AFRICAN METEORITES

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Bentham Books

African Meteorites

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ISBN (Online): 978-981-5136-29-6

ISBN (Print): 978-981-5136-30-2

ISBN (Paperback): 978-981-5136-31-9

First published in 2023.

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FOREWORD

Meteorites recovered in Africa represent more than 1/6 of all extraterrestrial rocks collected in the entire world. This means that Africa hosts the second-largest population of meteorites after Antarctica. The present book offers complete information on the origin and characteristics of meteorite falls and finds in Africa.

The book opens with an exhaustive synthesis of the formation and origin of meteorites, their categorization into “falls” and “finds” according to the circumstances of their discovery, the criteria for their identification, and the guidelines adopted for the nomenclature of meteorites and their classification. The second chapter deals with a statistical study of falls recorded in different African countries. It analyzes their evolution in time and space, provides information on the distribution of their masses, and characterizes their typological classification, focusing on the different factors likely to contribute to their detection on the ground and recovery. The following chapter is devoted to meteorite finds in Africa, pointing to the advantageous natural and human factors that enhance the discovery of new meteorites on this continent. Again, the distribution of meteorite masses collected and their typological classification are presented, drawing the reader’s attention to the influence of climate, terrestrial age, as well as sample porosity and mass, and the variation of the degree of weathering.

The subsequent chapters are devoted to other important aspects involving the study of African meteorites, such as the complex problematics connected to the nomenclature of North West African meteorites (NWA), therefore enhancing the scientific importance of the meteoritic heritage of northwest African countries and, consequently by providing detailed documentation on the circumstances of their recovery. A specific chapter is dedicated to Moroccan meteorites, as this region has proved to be one of the most prolific areas in the world for meteorite recovery. The following chapter deals with the Saharan meteorites, stressing the hypothesis that many new meteorites might be extracted from the Sahara Desert in the coming decades, as supported by the estimate that more than 90% of the desert surface has not yet been explored. The last chapter reports on the North East African meteorites and contains an up-to-date review of the confirmed and proposed meteorite falls and finds and of the possible related impact structures in Egypt, Sudan and Libya. The book ends with a summary of the most significant scientific results obtained from the various studies carried out on African meteorites.

I am honored to present this book that aims to become a reference text for university students, researchers, collectors, meteorite enthusiasts, museum curators, astronomers, and for all those readers interested in African meteorites and, more generally, in celestial rocks.

Finally, I would like to congratulate the editors, the authors and their collaborators, all with long-standing professional activity, for their contribution to the publishing of this comprehensive and well-balanced book on the extraordinary scientific heritage represented by African meteorites.

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PREFACE

According to Alain Carion, "At the beginning of the 20th century, in a book by the Marquis de Mauroy, he wrote that to discover meteorites, one had to read books, see, and possibly touch real meteorites. The authors, with their books on meteorites and the University Museum of Meteorites of Agadir created by some of them, are in line with the discoverers of knowledge". This is the sense that this book aims to deal with meteorites in Africa. The book that the reader has in his hands is a collection of works performed on meteorites in Africa, where arid and hot zones represent 60% of the continent's surface.

This book is a single item of reference for all researchers who require complete information on the origin and characteristics of meteorite falls and finds in Africa, which includes the second-largest population of meteorites on the Earth. This book also provides unique information related to meteorite classification, and can be an important reference on the favorable factors to collect meteorites in Africa, which still hides a huge number of undiscovered meteorites.

The book will be useful for researchers, meteorite hunters, meteorite enthusiasts, museums, astronomers, students, and any person interested in geology and astronomy.

As it is a voluminous subject, we might have missed some references. Readers are requested to bring such omissions to our notice to be included in future editions.

We thank Dr. Vanni Moggi Cecchi for writing the foreword of this book.

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INTRODUCTION

Meteorites are rocky or metalliferous fragments that have been ejected from a body of the solar system following impacts with other bodies and have arrived on Earth after traveling more or less long in space. The majority of meteorites come from the asteroid belt (rocky bodies orbiting between Mars and Jupiter) and some other meteorites, of lower frequency, can arrive from the Moon or the planet Mars. Meteorites provide information about the early stages of evolution of our solar system in general and Earth in particular, as they contain information about protosolar and even presolar material (DeMeo *et al*., 2015; Gounelle, 2017).

After the great meteorite discoveries in Antarctica starting in 1976 (Corti *et al*. 2003), several arid regions of the world were found to be "deposits" of ancient meteorite falls (Bevan *et al*., 1998). The hot deserts of the different continents are favorable places for their conservation, accumulation, and possible recovery. A large number of meteorites have been collected and studied in these places, namely: in Australia, the desert plain of Nullarbor (Bevan & Bindon, 1996; Bevan, 1998; Jull *et al*., 2010), in North America, the desert region of Roosevelt County in the southwestern United States (Hutson *et al*., 2013), in South America, the Atacama Desert in Chile (Hützler *et al*., 2016; Valenzuela & Benado, 2018) and in Asia, the desert of Oman (Al-Kathiri *et al*., 2005; Hofmann *et al*., 2018), the Lut desert in Iran (Pourkhorsandi *et al*., 2019) and the province of Xinjiang in China (Li *et al*., 2017; Zeng *et al*., 2018).

In Africa, where arid and hot zones represent 60% of the continent's surface, the first systematic studies were launched in the north of the continent (Sahara) at the end of the 20th century (Bischoff & Geiger, 1995; Schlüter *et al*. al., 2002; Ibhi, 2014, 2016; Khiri *et al*., 2017; Ouknine *et al*., 2019; Aboulahris *et al*., 2019). In total, the number of meteorites recovered in Africa represents more than 1/6 of all extraterrestrial rocks around the world (Khiri *et al*., 2017; Ouknine *et al*., 2019), which makes this continent a region that shelters the second largest population of meteorites after that of Antarctica. This prompted us to consider the conditions/factors favorable to the collection of extraterrestrial rocks in Africa, both of meteorites collected after the observation of their fall (falls) and those found after a more or less long time of residence on earth (finds).

To do this we have subdivided our book into seven main chapters, briefly presented below.

The first chapter is devoted to a bibliographical synthesis of meteorites features that includes an exhaustive and concise description of the formation and origin of meteorites, their categorization into "falls" and "finds" according to the circumstances of their discovery, the criteria for their identification, the guidelines adopted for the nomenclature of meteorites falls and finds, and their classification.

The second chapter deals with the statistical study of falls recorded in various African countries by analyzing their spatiotemporal evolution and masses distribution, and by characterizing their typological classification in order to evaluate the different factors likely contributing to their observation and recovery.

The third chapter is devoted to the study of meteorite finds in Africa, their spatiotemporal distribution, and the human and natural factors that favor their discovery. Then, the distribution of meteorite masses collected and their typological classification are described. Subsequently, the variation of the degree of weathering (W) of African meteorites finds is analyzed, and the degree of influence of certain weathering factors, including climate, sample mass, earthly age and porosity, is evaluated.

The fourth chapter deals with North West Africa (NWA) meteorites in an attempt to contextualize and document these meteorites, define the circumstances of finding each sample, and assign the country of collection to each of them.

The fifth chapter is devoted specifically to Moroccan meteorites. The Moroccan territory is a privileged place for the collection of meteorites and is one of the richest countries in the world in terms of meteorites finds. The rate of recovery of meteorites (falls + finds) in Morocco exceeds that of most other countries of similar size and climatic conditions. More than 95% of documented meteorites from Morocco, including many rare types, have been recovered from Eastern Morocco Sahara, which has proved to be one of the most prolific areas in the world for meteorite finds.

The sixth chapter deals with Sahara meteorites. It is estimated that more than 90% of the surface of this desert has not yet been explored and that it still contains important meteorite falls. The most optimistic forecasts suggest that many new meteorites will continue to be recovered from the great Sahara Desert in the coming decades. Preserving the desert properly is essential to assure science such important research materials as meteorites.

