# Characterization of Minerals, Metals, and Materials 2023

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# Preface

Materials characterization is a vital part of all science and engineering practice, as it is a fundamental process to achieving a good understanding of the processing-microstructure-property relationship. Various advances in characterization techniques and instruments in recent years have contributed, in a significant way, to an in-depth knowledge of the material's properties and structure on different scales. This enhanced understanding has also profoundly impacted the efficiency of existing industrial processes and how minerals, metals, and materials are applied in many fields.

This year, the Characterization of Minerals, Metals, and Materials symposium received 146 abstract submissions, of which 62 papers were accepted in 8 technical sessions. This symposium is among one of the largest in the TMS Annual Meeting & Exhibition. The proceedings volume includes state-of-art techniques used in modern minerals, metals, and materials characterization and the latest research in materials engineering and technologies. This proceedings publication is a valuable reference for academic scholars and industry professionals interested in advanced characterization methods and instrumentations that cover a wide range of research subjects. Readers will enjoy the diversity of topics in this book with innovative approaches to process and characterize materials at various scales and levels.

The Characterization of Minerals, Metals, and Materials 2023 symposium is sponsored by the Materials Characterization Committee under the Extraction & Processing Division (EPD) of TMS. The main focuses of this symposium include but are not limited to advanced characterization of Extraction and processing of minerals, process-microstructure-property relation of metal alloys, ceramics, polymers, and composites. New characterization methods, techniques, and instrumentations are also emphasized.

As a lead organizer of this symposium, I would like to take this opportunity to express my sincere gratitude to all authors for their contribution and generosity to share their research work. On behalf of the organizing committee, I would like to thank TMS for providing us with the valuable opportunity to publish this standalone proceedings volume. Much appreciation is also extended to the EPD for sponsoring this symposium.

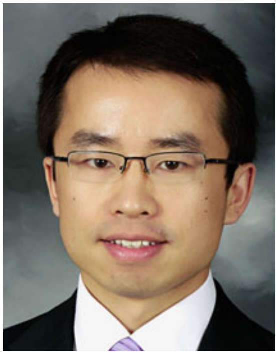
Most importantly, the success of this proceeding's publication would not be possible without the fabulous contribution and support from all members of the Materials Characterization Committee. I also would like to thank our publisher, Springer, for their timely and quality publication of this book.

Mingming Zhang
Lead Organizer

# Contents

# About the Editors

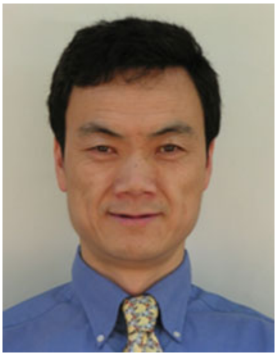
**Mingming Zhang** is currently a principal consultant at Wood Mackenzie. He has more than 20 years of experience in the field of mining, mineral processing, smelting and refining, and materials engineering. Before joining Wood Mackenzie, Dr. Zhang held lead engineer position at ArcelorMittal Global R&D in East Chicago, Indiana. He obtained his Ph.D. in Metallurgical Engineering from The University of Alabama and his master's degree in Mineral Processing from the General Research Institute for Non-ferrous Metals in China. Prior to joining ArcelorMittal, he worked with Nucor Steel in Tuscaloosa, Alabama where he was a metallurgical engineer leading the development of models for simulating slab solidification and secondary cooling process. Dr. Zhang has conducted a number of research projects involving mineral beneficiation, thermodynamics and kinetics of metallurgical reactions, electrochemical processing of light metals, metal recycling, and energy-efficient and environmentally cleaner technologies. He has published more than 50 peer-reviewed research papers and he is the recipient of several U.S. patents. Dr. Zhang also serves as editor and reviewer for a number of prestigious journals including *Metallurgical and Materials Transactions A* and *B*, *JOM*, *Journal of Phase Equilibria and Diffusion*, and *Mineral Processing and Extractive Metallurgy Review*. Dr. Zhang has made more than 30 research presentations at national and international conferences including more than 10 keynote presentations. He was the recipient of the 2015 TMS Young Leaders Professional Development Award. He has served as conference/symposium organizer and technical committee chair in several international professional organizations including The Minerals, Metals &Materials Society (TMS), the Association for Iron & Steel Technology (AIST), and the Society for Mining Metallurgy & Exploration (SME).



