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Mineralogy of Martian meteorites: A review of Raman spectroscopy investigation of silicates, sulfates and sulfides

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ABSTRACT

This work compiles Raman spectroscopy studies on eight different Martian achondritic meteorites and summarizes the characteristic Raman peaks of silicate, sulfate, and sulfide minerals commonly found in these meteorites. The meteorites examined include LAR 12095, MIL 03346, NWA 2975, NWA 10628, NWA 10720, RBT 04262, SaU 060, and Yamato 984028. The main contribution of this review is to provide a basis for the creation of a database of mineralogical components of Martian meteorites documented with Raman data. Spectral characterization of silicate (e.g., olivine, pyroxene, enstatite), sulfate (e.g., jarosite, gypsum, anhydrite), and sulfide (e.g., pyrite, pyrrhotite, marcasite) minerals is of critical importance in understanding the geological evolution and aqueous alteration processes of Mars. The compiled data aim to serve as a scientific source for both future comparative mineralogical analyses and data interpretation of Raman systems such as SHERLOC on the Martian surface.

I. INTRODUCTION

Mineralogical studies of meteorites provide detailed information about star formation and evolution, the formation and evolution of the solar system, the geological history of the Earth and the Moon, the development of life on Earth, and the early geological history of their source bodies. Stony meteorites are divided into two different subgroups: chondrites and achondrites. Chondrites are the most abundant type of stony meteorites. Almost all chondrites are 4.56 billion years old, have a similar texture, and share a similar chemical. Studying achondrites compared to chondrites has revealed that these meteorite types are more diverse. Achondrites are differentiated meteorites. These meteorites either melted entirely and differentiated into mineral zones within each parent body in the early stages of solar system formation, or they partially melted during sporadic attempts at differentiation. Achondrites also have some very different groups that are not from the asteroid belt between Mars and Jupiter. These achondrites came from the Moon and Mars [1, 2].

Meteorite fragments that break off from the surface of the Moon or Mars and fall to the Earth are called meteorites of Lunar and Martian origin. Martian meteorites are divided into three types from their namesake meteorites (Shergotty, Nakhla, and Chassigny): SNC (Shergottite, Nakhlite and Chassignite) group. The Shergottite meteorite (24° 33'N, 84° 50'E) fell near the town of Shergotty in Bihar, India, in 1865. Another Martian meteorite, the Nakhlite meteorite (31° 19'N, 30° 21'E), fell in the Egyptian city of Nakhla in 1911. The Chassignite meteorite (47° 43' 0''N, 5° 22' 53''E), named after a meteorite that fell in Chasigny, France in 1815, is the last meteorite of

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this group. Most SNC meteorites are thought to be cumulative igneous rocks formed at the bottom of a magma chamber [1, 3].

Martian meteorites provide important information about the characteristics of potential life on Mars. Classically, SNC meteorites are achondrites with magmatic compositions ranging from basaltic to ultramafic. However, some Martian meteorites, such as polymict breccia Northwest Africa (NWA) 7034 and orthopyroxenite Allan Hills (ALH) 84001, are not included in the customarily SNC group because they have different mineral assemblages than SNCs [1, 3]. Today, SNC meteorites form the basis of most of our current knowledge about the planet Mars. Considering the mineralogy, age and chemistry of the Shergotty and Zagami meteorites, which are Martian meteorites, it has been suggested that these meteorites came from the planet Mars [3-5]. Since the discovery of meteorites from the planet Mars, 395 Martian meteorites have been officially documented as of February 27, 2025, with 335 confirmed as shergottite, 32 nakhlite, and 3 chassignite subtypes [6].

In October 1999, nearly 26 years ago, two meteorites were found in Southern California's Mojave Desert. The high ratio of hydrogen to heavy hydrogen and the results of the composition of gas isotopes unique to the Martian atmosphere agreed with measurements taken by the Viking Mars mission in 1976. Additionally, the crystallization age of the meteorites was only 1.3 billion years, indicating that the meteorites were too young to be asteroids. The ages of these meteorites matched the ages of many other shergottites. Thus, these two meteorites were identified as Martian meteorites, specifically shergottites. Shergottites are the most common of the SNC group. Most have basaltic compositions containing pigeonite, augite, and maskelynite as major minerals [1]. Nakhlite meteorites are magmatic cumulates composed of olivine-containing clinopyroxenites as well as phenocrystal augite with minor mineral assemblages including titanomagnetite, fayalite, plagioclase, orthopyroxene, sulfides, phosphates, and alteration phases (iddingsite and sulfates) [7, 8]. Most nakhlites, such as Nakhla, Lafayette, ALH 84001, Yamato 000593, Miller Range (MIL) 03346 show the presence of carbonates (siderite), sulfates (Ca-sulfate, jarosite), phyllosilicates (smectite/illite), and Fe-oxides/hydroxides (magnetite, hematite, goethite, and ferrihydrite). The study of SNC meteorites contributes to revealing information about the surface and crust structure of the planet Mars and the resources (fluids) between the layers [3]. The dominant mineral in the Chassignite meteorite is olivine (~90% vol). Pyroxene (augite and orthopyroxene, ~5% vol.) and feldspar (<5% vol.) minerals, which are found in small amounts in the meteorite, are accessory minerals. [9]. In summary, Nakhlites are cumulates of calcium-bearing (clino-)pyroxene with trace amounts of olivine; Chassignite is composed of more than 90% olivine; and the Shergottite group is defined by basalts and basaltic cumulates made of pyroxene and plagioclase with or without olivine, exhibiting magmatic textures. Pyroxene-phyric basalts, lherzolites, olivine-phyric basalts (subtypes of Shergottites), clinopyroxenites (conventionally Nakhlites), dunites, and orthopyroxenites (classically Chassignites) are among the additional rock-type-based categories in the current Martian meteorite classification [10].