The seventh chapter provides an up-to-date review of the confirmed and/or proposed meteorite falls and finds and their impact structures in Egypt, Sudan, and Libya. Among the ~190 confirmed impact structures/sites on Earth crust, only less than 8 have been identified in NE Africa, in particular in Oasis (Libya) and Kamil (Egypt) areas.

The book ends with some general conclusions highlighting the results obtained from the various studies performed on meteorites in Africa.

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CHAPTER 1

Basic Issues on Meteorites: Origin, Formation, Identification, Nomenclature

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Abstract: Meteorites are rocky or metalliferous fragments that have been ejected from a body of the solar system following impacts with other bodies, and arriving on Earth after traveling more or less long in space. The majority of meteorites come from the asteroid belt (rocky bodies orbiting between Mars and Jupiter), and some other meteorites of lower frequency, can arrive from the Moon or the planet Mars. Meteorites provide information about the early stages of the evolution of our solar system in general and Earth in particular, as they contain information about protosolar and even presolar material. In this article, we will present an exhaustive synthesis of the formation and origin of meteorites, their categorization into "falls" and "finds" according to the circumstances of their discovery, the criteria for their identification, and the guidelines adopted for the nomenclature of meteorites falls and finds, and their classification.

Keywords: Categorization, Classification, Falls and finds meteorites, Identification, Nomenclature, Origin.

INTRODUCTION

Meteorites are fragments that were ejected from a body in the solar system following impacts with other bodies and arrive on Earth after a more or less long journey in space (Hughes, 1996). Rubin and Grossman (2010) offer a complete definition: a meteorite is a natural, solid object, larger than 10 µm, derived from a celestial body, which has been transported by natural means from the body on which it formed towards a region outside the dominant gravitational influence of this body, and which subsequently collided with a body larger than itself. Most of the known meteorites come from the asteroid belt (rocky bodies orbiting between Mars and Jupiter), and some other meteorites, of lower frequency, can arrive from the Moon or the planet Mars (Weisberg, 2018).

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Meteorites provide information about the early phases of evolution of our solar system in general and Earth in particular, as they contain information about protosolar, and even presolar, materials (DeMeo *et al*., 2015; Gounelle, 2017).

ORIGIN OF METEORITES: VESTIGES OF THE EVOLUTION OF THE SOLAR SYSTEM

The Composition of the Solar System

The solar system formed 4.56 billion years ago from a cloud of gas and dust, the Protosolar Nebula. In a molecular cloud, the gravitational collapse of a dense, cold-core gives rise to a dense, hot protostar at its center (Aikawa *et al*., 2008; Bardin, 2015) (Fig. **1**).

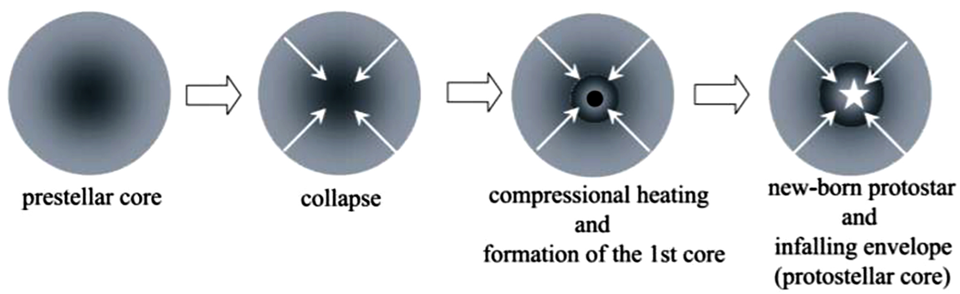

Fig. (1). Process of star formation, the Sun, for example (Aikawa *et al*., 2008).

Some objects that did not accrete enough matter remained as small bodies, smaller than a few hundred km, such as asteroids and comets. Indeed, the solar system is composed of a star, 8 planets, 167 satellites, and a multitude of small objects such as dwarf planets (Pluto, Sedna, *etc*.), asteroids (Ceres, Vesta, Hebe, *etc*.), trans-Neptunian objects, and comets (Kuiper belt, Oort cloud). The solar system can be divided into four different regions:

The sun: a star that concentrates about 99.9% of the mass of the solar system and is composed mainly of hydrogen and helium and a few percent of the heavier elements. With a radius of 700,000 km, the sun is a member of the yellow dwarf star family and derives all of its energy through nuclear fusion (Chapman, 2007). Temperatures in the center reach around 10-15×10^6 °C and 6500 °C at the surface.

The inner solar system represents about 10% of the mass of the remaining solar system. It groups the 4 telluric planets, Mercury, Venus, Earth and Mars and their satellites, as well as the objects in the asteroid belt. Telluric planets are rocky and metallic bodies (rich in heavy elements), a few thousand km in diameter, with a thermal history, allowing mantle-core segregation (Bardin, 2015). In addition, the asteroid belt contains asteroids of small sizes (only about fifteen with a radius greater than 100 km), but of a very wide variety. However, we can find more or less evolved or differentiated bodies, rich in silicates, metal and even organic compounds or ice (Trigo-Rodríguez and Blum, 2008).

Outer solar system groups the 4 gas giant planets, Jupiter, Saturn, Uranus, and Neptune. These planets make up 90% of the remaining mass and are mostly made up of hydrogen and helium. These planets are made up of a gigantic gas envelope, and at their center, there could be a rocky and/or icy core. In addition, they present many ice and rocky satellites.

Distant solar system groups objects from the Kuiper belt, such as Pluton or Sedna, and the Oort cloud. Most of the bodies in this region are mainly composed of ice and dust. The comets would come from this zone, in particular from the Kuiper belt.

Formation and Ages of Meteorites

During the formation of the solar system, the first solids agglomerated to form planetesimals (Remusat, 2005). Like all bodies in the solar system, meteorites began to form in the early nebula together with the sun and the planets within the Milky Way, our galaxy. As already mentioned above, a nebula of gas and dust collapsed, contracted, and gave birth to the sun. The dust grains agglomerated to give larger and larger grains, resulting in the embryos of planets. This was the phenomenon of accretion (Aikawa *et al*., 2008), which was accompanied by a very sharp increase in temperature. During this period, thermonuclear fusion appeared in the sun. In the rest of the cloud that divided into rings around the sun, the temperature started to drop, allowing the gas to condense into solid, future constituents of planetesimals and planets (Feigelson and Montmerle, 1999). After accretion, the original material of the Earth, planets and some asteroids (the largest) melted under a high temperature, and the mixture of homogeneous initial composition separated into several phases of different chemical compositions (DeMeo & Carry, 2014). In the case of planets, the starting material of solar composition was fractionated and separated into distinct layers: core (metallic), mantle (rich in olivine) and crust (silicate rocks).

Some objects that did not accrete enough matter remained as bodies smaller than a few hundred km, such as asteroids and comets. These are mostly undifferentiated objects that preserve the memory of the first million of years of the formation of the solar system (Bardin, 2015).

CHAPTER 2

Meteorite Falls in Africa

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Abstract: Collecting meteorites just after their fall is a fundamental element to continue to gather information on the history of our solar system. During the period 1800-2020, 170 observed meteorite falls were recorded in Africa. The mass of fragments collected for any African meteorite range from 1.4 g to 175 kg, with a predominance of cases from 1 to 10 kg. The average rate of observed falls in Africa is low, with only one recovery per 1.29 years (*i.e.*, 0.026 per year and per million km^2). The African collection of observed falls is dominated by chondrites (84.4%), as in the world collection. The achondrites (10%) include three famous Martian meteorite falls: Nakhla (Egypt), Tissint (Morocco), and Zagami (Nigeria), whereas the observed iron meteorite falls are relatively rare (*i.e.*, 5% of the collection). The rate of documented falls in Africa has been increasing since 1860, with 88% recovered during the period 1910-2020. Most of these falls have been observed and then collected in North-Western Africa, Eastern Africa and Southern Africa, in countries that feature a large area and a large but evenly distributed population. Other factors that are proven to be favorable to the observation and collection of meteorite falls on the African territory are a genuine meteorite education, the semi-arid to arid climate offering clear skies most of the time, cultivated land or sparse grassland and the possible access to the fall location favored by a low percentage of forest cover and a dense road network.

