Title: METEORITES FROM LUT DESERT (IRAN)

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Abstract:

We present for the first time a detailed report on the discovery of a new meteorite collection region in the Lut Desert, eastern-southeastern Iran. We describe the geological, morphological, and climatic setting of this region. Our search campaigns alongside with the activity of meteorite hunters yielded >200 meteorite finds. Here, we report their classification, spatial distribution, and terrestrial weathering.

All the collected meteorites are ordinary chondrites (OCs). The most abundant by far is for the highly weathered paired H5 meteorites distributed in the NW of Kalut area (central Lut). The second are well-preserved paired L5 meteorites found in Kalut too.

A detailed study of the geochemistry and mineralogy of selected meteorites reveals significant effects of terrestrial weathering. Fe,Ni metal (simply metal) and troilite are transformed to Fe oxides/oxyhydroxides. A rather unique type of troilite weathering to pyrite/marcasite is observed in most of the Lut meteorites. Magnetic measurements and X-ray diffractrometry show the presence of terrestrial weathering products, with the dominance of maghemite, goethite, and hematite. Mobile elements such as Li, Sr, Mo, Ba, Tl, Th, and U have increased contents with respect to fresh falls. Meanwhile, a decrease in the V, Cr, Co, Rb (and possibly Fe) due to metal oxidation is detectable. The total carbon and $CaCO_3$ is higher than in samples from other hot deserts. The weathering effects, observed in the Lut OCs can be used as distinctive indicators to distinguish them from the meteorites from other regions of the Earth.

Three measurements of terrestrial age (^{14}C) show a range of 10-30 ka, which is in the range of ages reported from meteorites from other hot deserts (except the Atacama Desert).

Considering the high potential of the Lut in meteorite preservation, systematic works in the future should lead to the discovery of more samples giving access to interesting material of future studies.

Keywords: Iran, Lut, Desert, Weathering, Chondrite

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1. INTRODUCTION

Besides Antarctica (Harvey 2003), hot deserts are suitable places for preservation, accumulation and the subsequent recovery of meteorites. High numbers of meteorites have been collected and studied from the arid regions of the planet, such as Atacama (Gattacceca et al. 2011; Hutzler et al. 2016; Muñoz et al. 2007), Sahara (Bischoff and Geiger 1995; Ouazaa et al. 2009; Schlüter et al. 2002), Australian deserts (Bevan and Binns, 1989; Bevan, 1992; Benedix et al., 1999), Arabian Peninsula (Al-Kathiri et al., 2005; Gnos et al., 2009; Hezel et al., 2011), and Central and SW USA (Kring et al. 2001; Rubin et al. 2000; Zolensky et al. 1990). Finding new meteorite dense collection areas (DCA) is important for discovering new types of meteorites (e.g., Bischoff, 2001; Kent et al., 2017; Pourkhorsandi et al., 2017), and provindng more samples for statistical works on the flux of extraterrestrial materials (e.g., Bland et al., 1996), studying meteorite fall process by mapping ancient strewnfields (e.g., Kring et al., 2001; Gnos et al., 2009), studying the alteration of extraterrestrial material on Earth (Bland et al. 2006; Pourkhorsandi et al. 2017b; Saunier et al. 2010; Uehara et al. 2012; Zurfluh et al. 2016) and their possible relationship with the past climate (Bland et al. 1998; Lee and Bland 2003; Pourkhorsandi et al. 2017b).

In this work, we evaluate the potential of Iran for meteorite recovery. Iran is located in SW Asia, in the mid-latitude belt of arid and semi-arid regions of the Earth. Arid and semi-arid areas cover more than 60% of the country. Despite its vast surface area and dry climate, few meteorites were recorded until recently in Iran. Only two Iranian meteorites, both falls, were cataloged in the Meteoritical Bulletin during the 20th century. Veramin, a mesosiderite fallen in 1880 (Graham and Hassanzadeh 1990; Ward 1901) and Naragh, a H6 chondrite fallen in 1974 (Adib and Liou 1979; Clarke 1975).

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Shahdad, the first meteorite find, was collected in 2005 from the western margin of the Lut Desert (Garvie 2012). Lut Desert, also known as Dasht-e-Lut, is located in east-southeast of the country (Fig. 1a). Considering its climatic, geological and geomorphological characteristics, Pourkhorsandi and

Mirnejad (2013) proposed it as a potentially suitable place for meteorite preservation and collection.

The first systematic studies on meteorites from Iran and especially from Lut, was initiated as a cooperation between CEREGE and the University of Tehran in 2014. The start of the project was concurrent with local media coverage on meteorites by the first author, which led to the interest of the Iranian public on this topic and the formation of meteorite hunting groups. These groups are active in different regions of the country, especially in the Lut region.

Now, less than 5 years after the start of the project, hundreds of meteorites have been collected from Lut and more than 200 meteorites from Lut have been classified and approved by the Meteoritical Society. Many more samples are under classification. Most meteorites were collected in two DCA from central Lut desert, Lut and Kerman, the latter one encompassing the Kalut geographic region (Fig. 1b). The other DCA located at the periphery of the Lut desert (Gandom Beryan to the North, Lut-e-Zangi Ahmad to the South) count only 8 meteorites.

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The classification of these meteorites can give insights into the proportion of different groups found in the area to study the flux of meteorites. In addition, pairing the samples evidences the possible occurrence of large meteorite showers. Weathering of these samples and its comparison with those from other hot deserts is another subject of interest, which can be used to study the weathering process and the palaeoclimatic conditions of the desert.

Here, we present the data on the classification, weathering and spatial distribution of the Lut meteorites and we report the results of detailed geochemical and mineralogical characteristic of 10 selected meteorites. In addition, we present the terrestrial age data of 3 of selected samples.

