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## Characteristics of the Sahara as a meteorite recovery surface

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**Abstract**—We describe the geological, geomorphological, and paleoclimatic setting of the Sahara of North Africa in particular, focused on the main meteorite dense collection areas (DCA; Morocco, Algeria, Tunisia, and Libya). We report on the outcome of several meteorite recovery field expeditions in Morocco and Tunisia since 2008, by car and by foot, that applied systematic search methods. The number of meteorites collected is 41 ordinary chondrites and one brachinite. The statistics of unpaired ordinary chondrites indicates that H chondrites are more abundant (21) than L chondrites (12), while LL chondrites are rare (2). Our meteorite density estimates for Tunisia and Morocco are in the order of magnitude of 1 met km<sup>-2</sup>. An estimate of the total maximum number of meteorites that could be recovered from the Sahara is 780,000 meteorites. We selected 23 meteorites from Aridal, Bou Kra, Bir Zar, and Tieret DCAs for <sup>14</sup>C dating. The results show a wide range of terrestrial ages from 0.4 to more than 40 kyr with a majority of meteorites showing ages between 0.4 and 20 kyr. The weathering degree of these meteorites is ranges from minor (W1) to strong (W4). The highest weathering grades result from repeated oscillations between high and low humidity in the Sahara. However, there appears to be no correlation between weathering grade and terrestrial age of meteorites.

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### INTRODUCTION

The most productive places for meteorite recovery (Table 1) are the cold desert of Antarctica (Righter et al. 2015), the stony deserts or “regs or serir” of the Sahara and Arabia (e.g., see Bischoff and Geiger [1995] and references therein; Schultz et al. 1998; Russell et al. 2004; Hofmann et al. 2009, Hofmann et al. 2014; Chennaoui Aoudjehane 2018) and the Atacama desert (Gattacceca et al. 2011; Hutzler et al. 2016). In these areas, there is little precipitation, with an average of 170 mm y<sup>-1</sup> in Antarctica (Van de Berg et al. 2006) and 100 mm y<sup>-1</sup> in Sahara (Le Houérou 1995), so the moisture level and the chemical weathering rates are

lower than in temperate environments (Zolensky et al. 1990). On these surfaces, meteorites are often easily recognized because of the color contrast between dark meteorites and “pale” country rock or ice.

Of the 61,418 meteorites officially published in the Meteoritical Bulletin database (accessed July 30, 2019), 20% (12,183) are from the Sahara including 15% (9696 meteorites) under the acronym North West Africa “NWA,” “Sahara,” and North East Africa “NEA,” without geographic coordinates. Only 2487 meteorites finds are reported from the Sahara with naming either as DCA or individual localities. These meteorites approved by the Nomenclature Committee (NomCom) mostly came from northern Sahara countries: Libya (1496),

Table 1. Number and ordinary chondrites proportion of official meteorite finds in Northwest Africa (NWA), compared to other large desert areas. Data are from *Meteoritical Bulletin Database* last consulted on July 30, 2019.

| Area                     | Total meteorites in the world | NWA  | Libya | Arabic Peninsula | Chile | Antarctica |
|--------------------------|-------------------------------|------|-------|------------------|-------|------------|
| Number of meteorites     | 61,418                        | 8735 | 1496  | 4402             | 1206  | 43231      |
| % of ordinary chondrites | 86                            | 61   | 88    | 85               | 92    | 81         |

Algeria (605), Morocco (152, including Moroccan Western Sahara), Egypt (78), and Tunisia (75). In the countries of the southern Sahara, only a small number of meteorites finds have been reported: Niger (31), Mauritania (13), Mali (5), and Chad (1).

NWA meteorites are found in the desert of Morocco and adjacent countries, with only vague information about their recovery locations, if any (Bischoff and Geiger 1995; Larouci et al. 2015). According to Chennaoui Aoudjehane (2018), 90.2% of brachinites, 85.7% of angrites, 77.4% of Martian, and 70.7% of lunar meteorites were collected from this area. Due to commercial activity, meteorite samples of rare types are available for research. In addition to these finds, Morocco experienced a very high number of falls since 2002 (14 events) Chennaoui Aoudjehane and Jambon 2016; Chennaoui Aoudjehane and Agee 2019). These finds and falls of meteorites represent an important contribution to meteoritics and planetary science (e.g., Chennaoui Aoudjehane et al. 2012; Agee et al. 2013).

The first NWA meteorite was officially reported in 2000 as NWA 001 (L6). The overall NWA collection is not representative of the composition of the meteorite flux, because most of these meteorites are purchased and remain in private collections without classification and submission to the Nomenclature Committee of the Meteoritical Society. This is especially the case for those with low economic value, such as ordinary chondrites. Their proportion of 61% in NWA region is lower than in other deserts (see ratio in Table 1) while rare meteorites show a higher percentage (Chennaoui Aoudjehane 2018). Besides selective declaration bias, another reason for the relative abundance of lunar (and Martian) meteorites in the NWA collection may be linked to the resistance to weathering of these metal-free rocks. Indeed, terrestrial ages >50 kyr reported from Sahara and Oman have been obtained on lunar and Martian meteorites, but not for metal-bearing ordinary chondrites (Jull 2006).

The number of meteorites recovered per unit surface, that is, meteorite density, can be determined if the surface can be considered as a passive and stable collector of the influx of meteorites. Antarctica is thus excluded due to ice-flow concentration mechanisms (Yoshida 2009).

A number of studies have estimated meteorite recovery densities between 0.15 and 86 met km<sup>-2</sup> in hot desert areas such as the southwestern USA (e.g., Zolensky et al. 1990;

Rubin et al. 2000), Australia (Bevan et al. 1998), the Arabian Peninsula (Hofmann et al. 2009), the United Arab Emirates (Hezel et al. 2011), and the Atacama (Gattacceca et al. 2011; Hutzler et al. 2016), see Table 2.

However, no attempt has been made so far to summarize such data for the Sahara, the largest hot desert of our planet, with a surface of 9 million km<sup>2</sup>. In the literature, several techniques for prospecting meteorites are reported: by car or on foot, with either random or systematic search patterns (Table 2). The systematic search by foot gives better results because a well-defined area can be fully covered and this allows the collection of smaller meteorites thus producing more reliable density estimates. The other methods remain exploratory research, where mainly larger meteorites are recovered and only a lower bound of density estimate can be retrieved.

The calculated density of meteorites in a hot desert depends on the search technique. For searches by car, the densities obtained are low, between 0.15 and 0.4 meteorites km<sup>-2</sup> (met km<sup>-2</sup>; Bischoff and Geiger 1995; Schlüter et al. 2002; Hezel et al. 2011). For parties applying systematic search by foot, the densities reported

Table 2. Comparative density of meteorites in different hot deserts using different searching techniques: systematic, by car, or random search. Data are from: Acfer (Bischoff and Geiger 1995), San Juan (Gattacceca et al. 2011), El Medano and Caleta el Cobre (Hutzler et al. 2016), Australia (Bevan et al. 1998), HaH and DaG (Schlüter et al. 2002), Oman (Hofmann et al. 2014), Roosevelt County (Zolensky et al. 1990), and UAE (Hezel et al. 2011).

| DCAs name                             | Surface covered (km <sup>2</sup> ) | Density (met km <sup>-2</sup> ) | Prospecting methods |
|---------------------------------------|------------------------------------|---------------------------------|---------------------|
| Acfer (Algeria)                       |                                    | 0.2                             | Car                 |
| San Juan (Chile)                      | 3.88                               | 9.3                             | Systematic search   |
| El Medano and Caleta el Cobre (Chile) | 0.5                                | 86                              | Systematic search   |
| Australia                             | 44.9                               | 1                               | Randomly search     |
| HaH and DaG (Libya)                   | 5500                               | 0.15                            | Car                 |
| Oman                                  | 148.5                              | 0.4                             | Systematic search   |
| Roosevelt County (USA)                | 11                                 | 3.61                            | —                   |
| UAE                                   | 100–150                            | 0.2–0.4                         | Car                 |

are in the range of 1–10 met km<sup>-2</sup> (Zolensky et al. 1990; Bevan et al. 1998; Gattacceca et al. 2011; Hofmann et al. 2014), except in the Atacama where values above 100 met km<sup>-2</sup> are reported in Hutzler et al. (2016), 86 met km<sup>-2</sup> after pairing correction, on a 0.5 km<sup>2</sup> surface. Hutzler et al. (2016) also tried to estimate the recovery bias (the number of meteorites present but not collected) leading to a corrected pre-pairing density of 150 met km<sup>-2</sup>. By contrast, little information is available for the Sahara, thus motivating the present work.

In order to improve these data, a number of searches were undertaken in the Sahara reflecting a significant time investment by recovery teams. Such an effort was recently undertaken in the deserts of Tunisia (Laridhi Ouazaa et al. [2009] and successive missions) and Morocco (Buhl et al. 2014) as well as a new meteorite hunting field trip by our team in May 2016. In this paper, we present the outcome of meteorite recovery expeditions that we have organized in Tunisia and Morocco with a total of 42 recovered meteorites. We also describe relevant geological, geomorphological, and paleoclimatic aspects of the North African Sahara. Finally, we also discuss the density and the terrestrial age of the meteorites as well as their statistical properties (type, mass distribution, weathering).

## GEOLOGY, GEOMORPHOLOGY, AND CLIMATE OF THE SAHARA

### Geological Overview of the Sahara

The Sahara is the largest hot desert in the world with an area exceeding 9 million km<sup>2</sup> covering 10 countries: Algeria, Chad, Egypt, Libya, Mali, Mauritania, Morocco, Niger, Sudan, and Tunisia. It is located between latitudes 16 and 32°N and longitude 17°W and 38°E and covers almost the one-third of the African continent. The desert is limited by the Atlas Mountains in the northwest, the Red Sea in the east, and the Atlantic Ocean in the west. In the southern Sahara, there is a sharp gradient of precipitation and vegetation; this transition zone is called the Sahel (Le Houérou 1980; Fig. 1).

The oldest Sahara formations correspond to the Precambrian African shield, composed of Precambrian rocks (Taylor et al. 2009) shared between pan-African chains and cratonic areas found in the Southern Sahara. However, the Sahara is made mainly of Paleozoic to Cenozoic sedimentary rocks of various lithologies, with the largest surface corresponding to post Paleozoic (Fig. 1).