High pressure (HP) minerals frequently occur in meteorites that have been subjected to shock. These minerals are formed by the processes of crystallization of the shock melt and solidification (solid state transformation) of mineral particles in contact with the melt. Especially for meteorites originating from the planet Mars, the transformation of mineral components into HP polymorphs must occur very rapidly. The rapidity of these transformations is due to the fact that in very high-speed collisions, shock-induced high-pressure pulses have short durations ranging from milliseconds to seconds. Therefore, solidification of olivine and pyroxene minerals occurs only in conjunction with shock melting, and this solidification process is associated with high temperature heterogeneities. Shock properties of the olivine mineral have been reported as olivine blackening in Martian meteorites, and this blackened olivine structure has been named “Brown olivine”. These structures are found only in Martian meteorites and are thought to have formed during a shock event on the planet Mars. [11] reported that Martian meteorites with brown olivine structure contain abundant shock veins but do not contain HP phases, while Martian meteorites without brown olivine structure contain fewer shock veins and generally have HP phases around these shock veins, and also in the same study, brown olivine it has been reported that the shock pressures of Martian meteorites containing the structure must be high enough to trigger the transformation of olivine into HP phases, because plagioclase completely transforms into maskelynite at >20-35 GPa pressure [11]. Many Martian meteorites, especially shergottite, were subjected to high shock pressure. It has been reported that shock textures and HP phases (such as silicate perovskite, magnesiowüstite, and ringwoodite) in Martian meteorites were exposed to high shock pressure reaching values of >19-25 GPa [11]. Many different features are considered indicators of shock in meteorites, including mosaicism (mosaic pattern), recrystallization and coloration of olivine, and deformation and planar properties, as well as disseminated metal or sulfur, feldspathic normal glass, and maskelynite, as well as darkening of silicates due to diffuse shock melting. Features resulting from differences between HP mineral zones and the host (source) rock mass provide information about the early history of thermal metamorphism. Since the bulk shock temperature is at 25 GPa pressure and only between 600-800 K, observable transformation of olivine or pyroxene minerals cannot occur in source rock located away from the shock melt. The relatively low temperature of the source rock limits the shock metamorphic effects of the deformation and planar features of the mosaic pattern and masklinite, other than shock melting. HP minerals, commonly observed in Martian meteorites, are considered definitive evidence of shock metamorphism in meteorites. For example, the presence of HP minerals in shergottites has been suggested as evidence of a very high shock phase close to the sequence of whole-rock melting, considering the results of mineral recrystallization and shock recovery experiments. Ringwoodite, a spinel-structured polymorph of the high-pressure mineral olivine commonly found in molten veins of highly shocked Martian meteorites, occurs as dark blue grains providing evidence of high shock. Maskelynite, an HP mineral and identified as a major component of the Shergotty meteorite, is an amorphous form of plagioclase. Martian meteorites subjected to strong shock have been reported to contain shock melt veins and maskelynite transformed from plagioclase [11, 12].

Raman spectroscopy is one of the most frequently used techniques in the elemental and mineralogical analysis of meteorites. Raman scattering is a powerful and effective analytical technique in the vibrational and structural characterization of minerals. Raman spectroscopy allows us to obtain detailed information about the minerals and functional groups in the sample without damaging the sample. Meteorites are rare and valuable specimens. Non-destructive analysis can be performed in small sample areas without the need for any physical intervention. Since Raman spectroscopy is very sensitive in distinguishing different chemical structures, it is preferred when more precise and accurate results need to be obtained. Each group of silicate minerals has characteristic Raman bands. Raman spectroscopy provides the necessary information to distinguish different structural groups and phases of silicate minerals. Therefore, Raman spectroscopy is an ideal technique for the rapid identification of silicate minerals and act as a potential chemical fingerprint [2, 13, 14].

Silicate minerals are found distributed throughout the solar system. Most silicate minerals are the main constituent of any igneous rocks. Additionally, silicates make up approximately 95% of the Earth’s upper mantle and crust.

The pyroxene mineral (Mg, Fe)SiO_3 is one of the most important components found in stony meteorites and the Earth's upper mantle. This group of pyroxene silicates, such as orthopyroxene (orthorhombic pyroxenes) and clinopyroxene (monoclinic pyroxenes), are important silicate mineral components found in meteorites, most asteroids, and the planet Mars. This aluminosilicate group is subdivided into orthopyroxene and clinopyroxene. While orthopyroxene crystallizes in the orthorhombic system, clinopyroxene crystallizes in the monoclinic system. Clinopyroxenes, formed under a high temperature and/or pressure conditions, are a group of inosilicate minerals, and this mineral is important in rock formation [2, 15]. Another important silicate mineral is olivine. Olivine mineral has two end members: Mg-bearing (Mg_2SiO_4; forsterite) and Fe-bearing (Fe_2SiO_4; fayalite). Olivine is a major component of stony meteorites (e.g., chondrites and achondrites) and their source bodies (asteroids), as well as meteorites of Martian origin. Iddingsite, a mineral derived from the alteration of olivine, is an important alteration phase component found especially in the vein structures of Martian meteorites. In general, the iddingsite alteration mineral, which is found as a mixture of smectite clay and Fe-oxides on Earth, has been reported to be related to the mixture of phases such as gypsum, siderite, and amorphous silicate gel within olivine-bearing 'iddingsite' alteration veins on the planet Mars and Mars-origin meteorites-Nakhla [3, 16].