2. ENVIRONMENT OF THE LUT DESERT

2.1. Geology and Geomorphology

Lut is a part of the Lut block which itself is a part of the Central Iranian microcontinent. Lut block is bounded to the north by Doruneh, to the east by

Nehbandam and to the west by Nayband fault systems. Probably, the South Jazmourian Fault confines the southern part of this block. More details on the geodynamical aspects of Iran and the region are discussed in Aghanabati (2004).

Based on the geographic characteristics, Lut is divided into three main units (e.g., Dresch, 1968): (i) Northern Lut, characterized by Cenozoic volcanic and sedimentary rocks and vast flat surfaces. (ii) Central Lut (CL) consists three different parts: (a) Kalut which are megayardangs occupying the western part of CL (Fig. 1 and EA-1) (Ehsani and Quiel 2008; Ghodsi 2017; Mashhadi et al. 2002). There are amongst the largest desert forms of their kind on the planet. Long hills with height around 10 m (and 50 m in some cases) made of clays, silt and sand and also containing evaporites and carbonates, separated by large wind-swept parallel corridors with a NW-SE direction extended in an 140 × 80 km area (Fig. EA-2); (b) Rig-e Yalan (Yalan Erg), the eastern unit of CL is a sand sea composed of a great massif of dunes and sand rises with heights up to 475 m that cover an area of ~ 50 × 100 km; (c) Playas, hammadas and sand sheet type plains form the middle part of CL. (iii) Southern Lut is characterized by playas and ravines.

Vicinity to the Shahdad-Nehbandan road and more importantly low abundance of terrestrial rocks has made the Kalut the main target for meteorite hunting. Except its northern part which is composed of highly saline Rude-e Shur river and the related clay-evaporite rich puffy soils, the rest of the Kalut is dry and is filled by coarse grain sand.

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2.2. Climate

High temperature precipitation rate below 50 mm/year, and high amounts of evaporation (5000 mm/yr) are the main climatic characteristics of the Lut (Fig. 2a). The De Martonne aridity index (a classic indicator of dryness) which uses temperature and rainfall data of central Lut is less than 1 and is 2-4 for the margins of the desert (e.g., Motamed, 1974). Data from *Aqua*/MODIS Climate Model Grid (CMG) shows that Rig-e Yalan of Lut has been the hottest area of the Earth in the years 2004, 2005, 2006, 2007 and 2009 with

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temperatures of 68.0, 70.7, 68.5, 69.0 and 68.6 °C, respectively (Mildrexler et al. 2006). Lut is the only area in Iran with a Tropical Hyperdesertic climate, the driest possible bioclimate in the Global Bioclimatic Classification System (Djamali et al. 2011).

In order to obtain the first "long-term" in situ climatic data, we placed an automatic thermometer/hygrometer (Lascar EL-USB-2) in Rig-e Yalan and in the location shown to be the hottest spot (coordinates here) (Mildrexler et al. 2006). The instrument working inside a wooden box 20-30 cm above the ground collected precise data with an interval record time of 60 minutes from April 2014 to February 2016. Temperature ranged from 0 to 61 °C and a humidity ranged from 3 to 61 %rh. Mean annual temperature and humidity for 2015 are 31.6 °C and 15.7 %rh, respectively. Fig. 2b shows the plotted data points for the mentioned parameters.

3. METHODLOGY

3.1. Searching Methods

Searches have focused on the Kalut area in the Kerman DCA. Systematic searches were conducted both by car and by foot. Low abundance of terrestrial rocks and the narrow valleys in the Kalut makes searching by car easier and more efficient than by foot. Contrary to the Kalut, the presence of dark-colored surfaces covered by volcanic rocks in the interdunal areas in Rig-e Yalan and in the Central hammada decreases the efficiency in finding meteorites. However, we have not done systematic work in these areas yet, but it seems that searching by foot in these two areas is more fruitful (similar to e.g., the Atacama Desert). Low abundance of terrestrial rocks in the sheet sand plains of the Rig-e Yalan makes the search by car a better option.

3.2. Laboratory Methods

Macroscopic observations were done both on the exterior and cut surface of the meteorites. Polished thin and thick sections were prepared at CEREGE and a Leica DM2500P optical microscope was used for petrographic observations.

Magnetic susceptibilities were measured on whole samples using a KLY2 susceptibility meter from Agico equipped with a large coil (nominal sample volume 65 cm^3) and a SM150 susveptibility meter from ZH instruments for smaller samples. Hysteresis properties for four selected samples were measured with a Princeton Micromag vibrating sample magnetometer (VSM) with a noise level of about 1 nAm^2 and a maximum applied field of 1 T. Hysteresis loops allow the determination of coercivity (B_C), saturation magnetization (M_S), saturation remanent magnetization (M_{RS}), high-field susceptibility (χ_{HF}, including both diamagnetic and paramagnetic contributions). Coercivity of remanence (B_{CR}) was evaluated through DC back-field demagnetization of the saturation remanence. The magnetic measurements were conducted at CEREGE.

X-ray Diffraction (XRD) powder patterns obtained using the D8 Discover Bruker diffractometer equipped with Cu-Kα tube and nickel filter located at Pontifícia Universidade Católica (PUC), Rio de Janeiro. The data collected from 10 to 90° 2θ with step-size and scan rate of 0.02° and 2.5s/step, respectively. Refinement of the XRD data done using the Bruker TOPAS 4.2© program with the fundamental parameters approach. Up to 18 different phases were considered during the Rietveld modeling. The phases were considered stoichiometric or with constant composition.

Chemical compositions of the mineral phases were determined with CAMECA SXFive and SX100 electron microprobes at the CAMPARIS facility (Paris), using natural and synthetic standards, focused electron beam (~1 µm in diameter), an accelerating voltage of 15 kV and a beam current of 10 nA.

