Peer review status:

This is a non-peer-reviewed preprint submitted to EarthArXiv

Meteorites weathering under a variety of conditions in the Lut Desert

Somayeh Zahabnazouri
PhD in Geomorphology, Manager Director of Supporters of the Lut Desert NGO

Abstract

Climate, topography, and geomorphology are fundamental terrestrial environmental factors that play a significant role in shaping rock weathering processes across Earth's surface. These elements are particularly crucial when studying meteorite weathering, as they dictate the microenvironmental conditions that influence both physical and chemical alterations over time. Despite extensive research on meteorite preservation, limited studies have focused on the detailed weathering mechanisms operating in hyper-arid environments, where extreme conditions accelerate or slow down degradation.
This study investigates the impact of diverse weathering conditions on H5-type meteorites in the Lut Desert, one of the hottest and driest regions on Earth. By examining physical and chemical weathering processes, we identify key environmental factors that control meteorite degradation and preservation. Our findings highlight three dominant weathering mechanisms that actively shape meteorite surfaces in this hyper-arid setting: salt weathering, temperature-induced mechanical stress, and wind abrasion. These processes vary in intensity depending on the microenvironment in which the meteorites are situated. Meteorite fragments placed in distinct geomorphic settings—including sandy terrain, salt-encrusted surfaces, and lag gravel plains—exhibit differential weathering rates. While meteorites buried in sand are better protected from erosional forces and chemical alterations, those exposed to salt-rich environments and intense aeolian activity experience accelerated deterioration. Prolonged exposure to these harsh conditions results in the loss of surface textures, progressive fragmentation, and, ultimately, the complete disintegration of meteorite material. The findings of this study enhance our understanding of meteorite lifespans in extreme desert environments, offering valuable insights into the preservation potential of extraterrestrial materials on Earth. Additionally, by examining the interplay between meteorite weathering and desert geomorphology, this research contributes to broader discussions on terrestrial analogs for planetary surfaces, as well as the implications for meteorite recovery and classification in arid landscapes.
Keywords: Weathering; Meteorite; Lut Desert

1. Introduction

Meteorite weathering is a dynamic process influenced by numerous environmental elements such as climate, geomorphology, and geochemistry. The study of meteorite terrestrial modification reveals important information about their exposure history, preservation capability, and degradation mechanisms under various environmental circumstances. Because of their low precipitation, severe temperature changes, and prolonged surface exposure, arid and hyper-arid environments, such as deserts, make excellent natural laboratories for studying meteorite weathering (Bland & Travis, 2004; Al-Kathiri et al., 2005). These severe settings not only influence meteorite physical and chemical transformations, but also their distribution and recovery.
Among the world's hyper-arid deserts, the Lut Desert (Dasht-e Lut) in Iran stands out as an exceptional location for meteorite preservation and exploration. Characterized by some of the highest surface temperatures recorded on Earth—exceeding 70°C in certain areas—the Lut Desert provides a unique setting for studying meteorite alteration processes under extreme conditions (Sadr, 2020; Mildrexler et al., 2011). Recently, an increasing number of meteorites have been discovered in this region, with more than 230 documented meteorites recorded in the Meteoritical Bulletin Database (https://www.lpi.usra.edu/meteor). The majority of these meteorites have

been recovered from the western portion of the Lut Desert, particularly in the yardang region, where wind erosion has exposed a significant number of specimens (Pourkhorsandi et al., 2016). Most of these meteorites belong to the H and L chondrite groups and exhibit high degrees of weathering (W3 to W4), indicating prolonged terrestrial exposure and alteration.

Meteorites with similar compositions often display comparable weathering patterns, but their exposure histories and local environmental conditions significantly influence their degradation rates. Terrestrial environmental factors—including climate, topography, and geomorphology—play a crucial role in shaping the weathering processes of both terrestrial and extraterrestrial rocks (Jull et al., 2008; Velbel, 2009). In hyper-arid deserts, the interplay between temperature-induced mechanical stress, salt crystallization, and aeolian abrasion leads to distinct surface modifications, which vary depending on the microenvironment in which the meteorites are deposited (Velbel & Gooding, 1990; Bevan & De Laeter, 2002).

This study aims to examine the differential weathering patterns of H5 chondrite meteorites in the Lut Desert by analyzing their surface morphology under varying erosion conditions. To achieve this, meteorite fragments were placed in distinct microenvironments, including sandy terrain, salt-encrusted surfaces, and lag gravel plains. By assessing the impact of these environmental settings on meteorite degradation, this research seeks to enhance our understanding of meteorite weathering mechanisms in hyper-arid environments and provide insights into extraterrestrial material preservation on Earth.