**Zhiwei Peng** is a professor in the School of Minerals Processing and Bioengineering at Central South University, China. He received his B.E. and M.S. degrees from Central South University in 2005 and 2008, respectively, and his Ph.D. degree in Materials Science and Engineering from Michigan Technological University, USA, in 2012. His research interests include dielectric characterization, ferrous metallurgy, microwave processing, comprehensive utilization of resources, waste valorization, powder agglomeration, low-carbon technology, process simulation, electromagnetic shielding, and synthesis of functional materials.

Dr. Peng has published over 190 papers, including more than 140 peer-reviewed articles in journals such as *International Materials Reviews*; *Journal of Hazardous Materials*; *ACS Sustainable Chemistry & Engineering*; *Resources, Conservation & Recycling*; *Journal of Cleaner Production*; *Waste Management*; *Metallurgical and Materials Transactions A*; *Metallurgical and Materials Transactions B*; *JOM*; *Journal of Power Sources*; *Fuel Processing Technology*; *Energy & Fuels*; *IEEE Transactions on Magnetics*; *IEEE Transactions on Instrumentation and Measurement*; *Ceramics International*; *Powder Technology*; and *Separation and Purification Technology*. He holds 65 Chinese patents and has served as an associate editor for *Mining, Metallurgy & Exploration*, as a guest editor for *JOM* and *Metals*, and as an editor for *PLOS ONE*. He has also been a member of editorial boards of *Scientific Reports*, *Journal of Central South University*, and *Journal of Iron and Steel Research International*, and has served as a reviewer for more than 70 journals.

Dr. Peng is an active member of The Minerals, Metals & Materials Society (TMS). He has co-organized 12 TMS symposia and co-chaired 24 symposia sessions since 2012. He is a member of the Pyrometallurgy Committee and the vice chair of the Materials Characterization Committee. He was a winner of the TMS EPD Young Leaders Professional Development Award in 2014 and the TMS EPD Materials Characterization Award Best Paper—1st Place in 2020.



**Bowen Li** is a research professor in the Department of Materials Science and Engineering and Institute of Materials Processing at Michigan Technological University. His research interests include materials characterization and analysis, metals extraction, ceramic process, antimicrobial additives and surface treatment, porous materials, applied mineralogy, and solid waste reuse. He has published more than 140 technical papers in peer-reviewed journals and conference proceedings, authored/co-authored 3 books, and edited/co-edited 12 books. He also holds 16 patents and has delivered more than 30 invited technical talks. Dr. Li received a Ph.D. degree in Mineralogy and Petrology from China University of Geosciences Beijing in 1998 and a Ph.D. degree in Materials Science and Engineering from Michigan Technological University in 2008. He has been an active member in The Minerals, Metals & Materials Society (TMS), Society for Mining, Metallurgy & Exploration (SME), and China Ceramic Society. At TMS, he has served as the chair of the Materials Characterization Committee and as a member of TMS CDDC Committee, Powder Materials Committee, and the Biomaterials Committee. He has also served as an EPD Award committee member, *JOM* subject advisor, and key reader for *Metallurgical and Materials Transactions A*. He has been organizer/co-organizer of a number of international symposia and sessions. He also served as an editorial board member of the *Journal of Minerals and Materials Characterization and Engineering*, *Reviews on Advanced Materials Science*, and *FUTO Journal Series*. He is the recipient of AIME Hal W. Hardinge Award (2022).