There are two distinct geomorphologies of the Sahara. The Erg or “sand sea” desert is the final

product of erosion reliefs, consisting of an extensive set of dunes constantly reshaped by wind covering about 20% of the area of the Sahara. The remaining 80% of the surface is mostly “reg,” which is a desert pavement or stony surface cleared of fine elements due to wind deflation (also known as “Hammada”). The sandstones in these areas are often affected by a brownish patina with meteorite-like pebbles.

In the Sahara, the most favorable geological formations for meteorite searches are light-colored marine clays and limestones, common in Mesozoic or younger formations. In particular, the search areas discussed below lie on Jurassic (Tunisia; Figs. 2a–b) to Meso-Cenozoic (Southern Morocco) limestone. The same is also true for the Libyan, Algerian, and Egyptian DCAs.

The searches discussed in this paper were focused on the apparently oldest surface in a given region, that is, mesas (tabular white limestones, formed of decimeter-thick layers, arranged almost horizontally; Fig. 2a). Sediments are dated to the terminal Cretaceous in Tunisia. In Southern Morocco, we searched near Quaternary drainage systems with very limited vegetation. We looked for deflated surfaces littered with ventifacts and desert-varnished rock fragments rather than ones with fine sand and gravel indicating past fluvial activity as well as eolian deposition.

### Present and Past Climate of the Sahara

The present climatic limits of the Sahara are approximately defined by the 100 mm y<sup>-1</sup> line (Fig. 1), coupled with temperature maxima exceeding 50 °C (Le Houérou 1995). These conditions are characterized by very rare or absent vegetation in summer, which is favorable for meteorite hunting.

The marked aridification at the beginning of the Quaternary period (DeMenocal 1995; Feakins et al. 2013) supports the idea that the age of Sahara does not exceed 2–3 Myr (Kroepelin 2006), although sand dune deposits in the northern Chad Basin yield an age of 7 Myr (Schuster et al. 2006). From that time, the climate has alternated between humid and dry periods. The last well-defined humid period affecting the Sahara is dated to between 5 and 15 kyr (Lézine et al. 2011; Kuechler et al. 2013; Armitage et al. 2015). During that period, numerous permanent lakes and rivers existed in the Sahara and the present DCAs were likely soil-covered and vegetated. As humidity increases chemical weathering, these conditions advance the destruction of metal-rich meteorites such as ordinary chondrites. Only metal-free (or metal-poor) Saharan meteorites of lunar and Martian origin have yielded older terrestrial ages (see Jull 2006).

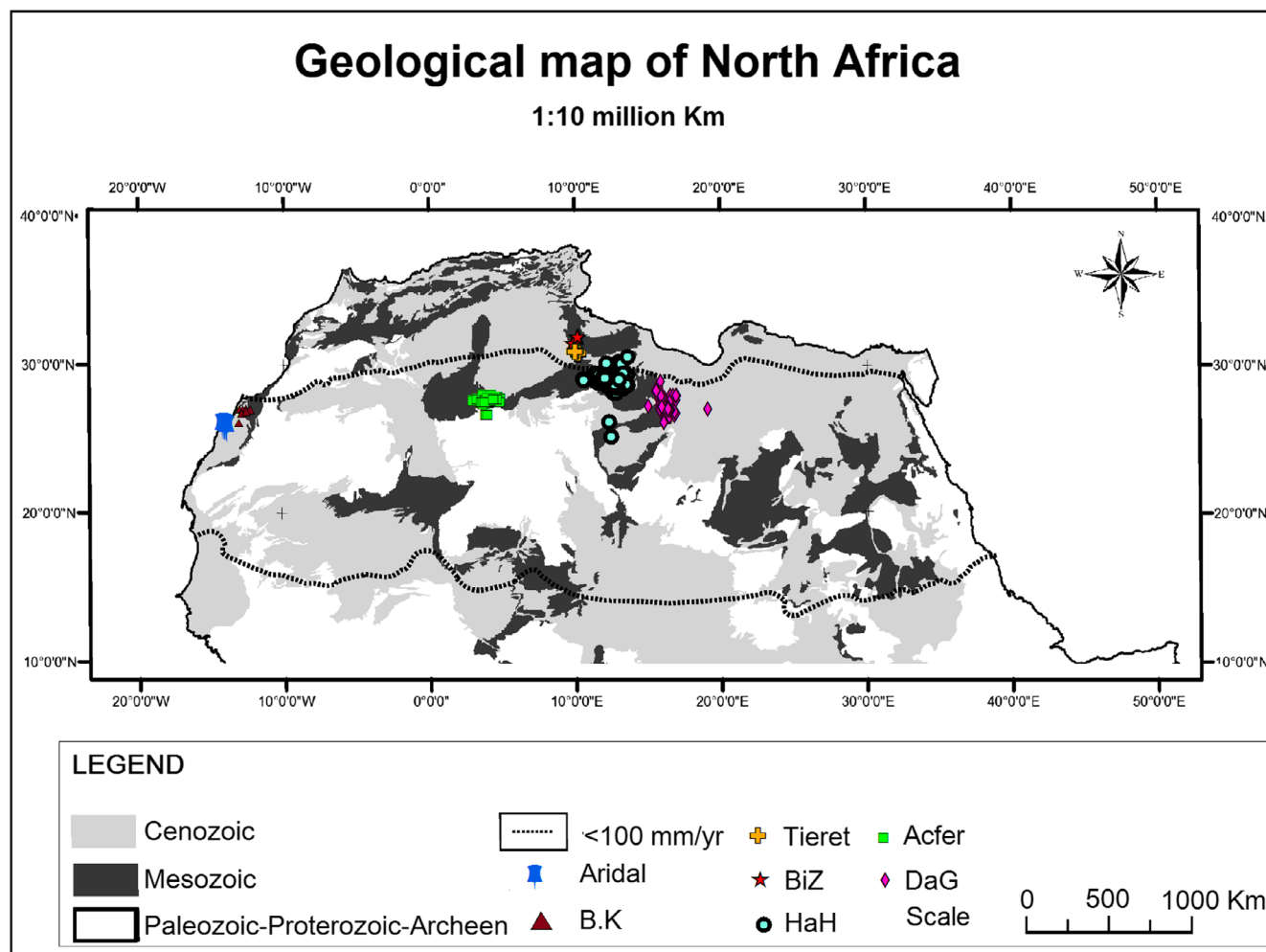


Fig. 1. Location of some Saharan meteorites dense collection areas (DCAs)—HaH (Hammadah al Hamra), DaG (Dar al Gani), and Acfer—reported on simplified geological map of North Africa at 1:10M scale by Thiéblemont (2016). The DCA studied in this work are reported: Aridal and B.K (Bou Kra) in Morocco; BiZ (Bir Zar) and Tieret in Tunisia. (Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com/doi/10.1111/maps.13398).)

## METEORITE SEARCH CAMPAIGNS AND ANALYTICAL TECHNIQUES

### The Tunisian and Moroccan Meteorite Search Missions

In this paper, we present the results of six distinct Saharan searches for meteorites. Three were conducted in Tunisia: in 2008 by the Université de Tunis El Manar and Università di Pisa and Siena, then in 2009 and 2010, a team from Centre Européen de Recherches et d'Enseignement en Géosciences de l'Environnement (CEREGE) joined a mission. In Morocco, two field campaigns were conducted by S. Buhl and his team in 2012–2013, and another by researchers from Hassan II University of Casablanca and CEREGE in 2016. This study also includes the Bou Kra DCA in Morocco, searched mostly by car by S. Buhl and others.

### Tunisian Meteorite Search Missions

The prospected areas are located in the southeast of Tunisia, in the Bir Zar (Laridhi Ouazaa et al. 2009) and Tieret regions (Fig. 3). The presence of oil companies operating in this sector encouraged and facilitated on-site logistics (travel and accommodation).

The local geology is characterized by rocks with tabular Cretaceous whitish flint-bearing limestone; dark flint as well as some vegetation made the search difficult (Figs. 2a–b). Magnetic susceptibility was sometimes measured in situ (Gattacceca et al. 2004; Folco et al. 2006) to discriminate between black-brown sedimentary silica pebbles and meteorites, and obtain preliminary pairing clues on the field.

Walking with six to eight persons, the team prospected and followed one grid of parallel lines, 10 m



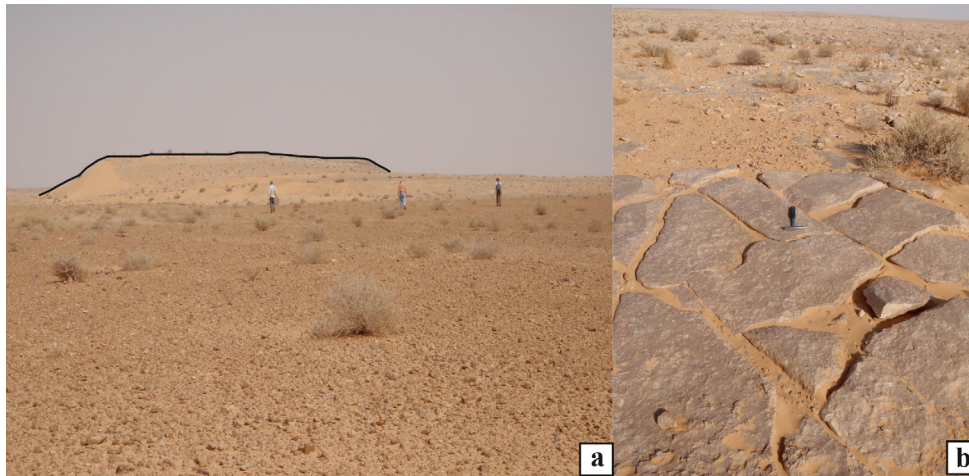


Fig. 2. Pictures of the geological surface and landscape of the prospected Saharan desert in Tunisia including (a) mesas, presented in the form of an elevated surface at the bottom of the photo, (b) soil with a clear color and no dark rocks and no vegetation, and red-colored outcrops of sedimentary rocks. Vegetation is disparate and very rare. (Color figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com).)

distant from each other (Fig. 2a). The average time for searching meteorites in the field was 8 h per day.