Keywords: Africa, Classification, Distribution factors, Observed meteorite falls, Statistics.

INTRODUCTION

Meteorites have persisted unaltered since their extremely old formation (4.55 Ga) (Wasson & Wetherill, 1979), thus, when they reach the Earth, they represent an invaluable source of information not yet available about the solar system history, its planets, and the question of life origin if meteorites contain organic molecules (Gounelle, 2009). For these reasons, meteorite collection is important, particularly

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in the case of observed falls that offer fresh material for scientific research. The Halliday study (2001) based on photographic data of fireballs from Canadian network cameras collected over eleven years shows that 4500 events per year dropped at least 1 kg of meteorites on Earth's land surface. Unfortunately, several of these extraterrestrial fragments disappeared as shooting stars (Kress, 2001) were lost while diving in the oceans or remained unnoticed on the land. The annual average of meteorites recovered around the world over the past two centuries does not exceed five to six pieces (Graham *et al*., 1985).

The main objective of this chapter is to describe, based on the analysis of statistical data, the "observed meteorite falls" in Africa in terms of number and class in time and space, and to examine the contribution of certain demographic and geographical factors to their recovery. Africa has been chosen due to the importance of its scientific contribution to the research and study of meteorites and the great scientific and cultural value of some meteorites falls in this continent. These include the carbonaceous meteorite Tarda (Meteoritical Bulletin Database, 2020) and the observed Martian falls Nakhla and Tissint (Ibhi, 2013a; Ibhi *et al*., 2013; Treiman, 2003) that contain extraterrestrial organic molecules (Treiman, 1993; Beech, 2003; McCubbin *et al*., 2013; Lin *et al*., 2014). The choice is also justified by the large surface area of the African continent (20% of all terrestrial area, *i.e.,* 30 million km^2) (FAO, 2002), its geographical location between the northern and southern hemispheres and the diversity of its landscapes (desert, forests, mountains) and climates. A significant part of the meteorite falls on Earth is hosted in this large area.

TEMPORAL AND SPATIAL EVOLUTION AND DISTRIBUTION OF METEORITE FALLS IN AFRICA

Based on the information provided in the Meteoritical Bulletin Database (www.lpi.usra.edu/meteor/metbull.php), spatial and temporal data on observed meteorite falls in 52 African countries between 1801 and 2020 have been collected, retaining only those falls that have been approved by the Meteorite Nomenclature Committee of the Meteoritical Society, whereas geographical and demographic data were obtained from various FAO reports.

Evolution of Numbers, Masses, and Classes of African Observed Meteorite Falls

Evolution of Falls Numbers

Since 1800, the year when meteorites were recognized as objects falling from the sky, scientists have recorded 170 observed meteorite falls in Africa, totaling a mass of 2914.7 kg. The oldest meteorite fall (L6) dates back to 1801 in Mauritius, while the most recent one, dated August 20, 2020, is a fragment of more than 4 kg of a carbonaceous chondrite (C2-ung) that exploded in the Tarda region in northern Morocco (Weather bulletin database, 2020).

Over 12.6% of all known meteorite falls worldwide through December 31, 2020, have been recorded in Africa. The number of these falls is similar to that recorded in the USA (163) and is higher than that of other regions in similar time periods (in Russia, 54 observed falls have been inventoried since 1805). These results confirm the important contribution of the African continent to the total observed meteorite falls. Furthermore, the ratio of falls to finds in Africa (1:60) is lower compared to that recorded in other continents or large countries of similar size (Australia 1:41, South America 1:17; United States 1:13; Canada 1:6; Russia 1:3 and India 1:1).

The cumulative number of observed meteorite falls since 1800 in Africa shows a constant increase (Fig. **1**). The recovery rate for these falls averages 0.77 falls per year over the past 220 years and 0.026 falls per year per 106 km^2.

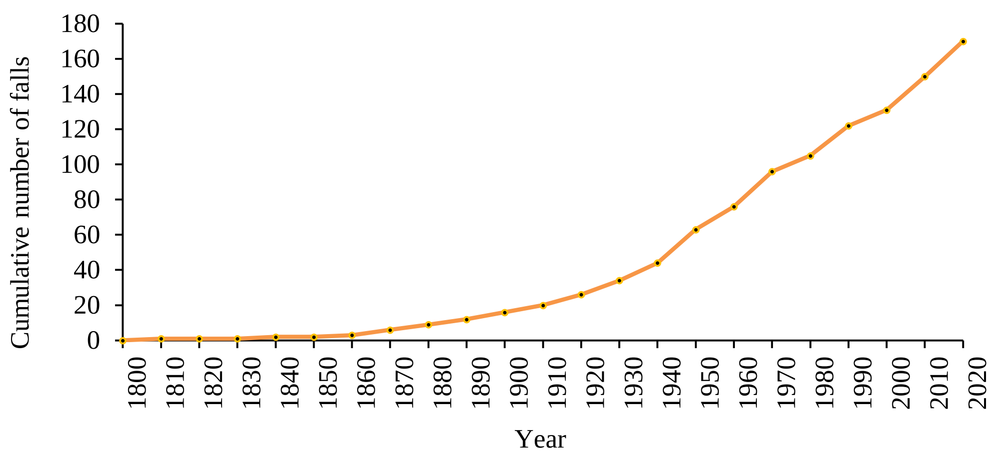

Fig. (1). Cumulative number of observed meteorite falls recorded in Africa.

The evolution of the number of observed meteorite falls every 10 years since 1800 Fig. (**2**) shows a variable temporal distribution. In particular, the falls rate increased from 0.017 meteorites/106 km^2 per 10 years (3 falls only) between 1800-1860 to 0.17 falls/106 km^2/10 years (41 falls) during the period 1860-1940. In particular, a small but uniform increase in the number of recoveries occurred during the period 1900-1940 (2 new records of meteorite falls per decade).

CHAPTER 3

Meteorite Finds in Africa

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Abstract: Africa is a favorable site for meteorite recovery, with a total number of recoveries amounting to more than 1/6 of all meteorites recovered from the entire world. This work deals with the classification of meteorite finds in Africa, the distribution of their masses, and their alteration/weathering grades as affected by various factors. The African meteorite population includes an abundance of stony meteorites with a high percentage of the world collection of rare meteorites, *i.e*., Martian meteorites (62%), Ureilites (51%), Rumuruti (59%), Lunar (47%), and HED (46%). Furthermore, an important increase in achondrite meteorites finds occurred in the last two decades, compared to the Australian and Antarctic collections. The mass distribution of the African meteorite population shows that most recoveries (72%) have masses bigger than 100 g with peaks of about 1 kg, compared to about 0.1 kg for the Australian collection and 0.01 kg for the Antarctic finds. The distribution of weathering grades (W) shows the predominance of W1 (32%) and W2 (34%), which proves a better preservation of meteorites in this continent. The factors influencing the mechanism and rate of alteration of African finds include climate as the main factor, the mass, the terrestrial age, and the initial porosity of the sample.

Keywords: Africa, Classification, Human and natural factors, Mass distribution, Meteorite finds, Weathering factors.

