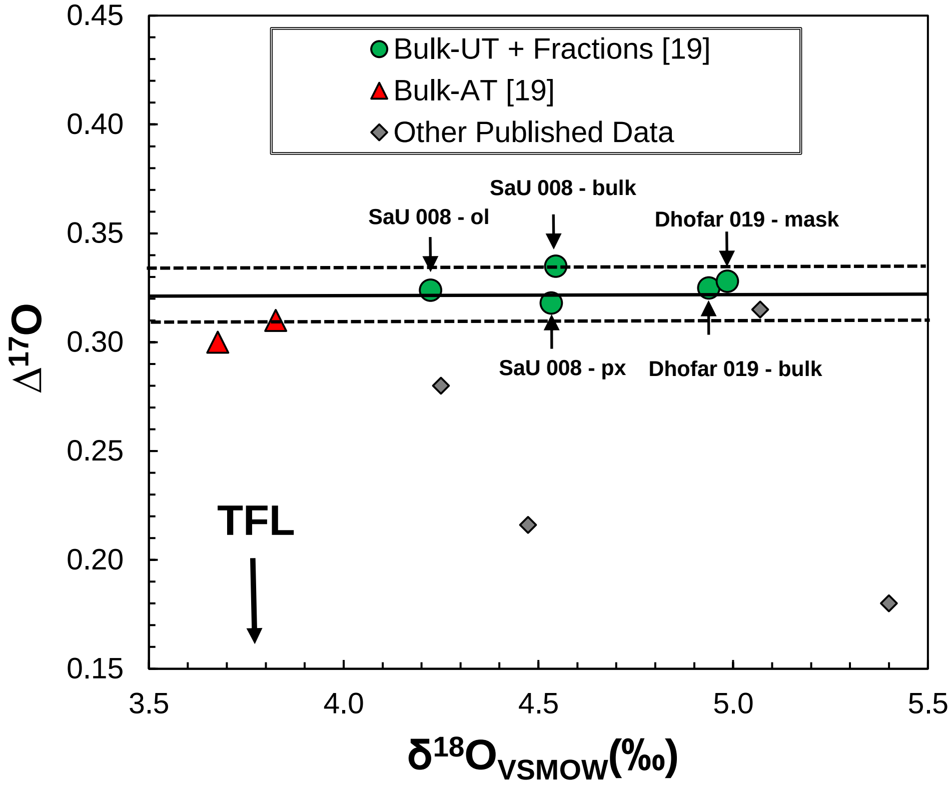


Figure 2. Comparison plot of δ^{17}O vs. δ^{18}O data published for bulk materials and separated fractions (i.e., px, ol, mask) of SNC meteorites from the Sultanate of Oman. Solid and dashed lines represent the Martian fractionation line [MFL; 19] and standard error respectively. UT = untreated. AT = acid-treated. px = pyroxene. ol = olivine. mask = maskelynite. TFL = terrestrial fractionation line. Other data sources: [32-33, 35-36].

Table 3. Sayh al Uhaymir (SaU) Martian meteorite finds in chronological order from the Sultanate of Oman.

Name	Location	Date	Latitude (N)	Longitude (E)	Pcs	Mass (g)	Finder/Main mass
SaU 005	Al Wusta	Nov. 26, 1999	20°59.76´	57°19.55´	3	1344	Anonymous/Anonymous
SaU 008	Al Wusta	Nov. 26, 1999	20°58.83´	57°19.14´	2	8579	Anonymous/Anonymous
SaU 051	Al Wusta	Aug. 01, 2000	20°58.435´	57°19.248´	1	436	Anonymous/Anonymous
SaU 094	Al Wusta	Feb. 08, 2001	20°59.469´	57°20.326´	1	223.3	M. H. & L. M. (Bern)/NMH
SaU 060	Al Wusta	Jun. 27, 2001	20°58.8´	57°19.1´	1	42.3	M. H. & L. M. (Bern)/NMH
SaU 090	Al Wusta	Jan. 19, 2002	21°00.0´	57°19.2´	2	94.8	Anonymous/Anonymous
SaU 150	Al Wusta	Aug. 10, 2002	20°59.313´	57°19.117´	1	107.7	R. & S. B. (Bart)/Bart
SaU 120	Al Wusta	Nov. 17, 2002	21°00.2´	57°19.3´	1	75	Anonymous/Anonymous
SaU 125	Al Wusta	Nov. 19, 2003	21°00.4´	57°19.3´	1	31.7	Not Given
SaU 130	Al Wusta	Jan. 11, 2004	21°00.2´	57°19.1´	4	278.5	Not Given
SaU 587	Al Wusta	Mar. 02, 2014	21°00.764´	57°19.238´	1	4.7	Anonymous/Anonymous