#### Moroccan Meteorite Search Missions

In the desert of Morocco, Svend Buhl and team went to the Bou Kra area to conduct exploratory

meteorite prospection (Buhl et al. 2014); the team collected four meteorites subsequently published as Bou Kra 002 to 005 (Ruzicka et al. 2015). Encouraged by these discoveries, subsequent fieldwork was organized in winter 2012 and 2013 by a team composed of six prospectors in three vehicles (Buhl

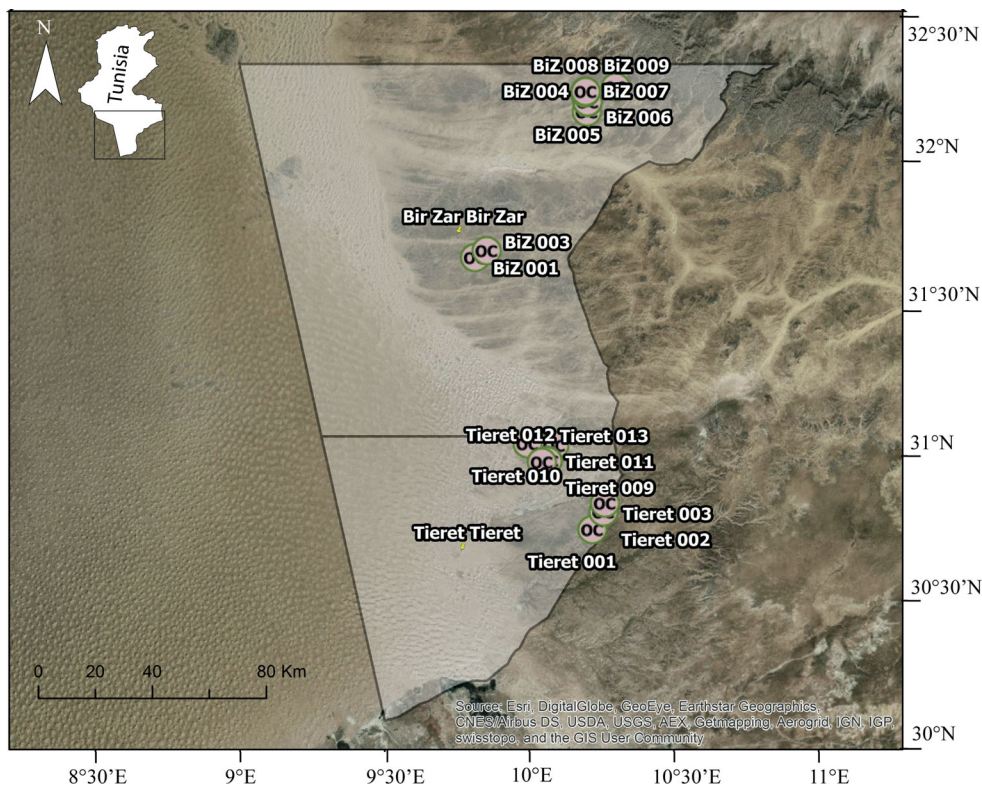


Fig. 3. Location of the meteorites recovered in Bir Zar and Tieret DCAs in Tunisia reported on a satellite image (Image Source: Esri, DigitalGlobe). (Color figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com).)

et al. 2014). They selected the Aridal area, located 150 km south of Laayoune (Fig. 4). The prospecting was conducted without following a systematic search method. The search was conducted mostly by car rather than on foot. The surface area covered was 58 km<sup>2</sup> in 20 days; the total search time was 960 h (8 h/person/day).

On May 2016, a 1-week field mission was conducted in the vicinity of the Aridal DCA applying a systematic search method.

Bou Kra and Assaquia Al Hamra DCAs were prospected as well as the Wad Al Khachbiyine area (Fig. 4). These areas were selected because of the favorable characteristics for meteorite prospecting: These topographies are flat with slightly elevated ground favoring deflation and the absence of water drainage. The surfaces are old (Cenozoic–Mesozoic) and covered by some Quaternary alluvium. They are characterized by little vegetation and light-colored limestones contrasting with the dark color of meteorites. The area is easily accessible (3 km from the main road) and safe.

The team of P. Rochette, H. Chennaoui, S. Makhoukhi, A. Laroussi, M. Aoudjehane, H. Pourkhorsandi, M. Aboulahris, and drivers A.

Bouragaa and A. Bouferra prospected during the first 2 days in the area of Dayet Hamada (Fig. 5a), 80 km SE of Laayoune. Search duration was 7 h per day. Then, we moved 20 km south of Dayet Hamada, Bou Kra, and Wad Al Khachbiyine areas. This place is more vegetated than the first one (Fig. 5c), and more frequented by nomads searching for areas to feed their camel and goat livestock. This suggests that previous meteorite hunting occurred in this area.

### Meteorite Classification

The classification of the meteorites was performed at different institutes (see Table 3). Magnetic susceptibility (e.g., Rochette et al. 2003) was measured using a Kappabridge KLY2 instrument from Agico, equipped with a large coil (65 cm<sup>3</sup>). Measurements were taken along two orthogonal axes to minimize anisotropy effects.

Thin and thick sections were prepared from all collected samples. Petrographic observations were performed using a Leica DM polarizing microscope. The Van Schmus and Wood (1967) classification criteria were used for ordinary chondrites. Weathering was estimated following Wlotzka (1993). Electron

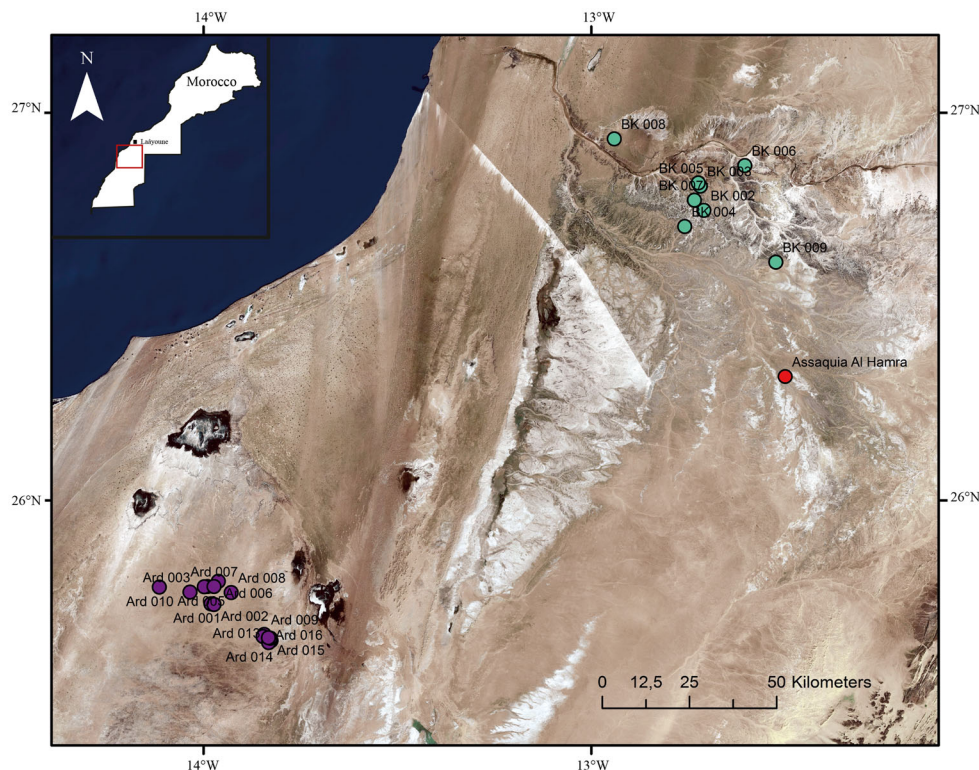


Fig. 4. Surfaces of Moroccan DCAs prospected in this work in Laayoune area, namely Bou Kra, Assaquia Al Hamra, and Aridal and surrounding ones. Location of this zone is shown in Moroccan map. Meteorite location finds by our team Bou Kra 009 (B.K), Aridal 001 to Aridal 016 (Ard), and Assaquia al Hamra are reported in the satellite image (Image Source: Esri DigitalGlobe). (Color figure can be viewed at wileyonlinelibrary.com.)