Sulfur, the most abundant moderately volatile element in the solar nebula, is rich on the planet Mars. It is thought that the sulfur-rich nature of Mars may have resulted in a Fe-(Ni-)S core that was liquid throughout the history of the planet Mars. Sulfate minerals, which contain sulfur atoms bonded to oxygen atoms, are important minerals found throughout the solar system, primarily in the Earth's lithosphere and hydrosphere, in meteorites, and on the surface of the planet Mars. Martian sulfates were formed primarily by the weathering of sulfide-rich basalts, which created locally acidic environments. The biological importance of sulphide minerals, particularly in the context of Mars, is quite remarkable. Especially in the search for astrobiology and ancient life traces, these minerals are likely to play a role both as tracers of biological processes and as energy sources for microorganisms. Mars has a surface rich in Mg- and Ca-sulfates. Sulfate minerals, especially those with a calcium sulfate phase, such as gypsum and anhydrite, provide information about the past environmental conditions and geological processes of the Earth and extraterrestrials such as the planet Mars. Hydrous alteration materials in Martian meteorites contain anhydrite and/or sulfate minerals such as gypsum, Mg-sulfate, jarosite, and S-bearing aluminosilicates (clays). These minerals can provide crucial information about the aqueous processes and chemistry of the planet Mars. Sulfates, which are important components of Martian meteorites, are very important for understanding the chemical hydrology of the planet Mars. Sulfide minerals, which are another abundant sulfur mineral on the planet Mars, in addition to being the main source of a wide diversity of metals found on Earth, constitute important groups of minerals. Pyrite is the most abundant sulfide mineral. It is known that very fine-particle iron sulfides are found in environments beneath the surfaces of sediments and soils largely consist of fine-particle mackinawite. Following the discovery of hydrothermal systems on the ocean floor that produce sulfur minerals and are associated with new life forms and ecosystems, minerals belonging to this group may have contributed to the emergence of life on Earth [17-22].

This summary of previous research of eight different Martian achondrite samples such as Larkman Nunatak (LAR) 12095, MIL 03346, NWA 2975, NWA 10628, NWA 10720, Roberts Massif (RBT) 04262, Sayh al Uhaymir (SaU) 060, Yamato 984028 rich in silicate, sulfate, and sulfide minerals was carried out on silicates, sulfates, and sulfides. The presence of silicate, sulfate, and sulfide minerals and their Raman signals were investigated by examining previous literature Raman studies of the above-mentioned Martian meteorite authors. Additionally, when previous studies are examined, it is seen that silicate, sulfate, and sulfide minerals are abundant in these achondrites. Detailed investigation of these abundant silicate, sulfate, and sulfide minerals will enable us to have more information and to interpret the alteration history of Martian origin meteorites and the planet of Mars. Therefore, in this literature overview on Martian achondrites, the aim is to construct a database by collecting the Raman spectra of silicate minerals such as olivine, fayalite, pyroxene, orthopyroxene, clinopyroxene, augite, enstatite, sulfate minerals such as gypsum, pyrrhotite, epsomite, mackinawite, marcasite, jarosite and sulfide minerals such as mackinawite, marcasite, pyrite and pyrrhotite obtained from Raman analyses and to contribute to future research on Martian origin meteorites.

On the other hand, the reason for this review is the need to eliminate the data confusion in the literature and to create a reference database for mineral spectra. Although these data were previously presented in different content and levels of detail, the information and spectral data regarding Raman data were disorganized. Therefore, the review aims to organize and bring together previous Raman spectroscopy studies conducted on eight different Martian achondrite meteorites and to create a database infrastructure. In addition, this review covers eight different SNC meteorites, unlike studies examining a single meteorite. This provides a valuable broad comparative perspective to the study. By focusing especially on silicate, sulfate, and sulfide minerals, components directly related to the geology of Mars and the potential for past life come to the fore. This study is one of the rare studies in which Raman peaks are classified according to wavelength. In addition, the comparative presentation of results obtained with different spectroscopy techniques (e.g., confocal micro-Raman spectrometer, Raman laser spectrometer and microRaman instrument) provides an original contribution.

In summary, unlike previous studies, this review aims to bring together Raman analyses of many Martian meteorites and create a systematic and usable resource to help understand the mineralogical evolution of Mars and contribute to future space missions.

II. METHOD

2.1 Martian Meteorites

Mars meteorites are Martian rocks that break away from the planet Mars through impacts and then fall to Earth as meteorites. There are three types of Martian meteorites: shergottites, nakhlites, and chassignites. These meteorites have a mineralogical content rich in silicates, sulfates, and sulfides. The data on selected Martian meteorites presented here were mainly retrieved from the Meteoritical Bulletin Database. SAO/NASA Astrophysics Data System, Web of Science and Mendeley were used to search the literature based on Raman studies of Martian achondrites. Micro-Raman spectroscopy offers a non-destructive method of investigating a large number of different SNC meteorite samples. Considerably broadening the basis of knowledge of SNC meteorites and therefore of the planet Mars. It was seen that there is diverse data regarding silicate, sulfate, and sulfide minerals. Therefore, it summarizes the Raman data from the literature to provide a better picture of the published Raman spectra as a kind of concise review.