M. H. & L. M.= Marc Hauser & Lorenz Moser. Bern = University of Bern, Switzerland. NMH = Natural History Museum Bern, Switzerland. R. & S. B. = Rainer & Sven Bartoschewitz. Bart = Bartoschewitz Meteorite Laboratory, Germany. Pcs = pieces.

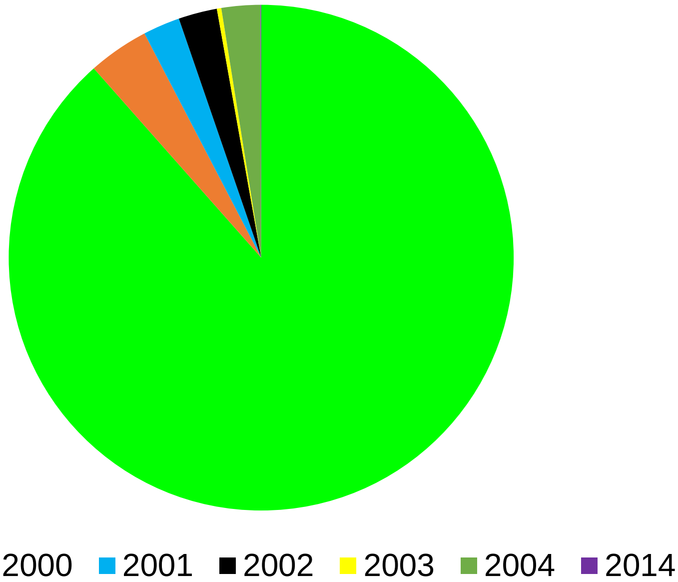
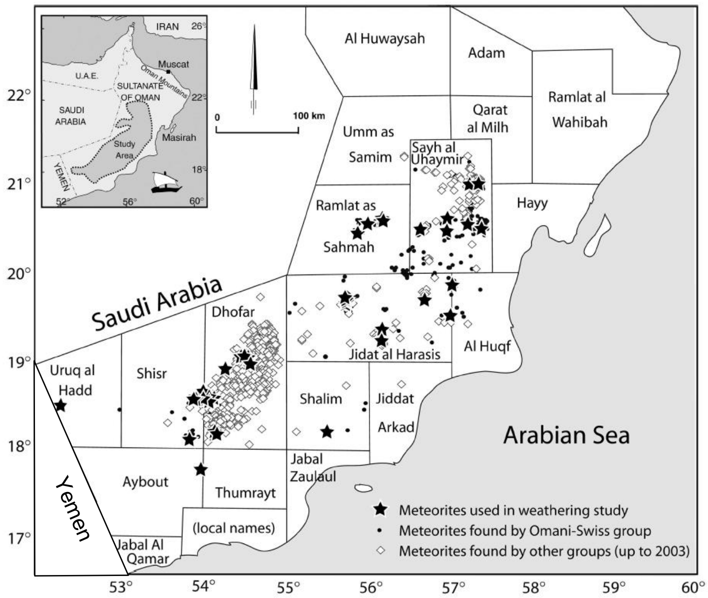


Figure 3. Pie chart showing recovered mass of the Sayh al Uhaymir (SaU) 005 Martian meteorite and its pairings found in various years from the Sultanate of Oman.