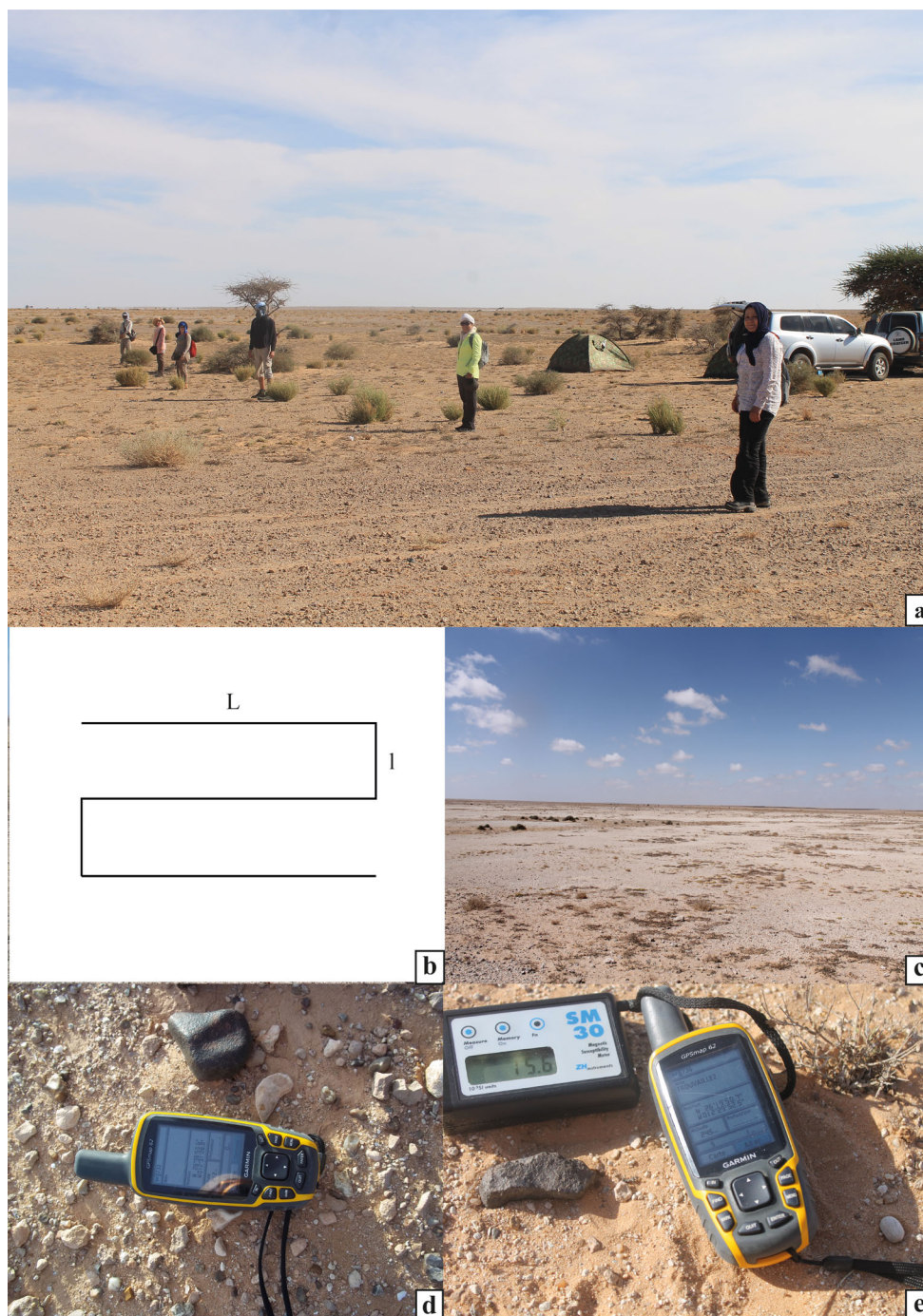


Fig. 5. Systematic research method, soil landscape of the Moroccan desert prospected zone, and meteorites recovered in the area during the field mission. Pictures: Maria Aboulahris. a) First search area Dayet Hamada: the soil is flat, characterized by the absence of vegetation and the presence of some small dark stones. b) Covered area is  $L =$  length,  $l =$  prospected band width on one path, width sizes about 75 m. c) Second search area Bou Kra and Wad Al Khachbiyine, 20 km south of Dayet Hamada with flat and escarped zones, more vegetation and more dark rock. d) Bou Kra 009 meteorite found in Dayet Hamada zone. e) Assaquia al Hamra meteorite found the last day of prospection. (Color figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com).)

microprobe analysis (EMPA) was performed with a Cameca SX100 or a Cameca SX Five calibrated with natural standards at Camparis Service, Paris 6 University in France.

#### Terrestrial Age Determination

Based on the weathering degree and the petrographic type of meteorites, we selected 25 ordinary



Table 3. Meteorite collected by our teams in Tunisia and Morocco; classification method and entity (CEREGE, UH2C, Museo Nazionale dell'Antartide, Siena Italy).

| Field missions        | Meteorites names                   | Date                        | Classification |                                  |
|-----------------------|------------------------------------|-----------------------------|----------------|----------------------------------|
|                       |                                    |                             | Entity         | Method                           |
| Tunisia               | Bir Zar 001 to Bir Zar 009         | April 2008                  | MNA-SI         | EMPA                             |
|                       | Tieret 001 to Tieret 007           | 2009 and 2010               | MNA-SI         | EMPA                             |
|                       | Tieret 008 to Tieret 013           |                             | CEREGE         | EMPA                             |
| Morocco<br>(Aridal)   | Aridal 001 to Aridal 010           | Winter 2012 and Spring 2013 | CEREGE         | Magnetic susceptibility and EMPA |
|                       | Aridal 011 to Aridal 016           |                             | UH2C           | EMPA                             |
| Morocco<br>(Laayoune) | Bou Kra 009 and Assaquiya al Hamra | From 9 to 14 Mai 2016       | CEREGE         | EMPA                             |

chondrites from our field collections in Tunisia and Morocco for determining the terrestrial ages.

We measured  $^{14}\text{C}$  terrestrial ages for these meteorites using the techniques described (Jull et al. 1989, 1990, 1993, 2010) for the Accelerator Mass Spectrometry (AMS) Laboratory, University of Arizona (USA). To remove carbonates formed during terrestrial weathering, we used 85% phosphoric acid for an average of 0.2 g of crushed sample at 70 °C. Then, we washed the residue with distilled water and they were dried in air at about 60 °C. We added ~2 g of iron chips as a combustion accelerator to the sample and placed the mixture in an alumina crucible, which is heated at 500 °C for 1 h to remove terrestrial contaminants. Afterward, we put the same crucible in an RF induction furnace at 1500 °C in a flow of oxygen, where evolved gases are converted to carbon dioxide in the excess of oxygen. The  $\text{CO}_2$  was removed from the oxygen stream cryogenically, the volume was recorded, and then we converted the  $\text{CO}_2$  to graphite and pressed into a target for AMS measurement. The  $^{14}\text{C}$  activities are calculated in  $\text{dpm kg}^{-1}$ .

## RESULTS

### Meteorites from Tunisia and Morocco, Recoveries, and Classification

In Tunisia, a total of 22 meteorites were collected during the fieldwork organized on 2008, 2009, and 2010 in Bir Zar and Tieret (Fig. 6). Total surface covered is 13.0  $\text{km}^2$  with a cumulated mass of 7.1 kg. Details of recovered meteorites numbers and origin as well as covered surface are presented in Table 4.

In Morocco, 29 meteorites were found in the Aridal area on a surface of 58  $\text{km}^2$  (Buhl et al. 2014) with a total mass of 11.0 kg (Figs. 4, 7, 8).

During the fieldwork conducted in the Bou Kra, Assaquia Al Hamra, and Wad Al Khachbiyine areas in 2016, we found two meteorites with a total mass of 204 g (Figs. 4, 5d, 8). The surface prospected was 1.97  $\text{km}^2$  (see details in Table 5).

The classification of Tunisian and Moroccan meteorites was performed through petrographic observations EMPA and magnetic susceptibility measurements; results are presented in Table 6. Tunisian



Fig. 6. a) Tieret 010 meteorite find place, b) pictures of all fragments of the meteorite Tieret 010. (Color figure can be viewed at wileyonlinelibrary.com.)

Table 4. Meteorite densities calculated in Tunisia with details of the covered surfaces and number of meteorites collected during the three fields missions organized from 2008 to 2010 in Bir Zar and Tieret DCAs.

| Year of the field mission | Area (DCA) | Surface covered (km <sup>2</sup> ) | Number of meteorites collected | Meteorites recovery density (met km <sup>-2</sup> ) |
|---------------------------|------------|------------------------------------|--------------------------------|---|
| 2008                      | Bir Zar    | 6.88                               | 9                              | 1.3   |
| 2009                      | Tieret     | 2.55                               | 7                              | 2.74  |
| 2010                      | Tieret     | 3.61                               | 6                              | 1.66  |
| Total                     |            | 13.04                              | 22                             | 1.64  |



Fig. 7. In situ picture of the Aridal 007, a 340g H5 chondrite, scale cube is 1 cm. Coarse grained, quartzitic alluvial gravel on silt matrix as typical for the higher altitudes of the Aridal DCA. Picture: S. Buhl. (Color figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com).)

meteorites are all ordinary chondrites, 14 H chondrites and 8 L chondrites. They were submitted to the NomCom and accepted under the names of Bir Zar 001 to Bir Zar 009 (Laridhi Ouzaa et al. 2009; Weisberg et al. 2009), Tieret 001 to Tieret 013 (Weisberg et al. 2010). These finds were used to identify two DCAs (Fig. 3).

Concerning the meteorites collected in Morocco, classification allowed us to identify 1 brachinite, 11 H chondrites, 6 L chondrites, and 2 LL chondrites (Table 6). They were submitted to the NomCom and published in the Meteoritical Bulletin as Aridal 001 to Aridal 016, Bou Kra 007 to Bou Kra 008 (Bouvier et al. 2017), Bou Kra 009, and Assaquia al Hamra.

## Weathering Grade

Weathering grade of all meteorites collected in Tunisia and Morocco, estimated using the scale of Wlotzka (1993), varies between W1 and W4 (Table 6; Fig. 9). The weathering grade was used to identify potentially paired meteorites and to compare the different hot deserts (Fig. 9).

In the Aridal DCA, 60% of meteorites have a degree of weathering of W3 or below (no W0 was observed) and 40% of W4. This corresponds to the most weathered meteorite DCAs in Sahara, perhaps because this DCA is close to the Atlantic Ocean, bringing significant air humidity and sea spray.

## Terrestrial Age of Meteorites

We measured the terrestrial ages of 26 meteorites from the following DCAs: Aridal, Bou Kra, Bir Zar, and Tieret. The results are presented in Table 7. The ages of 12 meteorites are between a recent fall 0.4 and 22 kyr, 10 have an age between 22 and 40 kyr, and 4 meteorites have an age greater than 40 kyr. Ages of these meteorites were compared to data from other hot deserts, namely Algeria, Saudi Arabia, Oman, and UAE (Fig. 10). Meteorites from Tunisia show mostly ages between 20 and 40 kyr, while in other hot deserts, the most abundant ages are between 0.4 and 20 kyr. A small number of meteorites is more than 40 kyr, most of them are from Oman, no meteorite with this age being reported in UAE.

## Mass Distribution

We binned meteorite weight in categories of (0.1–10, 10–100, 100–1000, 1000–10,000, 10,000–100,000 g) in order to compare this mass distribution to the other DCAs from hot deserts. We calculated the percentage of number of meteorites from each range in Morocco (Bou Kra, Aridal), Algeria (Acfer), Libya (HaH, DaG), Tunisia (Bir Zar, Tieret), Oman (Dhofar), UAE, Chile (San Juan, El Médano), and Roosevelt County (Table. 8; Fig. 11). Weight data are from Meteoritical Bulletin database (<http://www/lpi.usra.edu/meteor/metbull.php>).

## Pairing

To estimate the pairing of meteorites, we used the petrologic type, the weathering grade, the olivine and low-Ca pyroxene compositions, magnetic susceptibility (Table 6), the terrestrial ages (Table 7), and the spatial distance between individual find locations.