Here, using Raman Spectroscopy of an achondritic group of Martian meteorites such as LAR 12095, MIL 03346, NWA 2975, NWA 10628, NWA 10720, RBT 04262, SaU 060, Yamato 984028, published literature results regarding the general mineralogy of these meteorite types, especially the presence of silicate (e.g., olivine, fayalite, orthopyroxene, clinopyroxene, pyroxene, augite, enstatite), sulfate (e.g., gypsum, anhydrite, epsomite, rozenite and jarosite) and sulfide (e.g., mackinawite, marcasite, pyrite and pyrrhotite) minerals, were examined.

LAR 12095 shergottite-type Martian meteorite fell in Antarctica in 2012 and was collected by the US Antarctic Search for Meteorites program (ANSMET). The total mass of the meteorite is 133.1 g. Raman peaks obtained from the Raman study on the LAR 12095 Martian meteorite by [23], 819/848 cm^{-1} doublet for olivine and 332, 398, 538, 658/672 doublet, 940, 1003 cm^{-1} for pyroxene were found in the Raman spectra. Additionally, 216, 276 cm^{-1} for oxidized mackinawite, 214, 274, 385, 582 cm^{-1} for oxidized mackinawite and broad iron oxide bands, 216, 282, 329, 363, 396, 583 cm^{-1} for mackinawite, pyrrhotite, and broad iron oxide bands, and 220, 288, 400, 493, 601, 665 cm^{-1} for hematite peaks value were reported. Elemental sulfur and marcasite (M) were defined together at peak values of 149, 219, 244, 319 (M), 381 (M), 471 cm^{-1} in the Raman spectra of the meteorite sample. Moreover, 139, 224, 300, 355, 434, 454, 573, 625, 1007, 1051, 1103, 1153 cm^{-1} for jarosite, 138, 183, 224, 328, 416, 435, 495, 620, 674, 1009, 1103, 1138, 1454 cm^{-1} for gypsum and 984 cm^{-1} for epsomite peaks were found in the meteorite Raman spectra.

MIL 03346 nakhlite-type Martian meteorite (83° 22' 20"S, 156° 23' 53"E) fell in Antarctica in 2003 and was collected by the ANSMET. The total mass of the meteorite is 715 g. In the study based on the Raman analysis of the MIL 03346 Martian meteorite by [16], 412, 492, 618, 1008, 1141 cm^{-1} for gypsum, 227, 300, 360, 440, 574, 626, 1010, 1107, 1157 cm^{-1} for jarosite and 185, 299, 603, 692 (Si-O-Si bond), 983, 1135 cm^{-1} for iddingsite were found in the Raman spectra.

NWA 2975 shergottite-type Martian meteorite fell in Algeria in 2005. The total mass of the meteorite is 70.1 g. The presence of enstatite mineral was revealed by [24]. The authors defined enstatite and augite Raman peaks at 135, 331, 395, 550, 668, 1000 cm^{-1} for enstatite, 135, 320, 389, 554, 664, 1008 cm^{-1} for augite. Furthermore, 135, 224, 325, 395, 514, 535, 558, 667, 1000 cm^{-1} for enstatite with the contribution of augite and 131, 189, 317, 353, 386, 551, 662, 809, 918, 1008 cm^{-1} for augite with contribution of enstatite and pigeonite peaks were found in the Raman spectra of the meteorite sample. Additionally, 132, 289, 408, 447, 552, 606, 626, 957, 972 and 1084 cm^{-1} for merrillite, minor bands at 591 and 1047 cm^{-1} for apatite, 213, 276, 390, 488, 589, 645, 1291 cm^{-1} for pyrrhotite and 217, 280, 390, 476, 589, 646, 1282 cm^{-1} for mackinawite were defined in the meteorite. Moreover, 314, 385, 670, 990, 1007 cm^{-1} for pyroxferroite, 321, 389, 667, 1009 cm^{-1} for augite (clinopyroxene), 289, 479, 506 cm^{-1} for feldspar, 281, 711, 1087 cm^{-1} for calcite, 956 cm^{-1} for apatite, 222, 292, 408, 507, 605, 659, 1318 cm^{-1} for hematite, 658 cm^{-1} for magnetite and 209, 273, 378 cm^{-1} for pyrrhotite peaks value were found in the Raman spectra by the micro-Raman instrument. In addition, 316, 390, 668, 995, 1005 cm^{-1} for pyroxferroite, 326, 393, 665, 1013 cm^{-1} for augite (clinopyroxene) and 670, 962/976 cm^{-1} doublet for merrillite were also defined in the Raman spectra by the Raman laser spectrometer (RLS) instrument.