SaU 005+pairings find history and review of published data

Extremely fresh pieces of SaU 005/008 were recovered by anonymous meteorite hunters on November 26, 1999 (Table 3). However, a few cracks partially filled with calcite were seen owing to the terrestrial weathering processes. Both meteorites show porphyritic texture with large olivine phenocrysts (Table 4) in a fine-grained groundmass of pigeonite and maskelynite [39]. Olivine shows mosaicism and planar deformation and clinopyroxene grains (pigeonite) that are also twinned and fractured, all of which are possibly associated with the strongly shocked (S5) nature of these finds. In the following year, anonymous finders tracked down a piece of SaU 051 which is considered to be a pairing of SaU 005/008, based on texture, mineralogy (Table 4) and proximity in find locations. A shock stage S5 is assigned to this find and calcite veins [36] are also reported. The next year 2001, Marc Hauser and Lorenz Moser from the University of Bern, Switzerland, found SaU 060 and SaU 094, one stone apiece, during two separate expeditions. The main mass of the meteorites is curated at the Natural History Museum Bern, Switzerland. The mineralogical characteristics of these samples, e.g., large olivine phenocrysts (ave. max. size = 1.5mm) embedded in a fine-grained (ave. max. size = 0.3mm) groundmass of maskelynite and pigeonite [36], are comparable to those of SaU 005/008/051 and they are considered as pairs [40]. Moreover, both pieces display the same shock stage (S5) associated with shock twining, mosaicism and local oxidation in olivine [36]. It is also reported that SaU 094 has abundant partially recrystallized veins and pockets containing glass vesicles due to shock melting [36]. Compared to SaU 094, SaU 060 is slightly weathered with small rusty pockets of Fe-hydroxide, a likely replacement of an unknown pre-existing phase [36]. The porosity of meteorites plays an important role in terrestrial weathering caused by water and moisture. X-ray tomographic analysis of SaU 094 revealed pores of up to 3mm size and they constitute 0.4 vol% of the sample [36]. Sm-Nd data of ten fractions (e.g., wr, px) from SaU 005/094 form a linear array between $^{147}Sm/^{144}Nd$ and $^{143}Nd/^{144}Nd$ ratios yielding a crystallization age of 445±18 Ma [41]. Later, it was discovered that SaU 008 and SaU 094 have $\varepsilon^{142}Nd$ values of 0.647 and 0.569 [42] respectively which is significantly higher than the average chondritic (i.e., -0.18 ± 0.08) and terrestrial standard (i.e., 0 ± 0.03) values [43-44]. The $\varepsilon^{142}Nd$ enrichment in these samples is interpreted as being derived from an incompatible-trace-element-depleted source formed during the first 500 Ma of evolution of Mars.

(a)



(b)