Based on these data, we can assert that Tieret 001 is probably paired with Tieret 003 (8.6 km) and Tieret 012



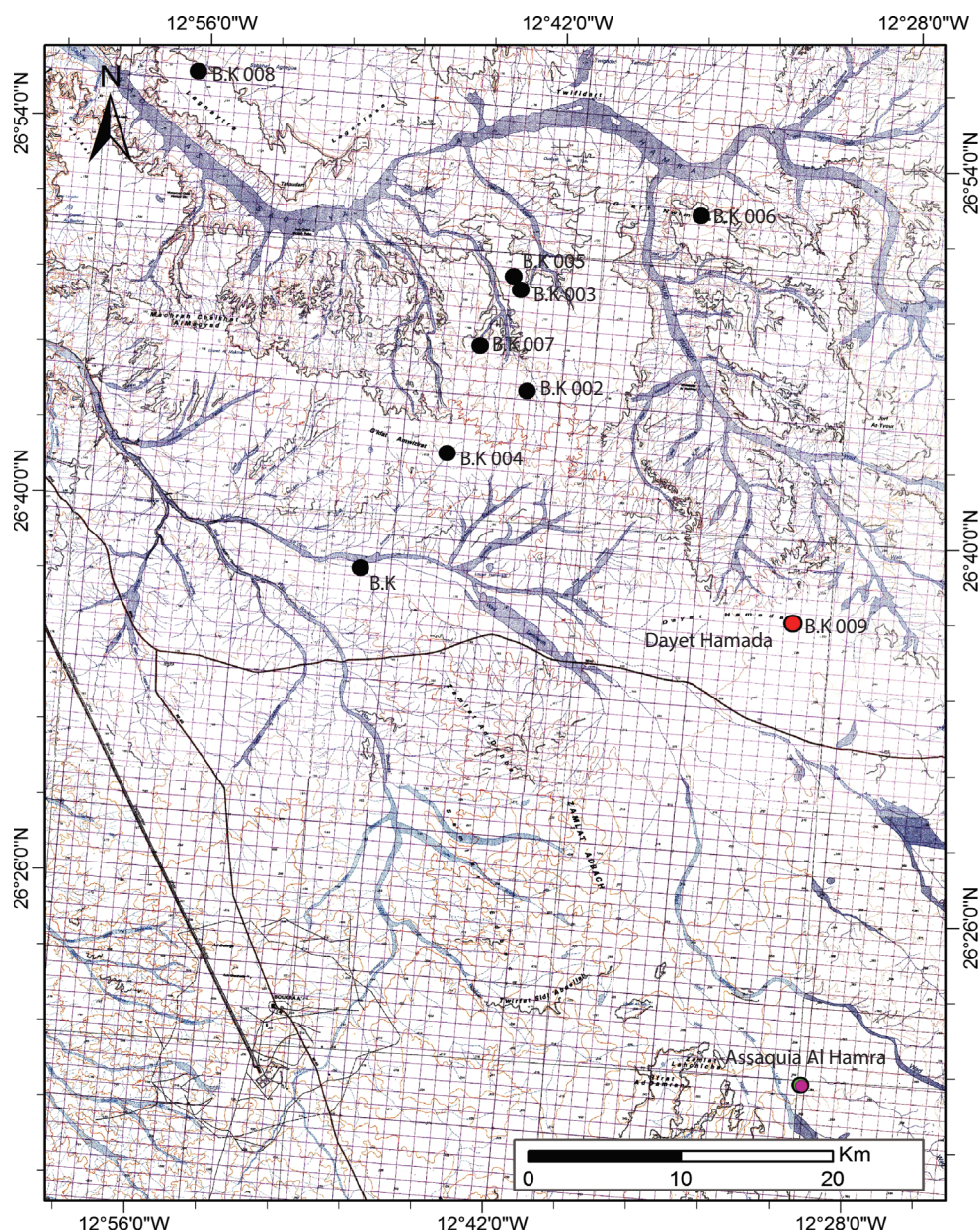


Fig. 8. Locations of Bou Kra (B.K) and Assaquia Al Hamra meteorites reported on a collage of four georeferenced topographic maps of Morocco: Assaquia Al Hamra, Bou Kra, Wad Al Khachbiyine, and Ramth Al Lbane drawn in 1989 on a scale 1:100000. (Color figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com).)

with Tieret 013 (1.7 km). Concerning the Aridal DCA, we were able to identify potentially paired meteorites, Aridal 014, Aridal 015 (1.4 km), and Aridal 016 (400 m) (for those meteorites, the terrestrial age was not measured).

### Meteorite Recovery Density

To calculate the meteorite recovery density in Morocco and Tunisia, we used meteorites from Bir Zar, Tieret, and the last fieldwork in 2016, since the

private collection did not result from a systematic recovery. The total calculated density before pairing in Tunisia is  $1.8 \text{ meteorite km}^{-2}$  ( $\text{met km}^{-2}$ ) and  $1.5 \text{ met km}^{-2}$  after correction for pairing with a total mass of 7080.2 g. The calculated density in the Buhl's mission is  $0.5 \text{ met km}^{-2}$  before pairing (Buhl et al. 2014) and we calculated the density after correction for pairing to be  $0.2 \text{ met km}^{-2}$  with a total mass of 11,776 g. The calculated density in Bou Kra, Assaquia Al Hamra, and Wad al Khachbiyine is  $1 \text{ met km}^{-2}$  with a total mass of 204.1 g (Table 5).



Table 5. Details of the field mission organized in Bou Kra, Assaquia Al Hamra, and Wad Al Khachbiyine area (May 2016).

| Days              | Surface (km <sup>2</sup> ) | Meteorites collected | Coordinates                     |
|-------------------|----------------------------|----------------------|---------------------------------|
| Monday, May 9     | 0.124                      | —                    |                                 |
| Tuesday, May 10   | 0.3                        | 1                    | N 26°36'55.6";<br>W 12°31'28"   |
| Wednesday, May 11 | 0.32                       | —                    |                                 |
| Thursday, May 12  | 0.57                       | 1                    | N 26°19'50.7";<br>W 12°29'52.5" |
| Friday, May 13    | 0.49                       | —                    |                                 |
| Saturday, May 14  | 0.17                       | —                    |                                 |
| Total             | 1.97                       | 2                    |                                 |

For Bir Zar DCA (Laridhi Ouazaa et al. 2009), as we applied a systematic search method, we recalculated the covered area using the method described in the Moroccan Meteorite Search Missions section).

## DISCUSSION

In order to estimate the flux of meteorites to the Earth, many studies since 1995 have been undertaken to calculate the recovery density of meteorites in several hot deserts (Bland et al. 1997), specifically the deserts of Sahara in Algeria (Bischoff and Geiger 1995), Australia (Bevan et al. 1998), Libya (Schlüter et al. 2002), Chile (Gattacceca et al. 2011; Hutzler et al. 2016), Oman (Hofmann et al. 2009; Zurfluh et al. 2016), United Arab Emirates (Hezel et al. 2011), and Saudi Arabia (Hofmann et al. 2018). We have summarized in Table 2 the various studies conducted in hot deserts, densities of meteorites recovered searching by car or on foot applying systematic or random methods.

The Sahara is a favorable area for the accumulation of meteorites (Table 1), similar to the deserts of Arabian Peninsula, Atacama, Australia, Roosevelt County, and Antarctica. The climate of this area is hyperarid, and therefore, meteorites are well preserved. This area was first identified as a good source of meteorites, thanks to the work of Bischoff and Geiger (1995) and Schlüter et al. (2002), who were the first to calculate the density of meteorites in the areas of Algeria and Libya, respectively.

Since 1999, thousands of meteorites have been collected in the Sahara under the acronym NWA followed by a number. Coordinates of those meteorites are unknown making the estimation of the densities of meteorites difficult. Big efforts are being made in Morocco to document these meteorites and to assign precise coordinates and proper location names

(Chennaoui Aoudjehane et al. 2014; Chennaoui Aoudjehane 2018). New rules of the NomCom are applied since 2014 to name meteorites from North West Africa: those with coordinates are included in DCA (e.g., Aridal, Bou Kra, etc.) while the others without coordinates have NWA naming (Chennaoui Aoudjehane 2017).

Most NWA meteorites reported in the Meteoritical Bulletin Database are ordinary chondrites (61%; see Table 1), the remaining 39% are achondrites (Chennaoui Aoudjehane 2018). This contrast with percentage of ordinary chondrites collected in other deserts (Table 1) as well as with our finds in Tunisia and Morocco, where only one achondrite Aridal 010 (Brachinite) was collected in a total of 42 meteorites (41 ordinary chondrites). This result is due to the commercial activity of meteorites hunters in North West Africa that focused on the classification of rare and commercial valuable meteorites rather than the others.

Systematic research applied by Hofmann et al. (2003), Zurfluh et al. (2016), Gattacceca et al. (2011), and Hutzler et al. (2016) was very successful and allowed us to provide precise and high densities of meteorites in Oman and Chile. This led us to consider field missions in the desert of Morocco and Tunisia.

Our work based on a systematic search indicates a density of 1 met km<sup>-2</sup> in the region Aridal, Bou Kra, Assaquia Al Hamra, and Wad Al Khachbiyine (Morocco; Table 5) and 1.5 met km<sup>-2</sup> in the desert of Tunisia after pairing correction (Table 4). In the south of Morocco, this lower density is probably a result of the presence of nomad living in the desert and well-organized local hunters team with a great expertise on meteorites identification. Also, the Moroccan desert is a safe and open area; everyone may go hunting (Bouragaa et al. 2014; Buhl et al. 2014), so the meteorites may have previously been collected. However, the South of Tunisia is protected by the military so those areas are also protected from unauthorized collections.

Densities by foot are between 86 and 1 met km<sup>-2</sup> while by car it is much lower (0.15 met km<sup>-2</sup> in Libya, see Table 2). The difference in estimated densities shows the importance of systematic search that allows recovery of small meteorites and covering a maximum surface area. Thus, we expect the density calculated using the method of the systematic search is more reliable for a best meteorite collection.