INTRODUCTION

The majority of meteorites collected on Earth originate from the “cold” Antarctica deserts, where they are embedded within the ice (Whillans *et al*., 1983; Corti *et al.* 2003), and “hot” deserts (Bland *et al*., 2000), such as the Sahara in North West Africa (NWA) (Bischoff and Geiger, 1995; Schlüter *et al*., 2002; Ibhi, 2014,

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2016; Khiri *et al*., 2017), the desert of Oman (Al-Kathiri *et al*., 2005; Hofmann & *et al*., 2018), the Atacama desert in Chile (Muñoz *et al*., 2007; Valenzuela & Benado, 2018), and the arid regions of Australia (Nullarbor) (Bevan & Bindon, 1996. Jull *et al*., 2010) and United States of America (Roosevelt County) (Bland *et al*., 2000; Jull *et al*., 2010). In particular, the African meteorite collection represents the second largest one after that of Antarctica and includes meteorites of great scientific value.

Globally, only 10 countries/regions can document more than 300 meteorite finds within their borders. These include five countries/regions in Africa, *i.e*., NWA with 9387 findings, Sahara with 476, Libya with 1504, Morocco with 1741 and Algeria with 609. Until January 1, 2021, a total of 12511 meteorite discoveries of African origin are listed in the Meteoritical Bulletin Database of the Meteoritical Society (www.lpi.usra.edu/meteor/metbull.php). Khiri *et al.* (2017) reported that almost all African countries bordering deserts have a relatively high meteorite recovery rate, which could simply be a consequence of their easy viewing of the desert surface.

The first part of this chapter aims to review the spatiotemporal distribution of meteorite finds in Africa and evaluate the human and natural factors that have favored their discovery. The second part is devoted to analyze the typology and classify the meteorites collected and their mass distribution. The third part deals with the alteration/weathering processes to which African meteorites have been subjected and the various influencing factors. The chapter ends with a brief summary and conclusion. Along with the entire review, the African meteorite features are compared with those of other meteorite populations, especially from Antarctica and Australia.

FACTORS INFLUENCING METEORITES FINDS IN AFRICA

Historical and Cultural Factors

The rate of African meteorite finds was low in the 18th and 19th centuries, with 2 and 10 meteorites collected, respectively, whereas the number of finds increased in the 20th century, especially towards its end and in the North of the continent with the collection of 2417 samples (Fig. **1**). In the 21st century, the meteorite recovery rate almost quadrupled between 2000 and 2016, with 9888 meteorites recorded.

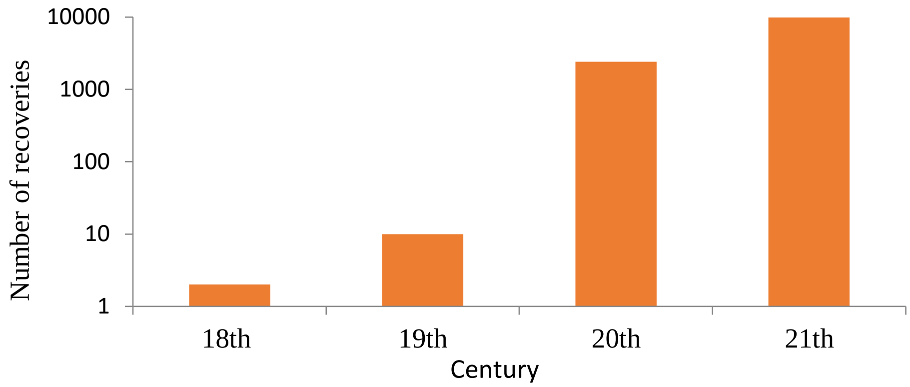

Fig. (1). Distribution by the century of meteorite finds in Africa.

The low rate of finds in the 18th and 19th centuries can be explained by the lack of knowledge and culture on meteorites. In antiquity, in many African countries, the passing of meteors was related to superstitious special events such as the death of someone or the passing of the devil (Khiri *et al*., 2017). Historians have described that many ancient African civilizations regarded both meteorites and the site of its fall as sacred. Often meteorites have been used as objects of worship or to produce handicrafts such as jewelry, weapons and practical items (Johnson *et al*., 2015; Comelli *et al*., 2016). The colonization of African countries in the 20th century modified the previous beliefs of natives about meteorites. Dodd (1986) and Bevan (1992) noted that historical and educational factors also contributed to meteorite recovery in Australia.

The period between the end of the 20th and the beginning of the 21st century (1986-2020) was characterized by the collection of hundreds or even thousands of meteorites by systematic expeditions organized particularly in the hot deserts of northern Africa, *i.e*., in Morocco, Algeria, and Libya. This was promoted by both (i) the major meteorite discoveries recorded in hot deserts around the world (Dhofar in Oman, Nullarbor in Australia, Atacama in Chile, and Roosevelt County in USA) as the result of systematic missions initiated at the start of the '70s, and (ii) the interest in planetary sciences with the birth of research teams focusing on meteorites in Morocco, Algeria and South Africa.

In some African countries, meteorites were often supplied by nomads and locals who swept the desert in search of meteorites to sell. Beech (2003) suggested that to recover more meteorites, we need both an educated and inspired local population and subject matter scientists in the field. In USA in the 30's, meteorite search missions were organized for the first time with the involvement of farmers

CHAPTER 4

Meteorites of Northwest Africa: Morocco, Algeria, Mali, Mauritania

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Abstract: The number of meteorite finds in Northwest of Africa (NWA), *i.e.*, Morocco, Algeria, Mauritania and Mali have recorded a considerable increase since 1999. However, the classification of these meteorites is done by the Meteorite Nomenclature Committee of the "Meteoritical Society", only attributes 8% of the total finds of this region to their specific country of origin, and leaves 92% of them under the mere appellation "NWA" (Northwest Africa) followed by a number. This work attempts to contextualize the 5678 finds of NWA meteorites by defining the circumstances of the find of every sample, according to the new Categorization of Finds and the new Guidelines for Meteorite Nomenclature adopted by the Meteorite Nomenclature Committee. Thus, in addition to the 1180 official NWA meteorites whose countries of find are approved by the Nomenclature Committee, 3240 meteorites are assigned to 4 countries of North-West Africa, *i.e.,* 2994 samples (92%) to Morocco, 79 samples (2.5%) to Algeria, 34 samples (1.1%) to Mauritania and 12 samples (0.1%) to Mali. Nevertheless, the remaining NWA meteorites (1267 samples) have no information indicating the country of finding. After the adoption of the naming "NWA", we notice a remarkable decrease in the number of meteorites bearing the names of official places versus a considerable increase in the number of NWA meteorites. On the other hand, the statistical analysis of NWA meteorites reveals that the population includes rare specimens of great scientific value, making them highly desired by both scientists and collectors from all over the world. In general, this work results in the creation of a new database of meteorites stemming from the Northwest of Africa.

Keywords: Classification, New database, NWA meteorite finds, Renaiming, Statistics.

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INTRODUCTION

In "cold" deserts like Antarctica, the collection of meteorites is prohibited (Schmitt, 2002), and is allowed exclusively for governmental scientific expeditions (especially from the United States and Japan), which possess all the technical capacities required to define the circumstances of meteorite finds (*e.g*., the geographic coordinates of the harvest places). During the last 30 years, the specialized institutions of NASA recovered in this region more than 33000 meteorite samples, which were studied by more than 500 researchers all over the world (NASA, 2015). In contrast, in the "hot" desert region, especially in Northwest Africa, the collection and sale of meteorites are authorized without limitation in Morocco, Mauritania and Mali, whereas in Algeria, the search for meteorites and their sale has been strictly forbidden since 2004.

Often, meteorite harvest is made by nomads and sometimes by equipped meteorite hunters (Ibhi, 2014), and the acquisition is made by meteorite collectors. Since the end of 1999, the number of meteorites collected in Northwest Africa has known a considerable evolution (Grossman, 2000; Connolly *et al*., 2007). However, the adopted legal and statutorily legislations (especially in Algeria) and lack of awareness on meteorites of more commercial interest often prevent nomads and meteorite hunters from revealing the harvest places. Consequently, the Meteorite Nomenclature Committee of the "Meteoritical Society", names most meteorites found in Northwest Africa with the acronym "NWA" (Grossman, 2000).