**Sergio Neves Monteiro** graduated as a metallurgical engineer (1966) at the Federal University of Rio de Janeiro (UFRJ). He received his M.Sc. (1967) and Ph.D. (1972) from the University of Florida, followed by a 1975 course in energy at the Brazilian War College, and a post doctorate (1976) at the University of Stuttgart. In 1968, he joined the Metallurgy Department of UFRJ as full professor of the postgraduation program in engineering (COPPE). He was elected as head of department (1978), coordinator of COPPE (1982), Under-Rector for Research (1983), and was invited as Under-Secretary of Science for the State of Rio de Janeiro (1985) and Under-Secretary of the College Education for the Federal Government (1989). He retired in 1993 from the UFRJ and joined the State University of North Rio de Janeiro (UENF), where he retired in 2012. He is now a professor at the Military Institute of Engineering (IME), Rio de Janeiro. Dr. Monteiro has published more than 2,000 articles in journals and conference proceedings and has been honored with several awards including the ASM Fellowship and several TMS awards. He is the top researcher (1A) of the Brazilian Council for Scientific and Technological Development (CNPq) and Emeritus Scientist of State of Rio de Janeiro (FAPERJ). He was president of the Superior Council of the State of Rio de Janeiro Research Foundation, FAPERJ (2012), and currently is coordinator of the Engineering Area of this foundation. He has also served as president of the Brazilian Association for Metallurgy, Materials and Mining (ABM, 2017–2019), as a consultant for the main Brazilian R&D agencies, and as a member of the editorial board of five international journals as well as associate editor-in-chief of the *Journal of Materials Research and Technology*. He is the author of 130 patents and a top world researcher in "Natural Fiber Composites" and "Ballistic Armor", Scopus 2020.

**Rajiv S. Soman** is currently with Purity Survey Analysis, Materials Sciences Division at Eurofins EAG Laboratories, USA, where he is responsible for developing new business opportunities, and expanding R&D initiatives. Prior to his current responsibilities, he served as Director, Purity Survey, Eurofins EAG Laboratories. He has over 33 years of professional experience in analytical chemistry and materials sciences. He earned a doctorate in Analytical Chemistry from Northeastern University, Boston, and M.Sc. in Applied Chemistry from the Faculty of Technology & Engineering, Maharaja Sayajirao University of Baroda, India. He commenced his professional career as an Advanced Analytical Chemist in the Engineering Materials Technology Laboratories of General Electric Aircraft Engines. Prior to joining EAG Laboratories, Dr. Soman served as Professor (Full) of Chemical Engineering, Chemistry, and Chemical Technology, and served as a faculty member for 21 years. He also served as Department Head and Associate Dean. He has received numerous awards for excellence in teaching and twice has been listed in *Who's Who Among America's Teachers*. Dr. Soman's research interests are in the areas of atomic and mass spectrometry, with an emphasis on trace element determination and chemical speciation in a wide range of complex sample matrices. He was an invited guest scientist at the prestigious research institute, Forschungszentrum Jülich, Germany, where he conducted research in elemental mass spectrometry. He has co-authored several peer-reviewed publications in international journals and has made numerous presentations at national and international conferences. He holds two U.S. patents. Dr. Soman has been a member of the Society for Applied Spectroscopy (SAS) and the American Chemical Society (ACS) since 1986 and has served in numerous leadership positions in the Professional Societies. He was an invited panel member for the American Chemical Society's National Initiative on *Preparing for the Workforce 2015*. He is a member of TMS, where he serves as a member of the Materials Characterization Committee and as Chair of the Poster Awards Committee. He has also served as co-organizer for several TMS Symposia and is a reviewer for the TMS proceedings volume *Characterization of Minerals, Metals, and Materials* and *JOM*.