Considering that 0.2 met km<sup>-2</sup> is the minimum density of meteorites found by car or on foot in a random manner in the Sahara, the area prospected to retrieve classified NWA samples is estimated to be about 40,000 km<sup>2</sup>, that is, a square of 200 km on each side. It is obvious that the majority of meteorites collected in the Sahara were not declared due to their

Table 6. Classification, chemical analysis (Fa and Fs), and physical properties (mass [g], W: Weathering grade [Wlotzka 1993], magnetic susceptibility given in  $\log \chi$  with  $\chi$  in  $10^{-9} \text{ m}^3 \text{ kg}^{-1}$ ) of meteorites recovered in Morocco and Tunisia. Bir Zar (BiZ abbreviation) data are from Laridhi Ouazaa et al. (2009).

| Official name     | Mass (g) | W        | Fa (%)  | Fs (%)  | $\log \chi$ | Class      |
|-------------------|----------|----------|---|---|-------------|------------|
| BiZ 001           | 627      | W2       | 17.4  | 15.6  | 4.9         | H6         |
| BiZ 002           | 331      | W1       | 22.6  | 19.9  | 4.79        | L4/5       |
| BiZ 003           | 39       | W3       | 20  | 12.7  | 4.08        | H3         |
| BiZ 004           | 19       | W3       | 17.7  | 15.8  | 4.39        | H6         |
| BiZ 005           | 17       | W2       | 16.8  | 15.8  | 4.88        | H4         |
| BiZ 006           | 21       | W3       | 16.8  | 16.1  | 4.36        | H6         |
| BiZ 007           | 5.2      | W1       | 22.9  | 19.5  | 4.94        | L6         |
| BiZ 008           | 200      | W4       | 17.2  | 15.4  | 4.38        | H6         |
| BiZ 009           | 21       | W3       | 16.9  | 15.2  | 4.53        | H5-6 br    |
| Tieret 001        | 602      | W2       | 18.2  | 15.9  | 4.89        | H6         |
| Tieret 002        | 23.5     | W2       | 22.9  | 20.2  | 4.22        | L6         |
| Tieret 003        | 17.1     | W2       | 17.3  | 15.7  | 4.79        | H6         |
| Tieret 004        | 10.6     | W3       | 18.3  | 15.9  | 4.44        | H5         |
| Tieret 005        | 18.3     | W3       | 23.4  | 20.4  | 4.11        | L6         |
| Tieret 006        | 20.7     | W1       | 22.5  | 19.0  | 4.74        | L4         |
| Tieret 007        | 11       | W2       | 16.8  | 15.2  | 5.02        | H5         |
| Tieret 008        | 28       | W1       | 23.5 ± 0.3  | 20.6 ± 0.4  | 4.85        | L4         |
| Tieret 009        | 9        | W4       | 19.1 ± 0.4  | 16.6 ± 0.0  | 4.30        | H5/6       |
| Tieret 010        | 5150     | W4       | 17.3 ± 5.9 (7.6–25.4.<br>PMD = 25.4. <i>n</i> = 16) | 6.7 ± 4.2 (2.7–16.1.<br>PMD = 53.5. <i>n</i> = 9) | 4.44        | H3         |
| Tieret 011        | 13.4     | W3       | 19.0 ± 0.2  | 16.6 ± 1.3  | 4.45        | H5/6       |
| Tieret 012        | 0.41     | W1       | 23.7 ± 0.2  | 20.1 ± 0.1  |             | L4         |
| Tieret 013        | 3.7      | W1       | 23.7 ± 0.1  | 20.0 ± 0.3  | 4.91        | L4         |
| Aridal 001        | 21.6     | W2       |   |   | 4.49        | L6         |
| Aridal 002        | 17.9     | W4       | 26 ± 0.58 ( <i>n</i> = 5)                           | 23.1 ± 1.2 ( <i>n</i> = 6)                        | 4.35        | L6         |
| Aridal 003        | 27.3     | W3       |   |   | 4.16        | L6         |
| Aridal 004        | 20.1     | W1       | 27.9 ± 0.20 ( <i>n</i> = 7)                         | 23.6 ± 0.2 ( <i>n</i> = 5)                        | 4.1         | LL6        |
| Aridal 005        | 8.1      | W2       | 24.8 ± 0.24 ( <i>n</i> = 14)                        | 20.9 ± 0.25 ( <i>n</i> = 9)                       | 4.59        | L4         |
| Aridal 006        | 42.9     | W4       |   |   | 4.81        | H6         |
| Aridal 007        | 24.5     | W3       |   |   | 4.75        | H5         |
| Aridal 008        | 22.1     | W2       | 18.9 ± 0.8 ( <i>n</i> = 7)                          | 16.5 ± 0.21 ( <i>n</i> = 7)                       | 4.83        | H6         |
| Aridal 009        | 26.3     | W4       | 25.4 ± 0.72 ( <i>n</i> = 6)                         | 23.8 ± 2.4 ( <i>n</i> = 6)                        | 4.20        | L6         |
| Aridal 010        | 42       | Strongly | 28.13 ± 0.72 ( <i>n</i> = 14)                       | 10.62 ± 0.19 ( <i>n</i> = 3)                      | 4.62        | Brachinite |
| Aridal 011        | 21.62    | W1       | 28.4 (27.4–28.8, <i>n</i> = 13)                     | 23.9 (22.8–29.1, <i>n</i> = 10)                   | 4.48        | LL5        |
| Aridal 012        | 26.81    | W3       | 19.3 (18.8–20.1, <i>n</i> = 21)                     | 16.8 (16.5–17.2, <i>n</i> = 7)                    | 4.82        | H4         |
| Aridal 013        | 22.87    | W3       | 19.0 (18.8–19.5, <i>n</i> = 17)                     | 16.9 (16.7–17.4, <i>n</i> = 6)                    | 4.85        | H5         |
| Aridal 014        | 45.61    | W4       | 19.0 (18.7–19.4, <i>n</i> = 14)                     | 16.7 (16.2–17.5, <i>n</i> = 10)                   | 4.65        | H4         |
| Aridal 015        | 36.7     | W4       | 19.4 (18.9–22.2, <i>n</i> = 16)                     | 16.9 (16.4–17.5, <i>n</i> = 6)                    | 4.52        | H4         |
| Aridal 016        | 26.42    | W4       | 19.0 (18.4–19.4, <i>n</i> = 17)                     | 16.7 (16.2–17.0, <i>n</i> = 6)                    | 4.78        | H4         |
| Assaquia Al Hamra | 44.1     | W3       | 25.0 ( <i>n</i> = 1)                                | 21.4 ( <i>n</i> = 1)                              | 4.53        | L6         |
| Bou Kra 007       | 20.46    | W1/2     | 19.0 (18.3–19.5, <i>n</i> = 16)                     | 16.8 (16.8–16.9, <i>n</i> = 3)                    | 4.60        | H5         |
| Bou Kra 008       | 23.23    | W1/2     | 18.6 (18.2–19.9, <i>n</i> = 18)                     | 16.3 (16.0–16.6, <i>n</i> = 6)                    | 5.04        | H4         |
| Bou Kra 009       | 160      | W3       | 19.0 ± 0.1 ( <i>N</i> = 3)                          | 17.0 ± 0.3 ( <i>N</i> = 7)                        | 4.86        | H5         |

assumed negligible commercial value. We may estimate that the real number of meteorite collected is an order of magnitude larger than the declared ones. From this assumption, the surface of Sahara already searched could be estimated to be of the order of 400,000 km<sup>2</sup>. This would roughly correspond to the entire Moroccan Sahara and the southern provinces of Morocco. This

would also confirm that a large proportion of NWA come from outside these areas.

So far, over 12,000 meteorite finds from the Sahara are reported in the Meteoritical Bulletin database. If we add an estimated upper bound of 90% undeclared NWA, we come up to 120,000 meteorites that have been already collected in the Sahara. We may also

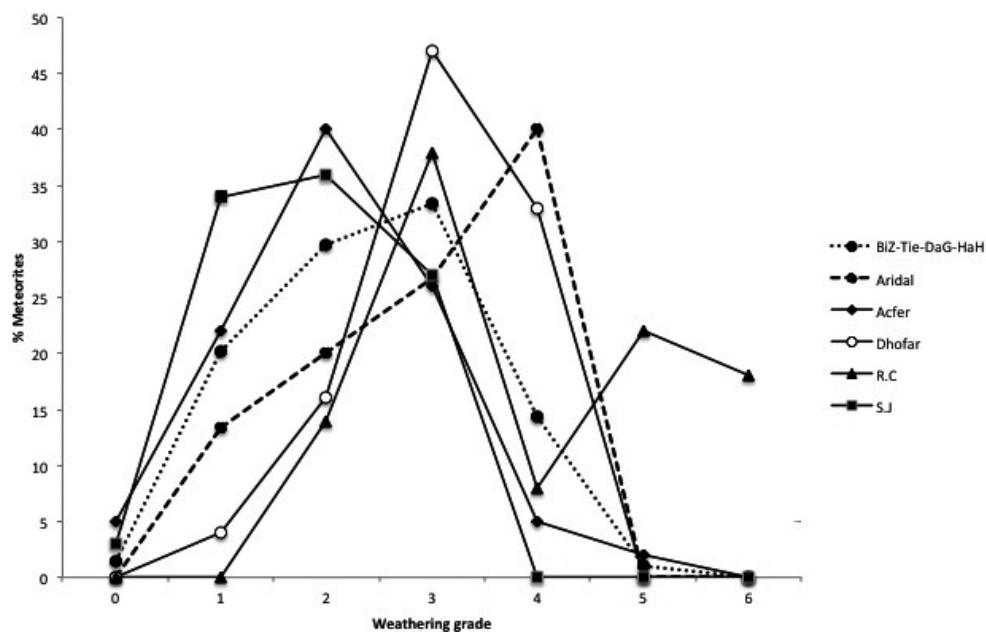


Fig. 9. Frequency distribution of weathering grades for meteorites from Sahara (Bir Zar, Tieret, Aridal, DaG, and HaH DCAs), San Juan (Gattacceca et al. 2011), and the other main DCA in hot deserts (Koblitz 2005). (Color figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com).)