Between 80-100 mg of powdered sample used to measure loss on ignition (LOI) contents on selected meteorites. Samples were heated up to 110 °C, 550 °C, and 850 °C, for 30, 60, and 60 minutes, respectively. Sample weighting followed after a 10 minutes of putting in the desiccator.

The total carbon (TC), total nitrogen, total organic carbon (TOC) measured with a FISONS NA 1500 elemental analyzer (Carlo Erba NA-1500 Elemental Analyser) at CEREGE, as described in Pailler and Bard (2002) and Soulet et al. (2011). Selected meteorite samples were crushed, and homogenized in an agate ball mill. 10-20 mg of the powders loaded in aluminum cups. The TC, nitrogen and the TOC contents of each sample were determined in two separate analyses. We measured TOC after an acid removal of the carbonate fraction. Each TOC measurement was duplicated. In order to calculate the dry weight percentages of calcium carbonate, the following equation was applied: $CaCO_3 = (TC - TOC) \times 8.33$. In the course of the measurements, acetanilide (C_8H_9NO) was used as standard.

For major element analysis, the whole rock powders of selected meteorites digested by alkali fusion method using lithium tetraborate. The analysis carried out using an Ultima-C, Jobin Yvon, Horiba Induced Coupled Plasma–Atomic Emission Spectroscopy (ICP-AES) at CEREGE.

The trace element contents of the selected meteorite samples were determined by Inductively Coupled Plasma-Mass Spectrometry (ICP-MS; Perkin-Elmer NexION® 300x) at the Pisa University's Dipartimento di Scienze della Terra. About 50-100 mg of each whole rock powder dissolved in a mixture of HF and HNO_3 on a hot plate at ~120 °C inside screw-top perfluoroalkoxy (PFA) vessels. Then the sample solutions were spiked with Rh, Re and Bi as internal standards (20 ng ml^{-1} in the final solutions) and diluted to 50 mL in polypropylene flasks. In each step of sample preparation, Mill-Q® purified water (18.2 M cm), ultrapure HF and HNO_3 were used. The correction procedure included (1) blank subtraction, (2) instrumental drift correction using internal standardization and repeated (every 5 samples) analysis of a drift monitor, and (3) oxide-hydroxide interference correction. The geochemical reference samples with basaltic composition WS-E and PM-S, and the Allende chondrite reference sample (USNM 3529, splite 20, position

22) dissolved and analyzed along with the unknown samples to check the accuracy of the results.

Soil samples from three different locations in Kalut collected in order to analyze the trace element contents (will be complete by Vinciane).

Terrestrial age measurement methodology here.

4. COLLECTED METEORITES

4.1. Classification

Classifications were based on optical microscopic observations, magnetic measurements, and chemical analyses of olivine and low-Ca pyroxene. Magnetic susceptibility (χ) is shown to be a useful proxy to differentiate various types of meteorites and/or to estimate weathering grade (Rochette et al. 2003a, 2008, 2009). It is expressed here as the decimal logarithm of χ in 10^{-9} m^3/kg in order to account for the 5 order of magnitude variation in rocks. For strongly magnetic material ($\log \chi > 3$), χ is proportional to the amount of metal, magnetite, maghemite, cohenite, and schreibersite, i.e., minerals with practically equal specific χ. A combination of magnetic susceptibility data with microscopic observations is efficient to classify ordinary chondrites and evaluate pairing. After random checking of olivine/pyroxene chemistry for different samples with identical petrographic and magnetic properties and obtaining similar coherent results, we did the classification of paired meteorites by only using magnetic susceptibility data and petrographic observations.

The list of studied meteorites along with their classification parameters are reported in Table EA-1. So far, all of the collected and classified meteorites from the Lut are ordinary chondrites (OCs). Fig. 3 shows the microscopic mosaic images of some of the collected meteorites. Here, we discuss two main meteorite types collected from the Lut (Fig. 4).

Amongst the Lut samples with approved names in the Meteoritical Bulletin (n=223), 191 are H5 (mostly from Kerman DCA). In addition to these 191

Commented [JG6]: give date of access to database samples, hundreds of additional probable H5 fragments have been recovered but not classified officially. These unclassified samples are not discussed here.

Microscopic petrography, magnetic susceptibility, and spatial distribution of the meteorites (section 4.2.) suggest that most of these H5 meteorites from the Kerman DCA are paired, which reveals the the existance of a large H5 strewnfield, formed by a single meteorite fall event.

Fig. 4a, b show the hand specimen images of the H5 paired samples. Under the microscope, they have a chondritic texture with a recrystallized matrix (Fig. 3a,c). Chondrules are readily delineated. Plagioclase average size is less than 20 µm. Most samples contain chromite-plagioclase assemblages. Melt veins and melts pockets are present. Troilite rim relicts occur around some chondrules. Metal and troilite are well separated from each other. Metal and troilite are monocrystalline. These H5 meteorites have an average $\log\chi$ = 4.60 ± 0.12 (n=187). The similar petrographic features, relatively narrow ranges of $\log\chi$,and spatial distribution of the meteorites are strong indicators for pairing the H5 fragments.

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The second most abundant meteorite type from Kerman DCA is L5 (Table EA-1; Fig. 3d-f and Fig. 4c,d). Similar to the H5 population, these meteorites are also likely paired which suggests the existence of another strewnfield. The L5 fragments show a well-preserved chondritic texture. However, the complete separation of metal from troilite and average plagioclase size below 50 µm indicate a petrologic type 5 (e.g., Van Schmus and Wood, 1967).