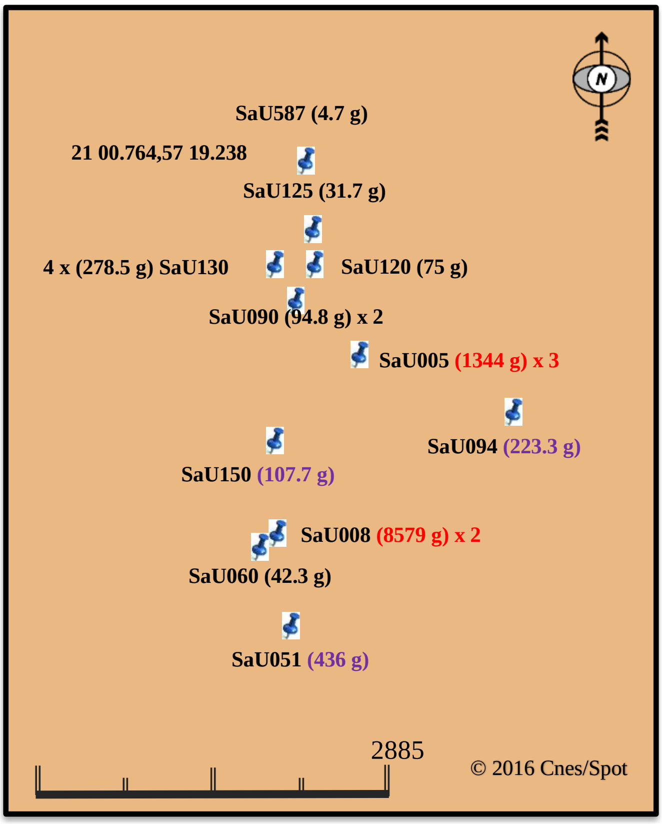


Figure 4. (a) A location map taken from [45]. (b) Find locations of various SaU 005 and pairing meteorites from Al Wusta, Oman. The recovery area is 2 km x 4 km. Approved names of all finds are shown with recovered masses (g) in brackets, along with number of pieces. Reds are the main mass of these fin ds, recovered during the first expedition in 1999. Purples were found as one piece having a mass of over 100g.

Four more pieces of SaU 090/120/150 were recovered during three separate searches in 2002. Two of the three searches were performed by anonymous hunters who recovered two pieces of SaU 090 and one piece of SaU 120, while in the third search Rainer and Sven Bartoschewitz from Bartoschewitz Meteorite Laboratory, Germany were successful in finding a piece of SaU 150 (Table 3). No textural and petrographic details of SaU 090 are provided in the Meteoritical Bulletin [34]. On the other hand, SaU 120 is reported as a gray-greenish stone with well-preserved fusion crust. The textural characteristics of SaU 120 are identical with other previously found pieces such as SaU 005/008/051/060/090/094 [37]. The SaU 150, a find by Rainer and Sven Bartoschewitz, was studied in detail for its geochemistry and oxygen isotopes [37]. It is an olive-brown colored stone of relatively angular shape with one small area of thin black-brown fusion crust. This piece was recovered on a Miocene fresh-water limestone gravel plateau. It displays a porphyritic texture with 2mm sized olivine phenocrysts embedded in a matrix of feldspathic glass and pigeonite. Minor Ca-poor pyroxenes with a composition of $En_{65-66}Fs_{34-35}$ are observed. Recrystallization of shock-melt veins and pockets is also noticed. A single piece of the SaU 125 was found by an unknown person in 2003 and it is considered as paired with SaU 005/008/051/060/090/094/120 [46]. The very next year, four pieces of SaU 130 were recovered by an anonymous finder and these samples were cited as paired with all the previously found meteorites including SaU 005/008/051/060/090/094/120/125 [46]. A compilation of petrographic, geochemical and isotopic data of SaU 005 and pairings found until 2004 is available at the Martian Meteorite Compendium [47]. Lastly, after a nine-year hiatus, a small piece (4.7 g) of the SaU 587 was recovered from the close vicinity of the previous find locations by an anonymous collector in early 2014. According to the Meteoritical Bulletin [38], it is a small greenish-gray stone with some fusion crust. Typical mm-sized olivine phenocrysts set within a fine-grained basaltic groundmass, dominantly of pigeonite and maskelynite, show a porphyritic texture. A high degree of shock metamorphism is associated with strong mosaicism of olivine, conversion of plagioclase to maskelynite and abundant melt veins and pockets [38]. Furthermore, intense fracturing is observed. However, this sample is moderately weathered, with only a few of the larger cracks being partially filled with calcite. It is paired with the SaU 005/008. Owing to the discovery of 10 pairings of the SaU 005 (Table 3) from the Al Wusta desert and strewn field (Figure 4b) with an area of 4 km by 2 km, it is suggested that a large piece of the rock may have broken down into several varyingly sized pieces before landing on the Earth's surface. The shattering of the rock may have been triggered by the frictional heat in the air, thus causing it to break twice, first in the air followed by the impact on the ground.

