Modification of REE distribution of ordinary chondrites from Atacama (Chile) and Lut (Iran) hot deserts: insights into the chemical weathering of meteorites

Hamed Pourkhorsandi[1*], Massimo D'Orazio[2], Pierre Rochette[1], Millarca Valenzuela[3], Jérôme Gattacceca[1], Hassan Mirnejad[4, 5], Brad Sutter[6], Aurore Hutzler[7], Maria Aboulahris[1, 8]

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[1]CNRS, Aix-Marseille Univ., IRD, Coll. France, CEREGE, Aix-en-Provence, France

[2]Dipartimento di Scienze della Terra, Università di Pisa, Via S. Maria 53, I-56126 Pisa, Italy

[3]Instituto de Astrofísica, Pontificia Universidad Católica de Chile, Vicuña Mackena 4860, Macul, Santiago, Chile

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[4]Department of Geology, Faculty of Sciences, University of Tehran, Tehran 14155-64155, Iran

[5]Department of Geology and Environmental Earth Sciences, Miami University, Oxford, Ohio, USA

[6]NASA, Johnson Space Center, Houston, Texas, USA

[7]Natural History Museum, Burgring 7, A-1010 Vienna, Austria

[8]Département de Géologie, Faculté des Sciences, Université Hassan II Casablanca, Casablanca, Morocco

[*]Corresponding author: pourkhorsandi@cerege.fr

Abstract- The behavior of rare earth elements (REEs) during hot desert weathering of meteorites is investigated. Ordinary chondrites (OCs) from Atacama (Chile) and Lut (Iran) deserts show different variations in REE composition during this process.

Inductively coupled plasma-mass spectrometry (ICP-MS) data reveals that hot desert OCs tend to show elevated light REE concentrations, relative to OC falls. Chondrites from Atacama are by far the most enriched in REEs and this enrichment is not necessarily related to their weathering degrees. Positive Ce anomaly of fresh chondrites from Atacama and the successive formation of negative anomaly with the addition of trivalent REEs is similar to the process reported from Antarctic eucrites. In addition to REEs, Sr and Ba also show different concentrations in OCs from different hot deserts.

The stability of Atacama surfaces and the associated old terrestrial ages of meteorites from this region give the samples the necessary time to interact with the terrestrial environment and to be chemically modified. Higher REE contents and LREE enriched composition sign a contamination by terrestrial soil. Despite their low weathering degrees, special care must be taken into account while working on the REE composition of Atacama meteorites for cosmochemistry applications.

In contrast, chondrites from Lut desert show lower degrees of REE modification, despite significant weathering signed by Sr content. This is explained by the relatively rapid weathering rate of the meteorites occurring in Lut desert which hampers the penetration of terrestrial material by forming voluminous Fe oxide/oxyhydroxides shortly after the meteorite fall.

1. INTRODUCTION

As soon as a meteoroid enters the Earth's atmosphere, it is subjected to terrestrial alteration (e.g., Bland et al., 2006). The meteorites which are used for cosmochemical studies are being collected immediately or thousands to several hundred thousands of years after their fall. It has been documented that the mineralogy and chemical compositions of these samples can be affected over a human lifetime (Bland et al. 1998; Pillinger et al. 2013; Socki et al. 1991). Even in shorter time scales of less than decades in laboratory environment (Velbel 2014) or tens of days in a humid natural environment (Bischoff et al. 2011). Initial investigations on the meteorite weathering processes commenced just after the recognition of high number of weathered hot deserts samples (e.g., Buddhue, 1939; Olsen and Fuchs, 1967). Since that time, discovery of large numbers of meteorites from cold and hot deserts has drawn the attention of researchers to document the effects of weathering on meteorites to avoid any inaccurate interpretation on their geochemical compositions.

The main purposes of meteorite weathering studies are: (i) understanding the weathering process occurring within a meteorite and its relationship to the finding place of the meteorite, and (ii) identifying the chemical and mineralogical modification during this process, to account for eventual bias in cosmochemical studies (Bland et al. 2006). Several studies have focused on the effect of weathering on the chemical and mineralogical compositions of meteorites from Antarctic and rare hot desert achondrites (White et al., 1967; Gooding, 1982; Koeberl and Cassidy, 1989; Torigoye-Kita et al., 1995; Swindle et al., 1998; Llorca et al., 2013). Compared to achondrites and considering their importance and also higher abundance such studies on the ordinary chondrites (OCs) have high importance.

Among the trace elements which are used in geochemical and cosmochemical studies of meteorites, REEs have a significant importance. Variations in the abundance of REEs are diagnostic proxies to study the evaporation/condensation processes in the nebula (Boynton 1975), parent-body aqueous alteration (Inoue et al. 2009), metamorphism (Murrell and Burnett 1983), magmatic differentiation (Boynton et al. 1976) and terrestrial weathering (Crozaz et al. 2003). REE mobilization during terrestrial weathering has been studied by Mittlefehldt and Lindstrom (1991) on Antarctic eucrites and Crozaz et al. (2003) on hot desert achondrites. REE sensitivity to weathering may also affect Nd isotopic composition.

Despite the high number of OCs, limited studies have been conducted on their REE mobilization during terrestrial weathering. Al-Kathiri et al. (2005) suggested a LREE enrichment in OCs from Oman, without presenting HREE concentrations. Saunier et al. (2010) mentioned the high amount of LREE in two highly weathered H5 and L6 OCs.

The goals of this study are to observe the possible differences between the REE contents of meteorites from different hot deserts (in particular Atacama and Lut) and to study the process of REE mobilization during weathering and its relationship to the finding region of the meteorite.

2. STUDIED METEORITES

In order to investigate the possible effects of meteorite recovery site on the concentrations of REE during weathering, OCs from two hot deserts with markedly different climatic settings were selected. The characteristics of the studied samples are described in the forthcoming subsections.

2.1. Ordinary chondrites from Lut Desert

With an annual precipitation of ≤ 28 mm/yr (in the marginal regions) and maximum ground temperature of up to 70 °C (inside the desert) (Djamali et al. 2011; Mildrexler et al. 2011) along with the increasing number of meteorite finds (Pourkhorsandi and Mirnejad 2013; Pourkhorsandi et al. 2016), Lut in Iran has the characteristics of a suitable place for preserving meteorites.

For this study, we selected a set of OCs from different regions of Lut whose characteristics and finding places are presented in Table 1 and Fig. 1-a. The analyzed samples comprise meteorites from LL, L and H groups with petrologic types varying between 3 and 6. Intense oxidation of Fe-Ni metal grains (>95 % of them) is the prevalent characteristic of these meteorites (Fig. 2-a). According to the method of Wlotzka (1993), weathering degrees of these samples are between W3 and W5. Iron oxides/oxyhydroxides occur as individual patches, veins (along and/or perpendicular to cracks) and lamellar structures occupying former Fe-Ni metal, troilite and silicate locations. Reflected light optical microscopy reveals the alteration of troilite to pyrite/marcasite - rather than Fe oxides/ oxyhydroxides – in some of these samples.

2.2. Ordinary chondrites from Atacama Desert

The central depression of the Atacama, the driest and oldest hot desert on Earth (Hartley et al. 2005), is responsible for the preservation of very old surfaces containing unique meteorite accumulation areas (e.g., San Juan, and El Médano). Other meteorite dense collection areas (DCAs) occur in the domain of the coastal range, known as La Yesera and Pampa de Mejillones DCAs, with a different climatic condition, due to the presence of oceanic aerosols and morning mist coming from the Pacific Ocean. Extreme aridity and the surface stability of the Atacama lowers the rate of chemical weathering of meteorites compared to those reported from other hot deserts (Gattacceca et al. 2011) - in this case Lut. Unlike the relatively low number of recovered meteorites from Lut, the Atacama hosts the highest number of meteorites per surface area reported so far (Gattacceca et al. 2011; Hutzler et al. 2016).

In this work, we used samples previously classified and described by Valenzuela (2011) from La Yesera and Pampa de Mejillones DCAs which are located near to the coast of Pacific (Fig. 1-b) and the considerable presence of coastal fog, which means higher amount of NaCl in the regional soils. Most of these samples were settled on sand dunes, in the context of Pleistocene sandstones with paleo-costal lines, with a the presence of carbonates in the soils.

To compare the chemical behavior of meteorites from different regions of the same desert, samples from San Juan and El Médano DCAs were chosen. Different from the coastal regions, they are in situated in much drier climatic conditions. Volcanic rocks cover the surface of these areas, with remarkable presence of gypsum and anhydrite as caliche layers.