**Jiann-Yang Hwang** is a professor in the Department of Materials Science and Engineering at Michigan Technological University. He is also the Chief Energy and Environment Advisor at the Wuhan Iron and Steel Group Company, a Fortune Global 500 company. He has been the editor-in-chief of the *Journal of Minerals and Materials Characterization and Engineering* since 2002. He has founded several enterprises in areas including water desalination and treatment equipment, microwave steel production, chemicals, fly ash processing, antimicrobial materials, and plating wastes treatment. Several universities have honored him as a guest professor, including the Central South University, University of Science and Technology Beijing, Chongqing University, Kunming University of Science and Technology, and Hebei United University. Dr. Hwang received his B.S. from National Cheng Kung University in 1974, M.S. in 1980 and Ph.D. in 1982, both from Purdue University. He joined Michigan Technological University in 1984 and served as its Director of the Institute of Materials Processing from 1992 to 2011 and the Chair of Mining Engineering Department in 1995. He has been a TMS member since 1985. His research interests include the characterization and processing of materials and their applications. He has been actively involved in the areas of separation technologies, pyrometallurgy, microwaves, hydrogen storage, ceramics, recycling, water treatment, environmental protection, biomaterials, and energy and fuels. He has more than 28 patents and has published more than 200 papers. He has chaired the Materials Characterization Committee and the Pyrometallurgy Committee in TMS and has organized several symposia. He is the recipient of the TMS Technology Award and of Michigan Tech's Bhakta Rath Research Award.

**Yunus Eren Kalay** is an associate professor in the Metallurgical and Materials Engineering Department and assistant to the president at Middle East Technical University (METU), Ankara, Turkey. Dr. Kalay received his Ph.D. degree with Research Excellence award from Iowa State University in 2009. His Ph.D. topic was related to the metallic glass formation in Al based metallic alloy systems. Following his Ph.D., he pursued postdoctoral research at Ames National Laboratory. In 2011, Dr. Kalay joined the Department of Metallurgical and Materials Engineering (METE) of METU as an assistant professor and in 2014 he was promoted to associate professor. His research interests span microstructural evolution in metallic alloys, rapid solidification of metallic alloys, nanostructured and amorphous alloys, high-entropy alloys, electronic packaging, and advanced characterization techniques such as scanning and transmission electron microscopy, electron and X-ray spectroscopy, atom probe tomography, and synchrotron X-ray scattering. Dr. Kalay was awarded the METU Prof. Dr. Mustafa Parlar Foundation Research Incentive Award, which is a very prestigious award that recognizes young scientists in Turkey with exceptional achievements and research productivity. He is also an active member of the TMS Materials Characterization Committee and served on organizing committees of three international and one national congress including IMMC, MS&T, and TMS. Dr. Kalay has also been involved in many synergistic activities such as being founding editor of Turkey's first undergraduate research journal, *MATTER*, and organizing the Materials Science Camps for K–12 students.

**Juan P. Escobedo-Diaz** is a senior lecturer in the School of Engineering and Information Technology (SEIT) at UNSW Canberra. He obtained his doctoral degree in Mechanical Engineering at Washington State University. Prior to taking up this academic appointment, he held research positions at the Institute for Shock Physics at Los Alamos National Laboratory. His main research interests center on the dynamic behavior of materials under extreme conditions, in particular high pressure and high strain rate. His focus has been on investigating the effects of microstructural features on the dynamic fracture behavior of metals and metallic alloys. He has published primarily in the fields of shock physics and materials science. He has been a member of The Minerals, Metals & Materials Society (TMS) since 2011. During this time, he has co-organized more than five symposia at the Annual Meetings including the symposium on Characterization of Minerals, Metals, and Materials since 2014. He was awarded a 2014 SMD Young Leaders Professional Development Award.