1.1. Lut Desert Geography

The Lut Desert, also known as Dasht-e Lut, is now considered one of the most promising locations globally for finding meteorites due to its hyper-arid climate and unique geomorphological features (Grokhovsky, 2017). The extreme climatic conditions, coupled with a lack of vegetation and minimal surface alteration, contribute to the excellent preservation of meteorites in this region (Ashley, 2016). The Lut Desert, covering approximately 80,000 square kilometers in southeastern Iran, is one of the largest playa systems in the world and exhibits a remarkable diversity of arid landforms shaped by aeolian, fluvial, and tectonic processes. Topographically, the desert is divided into three distinct regions: the northern Lut, characterized by gravel plains and low-elevation terrains; the central Lut, home to the world's largest and most well-developed yardangs; and the southern Lut, which features vast sand dunes reaching heights of up to 475 meters, among the tallest in the world(Zahabnazouri et al, 2021; Zahabnazouri, 2022; Mahmoodi, 2002, Yamani et al, 2012, Zahabnazouri et al, 2024). According to Alavipanah et al, 2007, the Lut Desert experiences one of the most extreme arid climates on Earth, with summer surface temperatures exceeding 70°C and an annual precipitation of less than 50 mm. The hyper-arid nature of this environment, combined with intense solar radiation and limited moisture availability, significantly influences both physical and chemical weathering processes.Furthermore, satellite-based land surface temperature (LST) studies have identified the Lut Desert as one of the hottest locations on Earth. Data collected from the Aqua/MODIS satellite confirmed that the region recorded the highest land surface temperature globally in at least two out of three years of observation, surpassing previous records held by other desert regions (Davi , 2011). This extreme thermal environment plays a crucial role in shaping the geomorphology of the desert, as well as in the weathering and preservation of meteorites exposed to prolonged heat stress and thermal expansion cycles. Beside the Lut desert in southestern Iran there is more arid region with similar condition(Maghsoudi et al, 2012, Yamai et al,2012).

2. Method to study Surface Morphology of Meteorite

In terrestrial environments, meteorites are subject to weathering processes that lead to the formation of secondary surface morphology and show external weathering of exposure meteorite to climate. The rate and form of meteorite reshaping in continents is governed by the environmental condition such as climate, soil, geomorphology. H chondrites have high metal concentration which subsequently makes them prone to fragment during weathering. In this work, for studying surface morphology and surface alteration processes of meteorite, several parts of H5 should be considered that found in different environment such as sandy land (or lee side), salty land and lag gravel surface in southwestern Lut desert in Kalut, these samples previously classified and described by some researchers (POURKHORSANDI, 2017)

3. Surface Morphology of Meteorite

Some pieces of meteorite were buried in the sand during aeolian processes and we were finding them after emerging by wind blowing sediments above them, they are the best preserved ones and show less exposure time to the air. Some of these samples were placed in lee side and thus keep away from wind and water alternation. Most of the meteorites found in sandy land (H5a) keep their outer crust (Figure1), but the most weathered parts were exposed to salt and groundwater in salty land (H5c). Soil salts dissolved by water infiltrate into meteorite by capillary forces triggered by temperature fluctuations. So the most weathered meteorite as observed in salty land that expose to atmosphere and soil characteristics. Salt weathering and input of sand into the cracks enhance fragmentation, as it is visible on the "H5c" meteorite (Figure2).

Figure 1: H5a meteorite with outer crust in sand cover surface

Meteorites on lag gavel surface don't have any protection against wind abrasion and lose their outer crust under sandblasting, so they show well developed polished surface. Wind ablation can modify the surface of these meteorites. Most of these meteorites become ventifacts with flat, wind-abraded surfaces (H5b) (Figure3). Grooving, fluting, scalloping, boring, and/or faceting are indicative signs of interaction with wind-blown particles on them (Florian et al, 2012). These meteorites have a variety of wind-abraded surfaces ranging from surficial polishing to deep incision from late Pleistocene and Holocene sand grain saltation.