4.2. Meteorite Spatial Distribution

Meteorites have been collected in four DCA defined in the Lut Desert. These DCAs, from highest to lowest number of the classified meteorites, include Kerman (n = 202), Lut (17), Gandom Beryan (n = 6), and Lut-e-Zangi Ahmad (n=2). (Table 1). Kerman DCA covers most of the Kalut area. Rig-e Yalan inside the Lut DCA is the second meteorite-rich region. The reason for the lesser number of meteorites from the central hammada is the dark lithology making it less attractive for meteorite hunting. Gandom Beryan DCA hosts the Gandom Beyran volcanic complex (Yousefi et al. 2017), is a well-known

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Commented [H9]: No actually geographically Ravar is off the Lut block (bordered by Nayband fault in the W).

geotourism site which attracts the adventurers and leads to an increase in meteorite finding chance along their route.

Focusing on Kerman DCA and Kalut, Fig. 5a shows the spatial distribution of the H5 strewnfield, located in the northwestrn part of the Kalut, and the other collected meteorites. The H5 meteorite do not appear spatially distributed as a function of mass (Fig. 5b). This indicates either a high angle meteorite fall or a post-impact disturbance caused by floods, which is unlikely in view of the dry climate of the region.

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4.3. Terrestrial Ages

The terrestrial ages calculated from the ^{14}C activities measured in three selected samples are reported in Table 2. These samples were collected from Kalut and Rig-e Yalan. Although the number of the analyzed samples is very low, the age range (10-30 kyr) is simiar to the values reported for meteorites from other hot deserts (Hezel et al. 2011; Jull et al. 2010; Welten et al. 2004), except for the older the Atacama desert population (Gattacceca et al., 2011).

5. SOIL COMPOSITION

The results of the analysis of the Lut soils samples are reported in Table 3. Normalizing our data and Oman soils samples (Al-Kathiri et al. 2005) to the mean upper continental crust (UCC) composition (Fig. 6) reveals the depletion of the majority of the elements. However, Sr in KS1, KS3, and Oman soils show a positive anomaly. This might be the result of higher carbonate content in soil. In general, Lut soils samples show a homogenous chemical composition. Except few elements such as Ni, Ga, and Rb, Oman and Lut soils are similar. A comparison of the Lut soils and UCC chemical composition with that of mean CI chondrites (Fig. 6) shows very similar geochemical behavior between the soils and UCC without any significant difference.

6. TERRESTRIAL WEATHERING EFFECTS

6.1. Mineralogy and Texture

6.1.1. Petrography

Lack of fusion crust, presence of a dark-brownish colored desert patina with attached sand grains, orange to brownish color of the broken or cut surfaces, cracks filled by desert sediments, the elevated number of small fragments (< 10 g), and the low number of metal and troilite grains, are common among the majority of the H5 samples (Fig. 3a,c and Fig. 4a,b). This points to the strong effect of terrestrial weathering on the texture and the mineralogy of these samples. Microscopic survey of the H5 sections shows that in ~80% of the meteorites more than 60% of the metal/troilite grains are replaced by Fe oxides/oxyhydroxides (Table EA-1), indicating a weathering grade W3 using the scale of Wlotzka (1993). Weathering products occur as both veins and pockets. W2 and W4 meteorites show similar abundances of 19%. Only one sample (Lut-e-Zangi Ahmad 001) with minor oxidation (W1) was recovered which is from the Rig-e Yalan and based on petrographic differences such as the troilite shape and size, is not related to the H5 strewnfield of the Kalut.

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Most L5 meteorites are fully or partly covered by a black fusion crust (Fig. 4c,d). Hygroscopic mineral products formed during the interaction of the meteorite with the water in the desert environment are visible as bulging spots on the exterior of the meteorites. Similar to the “sweating” behavior of Omani OCs described by (Zurfluh et al. 2013), the L5 meteorites show crystallization of hygroscopic mineral assemblages in the cut surfaces. Microscopically, the L5 samples are also less weathered than the H5 fragments, 82% of them being W2 (Table EA1).

Comparison of the macroscopic and microscopic data of the L5 and H5 fragments, indicate a lower terrestrial weathering and lower terrestrial age for the L5.

6.1.1.1. Troilite weathering

In most samples, troilite has a higher modal abundance than metal, which indicates its higher resistance to weathering. Alteration of troilite to pyrite or marcasite is a ubiquitous and unique characteristic of meteorites from Lut, especially visible in the Kalut H5 meteorites. Usually in desert meteorites with progressive weathering, in reaction with water, troilite releases sulfur as sulfuric acid, and the whole rock sulfur budget of the system decreases (Bland et al. 2006; Saunier et al. 2010). Subsequently, Fe oxides/oxyhydroxides replace the troilite grains. Differently, troilite weathering in the Lut occurs in at least in two steps. First troilite turns into pyrite or marcasite, indicating the presence of extra sulfur and sulfuric acid (Hyde et al. 2014; Schoonen and Barnes 1991), and later to Fe oxides/oxyhydroxides. In addition to the Lut meteorites, during the routine classification of meteorites in CEREGE, we have observed rare cases of similar phenomenon in OCs from Oman. Al-Kathiri et al. (2005) and Hyde et al. (2014) also mention alteration of troilite to pyrite and marcasite for Omani OCs and NWA 4872 brachinite, respectively.

6.1.2. Magnetic properties

Oxidation of metal in meteorites affects their magnetic properties (Munayco et al. 2013; Rochette et al. 2003b; Uehara et al. 2012). A decrease in the magnetic susceptibility compared to the average values for fresh and fall samples of each meteorite group is evident in the Lut meteorites. With an average logχ of 4.60 ± 0.12 (n=187) compared to the average value of 5.32 ± 0.10 for H5 falls (n=xxx)ref?, the paired H5 meteorites clearly show the significant effect of weathering. The same effect although less intense, is observed for the paired L5 fragments. The average logχ for the L5 fragments is 4.37 ± 0.15 (n=11), which is lower than the fall L chondrites (4.90 ± 0.09) xxx.