**John S. Carpenter** is a scientist within the manufacturing and metallurgy division at Los Alamos National Laboratory. Dr. Carpenter received his Ph.D. in Materials Science and Engineering from The Ohio State University in 2010 after performing his undergraduate studies at Virginia Tech. Dr. Carpenter's research focus is on enabling advanced manufacturing concepts through experiments employing novel processing techniques, advanced characterization, and small-scale mechanical testing. Currently, he is working on projects related to the qualification of additively manufactured components, development of new materials for high field magnets using severe plastic deformation and using high energy X-rays to study phase transformations during solidification in MIG cladding. Throughout his career he has utilized many characterization techniques including neutron scattering, X-ray synchrotron, XCT, PED, TEM, EBSD, and SEM. He has more than 75 journal publications, one book chapter, and 45 invited technical talks to his credit. With regard to TMS service, Dr. Carpenter is a past chair for both the Materials Characterization and Advanced Characterization, Testing & Simulation Committees. He is current chair for the Joint Commission for *Metallurgical and Materials Transactions A* and the SMD representative on the Content Development and Dissemination Committee. He is also the Program Committee Representative for the MS&T Conference. He recently received the McKay-Helm Award from the American Welding Society and is the 2018 recipient of the Distinguished Mentor Award at Los Alamos National Laboratory.

**Andrew D. Brown** serves as Technical Core and Mission Support for the Science of Extreme Materials Competency Branch at DEVCOM ARL Army Research Office, Durham, NC. He obtained his B.S. in Mechanical Engineering at North Carolina State University (2009) and his doctoral degree in Mechanical Engineering at Arizona State University (2015). He spent three years (2015–2018) at UNSW Canberra as a postdoctoral researcher where he oversaw the daily operations of the Impact Dynamics Laboratory, mentored undergraduate and graduate student research projects, and performed teaching duties. His research expertise is understanding microstructural effects on the mechanical performance and damage processes of materials subjected to high dynamic pressures (shock) and high strain rates, high-rate injury biomechanics research to improve injury outcome prediction and protect the U.S. Warfighter. He has been an active member of TMS since 2011; was a co-organizer for the symposium on Characterization of Minerals, Metals, and Materials in 2018; and has been the symposium's EPD Award Representative from 2017–2022. Dr. Brown has published over 40 peer-reviewed articles in the fields of mechanical engineering, materials science, and biomechanics.

**Shadia Ikhmayies** received a B.Sc. and M.Sc. from the physics department at the University of Jordan in 1983 and 1987, respectively, and a Ph.D. in producing CdS/CdTe thin film solar cells from the same university in 2002. Her research is focused on producing and characterizing semiconductor thin films and thin film CdS/CdTe solar cells. She also works in characterizing quartz in Jordan for the extraction of silicon for solar cells and characterizing different materials by computation. She has published 59 research papers in international scientific journals, 85 research papers in conference proceedings, and 3 chapters in books. She is the founder and editor of the eBook series *Advances in Material Research and Technology* published by Springer, and the editor-in-chief/editor of several books. Dr. Ikhmayies is a member of The Minerals, Metals & Materials Society (TMS) where she was the chair of the TMS Materials Characterization Committee (2016–2017), and the leading organizer of three symposiums;

Solar Cell Silicon 2017–2020, Mechanical Characteristics and Application Properties of Metals and Nonmetals for Technology: An EPD Symposium in Honor of Donato Firrao, and Green Materials Engineering: An EPD Symposium in Honor of Sergio Monteiro. Dr. Ikhmayies is also a member of the World Renewable Energy Network/Congress (WREN/WREC) 2010–present. She is a member of the international organizing committee and the international scientific committee in the European Conference on Renewable Energy Systems (ECRES2015–ECRES2022). She is a guest editor and a member of the editorial board of several journals including *JOM* and the *Journal of Electronic Materials*. Dr. Ikhmayies is a reviewer of 24 international journals and several international conference proceedings. She has received several international awards including the TMS Frank Crossley Diversity Award 2018 and World Renewable Energy Congress 2018 Pioneering Award.