NWA 10628 shergottite-type Martian meteorite fell in Algeria in 2014. The total mass of the meteorite is 24.1 g. The presence of pyroxene minerals (augite and kanoite) was revealed by [25]. The authors found augite and kanoite Raman peaks at 133, 190, 323, 361, 391, 511, 533, 557, 665, 1008 cm^{-1} for augite, 322, 542, 665, 1000 cm^{-1} for kanoite of the meteorite Raman spectra. In addition, feldspar, pyroxene, and calcite minerals were defined together as 183, 483, 511 cm^{-1} for feldspar, 318, 394, 666, 1003 cm^{-1} for pyroxene, and 282, 714, 1088 cm^{-1} for calcite. Feldspar and ilmenite minerals were also found and given together within the Raman spectra of the meteorite at peak values of 163, 478, 509 cm^{-1} for feldspar and 223, 369, 677 cm^{-1} for ilmenite. Fe-bearing olivine (fayalite) in the meteorite was defined from 156, 172, 243, 292, 313, 384, 508, 579, 814/839 doublet and 902 cm^{-1} peak values. Moreover, 301, 394, 476, 553 cm^{-1} for goethite, 990 cm^{-1} for rozenite and 227, 246, 295, 327, 390, 412, 500, 549, 610, 1008 (G) and 1018 (AN) cm^{-1} for hematite together with gypsum (G) and anhydrite (AN) peaks were defined in the Raman spectra. 224, 241, 291, 406, 609, 1311 cm^{-1} for hematite, 543, 663 cm^{-1} for magnetite and 1577 cm^{-1} for carbon were found in the Raman spectra as hematite and magnetite in the presence of carbon. Furthermore, 193, 392, 516, 639 cm^{-1} for anatase was found in the Raman spectra of the meteorite. The merrillite in the meteorite sample was defined from the peak values of 290, 408, 449, 556, 606, 628 and 958/974 cm^{-1} doublet. Calcite in the pyroxene matrix was also found in the Raman spectra. 154, 281, 713, 1086 cm^{-1} for calcite, 657 and 992 cm^{-1} for pyroxene were defined in the meteorite.

NWA 10720 nakhlite-type Martian meteorite fell in Mauritania in 2015. The total mass of the meteorite is 1015 g. In the Raman study by [3] on the NWA 10720 Martian meteorite, the Raman peaks of Fe-bearing pyroxene in the mesostasis were defined as 319 and 663 cm^{-1}, and the Raman peaks of orthopyroxene were defined as 323, 640 and 663 cm^{-1}. Raman peaks of some primary minerals in NWA 10720 have been reported as follows: 143, 397, 515 and 638 cm^{-1} for anatase, 305, 547 and 674 cm^{-1} for Ti-magnetite, 334, 367 and 677 cm−1 for ilmenite, 607 and 657 cm^{-1} for hematite, 481 and 509 cm^{-1} for plagioclase, 475 and 513 cm^{-1} for K-feldspar, 816/847 cm^{-1} doublet for olivine with Fe-oxide. Raman peaks in the Raman spectra of Fe sulfides, glassy inclusions and olivine alteration vein (iddingsite) are reported as follows: 185, 406, 575, 685, 964, 1313 and 1430 cm^{-1} for iddingsite, 185, 340, 494, 650, 720, 1314 and 1430 cm^{-1} for maghemite, 1086 cm^{-1} for calcite, 364 and 691 cm^{-1} for glassy inclusions, 962 cm^{-1} for apatite, 322, 342, 380, 428 and 710 cm^{-1} for pyrrhotite, 341, 380 and 428 cm^{-1} for pyrite. Additionally, the Raman spectrum of H_2O/OH vibration in the range of 2.800-4.000 cm^{-1}, consisting of iddingsite and apatite, has been reported. H_2O/OH Raman peaks were identified as 2881, 2937, 3399 and 3553 cm^{-1} for iddingsite and 2918, 3289 and 3485 cm^{-1} for apatite.

RBT 04262 shergottite-type Martian meteorite fell in Antarctica in 2004 and collected by the ANSMET. The total mass of the meteorite is 205 g. In the Raman study by Huidobro et al. (2021) on the RBT 04262 Martian meteorite, the Raman peaks of epsomite were found as 252, 366, 446, 459, 612, 984, 1060 cm^{-1}, and the Raman peaks of gypsum were found as 183, 415, 492, 620, 671, 820/849 doublet (O), 915 (O), 1009, 1136 cm^{-1} together with olivine (O) in the Raman spectra. Additionally, the authors reported peaks of 216, 278, 390 cm^{-1} for FeS, 154, 221, 437, 474 cm^{-1} for elemental sulfur, 330, 395, 656/674 doublet, 1002 cm^{-1} for orthopyroxene, and 818/848 cm^{-1} doublet for olivine. Moreover, 356, 410, 448, 547, 595, 622, 958, 974, 1046, 1082 cm^{-1} for merrillite, 494, 1008, 1136 cm^{-1} for gypsum and 302, 406, 526, 672, 818/846 doublet (O), 910 (O), 948 (O) cm^{-1} for titanomagnetite together with olivine (O) peaks were defined in the Raman spectra.

SaU 060 shergottite-type Martian meteorite (20° 58' 48''N, 57° 19' 6''E) fell in Oman in 2001. The total mass of the meteorite is 42.3 g. Raman peaks obtained from the Raman study on the SaU 060 Martian meteorite by [26], 280 and 1083 cm^{-1} for carbonate and 327, 395, 670, 1002 cm^{-1} for pyroxene were reported in the Raman spectra of the meteorite sample containing single calcite grains intergrown with pyroxene. Furthermore, 393, 512, 632 cm^{-1} for anatase and 327, 393, 670, 1002 cm^{-1} for pyroxene peaks were found in the Raman spectra of the meteorite.