To justify this decision, the Meteorite Nomenclature Committee considered that «the reliability of locality information associated with these meteorites is difficult to assess because of the anonymity of all of the finders and most of the original sellers». Furthermore, the Committee justified this resolution by the fact that «these meteorites are all sold as Moroccan finds, but there are plausible reports that some were actually collected in Algeria». Thus, for approving and naming meteorites collected in Morocco and in surrounding countries, the Nomenclature Committee bases itself on the conditions contained in the Guidelines for meteorite nomenclature (Weisberg *et al*., 2008), which requires that finds to be approved must be accompanied by documentation that includes the date of find, the name and address of finder, and reasonable proof of the location find (*e.g*., a single photograph showing the meteorite *in situ*, a length-scale and an active GPS unit displaying the geographic coordinates). This provision deprives Northwest African countries of their meteoritic heritage (Larouci, 2014; Oukníne *et al*., 2016). Fortunately, in February 2015, the Nomenclature Committee abolished the arrangement debated during its last meeting (Agee *et al*., 2015), so assessing the

same treatment for meteorites native to Morocco and neighboring countries during their approval.

The present chapter aims to contextualize and document NWA meteorites collected until December 31st, 2014, by attempting to define the circumstances of the find of every sample to attribute it to the country of harvest and consequently propose a name for it.

COUNTRY OF ORIGIN OF NWA METEORITES

During its decision to assign the name "NWA" to meteorites recovered from Northwest of Africa, the Nomenclature Committee has not explicitly defined the countries that constitute this region. According to Ibhi (2014) and Chennaoui (2008), NWA meteorites include all samples found in Morocco, Algeria, Mauritania, Mali, Niger and Nigeria. Furthermore, websites that are interested in meteorites, such as "www.galactic.stone.com" allocate NWA meteorites to the Northwest Africa countries Morocco, Algeria, Mauritania, and Mali and other countries without mentioning which one, whereas the website "www.allmeteorite.com" asserts that these meteorites are stemming from Morocco, Algeria, Mauritania and Niger.

The data extrapolated from the official website (http ://www.lpi.usra.edu /mete or/met bull.php) of the Meteoritical Society reveal that the major part (92%) of the 8107 meteorites recovered in Northwest Africa is declared under the acronym NWA, whereas only 8% are classified under the name of official places of recovery in four countries, *i.e.,* Morocco, Algeria, Mauritania and Mali (Fig. **1**). Most meteorites recovered in Algeria (83%) are attributed local names (5113 samples), whereas a high proportion of those recovered in the three other countries are declared under the acronym NWA. The results show that almost all meteorites (93%) found in Morocco are named NWA, and only 7% (74 samples) are classified with the name of the finding place. The number of meteorite finds is low in Mauritania, *i.e.,* 32 samples, of which 21 (66%) are assigned the name NWA, and only 15 finds are recorded for Mali, of which 11 samples with the acronym NWA. Noteworthy, three samples found in Libya are declared under the acronym NWA, *i.e.,* NWA 1237, NWA 1241, and NWA 1242, although this country is not situated in Northwest Africa.

CHAPTER 5

Meteorites of Morocco: Falls and Finds

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Abstract: Since the first recorded discovery of a meteorite in 1937 near the Mrirt village, a total of 1747 authenticated meteorites have been recovered in Morocco. The collection includes 21 meteorites from authenticated observed falls, which comprise five different types of meteorites, *i.e.*, 17 ordinary chondrites including four LL6, one EH7, one EH5, one H3-5, one H3-6, four H5, one CH, two L6 and two L4, one carbonaceous chondrite, one eucrite unbrecciated, one shergottite basaltic achondrites and one aubrite. The meteorite fall recovery rate in Morocco during the past 88 years (from 1932 to 2020) on a surface area of 712. 5 km^2 is relatively low, with approximately four falls recorded every 10 years, equivalent to 0.4 falls per year per 2.11 km^2. A total of 1747 distinct and authenticated meteorite finds with a total mass of 6.175 kg have been described, which include 1674 stones (442 achondrites and 1232 chondrites), 37 iron, 24 stony-iron and 12 ungrouped meteorites. The rate of recovery of meteorites (falls + finds) in Morocco exceeds that of most other countries of similar size and climatic conditions. More than 95% of documented meteorites from Morocco, including many rare types, have been recovered from the Eastern Moroccan Sahara, which has been proven to be one of the most prolific world areas for meteorite finds.

Keywords: Classification, Meteorite falls and finds, Morocco, Statistics.

INTRODUCTION

Morocco is one of the richest countries in the world in terms of meteorite discoveries because: (i) meteorites are easily revealed by their color in the desert context; (ii) the dry climate helps to preserve them much better than a humid climate; (iii) the political stability of Morocco secures and facilitates the search

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for meteorites. On February, 2016, with the aim of popularizing the science of meteorites, the Ibn Zohr University Museum of Meteorites was inaugurated in the heart of the university complex to host a permanent exhibition of meteorites that crashed in Morocco. Actually the plan of founding a meteorite museum was not new, but emerged from the propitious maturation of reflections elaborated over the past twenty years. Indeed, since 2006, the Ibn Zohr Scientific and Cultural Club of Agadir, in collaboration with Ibn Zohr University and the National Network for the Promotion and Diffusion of Scientific and Technical Culture of CNRST (Rabat), has organized several temporary exhibitions of meteorites and associated rocks in different cities of Morocco, *i.e.*, Agadir and Mir Left in 2006; Rabat and Guelmim in 2008; Casablanca in 2010; Tata in 2013 and 2015; *etc*.).

The Museum consists of two rooms; the one is a meteorite exhibition room that presents a collection of meteorites of great beauty that includes more than 150 meteorites, of which 50 impactites (tektites, shatter-cones, impact breccias, *etc*.) with rock engravings (Fig. **1**); the other is a projection room dedicated to conferences, presentations and documentary films addressed to a wide variety of neophytes, *i.e.*, collectors, prospectors, students, teacher, researchers and people interested in astro-tourism. In particular, since 2016, the Museum has been committed in organizing a number of workshops that raised the awareness of the audience on how to duly identify and collect meteorites. Noteworthy, this is the first museum exclusively dedicated to meteorites in Morocco, Africa and Arab countries.

The national meteorite heritage represents not only a scientific and educational tool, but also a significant source of income for thousands of inhabitants of the country, who, over time, have developed a factual knowledge in meteorite research and collection. Currently, meteorite hunting has become part of popular culture, and it is common to encounter locals holding magnets, or even metal detectors, in their search for meteorites. Thus, many people have become experts with an essentially economic interest. Finding a meteorite and selling it to foreign buyers is the dream of any prospector. Although the Ibn Zohr University Museum of Meteorites has done an excellent job in ensuring that at least part of this heritage remains in Morocco, nowadays, most Moroccan meteorites are unfortunately kept in collections outside the country.

Fig. (1). Meteorites **(1)** and petroglyphs **(2, 3)** displayed in the University Museum of Meteorites, and Museum visitors **(4)**. © University Museum of Meteorites.

METEORITES IN ANCIENT TIMES IN MOROCCO

Ancient Stone Carvings Confirm that Meteorites Struck Morocco

Regardless of the cultures involved, the observation of the sky and astronomical bodies has been of worldwide interest since prehistoric times. Petroglyphs have been found around the world and have been interpreted by researchers as signs of the Sun (Coimbra, 2009), the Moon (Olivera & Silva, 2010) and supernovae (Iqbal *et al*., 2009). However, very few of them have been interpreted as bolides (Coimbra, 2007), comets (Coimbra, 2010) and meteors or meteorites (Iqbal *et al*., 2010, Figueiredo *et al*., 2017). These events have been interpreted by early societies as bad or good manifestations of the gods and, therefore, carved on rocky surfaces to be admired by future generations (Sagan & Druyan, 1986). In particular, Bailey (1995) argues that phenomena related to meteors and comets have played an important role in the beliefs and social habits of most civilizations.