# Part I
# Advanced Characterization Methods I

# Characterization of Lunar and Martian Meteorites Using a Scanning Electron Microscope (SEM)

**Hussain Al Halwachi**

**Abstract** Lunar and Martian meteorites are rare rocks found on Earth and classified by meteoritical experts depending on their physical and chemical features. Three different types of certified lunar rock samples and one Martian rock sample were tested and scanned by a scanning electron microscope (SEM) to obtain the chemical composition, explore the elemental mapping, and provide a statistical comparison between the different types. The SEM was able by EDS detector to provide accurate chemical compositions, in addition to microstructure images and elements mapping. The data provided by SEM were treated statistically by the principal component analysis (PCA) technique to obtain the relation between the elements and obtain a statistical model to help in differentiating similar rocks in the future.

**Keywords** SEM · Lunar · Martian · PCA

## Introduction

The Moon and Martian meteorites are considered among the rarest space rocks available on Earth. They usually blast off from the surface of the Moon and Mars due to collisions occurring with possible asteroids and then are captured by Earth's gravity until they fall on Earth's surface after penetrating the atmosphere [1]. Meteorite classification and identification became a crucial step in the past decade since a lot of people are interested to own a genuine piece from space. The classification is carried out by international meteoritical societies and throughout the years an international database was generated for the certified meteorites [2]. The classification is carried out by experts in this field. The sorting and classification of meteorites are carried out by scientists depending on the meteorites' mineralogy and structures [2], using several analytical tools and isotope analysis [2]. In this study, I am exploring the chemical compositions of four certified meteorite samples that had been bought from Mr. Mendy Ouzillou, a trusted dealer in this field and recommended by the

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Meteoritical Society in the United States. Since the moon is not a uniform, homogeneous planet, and consists of different rocks formed in different ways and times [3], I had selected three genuine lunar samples carefully from different kinds to have a variety of Moon meteorites, in addition to a sample for Mars meteorite. The four samples measured by scanning electron microscope (SEM) and the data provided were treated statistically by principal component analysis (PCA) to obtain a better comparison between the different types of Meteorites.

## Four Meteorite Samples

The four certified meteorite samples were selected from different kinds of rocks, to allow me to study different rock natures and chemical compositions. The size and dimension of each sample were important criteria for selection. Smaller size samples will not be prepared and fit easily in SEM instrument. The price was also one of the selection criteria since the genuine certified meteorite samples are not cheap. I could not add more samples due to the high price of some rare pieces, i.e., Zagami Shergottite piece. The samples selected were big enough in size to take three SEM images for each sample with the flexibility to select the best position for mapping and measurements.

(1) **NWA 6963 Martian Shergottite**
Meteorite Northwest Africa (NWA) 6963 is a gabbroic Shergottite rock classified as a basaltic Martian meteorite [4]. The NWA 6963 was found in Guelmim Es-Semara, Morocco in 2011 [5], and based on its bulk chemistry and oxygen isotopes, it was classified as a Martian meteorite [4]. The mineralogical model of NWA was containing Pyroxene, Plagioclase, Opaques, and Melt pockets with no ferroan Olivine. The absence of olivine in Shergottite rocks indicates that they crystallized from fractionated magmas [6]. Shergottites are the most abundant of Martian rocks (50 out of 61), almost three-quarters of all Martian meteorites [7]. The name Shergottites is given after five Shergotties meteorites, which fell in India in 1965 in an area called Shergotty [2]. Figure1 shows the four meteorite samples.

(2) **Lahmada 020, Lunar rock**
Meteorite Lahmada 020 is a lunar meteorite that was found in Saguia el Hamra, Western Sahara in Morocco in November 2018 [5]. The rock was classified as feldspathic regolith melt breccia. The feldspathic lunar meteorites likely originated from the inner and outer regions of Fledspathic Highlands Terrane (FHT) on the Moon [8]. Furthermore, the lunar surface is covered by a layer of unconsolidated debris known as lunar regolith [3, 9]. Lunar regolith are rocks that were broken from underlying bedrock by collision with meteorites [1]. Lunar regolith meteorite is ejected from the Moon by the impact of the cratering process [1]. This type of meteorite reflects a broad range from different lunar lithological terraces [10], including FHT [1]. One type of lunar lithologies is


**Fig. 1** The four samples involved in the study

known as lunar regolith melt, which is formed when a meteorite impact melts the material, and then ejected from a crater, then solidifies before they land on earth [3, 11]. The geochemistry of Lahmada 020 rock includes Olivine, Pigeonite, and anorthite [5].