Table 4. Petrological data of Sayh al Uhaymir (SaU) 005 Martian meteorite and pairings from the Sultanate of Oman.

Name	Major Phases (write-up in Meteoritical Bulletin)	Minor Phases	Shock Stage	Ref.	Remarks
SaU 005	ol (Fo_{64-71}), pig ($En_{61-70}Wo_{6-13}$), mask ($An_{51-65}Or_{0.3-0.9}$)	aug, pho, opa	strongly shocked	[39]	
SaU 008	same as above	same as above	same as above	[39]	
SaU 051	ol (Fo_{61-68}), pig ($En_{60-68}Wo_{7-12}$), mask (An_{59-67})	not given	S5	[36]	paired with 005/008
SaU 094	ol (Fo_{65-69}), pig ($En_{60-68}Wo_{7-9}$), mask ($An_{55-64}Or_{5-9}$)	aug, chr, pyr	S5	[36]	
SaU 060	ol ($Fo_{63.1-70.8}$), pig ($En_{60-69.6}Wo_{7.1-8.6}$), mask ($An_{61.4-68.3}Or_{0.5-1.6}$)	aug (rare)	S5	[34]	aug = $En_{47}Wo_{35}$
SaU 090	not given	not given	not given	[34]	
SaU 150	ol (Fo_{67-74}), pig ($En_{62-69}Wo_{7-11}$), mask ($An_{53-66}Or_{0.3-0.8}$)	Ca-poor px	S5	[37]	a patch of fusion crust
SaU 120	not given	not given	not given	[37]	paired with all finds
SaU 125	not given	not given	not given	[46]	paired with all finds
SaU 130	not given	not given	not given	[46]	paired with all finds
SaU 587	ol ($Fa_{34\pm0.5}$), pig ($Fs_{25.2\pm2}Wo_{9.2\pm1.6}$), mask ($An_{60.4-65.9}Or_{0.4-o.6}$)	pho, sul, chr	not given	[38]	shock metamorphism

ol = olivine. pig = pigeonite. mask = maskelynite. aug = augite. pho = phosphate. opa = opaques. chr = chromite. pyr = pyrrhotite. px = pyroxene. sul = sulfide.

4. Conclusion

Martian meteorites provide an unprecedented means of information about Mars and are rarely found, compared to other types of meteorites. The Sultanate of Oman has contributed 17 approved Martian meteorites to the 137 found globally. Most of them were recovered from the Al Wusta desert in searches during the last15 years. The bulk of the main mass of SaU 005 and its pairings (i.e., 10.9 kg out of total 11.2 kg) recovered from the Sultanate is in possession of anonymous collectors, depriving Oman of its heritage and denying further research opportunities, given its associated scientific value. SaU 005 and its pairings are of the shergottite type of the Shergotty-Nakhla-Chassigny (SNC) meteorites which originate from the Martian mantle. The published oxygen isotope data of bulk and mineral fractions of SaU 008 and Dhofar 019 display a narrow range in $\delta^{18}O$ values. These data are indistinguishable in terms of $\Delta^{17}O$, and fall linearly on a Martian fractionation line above the TFL by +0.32‰, suggesting that Mars' mantle is homogeneous in oxygen isotopes. Petrographic and mineralogical data of SaU 005 plus pairings are identical, suggesting that all the pieces belong to the same meteorite. Up until 2014, eleven pieces of SaU 005 and its pairings have been recovered, and the strewn field has an area of 4 km by 2 km suggesting that the meteorite may have shattered twice, first in the air prior to landing on the Earth due to frictional heating, and secondly by impact with the ground.

5. Recommendations

The history of SaU 005 and its pairings demands a local meteorite museum and preliminary testing laboratory at Sultan Qaboos University (SQU) to protect this treasure trove of Omani heritage.

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