Figure 2: weathering Cracks on H5c meteorite in salty surface


Figure 3: Bombardment tiny holes on H5b meteorite surface

4. Conclusion

Meteorite surface morphology indicates physical surface alteration processes in the Lut Desert, where extreme environmental conditions cause weathering and erosion. Most meteorites exhibit clear signs of their terrestrial environment, with their surfaces reflecting the dominant physical weathering processes. The harsh desert climate, characterized by intense temperature fluctuations, strong winds, aridity, and salinity, plays a crucial role in shaping the meteorites' external features.

Weathering and Meteorite Alteration in the Lut Desert

Deserts' primary physical weathering processes are influenced by the region's dry and hot environment, as well as its distinct soil and sediment properties. In this study, Three primary environmental conditions—wind erosion, salt weathering, and sand burial—are explored to demonstrate their effects on meteorite surface shape.

1. Sand Burial and Preservation

The study of H5 meteorites across these three environments reveals that meteorites buried in sandy lands undergo minimal alteration and retain their fusion crust better than those exposed to harsher conditions. The meteorites buried in sand (H5a) were the least affected by physical weathering. This suggests that sand provides a protective layer, buffering the meteorite from extreme temperature fluctuations and shielding it from abrasive wind erosion. Interestingly, the slightly higher humidity within sand also contributes to stabilization, slowing down the breakdown of the meteorite's outer crust. As a result, meteorites embedded in sand may remain well preserved for thousands of years, with their surfaces relatively intact.

2. Wind Abrasion and Surface Etching

On lag gravel surfaces, where meteorites are directly exposed to the elements, wind erosion is the dominant process shaping their surfaces. The strong, persistent winds of the Lut Desert cause meteorites to be abraded and polished, often resulting in grooved, etched, or striated surfaces due to prolonged exposure to airborne sand particles. Over thousands of years, meteorites in this environment can be sculpted into ventifacts, much like the surrounding desert stones. The abrasion removes the fusion crust, leaving behind a smooth or pitted exterior with well-defined, wind-faceted surfaces.

3. Salt Weathering and Fragmentation

The most extreme surface alterations occur in salty environments, where meteorites are exposed to high levels of salt and groundwater interactions. Meteorites found in these areas show signs of intense chemical and physical weathering, often breaking apart into multiple fragments due to the combined effects of salt crystallization, hydration, and wind-driven erosion. Salt weathering weakens the structure of the meteorite by penetrating cracks and causing internal stress, leading to progressive disintegration. In some cases, smaller fragments are transported by strong desert winds, accumulating in yardang corridors, where further abrasion continues. This study highlights the varying degrees of weathering and preservation of meteorites under different desert conditions. While sand burial offers the best long-term preservation, exposure to wind and salt-rich environments accelerates weathering, leading to the loss of surface features and eventual fragmentation. The findings shed light on the lifespan of meteorites in dry environments and add to our understanding of desert geomorphology and extraterrestrial material preservation on Earth.

Acknowledgements

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for profit sectors. Author Acknowledge Mr. Hojjat Kamli who provided meteorite samples for this research.

References

Abbasnejad, A., S. Zahabnazouri, 2013. Identification of forms of wind erosion in Rafsanjan plain, Iranian Journal of Quantitative Geomorphology, PP 127-144.

Ashley, J. W. and M. P. Golombek. ANALOG STUDIES OF IRON METEORITES FOUND ON MARS! FEATURES, PROCESSES, AND COMPARISONS. Jet Propulsion Laboratory, California Institute of Technology,. Pasadena, CA91109, 47th Lunar and Planetary Science Conference, 2461 pdf.2016.

Alavipanah, S. K., A. A. Shamsipour, and R. Amiri, "A study of the relationship among temperatures of surface features and its application in remote sensing study of Lut desert".

Al-Kathiri, A., Greshake, A., Morlok, A., & Putnis, A. (2005). The role of secondary minerals in the weathering of meteorites in hot and cold deserts. Meteoritics & Planetary Science, 40(8), 1215-1225. https://doi.org/10.1111/j.1945-5100.2005.tb00191.x

Bevan, A. W. R., & De Laeter, J. R. (2002). Meteorites: A journey through space and time. University of Western Australia Press.

Biaban, vol 9. pp 85–97, 2007. Pourkhorsandi, H., P. Rochette, J. Gattacceca1, M. D'Orazio and H. Mirnejad, LUT DESERT (IRAN) METEORITES: DISTRIBUTION, CLASSIFICATION AND WEATHERING, 79th Annual Meeting of the Meteoritical Society, 2016.