Table 7. Terrestrial age of meteorites from Morocco and Tunisia calculated by  $^{14}\text{C}$  technique in the University of Arizona (Jull et al. 1989, 1990, 1993, 2010).

| Official name | Mass (g) | W  | Class | dpm $\text{kg}^{-1}$ |            | $^{14}\text{C}$ -age (kyr) | SD         |
|---------------|----------|----|-------|----------------------|------------|----------------------------|------------|
|               |          |    |       | Value                | SD         |                            |            |
| BiZ 001       | 627      | W2 | H6    | 0.39                 | $\pm 0.86$ | 40.3                       | $\pm 18.1$ |
| BiZ 003       | 331      | W1 | L4/5  | 0.44                 | $\pm 0.73$ | 39.3                       | $\pm 13.7$ |
| BiZ 004       | 39       | W3 | H3    | 3.58                 | $\pm 0.58$ | 22.0                       | $\pm 1.9$  |
| BiZ 005       | 19       | W3 | H6    | -1.02                | $\pm 0.58$ | >37                        | –          |
| BiZ 006       | 17       | W2 | H4    | 2.27                 | $\pm 0.69$ | 25.7                       | $\pm 2.8$  |
| BiZ 007       | 21       | W3 | H6    | 0.98                 | $\pm 0.68$ | 32.7                       | $\pm 5.9$  |
| BiZ 008       | 5.2      | W1 | L6    | -0.33                | $\pm 0.69$ | >35.6                      | –          |
| BiZ 009       | 200      | W4 | H6    | 1.28                 | $\pm 0.76$ | 30.5                       | $\pm 5.1$  |
| Tieret 001    | 602      | W2 | H6    | 4.10                 | $\pm 0.74$ | 20.9                       | $\pm 2.0$  |
| Tieret 002    | 23.5     | W2 | L6    | 0.30                 | $\pm 0.59$ | 42.4                       | $\pm 16.3$ |
| Tieret 004    | 10.6     | W3 | H5    | 4.77                 | $\pm 0.47$ | 19.6                       | $\pm 1.5$  |
| Tieret 005    | 18.3     | W3 | L6    | 2.43                 | $\pm 0.61$ | 25.2                       | $\pm 2.5$  |
| Tieret 006    | 20.7     | W1 | L4    | 0.26                 | $\pm 0.59$ | 43.5                       | $\pm 18.6$ |
| Tieret 007    | 11       | W2 | H5    | 10.64                | $\pm 0.74$ | 13.0                       | $\pm 1.4$  |
| Tieret 008    | 28       | W1 | L4    | 48.61                | $\pm 2.72$ | 0.4                        | $\pm 1.4$  |
| Aridal 003    | 27.3     | W3 | L6    | 19.51                | $\pm 0.46$ | 8.0                        | $\pm 1.3$  |
| Aridal 004    | 20.1     | W1 | LL6   | 2.66                 | $\pm 0.27$ | 24.4                       | $\pm 1.5$  |
| Aridal 006    | 42.9     | W4 | H6    | 32.42                | $\pm 0.59$ | 3.8                        | $\pm 1.3$  |
| Aridal 008    | 22.1     | W2 | H6    | 28.51                | $\pm 0.66$ | 4.8                        | $\pm 1.3$  |
| Aridal 009    | 26.3     | W4 | L6    | 1.93                 | $\pm 0.25$ | 27.1                       | $\pm 1.7$  |
| Aridal 012    | 26.81    | W3 | H4    | 0.09                 | $\pm 0.22$ | 52.8                       | $\pm 21.5$ |
| Bou Kra 002   | 606      | W2 | L5    | 7.45                 | $\pm 0.24$ | 15.9                       | $\pm 1.3$  |
| Bou Kra 003   | 50       | W1 | L6    | 78.18                | $\pm 1.91$ | -3.5                       | $\pm 1.3$  |

assume that the surface of the Sahara that is favorable for meteorite prospection may be  $\sim 10\%$  of its total, that is, 0.9 million  $\text{km}^2$ . Using a conservative density of

$0.2 \text{ met km}^{-2}$ , we may thus still have 60,000 more meteorites to be collected on favorable surfaces in Sahara. In case of a  $1 \text{ met km}^{-2}$  density, this number



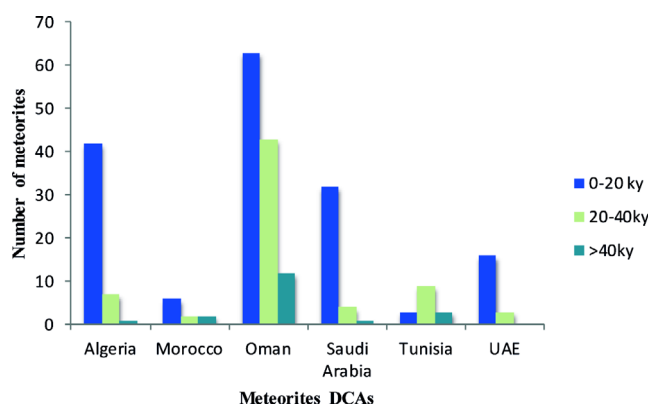


Fig. 10. Number of meteorites and their terrestrial age, divided on three intervals 0–20 kyr, 20–40 kyr, and more than 40 kyr, in different meteorite hot desert DCAs. Our terrestrial ages data measured for Tunisia and Morocco are compared to literature data, Algeria (Wlotzka et al. 1995; Jull 2006), Saudi Arabia (Jull 2006; Hofmann et al. 2018), Oman (Hofmann et al. 2003; Zurfluh et al. 2016), UAE (Hezel et al. 2011). (Color figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com).)

increases to 780,000. However, this may mean prospecting in less secure countries than the ones explored so far.

We note that there is a large (one or two orders of magnitude) difference between the densities calculated in the Atacama desert (Gattacceca et al. 2011; Hutzler et al. 2016) and those of the Sahara (Aridal, Bir Zar, and Tieret; Tables 2, 4, 5).

Terrestrial ages of meteorites from hot deserts of Algeria, Oman, UAE, Saudi Arabia, in literature, show that most meteorites are young (0–20 kyr), followed by (20–40 kyr) and a very small number of meteorites having an age exceeding 40 kyr (Fig. 10). These results

are consistent with estimates of 8% of meteorites for the Daraj DCA in Libya (Jull et al. 1990), 30% Dar al Gani DCA in Libya (Welten et al. 2004), 17% Acfer DCA in Algeria (Wlotzka et al. 1995; Neupert et al. 1997) that have an age exceeding 20 kyr. Our dating is consistent with ages of meteorites from these deserts in Morocco but different from Tunisia where most meteorites dated have an age between 20 and 40 kyr (Table 7; Fig. 10).

In contrast, terrestrial ages of meteorites from San Juan in Chile (Gattacceca et al. 2011) show that 54% have an age exceeding 20 kyr. This can be explained by the duration of hyperarid conditions. The desert of Atacama has been hyper arid for the last several Myrs (e.g., Dunai et al. 2005, Gattacceca et al. 2011) allowing for important accumulation of meteorites. By contrast, the Sahara is younger, known to have many wet and dry periods in the past 15 kyr (Lézine et al. 2011; Kuechler et al. 2013; Armitage et al. 2015).

In the Sahara, there is no correlation between the terrestrial age and the degree of weathering (Table 7; Fig. 12), which can be related to the local climatic effects, drought, and high humidity alternating periods over the last 20 kyr (Bland et al. 1998). This difference was already noted by Stelzner et al. (1999) for Acfer meteorites. The same lack of correlation was observed in the desert of Chile for San Juan meteorites (Gattacceca et al. 2011), Nullarbor meteorites (Jull et al. 2010), and Saudi Arabia (Hofmann et al. 2018), while Al-Kathiri et al. (2005) and Zurfluh et al. (2016) show a correlation between weathering and meteorite ages.

The terrestrial ages of meteorites from hot deserts are lower than those from Antarctica (Nishiizumi et al.

Table 8. Total number and percentage of meteorite masses (g) from different studied DCAs by systematic search and by car. Meteorites were binned on six mass intervals (0.1–1 g; 1–10 g; 10–100 g; 100–1000 g; 10–10,000 g; and 10,000–100,000 g).

| DCA name | Country              | Prospection type          | Total number | Percentage of meteorites mass (g) |      |                    |                                  |                                  |                                  |
|----------|----------------------|---------------------------|--------------|-----------------------------------|------|--------------------|----------------------------------|----------------------------------|----------------------------------|
|          |                      |                           |              | 0.1–1                             | 1–10 | 10–10 <sup>2</sup> | 10 <sup>2</sup> –10 <sup>3</sup> | 10 <sup>3</sup> –10 <sup>4</sup> | 10 <sup>4</sup> –10 <sup>5</sup> |
| Dho      | Oman                 | Systematic search by feet | 420          | 0                                 | 1    | 18                 | 55                               | 25                               | 0                                |
| BiZ      | Tunisia              |                           | 9            | 0                                 | 11   | 56                 | 33                               | 0                                | 0                                |
| Tieret   |                      |                           | 13           | 8                                 | 15   | 61                 | 8                                | 8                                | 0                                |
| EM       | Chile                | Car                       | 408          | 1                                 | 8    | 48                 | 30                               | 12                               | 1                                |
| SJ       |                      |                           | 67           | 0                                 | 3    | 39                 | 51                               | 7                                | 0                                |
| Aridal   | Morocco              |                           | 16           | 0                                 | 0    | 12                 | 56                               | 31                               | 0                                |
| Bou Kra  |                      |                           | 9            | 0                                 | 0    | 33                 | 67                               | 0                                | 0                                |
| RC       | USA                  |                           | 140          | 0                                 | 22   | 60                 | 16                               | 1                                | 0                                |
| DaG      | Libya                |                           | 1048         | 0                                 | 1    | 27                 | 60                               | 12                               | 1                                |
| HaH      |                      |                           | 340          | 0                                 | 0    | 10                 | 63                               | 24                               | 3                                |
| Acfer    | Algeria              |                           | 390          | 0                                 | 0    | 16                 | 71                               | 13                               | 1                                |
| AE       | United Arab Emirates |                           | 29           | 0                                 | 3    | 55                 | 38                               | 7                                | 0                                |