Similar to the Lut meteorites, OCs from LL, L and H groups are included (Table 1). The selected meteorites exhibit weathering degrees between W1-W5 with a mode at W3. In comparison to meteorites from other hot deserts, Atacama samples have long terrestrial ages. For instance, based on the $^{36}Cl/^{41}Ca$ terrestrial age determinations, Hutzler (2015) presents ages of 1900 ± 80 ka and 2590 ± 100 ka for El Médano 049 and Caleta el Cobre 006 meteorites, respectively. Gattacceca et al. (2011) and Valenzuela (2011) also report relatively old terrestrial ages (see Table 1 and Section 5).

In addition to these meteorites, an OC from the Sahara (Aridal 006) was selected for analysis.

3. METHODOLOGY

To prepare the powder used for measuring the abundances of REE in bulk meteorites, samples were examined under a stereomicroscope to check for the presence of any terrestrial material (e.g., cemented or enclosed sand grains inside cracks, fusion crust, desert varnish and other sedimentary crusts). Each of these material show different geochemical behaviors and their contamination can affect the analysis result. For instance, desert varnish tends to show high REE contents (Goldsmith et al. 2014). Thus, care was taken to separate the mentioned products from the exterior and interior of the meteorites. The samples extracted from the interior and the freshest parts, away from the possible fusion crust and mentioned terrestrial products. To have a representative aliquot of whole rock composition, approximately 1.5-2 g of each meteorite were finely hand-ground in an agate mortar and then carefully homogenized.

Inductively coupled plasma-mass spectrometry (ICP-MS) instruments (VG PQII Plus STE and Perkin-Elmer NexION® 300x) at the Dipartimento di Scienze della Terra of the Università di Pisa were used to determine the trace elements (herein REE, Sr and Ba) contents of the meteorite samples. The sample preparation for the ICP-MS analyses followed in this study, is basically similar to the procedure described by Folco et al. (2007). About 50-100 mg of each powder were dissolved in a mixture of HF and HNO_3 on a hot plate at ~120 °C inside screw-top perfluoroalkoxy (PFA) vessels. This dissolution procedure could incompletely dissolve celestine ($SrSO_4$) or barite ($BaSO_4$) eventually occurring into the samples. However, we always obtained very clear final sample solutions. 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, PM-S and BIR-1, and the Allende chondrite reference sample (USNM 3529, splite 20, position 22) were dissolved and analyzed along with the unknown samples to check the accuracy of the results. In Table 2 are reported the results for the four analyzed reference sample with literature values, and the detection limits for each analyte calculated as six times the standard deviation of the blank counts. The analytical precision is between 5 and 10% RSD for elements with concentrations > 0.5 µg/g and between 10 and 20% RSD for elements with concentrations < 0.5 µg/g.

To investigate the effect of surface soil chemical composition and to observe any possible significant anomaly, representative soil samples collected from a hilltop close to Estacion Catalina (25°12.673'S, 69°41.894'W) are used in this study. This region which occurs in the Catalina DCA, is composed of igneous rocks with the presence of caliche layers and has very similar lithology to San Juan and El Médano DCAs. Samples containing gravel and soils were collected from depths of zero to 0.5 cm and 0.5 to 5 cm. Then gravels and soils (< 2 mm) sieved and separated for subsequent analyses. Soil concentrate samples pulverized to 85% passing 75 µm in tungsten-carbide mill. Total chemistry for major and trace elements was determined using ICP-MS and ICP-AES after a lithium metaborate fusion of each soil sample at the ALS Geochemistry©.

REE anomalies represent deviations from neighboring elements based on the expected change in REE abundances as a function of atomic number and ionic radii (Lipin and McKay 1989). To calculate Ce and Eu anomalies, the values were normalized to the corresponding OC group (LL, L and H) by using the following equations (Dauphas and Pourmand 2015):

$$Ce/Ce^{*} = Ce_{N} / (La_{N}^{0.48} \times Pr_{N}^{0} Pr_{N}^{0.52}) \qquad (1)$$

$$Eu/Eu^* = Eu_N / (Sm_N^{0.45} \times Gd_N^{0} Gd_N^{0.55}) \qquad (2)$$

where N stands for the normalization of REE to mean OC composition.

The contents of Sr and Ba have been shown to be suitable chemical proxies to evaluate the amount of chemical weathering and differentiate the meteorite collection regions (Al-Kathiri et al. 2005; Folco et al. 2007; Zurfluh et al. 2012). During the same analysis, the concentrations of these elements were also measured.

4. RESULTS

4.1. Meteorite samples

REE, Sr and Ba concentrations of the studied meteorites are reported in Table 3. The REE data of each group are normalized to the corresponding mean composition reported in Wasson and Kallemeyn (1988). Masuda-Coryell diagrams of the studied meteorites together with the data of OCs from Oman (Al-Kathiri et al., 2005), UAE (Hezel et al., 2011), Sahara Desert (Saunier et al., 2010; Folco et al., 2007) and Europe (Folco et al., 2007) are shown in Fig. 3. Both enrichment and depletion elemental patterns compared to the corresponding OC mean composition can be seen in the diagrams.

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ΣREE values in the Atacama and Lut samples have a range of 3.55 - 5.77 (avg. 4.46) ppm and 2.98 - 3.76 (avg. 3.42) ppm for H, 2.97 - 6.45 (avg. 3.97) ppm and 3.26 - 2.93 (avg. 3.63) ppm for L and 3.21 - 9.82 (5.96) ppm (just for Atacama) for LL OCs, respectively (Table 3). These data shows a higher amount of REEs in Atacama meteorites than those of Lut.

A closer look at the normalized REE patterns (Fig. 3) reveals an enrichment in La for some samples. It goes up to 2.64 × H in El Médano 049, with an average amount of 1.79 × H (n

= 8) and 1.22 × H (n = 5) for Atacama and Lut meteorites, respectively. Likewise, La is enriched up to 2.98 × L in Caleta el Cobre 006 which is an L OC. Average La_N amounts of Atacama and Lut samples are 1.40 × L (n = 14) and 1.15 × L (n = 3), respectively. Among the studied meteorites, Paposo exhibits a remarkable La enrichment (4.05 × LL).

The general shape of the normalized spider diagrams (Fig. 3) indicates the occurrence of a fractionation between light REEs (LREEs) and heavy REEs (HREEs). Fig. 4 displays the values of La_N/Lu_N (as an indicative of LREE/HREE fractionation) vs. La_N for H and L OCs from different regions. Most of the samples show LREE/HREE ratios of more than one. The Atacama and Sahara samples tend to represent higher degrees of REE fractionation than Lut and UAE samples. The Gd_N/Yb_N (as an indicative of MREE/HREE fractionation) ratios for the studied samples are mostly less than one, but since the values are near the error zone, they will not be discussed further.

Cerium and Eu show both negative and positive anomalies (Table 3, Fig. 3). In H OCs, the variation range of Ce/Ce^* and Eu/Eu^* values for Atacama samples (0.60 – 1.69 and 0.56 – 1.08, respectively) is broader than those of Lut (0.92 – 0.96 and 0.96 – 1.29, respectively). In general, no pronounced difference in the amounts of Ce/Ce^* and Eu/Eu^* between different OC groups exists. A remarkable Ce positive anomaly is evident in Cobija (H6) and Lutschaunig's Stone (L6) (Fig. 3-a, b). Note that these meteorites are the least weathered samples (W1) studied in Atacama.

The negative Tm anomaly among the analyzed samples (Fig. 3) is similar to the Tm anomaly in the CI normalized patterns described from ordinary chondrites (e.g., Dauphas and Pourmand, 2015). However, it is not the case here for OC normalized samples. It should be noted that the seemingly more negative anomalies in H OCs relative to that of L OCs is not real but occurred as the result of the normalization errors.

Logarithmic plot of Sr vs. Ba for the OCs from Atacama, Oman and Sahara is shown in Fig. 5. Different chemical trends is particularly more pronounced among those from the Atacama and Oman.

4.2. Atacama soil samples

The major and trace element composition of the analyzed soil samples are reported in Table 4. As reflected in their SiO_2 content, the parent rock material is basaltic/andesitic but the soil consists more acidic (granitic) material than the gravels, which is blown from neighboring lithologies. Both CI normalized REE patterns of gravels and <2 mm fractions of the soils are fractionated, showing LREE enrichments and a relatively flat HREE (Fig. 6). LREE enrichment in the <2 mm soil is higher than the parent rock gravels (La_N/Lu_N mean values 9.1 vs. 6.7) which is related to the weathering of the parent rock and the higher mobility of LREE into the soils during rock weathering process (Kabata-Pendias and Pendias 2001). The same reason applies for the Eu negative anomaly of the soils compared to the gravels and more resistance of Eu hosting grains during weathering.