Yamato 984028 shergottite-type Martian meteorite fell in Antarctica in 1998 and was collected by the National Institute of Polar Research, Japan. The total mass of the meteorite is 12.3 g. The presence of clinopyroxene mineral in the exterior grain (EG) and orthopyroxene mineral in the interior grain (IG) was revealed by [27]. The authors identified clinopyroxene and orthopyroxene minerals from their corresponding Raman peaks at 228, 326, 360, 393, 532, 667 and 1013 cm^{-1}, especially at 326, 667, 1013 cm^{-1} (EG) and 236, 334, 410, 661, 682 and 1007 cm^{-1}, especially at 334, 661, 682, 1007 cm^{-1} (IG). The Raman peaks specifically mentioned for clinopyroxene (EG), and orthopyroxene (IG) minerals indicate the most informative peaks for obtaining information about the structure and composition of pyroxenes. The presence of olivine in (EG) Yamato 984028 Martian meteorite was identified from 821/852 doublet, 917 and 953 cm^{-1}. It has been reported that Raman peaks shift towards lower wave numbers with higher Fe content in olivine (fayalite).

2.2 Characterization of Martian Meteorites

Before analysis, the meteorite weighed 133.13 grams and its dimensions were 5.5 × 3.8 × 3.4 cm. However, for more detailed analysis, the meteorite sample was divided into thin sections. The weight of the LAR 12095 Martian shergottite sample after embedding in resin was 1.26 g and its dimensions were 1.3 × 1.0 × 0.2 cm. There is a greenish-gray matrix with cracks and vein-separated sections and some dark inclusions on both polished surfaces of the meteorite. It is known that the meteorite is consists of fine-grained olivine (16–17% by volume), maskelynite (21-23% by volume), and pyroxene (61-62% by volume). The meteorite component contains secondary minerals such as phosphates (mostly merrillite, with occasional apatite), oxides (1% by volume, chromite, and Ti-magnetite), and sulfides (1% by volume, primarily Fe-bearing pyrrhotite). In addition, microstructural features such as veins formed by shock metamorphism and darkened olivine are also observed in the meteorite. Molecular characterization of the meteorite sample was performed using a Renishaw inVia confocal micro-Raman spectrometer [23].

A polished thin section of the MIL 03346 nakhlite-type Martian meteorite was used in the Raman study by [16] and the spectra were collected using the confocal Raman microscope (alpha-300, WITec).

The Raman study of the NWA 2975 shergottite-type Martian meteorite was carried out by [24] on a thick section polished on both sides, weights 2.157 g and dimensions 35 × 27 × 4 mm (length × width × height). The meteorite sample is a medium gray tone and contains some black glass veins. Additionally, there are cracks and fractures on both sides of the meteorite. Molecular and mineral characterization of the meteorite sample was performed using the Renishaw inVia confocal micro-Raman spectrometer (CMRS), micro-Raman instrument (MRI) and Raman laser spectrometer (RLS) instrument.

In the Raman study by [25], the weight of NWA 10628 shergottite-type Martian meteorite is 0.190 g. The surface of the meteorite has a light brownish matrix with small fusion particles. The polished surface of the meteorite was used in the analysis. This polished surface is the outer surface of the meteorite most exposed to shock and thermal heating during its entry into the Earth. The analysis focused on the inner surface of the meteorite. The meteorite has a gray-brown rock-like structure. For this reason, no clear heterogeneous phases are seen in the smooth interior. Some dark cracks and holes are visible, which may form after the initial shock on the planet Mars or because of continuous heating and cooling cycles in the desert. Renishaw inVia confocal Raman micro-spectrometer was used for molecular and mineral characterization of this shergottite-type meteorite sample.

The thick polished section (~0.5 cm^2) of the 0.63 g fragment of the NWA 10720 nakhlite-type Martian meteorite was used in the Raman study by [3]. Primary magmatic minerals and secondary alteration phases were determined with the Renishaw inVia Raman system.

Grain sizes of up to 4 mm in a coarse-grained mixture of pyroxene, olivine, and maskelynite define RBT 04262 shergottite-type Martian meteorite. Meteorites also contain oxides, phosphate, chromite, and sulfides. Within the scope of the literature, the RBT 04262 meteorite is defined as a shergottite-type Martian meteorite consisting primarily of pyroxene, olivine and maskelynite, and small amounts of chromite, spinel, Ca phosphate, ilmenite, Fe sulfide crystals and glass with a composition of K feldspar. The Raman study conducted by [10], aimed to collect all the mineral phases that make up this meteorite and determine their origins such as primary, secondary, or weathering minerals. Elemental and molecular characterization of the RBT 04262 meteorite sample used in this study was carried out on a thin pieceweighing 1.12 g and dimensions of 1.4 x 0.6 x 0.2 cm (length x width x height), including the resin in which it was embedded. A light gray and dark yellow matrix is present on both polished surfaces of the meteorite, with some cracks and fractures. Molecular characterization of the meteorite sample was performed using a Renishaw inVia confocal micro-Raman spectrometer.

Raman study of SaU 060 shergottite-type Martian meteorite sample was carried out by [26] using Labram, Jobin Yvon micro-Raman spectrometer. In the summary of previous research, the presence of anatase was found for the first time in the SNC shergottite-type SaU 060 meteorite.

In the Raman study of the Yamato 984028 shergottite-type Martian meteorite by [27], two samples were used, from the interior grain (IG) of the meteorite, weighing 64 mg, and from the exterior grain (EG) of the meteorite, weighing 87 mg. Raman microprobe spectra were recorded using a HoloLab Series 5000 Raman microprobe from Kaiser Optical Systems, Inc.