The hysteresis properties are presented in Table 4 and Fig. EA-3. Comparison with the data of Gattacceca et al. (2014) for fall OCs shows the mineralogical modification and the reshaping of the hysteresis loops, in particular a strong increase of remanence and parameters typical of fine grained (pseudo-single domain) cubic iron oxide (maghemite or magnetite).

6.1.3. XRD data

The modal mineralogy deduced from XRD analysis of a selection of 10 samples is reported in Table 5. Besides the usual primary minerals (olivine, pyroxene, anorthite, metal, troilite) found in OCs, the following weathering products were detected: hematite, maghemite, goethite, akaganéite, and magnetite. Fig. EA-4 shows the diffractograms of Kerman 003 and Lut 009 that represent the least and most oxidized meteorites analyzed in this work. The weathering degree estimated by means of XRD phase analysis reveals that total oxidation (sum of the modal abundances of the weathering products) for Lut samples ranges from 11 to 27 wt% (or 42 to 78 at% Fe). Comparing the total oxide minerals abundance of the H and L chondrites from the Lut does not show any correlation between the group and the weathering of the meteorites. As shown in Fig. 7a, it seems that not only metal and troilite but also all Fe-bearing minerals including ferromagnesians are affected by weathering. A positive correlation exists between the abundance of maghemite and total oxides (Fig. 7b). More weathered samples show higher maghemite contents. A comparison between our data for Lut meteorites with meteorites from the San Juan DCA in the Atacama Desert (Munayco et al. 2013) shows differences between their oxidation products. Lut meteorites show higher oxides abundance and higher terrestrial alteration than those from San Juan. This is in agreement with the much wetter present day and past climate (over the Holocene) in Lut compared to the Atacama Desert. Maghemite, goethite, and hematite are the dominant weathering phases in Lut sample, however, goethite is the dominant phase in the San Juan samples and hematite is absent. The dominance of goethite in less weathered San Juan samples might be considered as a lower level of oxidation which is later followed by its transformation to hematite and later to maghemite (e.g., Stanjek 1987).

6.2. Geochemistry

6.2.1. Major and trace element composition

The whole rock major, minor, and trace element chemical composition of the selected samples along with two samples from Atacama (EM 049 and CeC 006) and one sample from Sahara Desert (Aridal 006) are reported in the Table 6. These 3 meteorites from other desert were chosen because of their high weathering grades (see Pourkhorsandi et al. 2017b). Chemical modification of the meteorites compared to the average composition of their corresponding chondrite groups is shown in Fig. 8.

Desert weathering has changed the chemical composition of the meteorites. Elements with higher abundance in the soil and relatively mobile behavior like Li, Sr, Mo, Ba, LREE, Tl, Th, and U are enriched in the meteorites. The higher contents of these elements in hot desert meteorites is reported by various workers (Al-Kathiri et al. 2005; Folco et al. 2007; Hezel et al. 2011; Pourkhorsandi et al. 2017b; Stelzner et al. 1999). A decrease in the contents of V, Cr, Co, Rb due to metal oxidation is detectable. In addition, Fe shows a possible depletion in the H chondrites. Some elements such as Cs and W show various behaviors. Possibly different contents of these elements in the underlying soil might be a reason for this observation.

6.2.2. Loss on ignition contents

Sequential LOI analysis is a common method to estimate the water content, organic matter, inorganic carbon and mineralogenic residue, in the terrestrial rock and sediment samples. Heating to different temperatures causes various phases to decompose which is usually reflected as the weight deviation from the initial mass (Heiri et al. 2001; Santisteban et al. 2004).

All meteorites (as well as Kilabo LL6 fall) lost 0.8% of their weight after heating up to 110 ºC (Fig. 9, Table EA-3). This temperature marks the removal of free water (moisture) from the samples. Record of the released organic carbon and combined water from hydroxyl iron minerals can be achieved by heating the sample up to 550 ºC. In average, hot desert meteorites lost up to 3.9% of the initial mass. Next step of heating (up to 850 ºC) leads to the decomposition of most carbonates and at the same time oxidation of iron (and troilite) to hematite which causes the weight increase and the color change in the samples. A weight loss is observed for the majority of Lut samples (e.g., Shahdad), indicating the presence of carbonates, especially calcite. In contrast, the weight increase after this heating step for samples like Kilabo, EM

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049, Kerman 002, and Aridal 006 shows their very low concentrations of carbonates.

6.2.3. Carbon and nitrogen contents

Decreasing TC content of the OCs resulting from parent body thermal metamorphism has been shown in different works (e.g., Moore and Lewis 1967). Terrestrial weathering is the other process known to be capable of changing TC, in this case as an increasing factor (Ash and Pillinger 1993; Gibson and Bogard 1978).

Indeed Lut meteorites have higher TC compared to falls (Fig. 10a, Table 7). Comparison of the TC, TOC, $CaCO_3$ contents show that the Lut samples are richer than those from the Atacama and Sahara deserts (Fig. 10b). TC shows a good correlation with the $CaCO_3$ content, which shows that $CaCO_3$ is more responsible than TOC for the higher TC content of these meteorites. In other way, it rules out the idea of higher TC in Lut samples because of a possible higher concentration of carbon in the unweathered samples.

Noteworthy is the strongly weathered (W4) Shahdad which shows the highest concentrations of these components as well as a abnormally high (0.104 wt%) nitrogen content. This might be related to the presence terrestrial nitrate minerals. Except Shahdad, the other samples show nitrogen abundances which are in the range of the values reported for other OCs (Kung and Clayton 1978).