Comparison of the analyzed samples with the REE composition of Upper Crust Composition (UCC) (Kemp and Hawkesworth 2004) and mean soil composition references (Govindaraju 1994; Kabata-Pendias and Pendias 2001) shows their similarity, which imply a well-mixed texture from various bed rocks. Dissimilar to the Atacama meteorites that generally show higher REE concentrations compared to the other hot desert meteorites, the soils show

REE chemical compositions comparable to the UCC and mean soil composition and without any significant compositional difference.

5. DISCUSSION

Our results show that terrestrial weathering may significantly modify the whole rock REE distribution of OCs from hot deserts. However, this modification varies among different deserts. Atacama OCs have higher concentrations of REE and their compositions has been affected to greater extent than those of Lut.

5.1. REE mobilization during meteorite weathering: a concise review

One of the first plausible evidence for REE mobilization during terrestrial weathering of meteorites was reported by Masuda et al. (1977) and Masuda and Tanaka (1978) on samples from Antarctica. These authors, however, considered the differences in the abundance of REE between the internal and external portions of meteorite samples to be intrinsic and primary rather than produced by terrestrial effects. Further studies on Antarctic achondrites attributed the modified REE compositions to cold desert weathering (Floss and Crozaz 1991; Kagi and Takahashi 1998; Mittlefehldt and Lindstrom 1991; Shimizu et al. 1983; Shinonaga et al. 1994; Swindle et al. 1998). Most prevalent results of weathering effects are LREE-enriched patterns with notable Ce (and in some cases Eu) anomalies produced by aqueous leaching. As proposed by Mittlefehldt and Lindstrom (1991) and confirmed by Floss and Crozaz (1991), during the exposure of a meteorite to atmosphere and its heating by the sun at the surface in Antarctica, surrounding meltwater can penetrate the meteorite through cracks and fractures. In equilibrium with atmospheric CO_2, this fluid becomes a weak carbonic acid solution which leaches the minerals such as Ca-phosphates and causes removal of trivalent REEs. In addition to being in +3 state, Ce and Eu occur as tetravalent and divalent ions, respectively. Since Ce^{+4} is less soluble than the +3 REEs and Eu is largely retained in the +2 state in plagioclase (which is relatively unaffected by weathering), they are preferentially retained in the sample and thus show their corresponding anomalies. Another study by Kagi and Takahashi (1998) showed a correlation between Ce anomalies and absorbed water content in Antarctic lunar meteorites that demonstrated its terrestrial origin.

Following the studies on the Antarctic meteorites, attempts were made to investigate the possible weathering effects on hot desert achondrites (both in mineral and whole rocks). In order to monitor the weathering of recently fallen meteorites, Barrat et al. (1999) analyzed fragments of Tatahouine diogenite recovered just sixty-three years after its fall. By comparing the REE composition with those of the fragments recovered immediately after the fall, elevated amounts of LREE was found in one of the fragments. This study revealed the disturbance of trace element composition of meteorites in relatively short time spans in a terrestrial environment. Crozaz et al. (2003) evaluated the mineral composition of different achondrite groups by secondary ion mass spectrometry (SIMS) and attributed the elevated levels of LREE in olivine and low-Ca pyroxene to terrestrial contamination. However, Barrat et al. (2003) did not find any significant weathering effects on whole rock REE composition of eucrites from the Sahara desert. A similar conclusion was made during a study of NWA 4872 brachinite by Hyde et al. (2014).

5.2. Effects of weathering on the REE composition of Atacama and Lut OCs

The aliquots analyzed in our work were from a large mass (about 2 grams) of well-mixed powder; so the formation of the observed REE patterns by nugget effect of REE-rich components is unlikely. Deviations of more than ± 10% from the mean composition of the corresponding meteorite groups assure that the enrichments/depletions are significant.

Unlike the Atacama OCs, those from Lut do not show profound changes in ΣREE (Table 3). Chemical modification of a meteorite during weathering, including changes in REE content, is controlled by several factors such as, primary chemical composition, modal composition, degree of recrystallization, shock stage, terrestrial age and locality (Crozaz et al. 2003). REEs which are mostly concentrated in Ca-phosphates and silicates (Ebihara and Honda 1984) are released during the weathering of these minerals. This process is facilitated by formation of sulfuric acid inside the meteorite as a result of troilite (FeS) oxidation in contact with meteoric water (e.g. Bland et al., 2006). With the development of primary mineral dissolution, REEs tend to concentrate in veins filled with iron oxides/oxyhydroxides (Thiagarajan and Aeolus Lee 2004).

Contrary to meteorites from Antarctic which release their REE during weathering on ice, an increase in REE concentration is expected for hot desert meteorites as a consequence of residing on a relatively REE-rich soil surface (Crozaz and Wadhwa 2001). Once a meteorite with its relatively high initial porosity falls on a hot desert surface, soil salts dissolved by water infiltrate into it by capillary forces triggered by temperature fluctuations (Zurfluh 2012). In addition, wind activity, burial in soil and desert varnish formation introduces terrestrial minerals containing REE, or develops the occurrence of primary minerals with modified REE patterns (Crozaz et al. 2003). We suggest that the notable increase in ΣREE contents of the Atacama OCs is caused by these kind of implementations.

Is the modification in REEs concentration controlled by the weathering degree of a meteorite? A look at the data of Lut OCs (Tables 1 and 3) shows that despite having high weathering degrees, their ΣREE does not change as much as the Atacama samples. For example, Kerman 001 (W4), which was half-buried in a valley in the Kalout formation of the Lut with a soil composed of clay, sand, evaporites and carbonates (Farpoor and Krouse 2008) at the time of recovery and exhibits well developed parallel weathering veins (Fig. 2-a), does not show any noticeable deviation from the mean composition. In comparison, the Atacama samples which generally are less weathered show higher ΣREE. For example, El Médano 049 which contains the highest ΣREE among the studied H OCs and was recovered from a igneous rocks deflation surface is also highly weathered (W3, Fig. 2-b), although less than Kerman 001. Comparing to samples from other regions, we see that three highly weathered H OCs from UAE (Hezel et al. 2011) and even weathered samples from Europe (Folco et al. 2007) represent ΣREE contents similar to Lut samples. However, ΣREE is elevated in highly weathered Saharan OCs (analyzed by Saunier et al., 2010) and Aridal 006 (W4). Therefore, the meteorite weathering as shown by weathering degree (Wlotzka 1993) and veins filled with secondary products is not the only factor responsible for ΣREE increase.

As for REEs, different chemical trends in Sr and Ba is also evident in meteorites from different regions (Fig. 5 & 7). Al-Kathiri et al. (2005) and Folco et al. (2007) showed that the weathering of meteorites in Oman and Sahara deserts (respectively) increases the Sr and Ba contents of meteorites. The carbonate basement and the Sr and Ba-rich soils in Oman deserts is responsible for the further enrichments of these elements in the recovered meteorites from the region. In some cases from Oman, high concentrations of Sr and Ba in the soil, leads to the formation of secondary celestine and barite inside the meteorites (Al-Kathiri et al. 2005). Meteorites from Atacama exhibit a different trend compared to Oman meteorites (Fig. 5). The majority of collecting site of the meteorites from Atacama is mostly made of volcanics and evaporites (Valenzuela 2011), which usually have lower concentrations of Sr and Ba than carbonates. The difference in the soil type can explain different trends in the Sr budget. Compared to the Omani and Atacama OCs, the samples from Lut desert have very low Ba contents (< 10 ppm). On the other hand, Sr concentrations of Lut OCs, are in the range of Omani meteorites. Considering Sr and La contents (Fig. 7), again we see difference in the chemical composition of meteorites from different regions. This differences can be used as proxies which allow distinguishing Atacama meteorites from Oman and Lut. Al-Kathiri et al. (2005) report a positive correlation between weathering degree and Sr, Ba concentration for Omani OCs, however we do not see any correlation between these parameters for the meteorites from Atacama and Lut samples.

The Atacama desert has exceptionally high meteorite concentrations compared to other hot deserts. In a study of 22 meteorites, Gattacceca et al. (2011) found half of the meteorites with terrestrial ages older than 20 ka, which is much older than the age ranges reported from other hot deserts. We may hypothesize that the generally high terrestrial age of the Atacama meteorites is responsible for their high ΣREE amounts. The similar effect of terrestrial age on REE content can be seen in higher amounts of La in very old meteorites from Atacama and in samples with terrestrial ages of more than >30 kyr from Oman (Al-Kathiri et al. 2005) (Fig. 3-a).