III. RESULTS AND DISCUSSIONS

Based on the literature overview, various data were collected on the identified selected silicate (e.g., olivine, fayalite, orthopyroxene, clinopyroxene, pyroxene, augite, enstatite), sulfate (e.g., gypsum, anhydrite, epsomite, rozenite, and jarosite), and sulfide minerals (e.g., mackinawite, marcasite, pyrite, and pyrrhotite) in those meteorites. The result of previous Raman studies on LAR 12095, MIL 03346, NWA 2975, NWA 10628, NWA 10720, RBT 04262, SaU 060, and Yamato 984028 achondrites by the above authors showed the presence of silicate and sulfate minerals in SNC-type Martian meteorites. In this paper, summaries of previous research on Raman studies of eight different Martian achondrites by the authors were examined, and these studies were compared to each other. As a result of the comparisons, the composition of silicate, sulfate, and sulfide minerals in meteorites and the Raman peak positions of these minerals were summarized, and the results were presented in Table 1 (silicates) and Table 2 (sulfates and sulfides). In addition, apart from silicates, sulfates, and sulfides, which occur abundantly in Martian achondrites, other minerals such as oxides, phosphates, and carbonates are summarized in Table 3 for these eight Martian meteorites.

In the Raman study by [23], the Raman peaks of the silicate (olivine and pyroxene), sulfate (jarosite, gypsum and epsomite) and sulfide (mackinawite, pyrrhotite and marcasite) minerals from the Raman peaks collected at 532 nm wavelength for shergottite-type LAR 12095 Martian achondrite were given in Table 1 and 2. Other minerals in the meteorite are given in Table 3.

[16] reported the Raman peaks of the silicate (iddingsite), sulfates (gypsum and jarosite) observed by 532 nm wavelength excitation in nakhlite-type MIL 03346 Martian achondrite. Raman peak values of these minerals are given in Tables 1 and 2. In the Raman study based on by [24], Raman peaks of silicates (augite, enstatite, feldspar, pigeonite, pyroxferroite) and sulfides (mackinawite and pyrrhotite) from the Raman spectra collected at 532 nm wavelength in shergottite-type NWA 2975 Martian achondrite were given in Table 1 and 2. Other minerals (phosphates and oxides) in the meteorite are given in Table 3.

In the Raman study by [25], Raman peaks of silicate (augite, kanoite, pyroxene, feldspar, calcite, and fayalite) and sulfate (gypsum, anhydrite, and rozenite) minerals from the Raman spectra were collected at 532 and 785 nm wavelengths in shergottite-type NWA 10628 Martian achondrite. Olivine (fayalite), which is rare in the meteorite, was obtained at 532 nm. The main excitation used in Raman analysis is 785 nm. Raman peak values of these minerals are given in Tables 1 and 2. Other minerals (carbonate, phosphates, and oxides) in the meteorite are given in Table 3. Raman investigation performed by [3], Raman peaks of silicates (Fe-bearing pyroxene, orthopyroxene, plagioclase, K-feldspar, olivine, and iddingsite) and sulfides (pyrite and pyrrhotite) were from the Raman spectra collected at 532 nm wavelength in nakhlite-type NWA 10720 Martian achondrite. Raman peak values of these minerals are given in Tables 1 and 2. Other minerals (carbonate, phosphate, and oxides) in the meteorite are given in Table 3.

In the Raman study by [10], the Raman peaks of the silicate (olivine and orthopyroxene), sulfate (gypsum and epsomite), and sulfide (FeS) minerals from the Raman peaks collected at 532 nm wavelength for RBT 04262 Martian achondrite were given in Tables 1 and 2. Other minerals (phosphates and oxides) in the meteorite are given in Table 3. [26] reported the Raman peaks of the silicate (pyroxene with calcite) observed by 532 nm wavelength excitation in shergottite-type SaU 060 Martian achondrite. Raman peak values of this pyroxene are given in Table 1. Other minerals (carbonate and oxide) in the meteorite are given in Table 3. In the Raman study based on [27], Raman peaks of silicates (olivine, clinopyroxene, and orthopyroxene) from the Raman spectra collected at 532 nm wavelength in shergottite-type Yamato 984028 Martian achondrite were given in Table 1.

The abundance of silicate, sulfate, and sulfide minerals in Martian achondrites provides us with information about the origin of the planet Mars. Therefore, it is of great importance to investigate these achondrites and the silicate, sulfate, and sulfide minerals they contain in detail. As a result, in this study on Martian achondrites, the presence of silicate, sulfate, and sulfide minerals in eight Martian achondrites, selected based on previous studies and summarized in detail above, was investigated and silicate minerals such as olivine, fayalite, orthopyroxene, clinopyroxene, pyroxene, augite, enstatite, gypsum, The presence of sulfate minerals such as anhydrite, epsomite, rozenite and jarosite and sulfide minerals such as mackinawite, marcasite, pyrite and pyrrhotite have been observed. A summary table of the above-mentioned Raman peaks based on previous Raman studies of eight Martian achondrites is presented in Table 1 for silicate minerals, Table 2 for sulfate and sulfide minerals, and Table 3 for other minerals (e.g., phosphates, carbonates, oxides).

Silicate minerals are important in understanding the geological evolution of Mars and igneous processes. The data summarized in Table 1 quantitatively support this information, with the presence of specific mineral phases and Raman signals showing comparatively which meteorites contain these minerals. This allows for rapid examination of mineralogical similarities and differences. Sulfate and sulfide minerals, summarized in Table 2, are important indicators for the presence of water, acidic alteration, and hydrothermal processes on Mars. Raman data of these minerals provide direct evidence for the environmental processes described in the review. In particular, the presence of minerals such as jarosite and gypsum in particular is of great importance as evidence of the past existence of water on Mars. Sulfide minerals may contribute not only to geochemical processes on Mars but also to the emergence of life and astrobiological potential. These minerals are also valuable as potential biogenesis indicators. These indicators provide geobiological clues to understand whether these minerals were formed as a result of microbial activities. MIL 03346, RBT 04262, and LAR 12095 meteorites stand out as examples with the potential to be associated with microbiological processes due to their mineralogical contents and aqueous alteration phases. The minerals summarized in Table 3 are mostly found as accessory minerals, especially phosphates and oxides, which have been associated with redox conditions and potential biotic processes on Mars. Iron oxides, especially hematite and magnetite, are indicators of oxidation processes and possible biological activities on Mars. Table 3 is valuable for showing the distribution of these minerals.