7. CONCLUSIONS

With over 200 meteorites collected and classified, our field work confirm the suitability of the Lut Desert, at least Kalut, for preservation and accumulation of meteorites. So far, all of the collected meteorites from the Lut are ordinary chondrites. The majority of the collected samples belong to two main strewnfields (H5 and L5) located in Kalut. Better preservation of the L5 meteorites compared to the H5 meteorites suggests a younger fall for the former. In the hypothesis that all H5 and L5 from these identified strewnfields represent only two unpaired meteorites and that the other finds are unpaired, the total of unpaired meteorites found in Lut would be 32.

Terrestrial weathering is intense and has modified the geochemistry and mineralogy of the Lut meteorites. Mobile elements such as Li, Sr, Mo, Ba, Tl, Th, and U are enriched in the analyzed samples. While a decrease in the V, Cr, Co, Rb (and possibly Fe) due to metal oxidation is detectable. The contents of TC, TOC, $CaCO_3$, and total abundance of iron oxides/oxihydroxides are higher in these meteorites compared to the fall and find samples from other regions. The mineralogy of the weathering products shows differences compared to other hot deserts, with a dominance of maghemite, goethite, and hematite, and the weathering of troilite to marcasite and pyrite. The abundance of some trace elements such as Ba, Sr, and LREEs in Lut OCs are different from those from other hot deserts. These weathering effects can be used as distinctive indicators to distinguish them from the meteorites from other regions of the Earth.

Although based on only three meteorites, the terrestrial ages range is similar that for other hot desert meteorites (expect for the Atacama Desert).

Our work, although preliminary work, indicates the high potential of the Lut area for the preservation of meteorites.

Safety Advices

Drug smugglers are present in the Lut Desert. Beside this, the Iranian police has planted landmines in some regions of the desert to block smuggling ways. Therefore any field trip in the region, especially for foreign groups, should be done after obtaining proper permissions and guidance from the corresponding authorities.

Acknowledgments

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Figure captions:

Fig. 1: a) Map of the Central Lut Desert; adapted from Pourkhorsandi et al. (2017b). Circles on the Iran map show the location of Yazd, Abarkouh, and Sarvestan meteorites, respectively from north to south. b) Landsat 8 satellite image of the Central Lut Desert and the surrounding areas. Dashed quadrangles show the position of Kerman (west) and Lut (east) DCAs.

Fig. 2: a) Climate diagram of Ziaratgah-Deh-Seyf weather station near Shahdad. Note that the dry season (P<2T) lasts for 12 months. Data from Iran Meteorological Organization. b) One and half a year record of near ground surface variations in temperature and relative humidity. Data collected using a Lascar EL-USB-2 data logger with 1-hour interval records.

Fig. 3: Representative microscopic images of the Lut Desert meteorite in reflected optical light. a) Kerman 046 (H5, W3). b) Lut 010 (LL6, W2-4). c) Kerman 034 (H5, W1-3). d) Kerman 141 (L5, W1/2). e) Kerman 135 (L5, W2). f) Kerman 139 (L5, W2).

Commented [JG14]: remove "chondrules " from the images. MAPS readers should e able to tell!

Fig. 4: Hand specimen images of the paired H5 (a, b) and L5 fragments (c, d). The longest dimension of the H5 (a) is 12 cm. Scale bar is 1 × 1 cm.

Fig. 5: a) Spatial distribution map of the Kerman DCA meteorites showing the paired H5 and other chondrites. b) Location and the mass of the H5 paired fragments collected from Kalut.

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Fig. 6: Bulk geochemistry of Kalut soil samples (KS1-KS3) and soils from Oman (Al-Kathiri et al. 2005) normalized to upper continental crust composition (Kemp and Hawkesworth 2004; Rudnick and Gao 2003). The upper right diagrams shows the Kalut soils (black) and UCC (grey) normalized to mean CI chondrites (Wasson and Kallemeyn 1988).

Fig. 7: a) Comparison of the total oxides (wt%) versus silicates in Lut and San Juan (Atacama Desert) meteorites. b) Total oxides versus maghemite contents in the Lut meteorites. Data obtained by XRD. San Juan data from (Munayco et al. 2013).

Fig. 8: Normalized spider diagrams of (a) H, and (b) L(LL) OCs from the Lut and Atacama Desert. Strontium, Ba, and the REE composition data source: Pourkhorsandi et al. (2017b). The normalization data source: Wasson and Kallemeyn (1988).

Fig. 9: Plotted data of sequential combustion showing mass differences as a function of heat.

Fig. 10: a) Comparison of total carbon contents of find and fall petrologic type >3 OCs with Lut meteorites. Data source of the non-Lut samples: Moore and Lewis (1967). b) Total carbon versus carbonate content of the Lut OCs compared to three samples from the Atacama (CeC 006 and EM 049) and Sahara (Aridal 006) deserts.

Commented [JG16]: the L/LL is misleading (intermediate classification). Use L & LL, or L and LL, or L+ LL

Commented [JG17]: H and L/LL have same symbols

Commented [JG18]: SYmbols not coherent from a to b. Use the same red symbol for Lut meteorites in b. Well, harmonize a and b! Better us different symbols for different, and different colours for different geographic origin.

CAPTIONS FOR SUPLEMENTARY FIGs ??

Units on the EA3 figures not good: should be T (or mT) on X axis, and Am2 for Y axis. 1 T = 10 000 Oe, 1 emu = 10-3 Am2 fig EA2 is no nice it should go in the main text if possible

fig EA1: nice, but can be improved (altitude scale to long vertically, ugly yellowish strip at the bottom. etc

Table headings:

Table 1: Statistics of meteorite types and frequency in different DCAs from the Lut Desert.

Table 2: The calculated terrestrial ages of three selected Lut meteorites based on their ^{14}C activities.

Table 3: Trace element chemical composition of three soil samples (KS1-3) from the Kalut region of the Lut Desert and two reference materials (BHVO-1, BHVO-2) analyzed by ICP-MS.