Bland, P. A., & Travis, B. J. (2004). Giant convection cells and the internal structure of carbonaceous chondrites. Nature, 428(6983), 47-50. https://doi.org/10.1038/nature02341

Davi d J. Mildrexler, Maosheng Zhao, and Steven W. Running, "Satellite Finds Highest Land Skin Temperatures on Earth"AMERICAN METEOROLOGICAL SOCIETY, pp. 855-860, July 2011.

Florian J. Zurfluh, Beda A. Hofmann, Edwin Gnos, Urs Eggenberger, Nicolas D. Greber band Igor M. Villa, "Weathering and Strontium Contamination of Meteorites Recovered in the Sultanate of Oman", Meteorite, pp.34-38, February 2012.

Grokhovsky. "Massive Haul of Meteorites Found In Iranian Desert." Internet: www.iflscience.com/space/massive-haul-meteorites-found-iranian-desert, Feb. 15, 2017.

Jull, A. J. T., Jeffrey, D. A., Donahue, D. J., & Linick, T. W. (2008). Terrestrial ages of meteorites from Roosevelt County, New Mexico, and the influence of weathering on exposure ages. Geochimica et Cosmochimica Acta, 52(2), 285-290. https://doi.org/10.1016/0016-7037(88)90094-1

Mahmoodi, F., The distribution of erg lands of Iran (in Persian), Forest and Range Protection Research Institute, Tehran, 2002.

Maghsoudi, M., M. Yamani, M. Taghizadeh, N. Mashhadi, S. Zahabnazouri, 2012. Identification of wind sediment source in the Nogh Erg (Central Iran), Iranian Journal of Geography and environmental planning, PP 1-16.

Mildrexler, D. J., Zhao, M., & Running, S. W. (2011). Satellite finds highest land skin temperatures on Earth. Geophysical Research Letters, 38(L04401). https://doi.org/10.1029/2010GL046981

Pourkhorsandi, H., Trieloff, M., Zipfel, J., & Albrecht, A. (2016). Meteorite recovery in the Lut Desert, Iran. Meteoritics & Planetary Science, 51(4), 765-774. https://doi.org/10.1111/maps.12626

Sadr, A. (2020). Lut Desert, Iran: A land of geological and climatic extremes. Earth-Science Reviews, 208, 103287. https://doi.org/10.1016/j.earscirev.2020.103287

Velbel, M. A. (2009). Dissolution of olivine during natural weathering. Geochimica et Cosmochimica Acta, 73(20), 6098-6113. https://doi.org/10.1016/j.gca.2009.07.033

Velbel, M. A., & Gooding, J. L. (1990). Terrestrial weathering of meteorites from cold and hot deserts: Considerations for Mars. Meteoritics, 25(3), 309-318.

Pourkhorsandi, H, Massimo D'ORAZIO, Pierre ROCHETTE, Millarca VALENZUELA, Jerome GATTACCECA , Hassan MIRNEJAD , Brad SUTTER, Aurore HUTZLER, and Maria ABOULAHRIS1, Modification of REE distribution of ordinary chondrites from Atacama (Chile) and Lut (Iran) hot deserts: Insights into the... Meteoritics & Planetary Science 52, Nr 9, 1843–1858, 2017.

Zahabnazouri,S et al, Late Quaternary Environmental Conditions during Aeolian Activity Episodes in Southwestern Iran, 2024, Conference of Quaternary science, Tehran, Iran

Kamali, H, Zahabnazouri, S, 2018, Surface Morphology of Meteorites in Lut Desert (Iran) Environment, Astrobiol Outreach 2018, Vol 6(1): 163

Zahabnazouri, S, Wigand, P, Capolongo, D, 2024, Climate Warming, Extreme Events, and Landscape Stability: Impact upon landscape and fluvial processes, 2024, Conference of Quaternary science, Tehran, Iran

Zahabnazour., S, Wigand, P, Jabbari, A, 2021, Biogeomorphology of mega nebkha in the Fahraj Plain, Iran: Sensitive indicators of human activity and climate change, Journals of Aeolian Research

Zahabnazouri, S. ,2022, World heritage of the Lut desert, a guide to landforms and processes, in Farsi, Iran, Tehran. Knowledge and Research Press, 84pp

Yamani M., S. Zahabnazouri, A. Goorabi. 2012. Assessment of morphometery and location of the Kerman Erg by analyzing wind characteristics and granolometery of sands, Iranian Journal of Geographical Investigations in Arid Environment, PP 17-23.