Meteors and meteorites have fascinated humans since they were first spotted in the night sky, but ancient cultures often explained these phenomena based on myths and legends. The study of meteoritic phenomena described in the indigenous oral traditions has been a topic of research interest for several years. In particular, the research in the disciplines of "astromythology" and "ethnoastronomy" involves the investigation of oral traditions in the descriptions of past astronomic events and may provide insights both into the culture that observed and recorded them and into the event itself that may contribute to the

CHAPTER 6

Meteorites of Sahara

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Abstract: The number of meteorites collected in the North African Sahara Desert is very relevant, as their conservation is facilitated by the dry climate, thus it represents one of the most important regions to recover rocks from space, along with Antarctica, Atacama and the great deserts of North America. However, more than 90% of the desert surface feasibly preserving important meteorites is estimated to be not yet explored. New finds are classified annually, and countries such as Mauritania, Mali and Egypt are emerging. The most optimistic forecasts suggest that many new meteorites will continue to be extracted from the great Sahara Desert in the coming decades. Collecting and preserving them properly is essential to bequeath to science such important research materials such as meteorites.

Keywords: Climatic conditions, Documentation, Meteorite finds, Preservation, Searching meteorites, Sahara Desert.

INTRODUCTION

The Sahara Desert is claimed to cover more than 9.400.000 km^2, (Española, 2004), thus being the largest hot desert in the world and the third largest desert after the frozen deserts of the Arctic and Antarctica. The Sahara Desert stretches majestically through Algeria, Chad, Egypt, Libya, Mauritania, Mali, Morocco, Tunisia, Sudan and Niger, bordering at east with the Red Sea, at west by the Atlantic Ocean, at north with the Mediterranean Sea, and at south with the Sahel, from which Sub-Saharan Africa begins. This vast extension of land is dominated by “erg” or dune fields shaped by the wind, and by “Hammada,” or extensive valleys of rocky soils (Grove, 1958). Furthermore, the Sahara includes plains of gravel soils, called “reg”, huge dry valleys and salt flats are known as “Shatt”.

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In these primeval lands of the great Sahara Desert, a treasure is hidden (Milich, 1997).

In April 2015, the senior author conducted his first meteorite search trip to the Sahara with the aim of collecting samples for laboratory studies. Its plane landed at Laayoune, from where he travelled to different regions of the Sahara on a trip of several days, during which he met numerous meteorite seekers. Meteorites recovered in Sahara are not only abundant in number, but vary in typologies, including the rarest and most unknown rocks in the solar system. In Sahara, the search for meteorites does not obey any rule, and it is done legally, but in a disorderly manner. The senior author frequently met people living in their Khaimas in the desert keeping black stones that, after an examination, turned out to be meteorites. It is also frequent to stand on the terrace of a bar or cafe and talk about meteorites, and have someone show up with meteorites in an attempt to sell them to the highest bidder. Despite the economic and social situation in the Sahara is quite precarious, and that some people still try to get money selling meteorites, the situation has changed a lot in recent decades, as meteorite typologies have been established, their characteristics, rarity and abundance are known, and their cost is established.

The history of meteorites in the Sahara dates back to 1986-1987, when a German team installing seismic stations for the exploration of oil beds discovered 65 meteorites in a desert plain about 100 km southeast of Dirj, Libya. This was the first indication that large numbers of meteorites could be found in Sahara. A few years later, an anonymous engineer who was a fan of the desert looked at some photographs of meteorites found in Antarctica and recalled observing similar rocks in areas he had travelled in North Africa. Thus, in 1989 he returned to Algeria and recovered about 100 meteorites from at least 5 locations. In the next 4 years, he and other followers found at least 400 more meteorites in the same locations, and in some new areas in Algeria and Libya. The locations where they found the meteorites are known as reg and hamada, which are flat areas covered only by pebbles and small amounts of sand, where they have been very well preserved due to the arid climate of the region and can be easily spotted (McCall *et al*., 2006). Although meteorites have been sold commercially and collected by hobbyists for several decades until the time of the Sahara finds in the late 1980s and early 1990s, most meteorites were deposited or purchased by museums and similar institutions where they were exhibited and made available for scientific research. However, the rapid availability of a large number of meteorites that could be found relatively easily in places that were easily accessible, led to the rapid increase in the commercial collection of meteorites, which was accelerated in 1997 when the first meteorites from the Moon and Mars were found in Libya. By the end of the 1990s, private meteorite search expeditions had been launched across the Sahara, so that, although some specimens were recovered by researchers, most of the material was sold to private collectors. By now, these expeditions have recovered about 14000 officially classified meteorites in Northwest Africa, and hundreds of thousands never officially classified, so generating a lack of information on both the number and type of meteorites.

The official database of the Meteoritical Society, *i.e*., the Meteoritical Bulletin, includes more than 13100 meteorites with the NWA designation, of which 109 are Acapulcoites-Lodranites, 30 Angrites, 21 Aubrites, 42 Brachinites, 1199 carbonaceous chondrites, 126 are from the enstatite group of chondrites, 1549 belong to some types of Vesta HED family, 129 are iron, 374 originate from the Moon, 250 from Mars and belong to the group SNC, Mesosiderites are 146 and Pallasites 51, Ureilites are 357, Winonaites 48, Rumurutites 198, the group of ordinary chondrites has 6386 classified specimens. The group of ungrouped meteorites counts up to 20 irons, 39 chondrites and up to 96 achondrites. Furthermore, more than 2000 NWA meteorites are registered in the official database with a provisional status, the analysis and typology of which have never been updated. Thus, practically all known types of meteorites have been recovered in the Sahara. Actually, Sahara meteorites are very often referred with "provisional" names in the databases with not updated or erroneous information, or as "pairing" to others. Sometimes the same meteorite has been classified at different times with different names, which is a problem that needs to be addressed by the authorities who control the classification processes. Since the first meteorite markets were created, especially in Morocco, supported by nomads and local people who dug into the desert in search of specimens for sell, tons of meteorites, the so-called NWA meteorites have been distributed, most of which with no information on how, when and where they were discovered.

A lucrative trade was established in some localities, especially Erfoud, Marrakesh and Zagora, and more recently Laayoune and Agadir, and even in Nouakchott, the capital of Mauritania, where no law regulates the searching and selling of meteorites. Differently, in Algeria, anything that has to do with the ground (sand, fossils, minerals, meteorites, *etc.*) is controlled by severe restrictive measures, and punished with fines and even jail. In Morocco, the possession and trade of meteorites are legal, but their export abroad is subject to regulatory restrictions. Since June 2019, the Moroccan mining regulation includes meteorites as a mining resource that subject them to some kind of exploitation law. In particular, Article 3 of the mines code establishes that the exploitation of mine resources can only be exploited by authorization of the state. The exploration, investigation and exploitation of mine products can be carried out by virtue of a mining title issued in accordance with the provisions of this law and related text. The search permit and mines license constitute real estate rights, of limited duration and distinct

CHAPTER 7

Meteorite Falls, Finds and Impact Craters in North East Africa: Egypt, Sudan and Libya

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Abstract: The aim of this chapter is to provide an updated review of the available data concerning the confirmed and proposed meteorite falls and finds and their impact craters in Egypt, Sudan, and Libya. Among the 190 confirmed impact/sites on the Earth crust, only less than 8 have been identified in northeast Africa, in particular, BP and Oasis in Libya and Kamil in Egypt. Very few other structures of alleged impact are located in these countries have been described in the literature. The record of meteorites and their impact craters in North East Africa are still incomplete and debated. The only criteria that provide evidence of an impact are the occurrence of circular geological features and their shock-metamorphic effects on the target rocks (shatter cones and diagnostic shock-metamorphic mineral deformations). These effects are evident in the Kamil crater (Egypt) and most impact craters in Libya. The discovery of preserved meteorite fragments and the detection of the geochemical signature of meteoritic indicators should be considered carefully during fieldwork and advanced further studies.