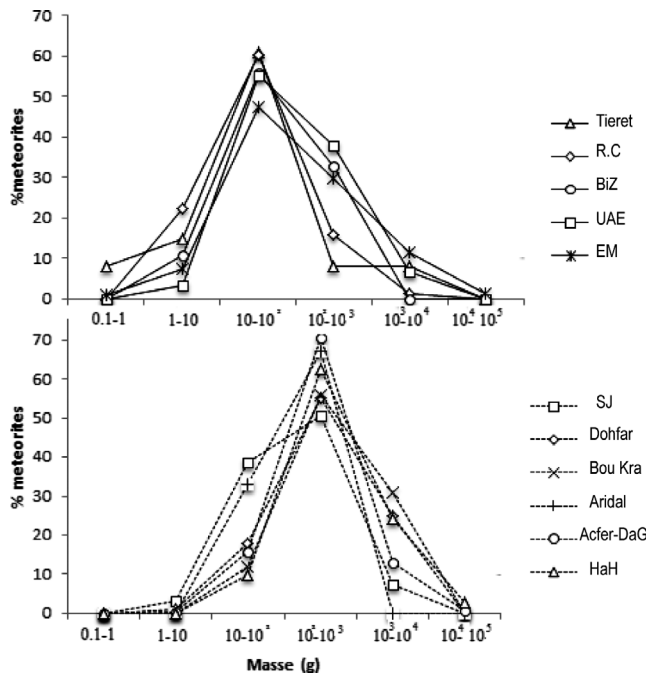


Fig. 11. Mass frequency distribution of meteorites from different hot desert DCAs (Oman: Dhofar, Chile: El Médano and San Juan, USA: Roosevelt Country, Algeria: Acfer, Libya: Hamada Al Hamra and Dar Al Ghani and United Arab Emirates) data taken from the Meteoritical Bulletin Database. Our data are: Aridal, B.K (Bou Kra), BiZ (Bir Zar), and Tieret.

1989; Jull 2006) where meteorites with a terrestrial age up to 3 Myr have been observed (Welten et al. 2008).

Our estimate of meteorite density ( $1 \text{ met km}^{-2}$ ) combined with an average terrestrial age in the 10 ka range corresponds to a flux of the order of 100 meteorites per year and million  $\text{km}^2$ . This order of magnitude is consistent with flux reported by Bland et al. (1996) with 159 events per year per 1 million  $\text{km}^2$  ( $>20 \text{ g}$ ). It is also similar to the flux calculated by Halliday et al. (1989) with 100 meteorites per year per 1 million  $\text{km}^2$  ( $>10 \text{ g}$ ) based on meteor detections and mathematics calculation model, as well as the flux estimated by Drouard et al. (2019) with 222 meteorites larger than 10 g per  $\text{km}^2$  per Myr.

Mass distribution of meteorites from Tieret, Bir Zar, UAE, Roosevelt County, and El Médano shows a maximum of meteorites with a mass between 10 and 100 g, while those from San Juan, Dhofar, Acfer, HaH, Aridal, and Bou Kra are mainly between 100 and 1000 g.

Systematic prospections by foot promote findings of small meteorites (Tieret, Bir Zar, and El Médano), while searching randomly by foot or by car (HaH, Acfer, Aridal, Bou Kra) favors bigger finds.

Numbers of ordinary chondrites of each type (H, L, LL) from different hot deserts were plotted (Fig 15): Acfer (188H/117L), Dar al Gani (459H/398L), Oman (647H/515L), Hammadah al Hamra (147H/135L), Roosevelt County (72H/65L), San Juan (40H/25L), and Saudi Arabia (48H/16L) (data from the Meteoritical Bulletin Database <http://www.lpi.usra.edu/meteor/metbull.php>). Classification of ordinary chondrites recovered from Morocco (12H/8L) and Tunisia (14H/8L; Table 5)

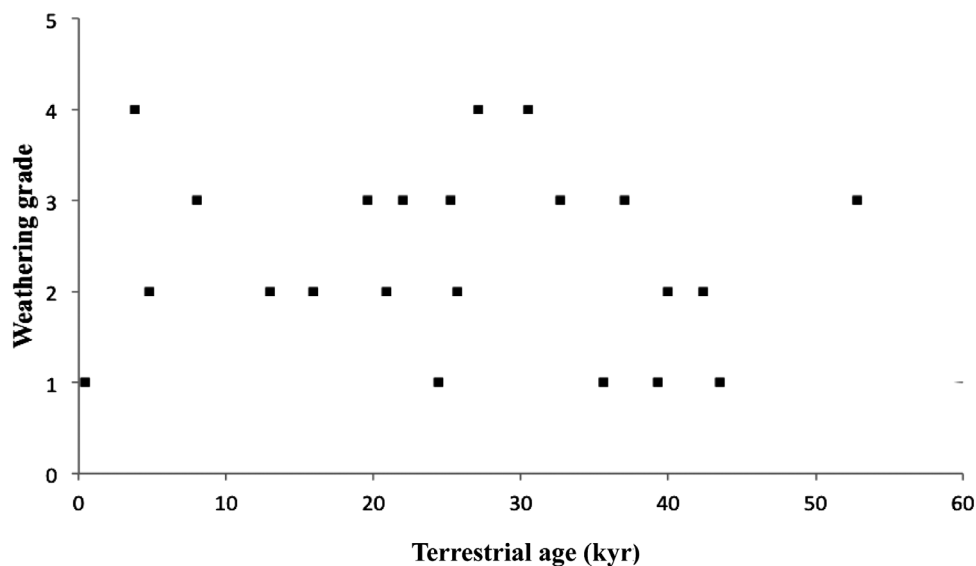


Fig. 12. Weathering grade versus terrestrial age of meteorites from Aridal, Bou Kra, Bir Zar and Tieret DCAs (data from Table 7).

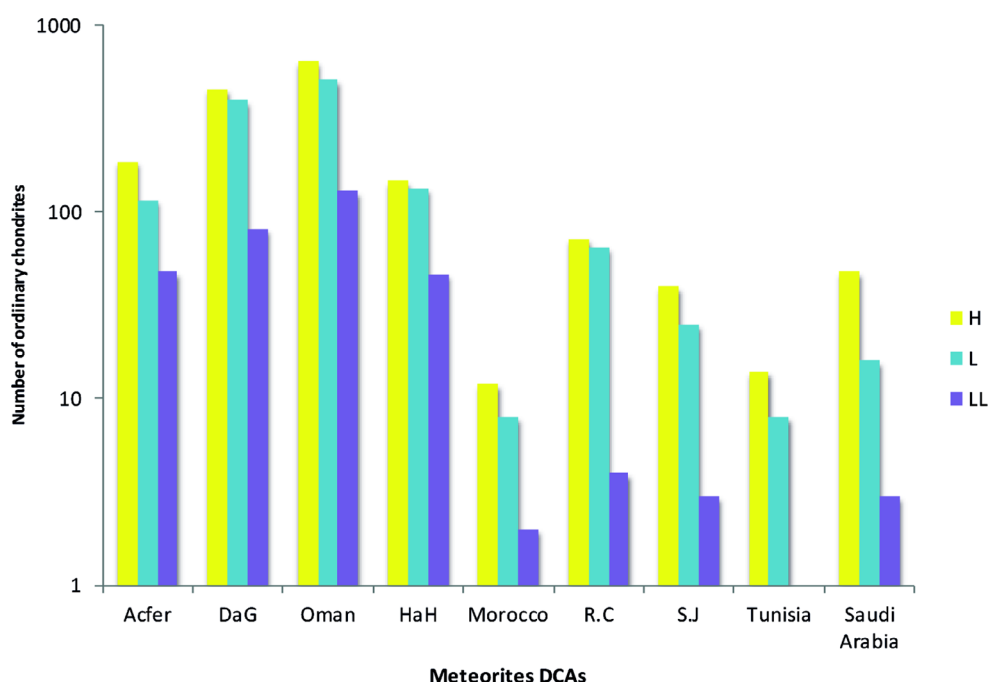


Fig. 13. Number of ordinary chondrites H, L, LL in different hot desert DCAs. Data for San Juan (S.J), Dar al Gani (D.G), Hammadah al Hamra (HaH), Acfer, Roosevelt County (R.C) are from Meteoritical Bulletin Database; for Saudi Arabia (Hofmann et al. 2018) and for Oman (Zurfluh et al. 2016). Concerning Morocco and Tunisia meteorites data are from this work (Table 6). (Color figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com).)

is compared to the previous ones (Fig. 13). The distribution of the types of chondrites in these deserts is similar (Fig. 13); we note that H chondrites are the most abundant, followed by L, and then LL chondrites. No LL chondrite find has been so far recovered in Tunisia, probably because of the low number of meteorite finds.

## CONCLUSIONS

In the Sahara, flat surfaces on light-colored limestones without water drainage, little vegetation, and Quaternary alluvium soil are favorable for meteorite recovery.

Since 2008, seven field missions have been organized by our teams, in Tunisia and Morocco, in order to apply the same method of systematic prospecting previously used in Chile and Oman, which was successful for meteorite density estimates.

In the deserts of Tunisia and Morocco, 41 meteorites were classified as ordinary chondrites and one brachinite. Less abundant are LL chondrites (2), followed by L chondrites (12) and H chondrites (21). These numbers show that ordinary chondrites have the same abundance as in the other deserts. This contrasts with statistics of submitted meteorites from NWA characterized by a big number of achondrites. This statistical bias is caused by

the underdeclaration of ordinary chondrites because of their lower economic value.

Our meteorite densities in Tunisia and Morocco are estimated to be  $1 \text{ met km}^{-2}$  with a median mass  $M = 26 \text{ g}$  (Table 6). This density is nearly one order of magnitude higher than previously published one for other Saharan DCA (of the order of  $0.2 \text{ met km}^{-2}$ ). The factor 5 can be explained as previous estimates were obtained through searches by car, which tend to miss the smaller meteorites. We thus propose that the meteorite density in the Sahara is on the order of  $1 \text{ met km}^{-2}$ .

An estimate of the total number of meteorites that were present before meteorite hunting on the 10% of the surface of the Sahara which can be assumed to be favorable to meteorite searches (based on rock color, surface age, and accessibility), may be 900,000 meteorites. Even assuming that the declared meteorites make only 10% of the total collection, the present collection available is only a minor fraction of what remains in the field.

The measured terrestrial ages of meteorites from Sahara varies from 0.4 to more than 40 kyr with a maximum between 0.4 and 20 kyr. This young age is related to the paleoclimate humidity fluctuation of Sahara. No correlation between weathering grade and terrestrial age of meteorites is observed.



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