Most of the Atacama and some highly weathered Saharan OCs show differentiated REE patterns (Fig. 3 and Fig. 4). Since the soil and sedimentary materials typically exhibit higher LREE contents (Aide and Aide 2012), as observed in our analyzed samples from the Atacama, the residence of a meteorite on a soil surface increases the LREE content of the meteorite (Al-Kathiri et al. 2005; Crozaz et al. 2003; Dreibus et al. 2001). The studied meteorites and their patterns which tend to converge toward that of the surface material is consistent with the assumption that soil has affected their chemical composition (Fig. 6). Taking into account the different soil types of the meteorite collecting sites (carbonate in Oman versus volcanic/evaporitic in Atacama and clay/sand in Lut), it can be deduced that nearly all of the meteorites represent approximately similar LREE-enriched patterns which forms as a result of both: (i) higher abundance of LREE in soils and (ii) higher solubility of LREE (Aide and Aide, 2012 - and references therein).

Different clay and iron oxide/oxyhydroxide minerals display specific Ce and Eu anomalies. These minerals which are the main components of soils, occur in different proportions based on the soil type; as a result different Ce and Eu anomalies is exhibited in different soils (Laveuf and Cornu 2009). Although most of the Ce anomalies in our data are small and hardly significant, two slightly weathered (W1) meteorites (Cobija and Lutschaunig's Stone) display notable positive Ce anomalies (Fig. 3a, b) that might reveal the incipient phase of REE modification during weathering. Cerium is the most abundant REE in the average soil composition (Aide and Aide 2012). Once the meteorite falls, the initial physical soil contamination through cracks and fractures gives it a positive Ce anomaly. By developing the chemical weathering, trivalent REEs of the soil with higher solubility rates than Ce^{+4} infiltrate the meteorite and most of the Ce oxides to Ce^{+4} and preferentially retains in the soil. Progressive alteration of the meteorite and the addition of trivalent REEs removes the initial Ce positive anomaly. At higher residence times and more interaction of terrestrial contaminants with meteorite, the amount of La and Pr exceeds the Ce concentration and creates a negative Ce anomaly that is evident in the REE patterns of some meteorites with high terrestrial ages such as, La Yesera 003, Caleta el Cobre 006, Paposo and El Médano 049 (Fig. 3). Variation in Eu anomalies among studied meteorites can result from contamination by different soil components, although the presence of possible primary plagioclase should not be excluded.

Putting these data together, we hypothesize that terrestrial age rather than weathering degree is the main governing factor of REE content and its modification in hot desert OCs, even though weathering degree and terrestrial age at a given recovery site show a positive correlation (e.g. Bland et al., 2006). Indeed, the formation of secondary oxidation products decreases the porosity of the meteorite by filling the fractures and cracks which are the pathways for REE containing terrestrial fluid to circulate and solid materials to penetrate (Bland et al. 2006). The earlier this process initiates, the lower the possibility that a terrestrial material is able to affect the REE composition of the meteorite. But in areas with low weathering rates (like Atacama), greater amounts of soil and fluid penetrate the meteorite and modify the composition readily.

We observe that since the meteorites from Atacama are older than those from Lut and other regions (Sahara, Oman), and also owing to low weathering rates in the former, more time has been available for the terrestrial environment to affect the chemistry of Atacama OCs by means of different interactions. The terrestrial ages of Saharan meteorites used in this study are not determined, however by comparing weathering degree with terrestrial age of other meteorites collected from this desert (e.g. Welten et al., 2004), their terrestrial ages is probably high. The prevailing humid environment for UAE and Europe and thus higher weathering rates (Folco et al. 2007; Hezel et al. 2011), might have prevented the formation of a pronounced ΣREE increment in meteorites from these area. We believe that the terrestrial age range of highly weathered Lut meteorites shall be in the range of UAE meteorites. The occurrence of archeological sites in the surroundings of Lut (e.g. Muscarella, 2001), points to wetter climatic conditions, at least periodically over the last 10 kyr compared to nowadays. This is in agreement with the high weathering degree and the lack of a pronounced ΣREE change in the chemical composition of Lut OCs.

A large number of meteorites from Atacama is expected to be recovered in the future (Gattacceca et al. 2011; Hutzler et al. 2016). So care must be taken into account while working on the REE composition of even “fresh-looking” Atacama meteorites.

6. CONCLUSIONS

The chemical compositions of OCs from Atacama and Lut along with the published data from other hot desert areas reveal a difference in the effects of terrestrial weathering on REE distribution between these populations. Optimal conditions for meteorite preservation in the Atacama desert (i.e., high stability of the surface and low meteorite weathering rates) provide enough time for the meteorites to interact efficiently with terrestrial materials. In contrast, higher weathering rates of the meteorites from other hot deserts (specifically Lut) prevent such interaction. As a consequence, the highly weathered meteorites from Lut desert have lower ΣREE contents than those of the moderately weathered meteorite from Atacama. In some cases, even the OCs with minor weathering from Atacama show modified REE patterns with notable Ce positive anomalies. These anomalies may have been created by the initial physical contamination (the addition of soil or dust directly into the fractures, rather than more time-consuming chemical weathering) and then by the addition of trivalent REEs. Notwithstanding the lack of terrestrial age data for Lut meteorites, it is envisaged on the basis of almost unaffected REE compositions and high weathering degrees that this area was wetter than nowadays during the last tens of thousands of years and generally had a climate like UAE and Oman deserts.

Future investigations on the mobilization of REE isotopes, which are being used frequently in cosmochemistry, are needed to estimate their behavior during weathering.

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Tables heading:

Table 1: Meteorites studied in this work.

Table 2: Concentrations (µg/g) of Sr, Ba and REE in the four geochemical reference materials analyzed by ICP-MS along with the unknown samples. Literature values for these reference materials are also reported. The last column reports the detection limits (µg/g) of the used analytical method.

Table 3: Strontium, Ba and bulk REE composition (µg/g) and the calculated ratios of the studied meteorites.

Table 4: Major and trace element chemical composition of soil and gravel sample from Estacion Catalina in the Atacama Desert. Trace element concentration unit is ppm.

Figure captions:

Fig. 1: a) Map of the central Lut Desert and the finding places of the studied meteorites. b) Map of the Atacama Desert and the location of the dense collection areas which their meteorites were used in this study.

Fig. 2: Mosaic pictures of a) Kerman 001 and b) El Médano 049 prepared in reflected polarized light show the different weathering types of the meteorites. Kerman 001 contains clear parallel veins filled with weathering products and represents much strong weathering than El Médano 049 whose Fe-Ni metal and troilite are not completely altered yet.

Fig. 3: Normalized REE spider diagrams of a) H, b) L and c) LL ordinary chondrites. For comparison, the data of OCs from Oman (the average values for different age classes) (Al-Kathiri et al., 2005), U.A.E. (Hezel et al., 2011), Sahara Desert (Saunier et al., 2010; Folco et al., 2007) and Europe (Folco et al., 2007) are used along the data of this work. PdM is the abbreviated form of Pampa de Mejillones.

Fig. 4: La_N/Lu_N vs. La_N for H and L OCs from different regions. For comparison, the data of OCs from Oman (Al-Kathiri et al., 2005), U A EE (Hezel et al., 2011), Sahara Desert (Saunier et al., 2010; Folco et al., 2007) and Europe (Folco et al., 2007) are used along the data of this work.

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Fig. 5: Sr vs. Ba logarithmic plot showing OCs from various areas. The data of OCs from Oman (Al-Kathiri et al., 2005), Sahara Desert (Saunier et al., 2010; Folco et al., 2007) and Europe (Folco et al., 2007) are used along the data of this work. Some samples from Lut with Ba <10 ppm are also included.

Fig. 6: REE chemical composition of Estacion Catalina soil composition compared to the mean soil compositions (Govindaraju 1994; Kabata-Pendias and Pendias 2001). The Atacama H and L OCs show LREE enrichment in relation to falls in an attempt to reach equilibrium during the hot desert terrestrial weathering.

Fig. 7: Different chemical trends of OCs from different regions can be seen in the Sr vs. La_N plot. The data of L and H OCs from Oman, in different age classes (Al-Kathiri et al., 2005), Sahara Desert (Saunier et al., 2010Saunier et al., 2010; Folco et al., 2007) and Europe (Folco et al., 2007) are used along the data of this work.

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Table 1 (Pourkhorsandi et al.)