Table 4: Magnetic properties of selected ordinary chondrites from the Lut Desert.

Table 5: Phase modal abundances of selected ordinary chondrites from the Lut Desert obtained by XRD analysis.

Table 6: Whole rock major, minor, and trace element chemical composition of selected Lut Desert OCs along with two from Atacama (EM 049 and CeC 006) and one sample from the Sahara Desert (Aridal 006).

Table 7: Total carbon, total nitrogen, total organic carbon, and $CaCO_3$ contents of analyzed samples.

Tables:

Table 1 (Pourkhorsandi et al.)

	Meteorite Type										
DCA name	H3	H4	H5	H6	L3	L4	L5	L6	LL3	LL6	**To**
Kerman	1	0	183	1	0	0	12	4	0	1	
Lut	1	4	4	0	1	1	0	2	3	1	
Gandom Beryan	0	1	5	0	0	0	0	0	0	0	
Lut-e-Zangi Ahmad	0	0	1	0	1	0	0	0	0	0	

Table 2 (Pourkhorsandi et al.)

Meteorite	**^{14}C total**	**^{14}C (dpm/kg)**	**Terrestrial Age (kyr)**
Kerman 001	3.502E+06	8.16 ± 0.71	14.4 ± 1.5
Lut 006	5.940E+06	5.87 ± 0.30	18.5 ± 1.4
Lut 010	1.523E+06	1.70 ± 0.33	28.8 ± 2.1

Table 3 (Pourkhorsandi et al.)

ppm	**KS1**	**KS2**	**KS3**	**BHVO-1**	**BHVO-2**
Cr	51.2	80.1	60.8	295.2	284.3
Co	7.4	10.2	7.8	46.2	45.1
Ni	19.4	36.3	21.8	125.8	121.8
Cu	14.0	20.6	14.8	129.9	128.4
Zn	44.0	57.8	46.6	96.6	94.1
Ga	9.8	12.5	10.0	21.5	20.4
Ge	1.0	1.0	0.8	1.4	1.4
Rb	56.0	61.0	56.0	8.4	7.9
Sr	687.0	201.3	647.2	360.4	356.1
Y	13.3	16.2	12.5	23.6	23.5
Zr	284.4	152.9	128.5	154.1	153.6
Nb	8.6	8.2	7.8	16.1	16.0
Ba	561.9	331.7	483.0	126.1	126.4
La	18.8	22.4	18.9	15.5	15.6
Ce	35.7	43.5	36.8	37.2	37.6
Pr	4.0	5.0	4.1	5.1	5.2
Nd	15.3	18.2	14.9	23.6	24.0
Sm	3.3	3.8	2.9	5.8	5.9
Eu	0.8	0.8	0.7	2.0	2.0
Gd	2.9	3.6	2.9	6.3	6.4
Tb	0.4	0.5	0.4	0.9	0.9
Dy	2.4	3.1	2.4	5.2	5.3
Ho	0.5	0.6	0.5	1.0	1.0
Er	1.5	1.7	1.4	2.4	2.6
Tm	0.2	0.3	0.2	0.3	0.3
Yb	1.5	1.8	1.4	2.0	1.9
Lu	0.3	0.3	0.2	0.3	0.4
Hf	6.9	4.2	3.5	4.2	4.4
Ta	0.7	0.7	0.7	1.2	1.2
Pb	14.2	11.5	13.2	1.3	1.4
Th	6.2	7.1	7.2	1.2	1.3
U	2.0	2.2	2.0	0.4	0.5

Table 4 (Pourkhorsandi et al.)

Meteorite	**Ms (Am^2/kg)**	**Bc (mT)**	**Bcr (mT)**	**Mrs/Ms**	**Bcr/Bc**
Kerman001	5.528	11.63	24.6	.16	2.12
Kerman002	2.958	10.28	24.47	.12	2.38
Kerman003	2.435	15.77	26.79	2.77E-	1.70

				01	
Lut001	3.613	14.78	27.35	2.38E-01	1.85
Lut003	5.066	13.35	24.33	2.46E-01	1.82

Table 5 (Pourkhorsandi et al.)

Meteorite	**Type**	**Silicates**			**Opaques**		**Iron oxides**				
		Olivine	**Pyroxene**	**Anorthite**	**FeNi metal**	**Troilite**	**Goethite**	**Hematite**	**Maghemite**	**Magnetite**	**Akaganéite**
Kerman 001	H5	42.36	40.09	1.75	0.00	3.10	5.60	0.00	7.11	0.00	0.00
Kerman 002	L6	49.5	33.75	3.26	0.00	0.94	1.61	2.61	8.33	0.00	0.00
Kerman 003	L5	47.64	33.58	6.1	0.00	1.93	5.07	2.19	3.49	0.00	0.00
Lut 001	H5	37.79	37.82	7.11	0.00	1.31	7.27	0.00	8.71	0.00	0.00
Lut 003	L3	35.11	32.35	6.59	0.00	1.14	8.25	1.66	14.91	0.00	0.00
Lut 006	LL3	55.33	11.45	8.38	0.11	0.08	5.08	1.71	13.21	1.15	3.51
Lut 008	H4	35.82	32.68	5.48	0.00	1.95	6.20	7.05	10.82	0.00	0.00
Lut 009	H4	41.17	21.34	10.04	0.00	0.26	8.35	0.51	18.33	0.00	0.00
Shahdad	H5	37.42	29.86	8.62	0.00	2.48	8.58	1.63	11.41	0.00	0.00

Table 6 (Pourkhorsandi et al.)