Keywords: Impact craters, Meteorite falls and finds, Northeast africa, Shock-metamorphic effects.

INTRODUCTION

The African countries richer in meteorite finds and falls are Morocco, Algeria, Libya, Egypt, Sudan, Tunisia, and Mauritania (Ouknine *et al*., 2019). However, these meteorites are almost totally exported out of their countries of find by dealers, collectors and foreign scientists. Most classes of meteorites, including Martian (major) and lunar (minor), are found in the African hot deserts.

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Abderrahmane Ibhi, Giorgio S. Senesi, Lahcen Ouknine, Fouad Khiri (Eds.)

The current chapter focuses on the distribution of North East African (Egypt, Sudan and Libya) meteorites (falls and finds) in combination with impact craters if present, and on related phenomena that have caused powerful shock effects. This chapter is very urgent for junior geologists, astronomers, astrophysicists and other researchers.

EGYPT

Egypt is located in the extreme northeastern part of Africa. It occupies about 1,000,000 Km^2, bordering at the north with the Mediterranean Sea, at east with the Red Sea, at west with Libya and at south with Sudan. The first record of meteorite falls in Egypt was on June 28, 1911, at 9:00 am, when suddenly a number of meteorites slammed on the Egyptian village of El-Nakhla El-Baharia located in the Delta Nile, Abu Hommos region (Figs. **1** and **2**) (Hume, 1911; Ball, 1912; Prior, 1912 and Attia *et al*., 1955). Recalling the fall site, this meteorite is called Nakhalite. Many investigators have studied and characterized this meteorite (Treiman, 2005; Sautter *et al*., 2006; Imae and Ikeda, 2007), concluding that it is of Martian type, very rich in olivine and pyroxene. Subsequent studies (Domeneghetti *et al*., 2013; Alvaro *et al*., 2015) found that the augite mineral in this meteorite crystallized at 600°C, and was cooled within lava flows at a burial depth of 85 m.

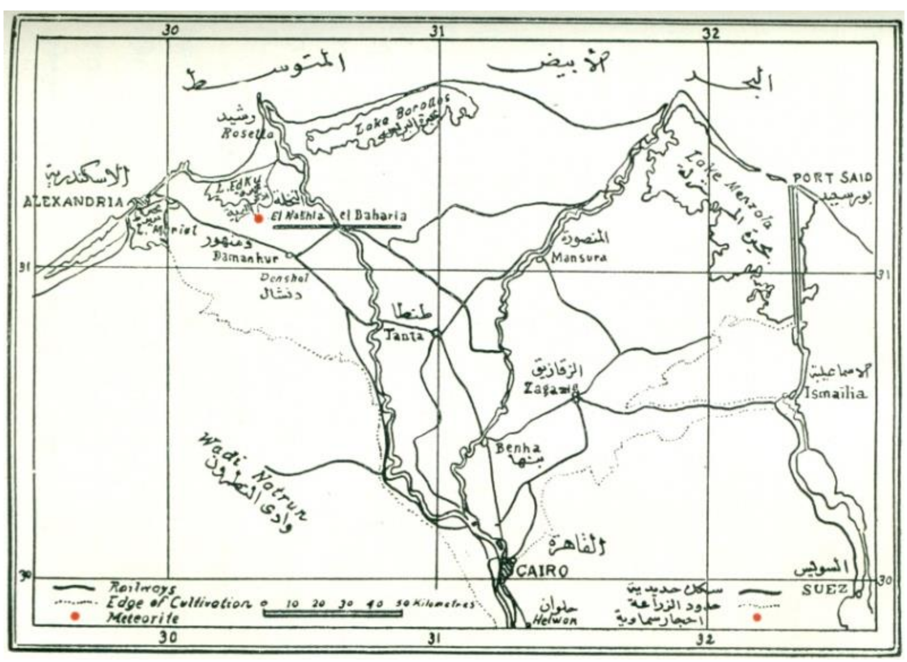

Fig. (1). Map showing the Nile Delta in Egypt. The red circle indicates the El-Nakhla El-Baharia site.

Fig. (2). A piece of the meteorite that fell near El-Nakhla El-Baharia in northern Egypt.

Recently, a number of meteorites were discovered in El-Gilf El-Kebir, which is located in the southwestern parts of the Egyptian Western Desert (Paillou *et al*., 2004). Most meteorite components are of an iron type and silica glass, therefore, the area where these meteorites were recovered was called Wadi El Crystal (Bewdian name).

The first well-preserved impact crater in Egypt was identified in 2010 by a professional Egyptian-Italian teamwork nearby Gebel Kamil (22°01′ N–26°05′ E) in southern Egypt and was named Kamil Crater (Folco *et al*., 2010, 2011) (Fig. **3**). The discoverers described it as a bowl-shaped cavity of 45-m diameter and 10-m depth on a Cretaceous sandstone target with a well-preserved ejecta blanket (Figs. **3** and **4**), also displaying some well-developed ejecta rays (Figs. **5** and **6**). These features highlight the exceptional freshness of the structure to which an estimated age between 1600 and 400 BC was attributed (Sighinolfi *et al*., 2015). A geophysical expedition was undertaken under the leadership of Profs. Folco and El Sharkawy and their teamwork (Fig. **7**) in February 2010 revealed that the crater shows an upraised rim of about 3 m above the pre-impact surface, which is typical of simple craters. The true crater floor depth is about 16-m deep and is overlain by about 6-m thick crater-fill material (Urbini *et al*., 2012). Cm-scale masses of scoriaceous impact melt glass occur in and close to the crater, which indicates local shock pressures.

CONCLUSION

Africa is a suitable continent for meteorite recovery as the total collected number (falls and finds) represents more than 1/6 of all extraterrestrial rocks collected on the Earth. The high number of meteorite recoveries in Africa is favored by its large surface area, its geographical location between the northern and southern hemispheres, and the wide diversity of climate and natural environments (deserts, forests, mountains).

Since 1800, the number of meteorite falls in Africa has continued to grow, with 80% of them recorded during the period 1910-2014. At the end of August 2020, twenty-one official observed meteorite falls were recorded only in Morocco. The meteorite falls recovery rate during the past 88 years (from 1932 to 2020), for a surface area of 712.5 $km^{2,}$ is low on average, *i.e.*, approximately four fall recovery every 10-years, equivalent to 0.4 fall per year per 2.11 km^2. The average rate of falls is low in Africa, with only 0.023 per million km^2 per year, but it is twice that recorded in Australia. The classification of meteorite falls in Africa shows an abundance of chondritic falls (76%) and a deficit of achondritic ones (17%). In particular, iron meteorite falls are relatively rare globally, accounting for only 5.9% of the fall population in Africa, which include three Martian meteorites (Nakhla from Egypt, Tissint from Morocco, and Zagami from Nigeria), but no Lunar meteorites. Moreover, the spatial distribution of recorded meteorite falls reveals that most of them were recovered in the Northwest, East, and South of the continent, whose countries combine a number of favorable human and geographical factors, *i.e.*, a large population with a uniform distribution, a local population giving importance to the observation of meteorite falls, a large area with a low percentage of forest cover, a semi-arid to arid climate, and access to the place of fall.