Meteorite	Type	Weathering degree	Terrestrial age (ka)[a]
Ordinary chondrites from Atacama			
La Yesera 001	H6	W3	10.79 ± 1.56
La Yesera 002	LL5	W2	25.44 ± 4.45
La Yesera 003	L4	W4	16.98 ± 2.47
La Yesera 004	L6	W3	34.07 ± 1.92
Pampa (a)	L6	W2	25.08 ± 1.46
Pampa (b)	L4/5	W3	21.29 ± 2.45
Pampa (c)	L4	W4	13.89 ± 2.08
Pampa (d)	L5	W2/3	14.18 ± 1.91
Pampa (g)	L5	W3	14.34 ± 1.62
Pampa de Mejillones 002	H5	W3	3.86 ± 1.36
Pampa de Mejillones 004	L6	W4/5	23.98 ± 4.40

Pampa de Mejillones 007	L6	W4	>27.9
Pampa de Mejillones 010	L5	W3	18.06 ± 1.90
Pampa de Mejillones 011	L5	W5	4.35 ± 1.34
Pampa de Mejillones 012	H4/5	W5	>34.3
Pampa de Mejillones 014	L/LL4-6	W2	12.54 ± 1.95
San Juan 01	L5	W2	>28.1
San Juan 02	H6	W2	19.44 ± 1.69
El Médano 049	H4	W3	1890 ± 80
Estacion Imilac	H5	W1	-
Cobija	H6	W1	19.7 ± 4.20
Rencoret	H6	W3	25.3 ± 6.4
Lutschaunig's Stone	L6	W1	9.2 ± 1.6
Caleta el Cobre 006	L6	W3	2345 ± 80
Paposo	LL6	W2	>49.2
Ordinary chondrites from Lut			
Lut 001	H5	W3	-
Lut 003	L3	W3	-
Lut 006	LL3	W3	-
Lut 008	H4	W5	-
Lut 009	H4	W4	-
Kerman 001	H5	W4	-
Kerman 002	L6	W3	-
Kerman 003	L5	W2	-
Shahdad	H5	W4	-
Ordinary chondrites from Sahara			
Aridal 006	H6	W4	-

[a] Terrestrial age data from Valenzuela (2011) by ^{14}C, and Hutzler (2015) by ^{36}Cl/^{41}Ca.

Table 2 (Pourkhorsandi et al.)

Element	**Allende (this work)**	**Allende (literature)[a]**	**BIR-1 (this work)**	**BIR-1 (literature)[b]**	**WS-E (this work)**	**WS-E (literature)[c]**	**PM-S (this work)**	**PM-S (literature)[c]**	**detection limit**
Sr	14.5	12 ± 3	122	108	450	410 ± 5	307	280 ± 5	0.5
Ba	4.5	4 ± 1	< 10	7	342	338 ± 6	139	148 ± 3.2	0.6 - 10
La	0.49	0.52 ± 0.04	0.62	0.62	27.6	27 ± 1.1	2.63	2.8 ± 0.17	0.02
Ce	1.24	1.33 ± 0.08	1.90	1.95	60	61 ± 1.4	6.5	6.8 ± 1.25	0.06
Pr	0.21	0.21 ± 0.01	0.39	0.38	8.0	7.8 ± 0.4	1.05	1.08 ± 0.16	0.007
Nd	1.01	0.99 ± 0.03	2.45	2.5	33.3	33 ± 0.7	5.4	5.5 ± 0.25	0.03

Sm	0.33	0.34 ± 0.02	1.10	1.1	8.8	8.8 ± 0.3	1.78	1.75 ± 0.05	0.02
Eu	0.09	0.11 ± 0.01	0.53	0.54	2.31	2.25 ± 0.04	1.04	1.07 ± 0.04	0.05
Gd	0.39	0.42 ± 0.02	1.96	1.85	7.4	7.2 ± 0.23	2.05	2 ± 0.1	0.004
Tb	0.07	0.081 ± 0.010	0.38	0.36	1.10	1.1 ± 0.04	0.35	0.36 ± 0.02	0.002
Dy	0.46	0.42 ± 0.03	2.78	2.5	6.5	6 ± 0.16	2.18	2 ± 0.1	0.005
Ho	0.10	0.10± 0.01	0.59	0.57	1.18	1.2 ± 0.06	0.42	0.42 ± 0.03	0.006
Er	0.29	0.29 ± 0.01	1.81	1.7	3.17	3 ± 0.11	1.19	1.1 ± 0.06	0.01
Tm	0.05	0.0572	0.26	0.26	0.42	0.43 ± 0.03	0.16	0.17 ± 0.01	0.003
Yb	0.31	0.30 ± 0.02	1.70	1.65	2.56	2.5 ± 0.1	0.96	1 ± 0.05	0.007
Lu	0.04	0.052 ± 0.006	0.26	0.26	0.36	0.37 ± 0.01	0.14	0.15 ± 0.01	0.002

[a]Jarosewich et al. (1987).
[b]Govindaraju (1994).
[c]Govindaraju (1995).

Table 3 (Pourkhorsandi et al.)

Meteorite	Sr	Ba	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	ΣREE	Ce/Ce*	Eu/Eu*	Tm/Tm*	La_N/Lu_N	La_N/Sm_N	Gd_N/Yb_N	Sr/Ba
La Yesera 001	30.6	38	0.76	1.63	0.22	1.01	0.27	< 0.05	0.31	0.05	0.38	0.08	0.23	0.03	0.22	0.03	5.3	0.92	0.56	0.86	2.27	1.73	0.98	0.79
La Yesera 002	26.3	50	0.54	1.54	0.18	0.81	0.23	0.10	0.31	0.05	0.39	0.08	0.25	0.04	0.25	0.03	4.8	1.08	1.28	1.13	1.73	1.52	0.90	0.53
La Yesera 003	37	12.6	0.45	1.12	0.17	0.86	0.26	< 0.05	0.29	0.05	0.38	0.09	0.27	0.04	0.25	0.05	4.3	0.90	0.58	0.92	1.04	1.07	0.83	2.99
La Yesera 004	12.4	7.5	0.31	0.81	0.13	0.61	0.20	0.07	0.25	0.05	0.31	0.08	0.21	0.03	0.21	0.03	3.3	0.93	1.03	0.87	0.93	0.97	0.84	1.67
Pampa (a)	18.1	4.1	0.30	0.85	0.12	0.61	0.21	0.10	0.24	0.05	0.33	0.08	0.22	0.03	0.23	0.03	3.4	0.99	1.41	0.88	1.16	0.93	0.75	4.41
Pampa (b)	21.1	5.0	0.29	0.75	0.12	0.52	0.23	0.07	0.23	0.04	0.29	0.07	0.19	0.03	0.20	0.03	3.06	0.91	0.97	0.93	1.14	0.81	0.84	4.21
Pampa (c)	31.8	14.6	0.40	0.94	0.15	0.70	0.23	0.09	0.29	0.05	0.35	0.08	0.26	0.04	0.25	0.04	3.9	0.86	1.06	0.89	1.17	1.10	0.81	2.18
Pampa (d)	21.3	4.8	0.26	0.70	0.11	0.59	0.19	< 0.05	0.24	0.04	0.31	0.07	0.21	0.03	0.19	0.03	3.0	0.95	0.75	0.92	0.87	0.84	0.87	4.39
Pampa (g)	38.6	42	0.55	1.08	0.17	0.82	0.26	< 0.05	0.32	0.05	0.35	0.09	0.26	0.03	0.23	0.04	4.2	0.81	0.55	0.83	1.39	1.31	0.99	0.92
Pampa de Mejillones 002	17.6	5.9	0.43	1.22	0.17	0.73	0.23	0.07	0.25	0.05	0.31	0.08	0.23	0.03	0.23	0.03	4.1	1.05	0.95	0.84	1.45	1.19	0.76	2.96
Pampa de Mejillones 004	23.6	8.3	0.39	0.97	0.14	0.68	0.21	0.08	0.25	0.05	0.31	0.07	0.20	0.03	0.21	0.03	3.6	0.92	1.07	0.97	1.24	1.16	0.85	2.82
Pampa de Mejillones 007	42	66	0.66	1.13	0.20	0.92	0.25	0.10	0.32	0.06	0.37	0.08	0.25	0.03	0.23	0.03	4.6	0.70	1.13	0.88	1.91	1.65	0.98	0.64
Pampa de Mejillones 010	26.1	5.3	0.29	0.88	0.12	0.55	0.21	0.08	0.26	0.05	0.31	0.07	0.19	0.03	0.23	0.03	3.3	1.06	1.10	0.85	0.97	0.90	0.80	4.91
Pampa de Mejillones 011	11.3	5.1	0.32	0.82	0.12	0.62	0.22	0.07	0.27	0.05	0.33	0.08	0.24	0.04	0.22	0.03	3.4	0.94	0.94	1.02	1.19	0.90	0.85	2.19
Pampa de Mejillones 012	39	21.3	0.43	1.07	0.14	0.68	0.20	0.07	0.25	0.05	0.33	0.07	0.23	0.03	0.21	0.02	3.8	1.00	1.08	0.84	1.69	1.36	0.80	1.85
Pampa de Mejillones 014	18.4	12.5	0.27	0.92	0.12	0.59	0.19	< 0.05	0.25	0.05	0.30	0.08	0.200	0.03	0.19	0.03	3.2	1.11	0.74	1.08	0.92	0.88	0.94	1.47
San Juan 001	71	52	0.57	1.17	0.18	0.77	0.24	0.11	0.27	0.05	0.34	0.07	0.20	0.03	0.21	0.03	4.3	0.83	1.35	1.00	1.77	1.48	0.89	1.37
San Juan 002	39	9.4	0.38	0.91	0.14	0.69	0.18	< 0.05	0.24	0.05	0.32	0.08	0.24	0.03	0.21	0.03	3.5	0.92	0.77	0.75	1.12	1.28	0.80	4.24
El Médano 049	45	270	0.78	1.34	0.25	1.22	0.31	0.10	0.44	0.07	0.49	0.10	0.30	0.04	0.27	0.04	5.8	0.69	0.91	0.82	1.87	1.56	1.13	0.17
Estacion Imilac	11.8	9.8	0.44	1.03	0.16	0.71	0.21	0.07	0.27	0.05	0.34	0.08	0.24	0.03	0.24	0.03	3.9	0.90	0.97	0.82	1.35	1.29	0.78	1.20
Cobija	15.8	6.2	0.33	1.48	0.12	0.62	0.19	0.07	0.25	0.04	0.33	0.07	0.21	0.03	0.19	0.03	4.0	1.69	1.05	0.85	1.03	1.08	0.89	2.57
Rencoret	26.1	12.9	0.68	1.62	0.22	1.01	0.27	0.09	0.32	0.05	0.35	0.08	0.25	0.04	0.24	0.03	5.2	0.97	0.97	0.81	2.04	1.58	0.89	2.01
Lutschaunig's Stone	10.4	4.2	0.35	1.83	0.14	0.69	0.22	0.07	0.30	0.05	0.38	0.09	0.25	0.03	0.23	0.03	4.7	1.84	0.92	0.89	1.06	0.98	0.92	2.48
Caleta el Cobre 006	72	326	0.92	1.89	0.28	1.22	0.32	0.10	0.40	0.07	0.48	0.10	0.31	0.04	0.28	0.04	6.4	0.85	0.87	0.90	2.46	1.80	1.01	0.22