	Kerman 001	**Kerman 002**	**Kerman 003**	**Lut 001**	**Lut 003**	**Lut 006**	**Lut 008**	**Lut 009**	**Shahdad**	**Aridal 006**	**CeC 006**	**EM 049**	**Killabo**
SiO_2	32.98	38.90	36.46	37.76	35.77	43.24	34.33	35.22	32.12	36.33	34.94	34.63	40.30
TiO_2	0.11	0.12	0.12	0.11	0.11	0.12	0.11	0.10	0.10	0.11	0.12	0.11	0.12
Al_2O_3	2.00	2.19	2.14	2.12	1.98	2.27	2.02	1.95	1.86	2.05	2.21	2.05	2.36
Fe_2O_3	33.19	29.40	34.35	29.48	37.45	25.14	38.00	32.86	35.35	31.89	32.71	39.06	29.89
MnO	0.30	0.36	0.32	0.34	0.30	0.38	0.30	0.31	0.28	0.34	0.35	0.32	0.38

MgO	23.42	27.19	23.96	25.85	23.87	25.71	20.38	22.65	21.75	25.88	22.85	22.98	30.13
CaO	1.73	1.87	1.86	1.31	1.88	1.83	1.43	1.36	1.50	1.54	1.51	1.56	1.81
Na_2O	0.87	0.92	1.04	0.89	0.91	1.05	0.88	0.85	0.87	0.45	0.62	0.52	0.99
K_2O	0.11	0.10	0.11	0.11	0.13	0.19	0.12	0.10	0.10	0.09	0.14	0.14	0.11
P_2O_5	0.25	0.26	0.24	0.18	0.27	0.21	0.26	0.18	0.22	0.27	0.19	0.28	0.29
Li	4.60	1.99	2.30	4.50	8.80	8.20	2.25	3.90	5.20	1.93	13.00	6.10	n.d.
Be	0.04	0.04	0.03	0.03	0.04	0.04	0.03	0.03	0.03	0.03	0.10	0.08	n.d.
Rb	2.02	2.84	1.52	2.33	1.93	3.10	2.27	1.04	2.31	1.59	5.26	3.32	n.d.
Y	2.14	2.23	2.20	1.68	1.90	2.31	1.95	1.89	1.87	1.60	2.81	2.91	n.d.
Zr	5.4	5.3	5.6	5.6	4.9	7.6	4.8	5.2	5.1	5.2	5.8	5.5	n.d.
Nb	0.46	0.42	0.44	0.46	0.44	0.46	0.39	0.47	0.42	0.47	0.47	0.44	n.d.
Th	0.07	0.07	0.09	0.22	0.07	0.15	0.06	0.10	0.21	0.09	0.19	0.15	n.d.
Pb	0.57	1.08	0.27	0.30	0.55	0.37	0.36	0.36	0.55	0.17	0.43	0.33	n.d.
Ga	4.9	4.7	4.3	5.0	5.2	4.6	4.7	2.9	4.0	4.5	4.8	4.6	n.d.
Zn	40	59	43	41	47	59	42	49	18	37	57	29	n.d.
Cu	88	80	98	92	93	73	112	79	77	76	99	96	n.d.
Ni	14715	10821	11440	14082	14117	5919	14183	11742	14063	11259	10782	13843	n.d.
V	51	55	45	61	55	75	52	59	49	43	114	61	n.d.
Cr	2167	2389	1821	2660	2666	3774	2269	2808	2128	1455	3135	2359	n.d.
Hf	0.16	0.15	0.15	0.16	0.14	0.22	0.13	0.14	0.15	0.16	0.16	0.16	n.d.
Cs	0.29	0.21	0.03	0.04	0.15	0.21	0.39	0.18	0.18	0.04	0.37	0.88	n.d.
Sc	7.7	7.0	8.8	9.4	7.7	9.0	7.8	8.0	8.2	8.3	8.1	9.2	n.d.
Ta	0.02	0.03	0.02	0.03	0.02	0.03	0.02	0.03	0.03	0.03	0.03	0.03	n.d.

Co	600	523	567	455	667	255	628	507	674	396	494	734	n.d.
U	0.10	0.07	0.06	0.07	0.09	0.38	0.04	0.28	0.18	0.04	0.27	0.10	n.d.
W	0.07	0.13	0.19	0.06	0.49	0.02	0.29	0.22	0.16	0.07	0.81	0.19	n.d.
Mo	5.2	4.0	4.2	5.1	9.3	3.5	5.0	5.8	5.3	4.4	4.6	6.7	n.d.
Tl	0.37	< 0.01	< 0.01	0.14	0.18	0.17	0.03	0.14	0.29	< 0.01	0.27	0.13	n.d.

n.d. = not determined.

The units for the major and trace elements is wt% and μg g^{-1}, respectively.

Table 7 (Pourkhorsandi et al.)

Meteorite	**Type**	**Weathering grade**	**N**	**TC**	**TOC**	**$CaCO_3$**
Kerman 001	H4	W4	0.011	0.328	n.d.	n.d.
Kerman 002	L6	W3	0.002	0.072	0.042	0.249
Kerman 003	L5	W2	0.003	0.132	0.066	0.548
Lut 001	H5	W3	b.d.l.	0.187	0.088	0.831
Lut 003	L3	W3	0.002	0.221	0.066	0.548
Lut 006	LL3	W3	0.003	0.124	n.d.	n.d.
Lut 008	H4	W5	b.d.l.	0.126	0.064	0.515
Lut 009	H4	W4	0.009	0.114	0.086	0.233
Shahdad	H5	W4	0.104	0.245	0.074	1.424
Aridal 006	H6	W4	0.006	0.073	0.051	0.181
Caleta el Cobre 006	L6	W3	0.009	0.067	0.051	0.135
El Medano 049	H4	W3	0.014	0.084	0.040	0.367

The unit is wt%. n.d. = not determined. b.d.l. = below detection limit.