Over 300 years (1716-2017), 9660 meteorites have been discovered in Africa, with 3.18 discovered per 10,000 km^2. Of them, 2399 samples (25%) were found in 23 countries and bear the name of the official collection site, and 7261 meteorites (75%) are without filiation (6781 under the acronym Northwest Africa “NWA”, 476 called “Sahara”, and 5 called Northeast Africa “NEA”). The temporal evolution of African meteorite finds shows that most of them were collected in the early 21st century, which can be mostly attributed to the expertise acquired by the rural population of the hot deserts. In particular, the rate of meteorite finds does not seem to depend on the population density or its distribution, but is related prevalently to a category of the population, *i.e.*, nomads, passionate people, experienced searchers, scientists, *etc*., interested in meteorites and endowed with a specific skill necessary to access privileged hunting grounds and distinguish extraterrestrial rocks from terrestrial rocks.

Currently, fragments from a total of 1747 distinct and authenticated meteorites from Morocco with a total mass of 6175 kg have been described. Most of these meteorites were found in the Tata, Zogora, Errachidia, Es Smara and Erfoud regions of Eastern and Southern Morocco. To date, the largest quantity of a single meteorite fall in Morocco remains that of Agoudal iron found in 2012 on the Imilchil region in Moroccan Haut Atlas, with several tons distributed in samples from a few grams to several hundred kilograms.

The meteorite classification of African discoveries indicates that this collection includes all types of meteorites known to date, and is characterized by an abundance of stony meteorites with significant rates of rare meteorites. Over the past three decades, African discoveries have seen a decrease in chondrites, especially ordinary chondrites, and a significant increase in the number of carbonaceous chondrites and achondrites. This result can be explained by economic reasons, *i.e.*, the increase in prices of carbonaceous chondrites and achondrites, and by the non-declaration of ordinary chondrites to the Nomenclature Committee. Similar to Australian and Antarctic collections, the finds in Africa feature a low abundance of metallic meteorites, which may be mostly explained by the recovery and use of this type of meteorite in prehistoric and historic times by Northern African civilizations.

The distribution of sample masses of African finds shows that many meteorites (54%) have average masses between 100 and 1000 g. Most small meteorites are concentrated in the northern hemisphere, while the majority of the heaviest ones have been collected in the southern hemisphere. The collection of African meteorites shows a distribution of masses typical of areas where the search for meteorites is carried out on foot by nomads or by car by meteorite hunters, especially in the desert areas of Morocco, Algeria and Libya.

African meteorites show weathering grades ranging from W0 to W6, with most samples (66%) featuring a weathering degree lower than W3, which proves their better preservation. The factors that influence the mechanisms and the degrees of alteration of African meteorites include: (i) *Climate*. This is the main factor allowing the preservation and accumulation of meteorites in North (Sahara desert) and South-West Africa (Namib and Kalahari deserts) thanks to favorable semi-arid to arid conditions, whereas in the tropical zones and in the southeast of the continent, meteorites disappear because of the warm and humid climate; (ii) *Mass of the sample*. The existence of an apparent correlation between the masses of meteorites and the degree of their alteration reveals that small samples are altered more than big ones; (iii) *Terrestrial age of the sample*. The apparent correlation existing between the degree of weathering and the terrestrial age of the sample shows that the African finds collection is less altered due to its relatively recent age (80% of the samples have terrestrial ages below 20 kyrs); and (iv) *Porosity of the sample*. The collection comprises 49% of samples featuring a shock level between S0 and S2 and 51% having shock levels between S3 and S6. Using this parameter as an indication of the initial porosity, meteorites with higher initial porosity (S0 - S2) result generally more weathered than meteorites with lower initial porosity (S3 - S6). Thus, the initial porosity is an important factor controlling the weathering process of meteorite finds in Africa.

In general, African meteorites are dominated by low altered stony meteorites, almost all of which (99%) are recovered from the continent hot deserts that allow their preservation and accumulation, and simplify their search. This explains why the African continent is one of the most prolific sites for meteorite recovery in the world.

After the adoption of the appellation “NWA meteorite” in 2000, almost all meteorites found in Northwest Africa are declared under this acronym. In particular, most NWA meteorites collected until January 1st, 2015, originating from Morocco, and only 23% of them have no information on their country of origin. The lack of information noted by the Nomenclature Committee on this population of meteorites can be explained by: (i) the strict legal and regulatory measures (especially in Algeria), (ii) the modest socio-cultural and socio-economic conditions that characterize certain areas of the region, and (iii) the security disturbances that have reigned in Northwest Africa (Sahelian belt) over the past decade.

The typology of the NWA collection shows the predominance of stony meteorites (97%) and the presence of mixed and metallic meteorites with identical proportions (1.5%). However, rare types of significant scientific value are included. To highlight this collection, a new database of NWA meteorites has been developed, and a re-nomenclature of NWA meteorites has been proposed, according to the guidelines of the new Guide to meteorite nomenclature. This action is believed to enhance the inestimable scientific and socio-economic value of the meteoritic heritage of Morocco and other countries of Northwest Africa.

In particular, meteorites found in Morocco are playing an increasingly important role in fundamental research across a wide spectrum of disciplines, with new groups of meteorites being recovered that are extending our knowledge of the early Solar System. The astronomical representations engraved on the rocks would confirm the ancient concern in observing meteors and meteorites. In particular, three petroglyphs found near Ida Ou Kazzou (approximately 100 km north of Agadir) would suggest that ancient Moroccans observed meteorite falls.

The record of meteorites impact craters in North Eastern Africa is still incomplete and debated. Of the 190 confirmed impact structures/sites on the Earth crust, only less than 8 have been identified in North Eastern Africa, including Oasis in Libya and Kamal in Egypt. The only criterium that provides evidence for an impact origin of circular geological structures is the occurrence of shock-metamorphic effects, *i.e*., the presence of shatter cones and diagnostic shock-metamorphic mineral deformation and transformation phenomena, in the target rocks. These effects are evident in the Kamal crater (Egypt) and most impact craters in Libya, whereas a few other structures of alleged impact origin are still controversial. The discovery of preserved meteorite fragments and the detection of the geochemical signature of meteoritic indicators should be considered very carefully during fieldwork and further advanced studies.

In Morocco, two meteorites finds could be associated with impact craters: (i) 300 kg of mesosiderite fragments were collected from an area of 50 x 100 m elongated roughly along the southwest to northeast axis (N30) in the Toufassour region in the year 2003, and (ii) after the first fragment was collected by a nomad in 2007, more than a ton of specimens weighing 100 g to more than 196 kg were harvested over a period of 6 years in the Agoudal iron meteorite strewnfield. Some sources speculate that even a still bigger quantity (up to 2 tons) has been recovered. The Agoudal area is a unique site in Morocco where the relics of several possible impact structures have been discovered.

In the Sahara Desert, a very relevant number of well-preserved meteorites has been collected, as their conservation was facilitated by the desert dry climate in which a meteorite would require centuries to degrade. The recovery of meteorites as quickly as possible after their fall guarantees their preservation and provides a scientific material of quality that allows to infer questions about the conditions of their formation and development prior to fall and residence. However, the Sahara Desert continues to provide findings from large meteorite falls several years after the first discovery, but the first and last recoveries seem not to be the same. The physical aspect and sometimes some chemical parameters are different, which is due to the alteration that meteorites undergo over the years.

In conclusion, the North African region, *i.e*., the Sahara desert, has become one of the most important places to recover meteorites, together with Antarctica, Atacama and the great deserts of North America. Nevertheless, it is estimated that more than 90% of the desert surface has not yet been explored, and it is still expected to hide a huge number of meteorites. New finds are classified annually, and countries such as Mauritania, Mali and Egypt are emerging in this, attracting competition. The most optimistic forecasts suggest that many new meteorites will continue to be recovered from the great Sahara Desert in the coming decades. Preserving them properly will be essential to provide science with such important objects.

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