(3) **NWA 11474 Lunar**
Meteorite (NWA) 11474 was found in Northwest Africa in 2017 and classified as lunar feldspathic breccia [5]. The geochemistry includes Olivine, Pigeonite, pyroxene, and Plagioclase [5].

(4) **Meteorite NWA 10203**
Meteorite (NWA) 10203 was found in Northwest Africa in 2015 and classified as Polymict lunar [5]. Polymict (or polylithologic) breccias are a mixture of many different types of rocks, which result from the mixing of different lithologies formed under different conditions [9]. The Geochemistry of NWA 10203 includes Olivine gabbro, clinopyroxene, and plagioclase [5].

## Experimental Method

SEM is a non-destructive technique used to magnify images up to at least 1,000,000X times [12]. SEM was used to produce magnified images for the four meteorite samples. The samples were fitted with special clamps to avoid destruction during measurement under a vacuum medium. Micro-mapping of the sample was carried out to determine the microtopographic locations of each element. SEM is equipped with an EDS detector that can produce quantitative analysis. The measurements were carried out in Louvre Museum Laboratory in Abu Dhabi, using SEM instrument from Thermo Fisher company (Fig. 2 and 3).

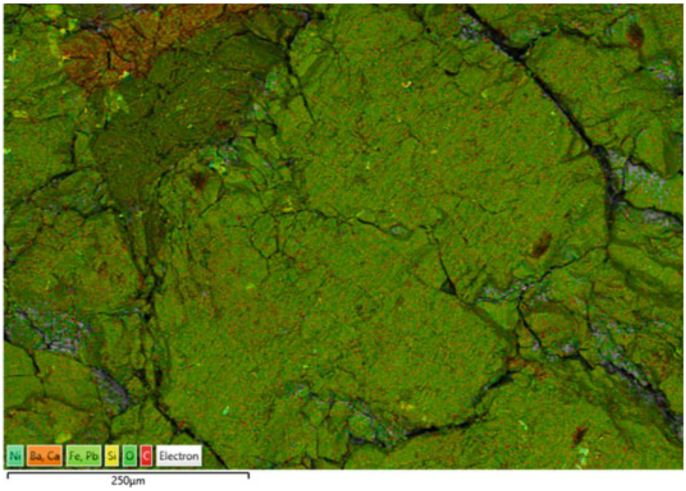


**Fig. 2** SEM image for sample NWA 6369 overlapped with EDS maps, showing the microtopographic locations of the elements