Paposo	41	70	1.48	3.49	0.50	1.88	0.46	0.10	0.48	0.08	0.52	0.11	0.31	0.05	0.30	0.05	9.8	0.88	0.68	0.99	2.92	2.06	1.15	0.58
Lut 001	62	<10	0.30	0.72	0.11	0.50	0.18	0.08	0.23	0.04	0.30	0.06	0.20	0.03	0.20	0.03	2.98	0.92	1.28	0.82	1.02	1.06	0.80	6.2
Lut 003	91	<10	0.34	0.81	0.12	0.58	0.18	0.07	0.26	0.04	0.33	0.07	0.20	0.03	0.19	0.03	3.26	0.90	1.01	0.94	1.20	1.20	0.94	9.1
Lut 006	126	20.8	0.37	0.92	0.14	0.68	0.23	0.08	0.29	0.06	0.37	0.08	0.24	0.04	0.26	0.03	3.8	0.86	1.01	0.96	1.10	1.04	0.82	6.1
Lut 008	72	<10	0.31	0.79	0.12	0.62	0.20	0.07	0.26	0.05	0.32	0.07	0.20	0.03	0.20	0.03	3.28	0.96	0.96	0.86	1.01	0.99	0.87	7.1
Lut 009	497	14.3	0.33	0.84	0.12	0.62	0.19	0.07	0.25	0.05	0.31	0.07	0.20	0.03	0.20	0.03	3.3	0.95	1.08	0.86	1.03	1.08	0.85	34
Kerman 001	165	<10	0.38	0.93	0.14	0.70	0.21	0.08	0.30	0.05	0.36	0.08	0.22	0.03	0.22	0.03	3.7	0.93	0.99	0.87	1.16	1.12	0.96	16.5
Kerman 002	33	<10	0.35	0.90	0.14	0.66	0.22	0.08	0.29	0.05	0.38	0.08	0.24	0.03	0.23	0.04	3.7	0.91	1.00	0.89	1.07	1.02	0.88	3.3
Kerman 003	41	<10	0.43	1.00	0.14	0.70	0.22	0.08	0.30	0.05	0.37	0.08	0.24	0.03	0.24	0.04	3.9	0.92	1.06	0.87	1.27	1.23	0.89	4.1
Shahdad	141	<10	0.47	1.04	0.14	0.66	0.20	0.07	0.25	0.05	0.33	0.07	0.20	0.03	0.21	0.03	3.8	0.93	1.07	0.85	1.63	1.46	0.79	14.1
Aridal 006	17.9	23.7	0.29	0.70	0.10	0.49	0.16	0.08	0.21	0.04	0.28	0.06	0.18	0.03	0.18	0.03	2.84	0.94	1.49	0.82	1.01	1.14	0.80	0.76

Table 4 (Pourkhorsandi et al.)

	SV2 < 2mm soil				SV1 gravels			
	CS-Surface-01	CS-Surface-02	CS-1-01	CS-1-02	CS-Surface	CS-1-01	CS-1-02	CS-5
Depth (cm)	0-0.5	0-0.5	0.5-5	0.5-5	0-0.5	0-0.5	0.5-5	>34
SiO_2	59.8	60.4	58	58	53	52.5	57.8	52.5
Al_2O_3	14.65	14.65	14.6	14.65	17.35	17	16.6	17.15
Fe_2O_3	8.09	7.88	7.56	7.62	8.13	8.29	6.99	8.21
CaO	4.42	4.11	3.9	3.97	8.88	8.72	7.46	9.44
MgO	2.11	1.98	2.19	2.23	5.52	5.51	3.82	5.55
Na_2O	2.96	2.84	2.48	2.53	2.94	2.8	2.75	3.04
K_2O	2.42	2.37	2.31	2.31	1.17	1.12	1.3	1.11
Cr_2O_3	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
TiO_2	1.19	1.16	1.08	1.1	1.05	1.06	0.98	1.07
MnO	0.14	0.16	0.12	0.13	0.13	0.14	0.15	0.13
P_2O_5	0.19	0.2	0.21	0.23	0.27	0.23	0.23	0.23
Total %	96.14	95.92	92.6	92.92	98.6	97.53	98.27	98.58
Rb	84.1	85.4	95	91.6	30.5	25.4	35.6	19.2
Sr	525	483	423	421	931	865	878	921
Ba	931	954	789	782	412	384	779	360
La	25.8	26.1	26.1	25.8	19.6	18.8	20.1	17.9
Ce	52	53	52.6	52.4	42.2	40.4	45.6	38.7
Pr	6.3	6.4	6.4	6.4	5.3	5.1	5.3	4.9
Nd	24.3	24.3	25	24.4	21.8	21.1	21.5	20.5
Sm	4.9	4.6	4.9	4.8	4.3	4.3	4.3	4.1
Eu	1.2	1.3	1.2	1.2	1.4	1.4	1.4	1.4
Gd	5	4.7	5	4.7	4.8	4.4	4.8	4.4
Tb	0.7	0.7	0.7	0.6	0.7	0.6	0.7	0.6
Dy	3.7	3.7	3.8	3.8	3.8	3.8	3.9	3.6
Ho	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
Er	2.3	2.2	2.3	2.2	2.2	2.2	2.3	2.1
Tm	0.3	0.3	0.3	0.3	0.3	0.2	0.3	0.3
Yb	2.1	2.1	2.1	2	2	1.9	2.1	1.9
Lu	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
La_N/Lu_N	9.1	9.2	9.2	9.1	6.9	6.6	7.1	6.3

Fig. 1-a. (Pourkhorsandi et al.)