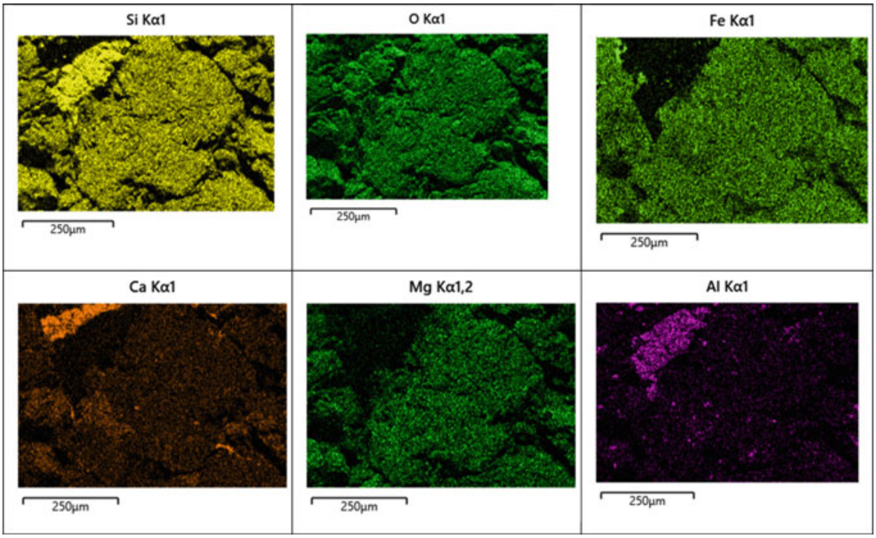


**Fig. 3** EDS maps, the elementary micro-mapping of main elements for sample NWA 6369

## *Results*

The main elements found in the four samples are oxygen, silicon, iron, carbon, calcium, magnesium, and aluminum, while other elements are found in the trace levels. The level of oxygen found in the four samples is from 40 to 45.9%, which is

**Table 1** Semi-quantitative EDS analysis for NWA 6963 and Lahmada 20

| NWA 6963- Martian | | | | Lahmada 020 | | | |
|---|---|---|---|---|---|---|---|
| Element | Image1 | Image 2 | Image3 | Element | Image1 | Image 2 | Image3 |
| | Weight % | Weight % | Weight % | | Weight % | Weight % | Weight % |
| O | 42.0 | 43.0 | 42.9 | O | 42.8 | 42.6 | 43.9 |
| Si | 18.3 | 18.6 | 17.3 | Si | 18.6 | 15.4 | 18.3 |
| Fe | 16.2 | 16.2 | 14.3 | Fe | 4.8 | 3.6 | 2.9 |
| C | 8.5 | 8.7 | 9.0 | C | 5.7 | 9.7 | 5.9 |
| Ca | 5.5 | 4.6 | 6.1 | Ca | 9.4 | 13.1 | 11.2 |
| Mg | 5.2 | 5.4 | 4.6 | Mg | 3.7 | 1.8 | 1.8 |
| Al | 1.9 | 1.0 | 2.7 | Al | 13.7 | 12.8 | 15.2 |
| Na | 0.7 | | 1.0 | Ba | 0.6 | | |
| P | 0.6 | 0.6 | 0.6 | | | | |
| Mn | 0.5 | 0.5 | | | | | |

expected since minerals always occur in oxide form and exist in crystalline form. The level of silicon was almost around 18% in NWA6963, Lahmada 020, NWA10203, and lower than 18% in NWA11474. The level of iron was one of the characteristic elements for each sample. Iron was high in NWA 6963 at the level of 15%, and at the level of 10% in NWA10203, while it was lower in Lahmada 020 and NWA11474.Carbon: the level of Carbon differed from one sample to another. It was high in NWA11474 at around 20% and lower in NWA 6963 and Lahmada and no carbon was detected in NWA 10203. Lahmada 020 and NAW 10203 contained a high level of calcium (higher than 10%) compared with NWA 6963 and NWA 11474. The level of magnesium was almost lower than 4% in Lahmada 020 and NWA 11474, and slightly higher in NWA6963 and NWA 10203. The level of aluminum was characteristic for NWA 6963. The level in NWA 6963 was low compared with the other three samples (Tables 1 and 2).

## *PCA Multivariate Statistical Analysis*

In order to identify the similarities and differences between the four meteorite samples, an unsupervised type of statistic was applied. It should be remembered that an unsupervised statistical technique allows a display of multivariate data (multiple variables) and allows for the identification of groups within the proposed data set. For our research, we have a data set consisting of 15 variables (O, Si, Fe, C, Ca, Mg, Al, Na, P, Mn, K, S, Ba, Ni, Sn). The samples consist of 3 Moon rocks and one Mars rock. The three Moon rocks are from different types of lunar rocks. Before starting the statistical treatment, the dataset was cleaned and the missing values were