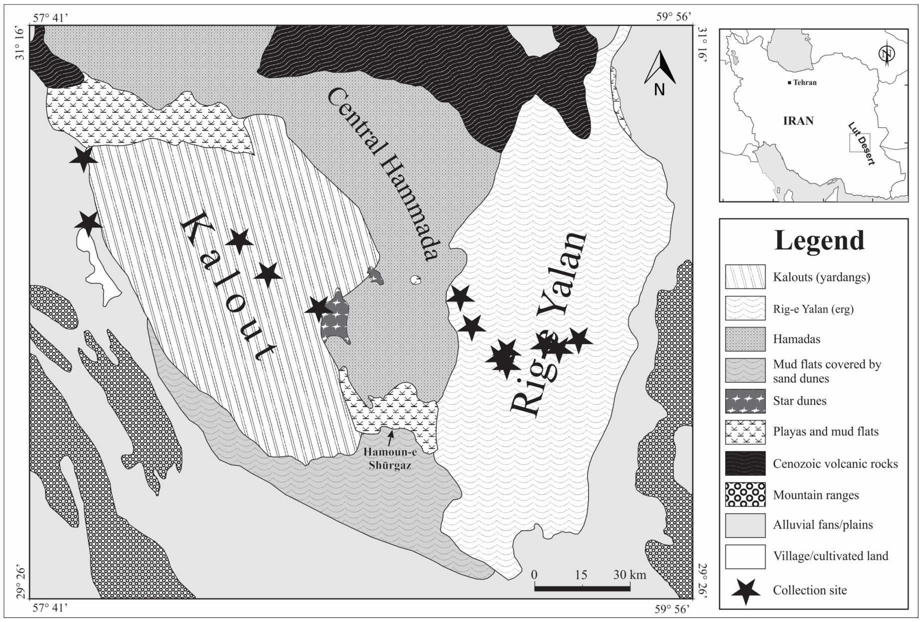


Fig. 1-b. (Pourkhorsandi et al.)

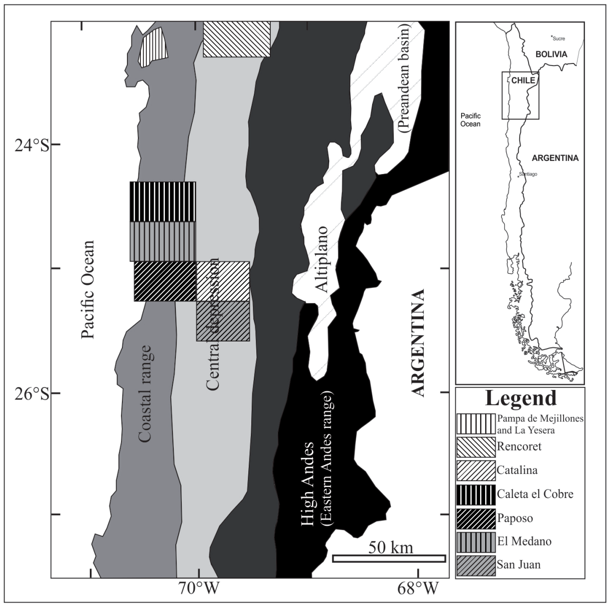


Fig. 2. (Pourkhorsandi et al.)

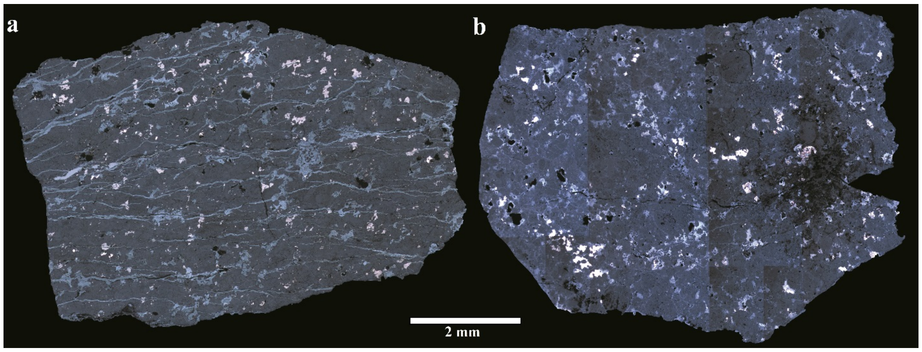


Fig. 3-a. (Pourkhorsandi et al.)

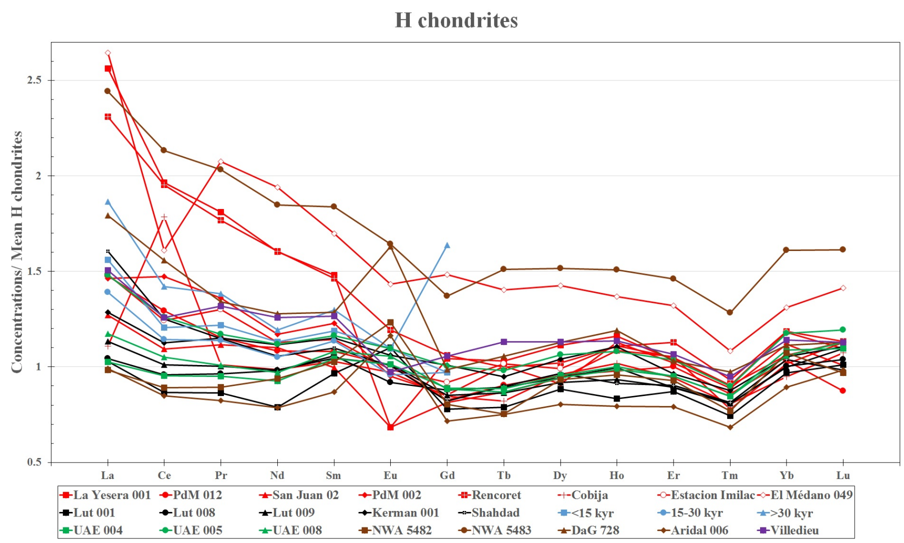


Fig. 3-b. (Pourkhorsandi et al.)

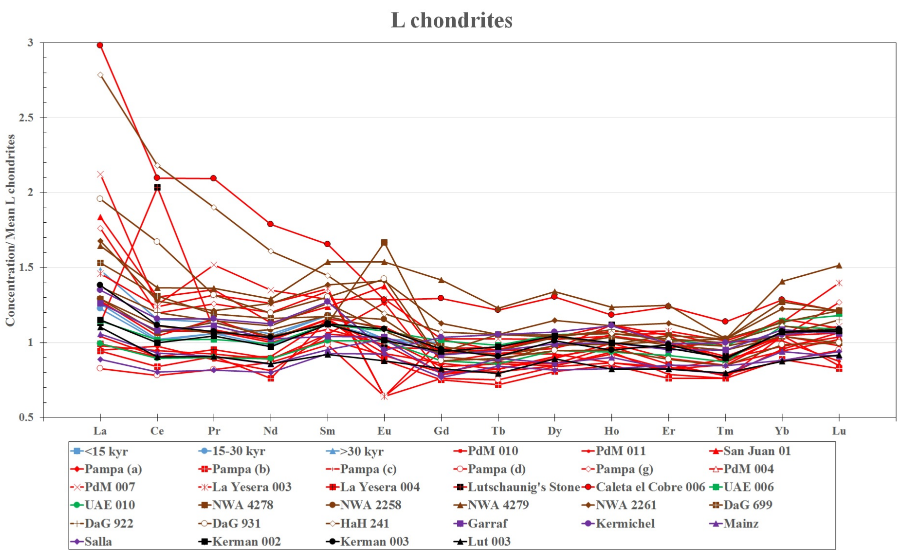


Fig. 3-c. (Pourkhorsandi et al.)

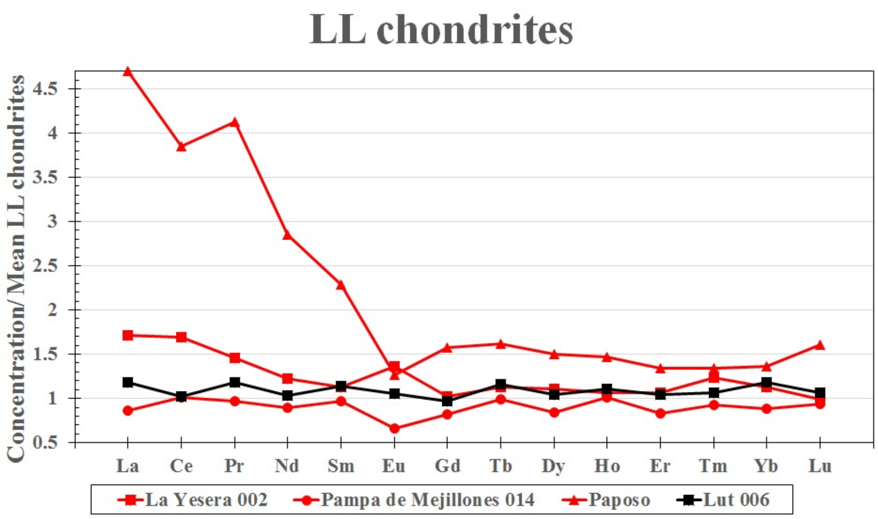


Fig. 4. (Pourkhorsandi et al.)

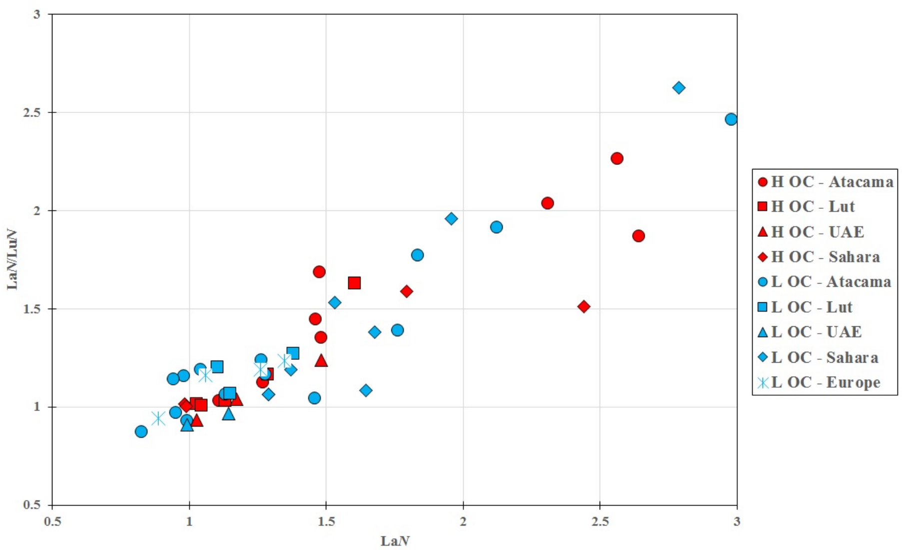
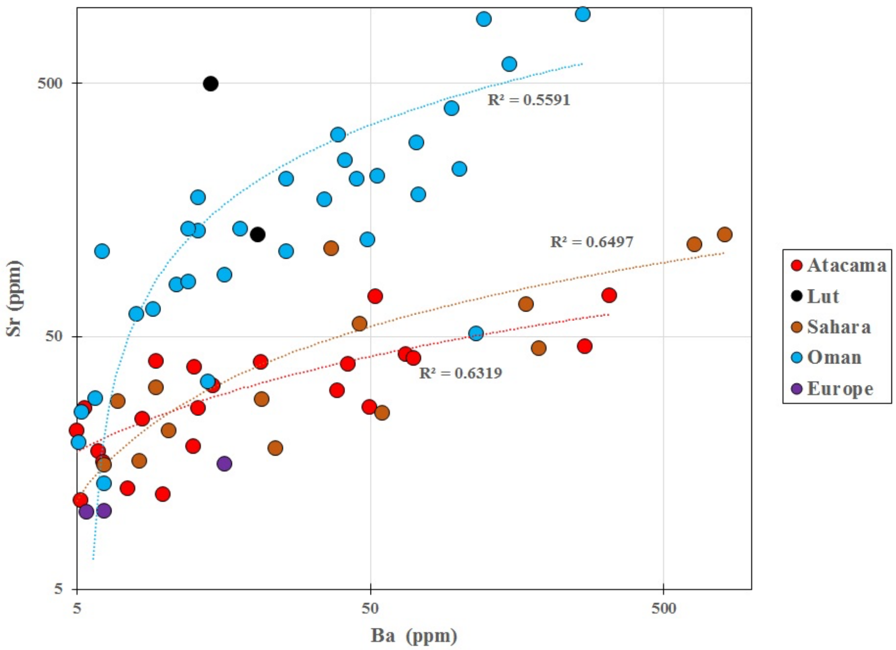
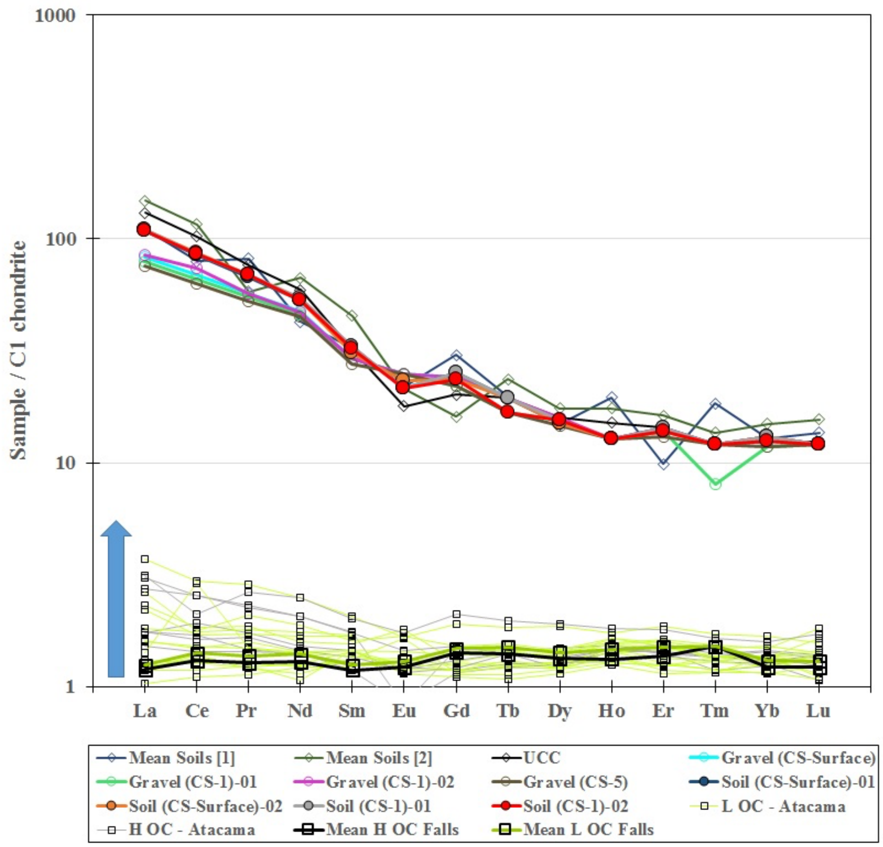


Fig. 5. (Pourkhorsandi et al.)



815 Fig. 6. (Pourkhorsandi et al.)



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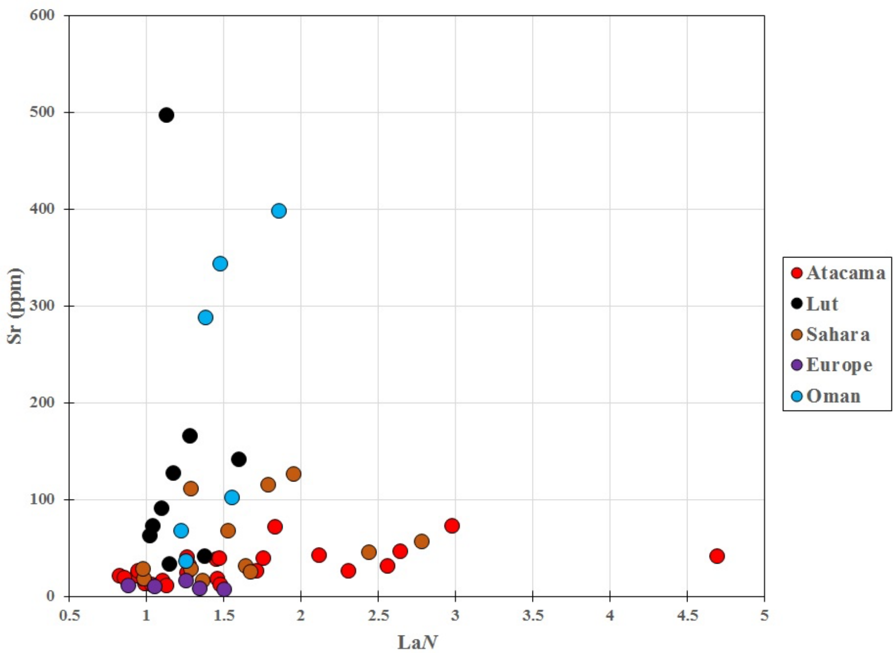
821 Fig. 7. (Pourkhorsandi et al.)



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