The Raman peak positions presented in Table 1 show that silicate minerals (especially pyroxene subgroups and olivine) vary among meteorites. This distribution indicates the diversity of rocks formed in different magmatic environments on Mars. For example, the prominent clinopyroxene signals in sample Yamato 984028 suggest that this meteorite was derived from a more mafic rock.

According to Table 2, MIL 03346, NWA 10628 and RBT 04262 stand out among the meteorites with the highest amount of sulfate minerals. The presence of sulfate phases, particularly gypsum, jarosite and epsomite in Table 2, provides important evidence for the existence of local aqueous and acidic conditions on the Martian surface. The coexistence of such phases in meteorites such as MIL 03346 and NWA 10628 may indicate that these samples came from regions exposed to liquid water. Formation of jarosite generally occurs oxidizing conditions, which may be an indicator of areal climatic variations on Mars. Moreover, sulfide minerals such as mackinawite, pyrrhotite, and pyrite can form under both reducing and slightly oxidizing conditions. The presence of both mackinawite and hematite in LAR 12095 in particular suggests the existence of a redox gradient in this sample. This suggests that chemical heterogeneities may exist on the Martian surface at microscopic scale.

Shergottites are generally rich in pyroxene, while nakhlites are more abundant in gypsum and jarosite. This distribution reflects differences in the environments in which the meteorites formed or were altered. For instance, the presence of iddingsite in nakhlites suggests that olivine alteration was widespread and that this alteration occurred under the influence of liquid water on Mars. Alteration minerals such as iddingsite may be evidence of long-term contact with groundwater. These data suggest that milder, more water-accessible environmental conditions existed on early Mars.

Table 1. Raman peak positions (cm^{-1}) of silicate minerals for LAR 12095, Yamato 984028, MIL 03346, NWA 2975, NWA 10628, NWA 10720, RBT 04262 and SaU 060 Martian achondrites, respectively (CMRS: Confocal micro-Raman Spectrometer, MRI: microRaman Instrument, RLS: Raman Laser Spectrometer)

Minerals	**[a]LAR 12095 (532 *nm*)**	**[b]Yamato 984028 (532 *nm*)**	**[c]MIL 03346 (532 *nm*)**	**[d]NWA 2975 (532 *nm*)**			**[e]NWA 10628 (532 and 785 *nm*)**			**[f]NWA 10720 (532 *nm*)**	**[g]RBT 04262 (532 *nm*)**	**[h]SaU 060 (532 *nm*)**
		Interior Grain (IG) / Exterior Grain (EG)		**CMRS**	**MRI**	**RLS**	**532 nm**	**785 nm**				
Augite	---	---	---	135	---	---	---	133	---	---	---	---
	---	---	---	---	---	---	---	190	---	---	---	---
	---	---	---	320	321	326	---	323	---	---	---	---
	---	---	---	---	---	---	---	361	---	---	---	---
	---	---	---	389	389	393	---	391	---	---	---	---
	---	---	---	---	---	---	---	511	---	---	---	---
	---	---	---	---	---	---	---	533	---	---	---	---
	---	---	---	554	---	---	---	557	---	---	---	---
	---	---	---	664	667	665	---	665	---	---	---	---
	---	---	---	1008	1009	1013	---	1008	---	---	---	---
Augite with contribution of enstatite and pigeonite	---	---	---	131	---	---	---	---	---	---	---	---
	---	---	---	189	---	---	---	---	---	---	---	---
	---	---	---	317	---	---	---	---	---	---	---	---
	---	---	---	353	---	---	---	---	---	---	---	---
	---	---	---	386	---	---	---	---	---	---	---	---
	---	---	---	551	---	---	---	---	---	---	---	---
	---	---	---	662	---	---	---	---	---	---	---	---
	---	---	---	809	---	---	---	---	---	---	---	---
	---	---	---	918	---	---	---	---	---	---	---	---
	---	---	---	1008	---	---	---	---	---	---	---	---
Enstatite	---	---	---	135	---	---	---	---	---	---	---	---
	---	---	---	331	---	---	---	---	---	---	---	---
	---	---	---	395	---	---	---	---	---	---	---	---
	---	---	---	550	---	---	---	---	---	---	---	---
	---	---	---	668	---	---	---	---	---	---	---	---
	---	---	---	1000	---	---	---	---	---	---	---	---
Enstatite with contribution of augite	---	---	---	135	---	---	---	---	---	---	---	---
	---	---	---	224	---	---	---	---	---	---	---	---
	---	---	---	325	---	---	---	---	---	---	---	---
	---	---	---	395	---	---	---	---	---	---	---	---
	---	---	---	514	---	---	---	---	---	---	---	---
	---	---	---	535	---	---	---	---	---	---	---	---
	---	---	---	558	---	---	---	---	---	---	---	---
	---	---	---	667	---	---	---	---	---	---	---	---
	---	---	---	1000	---	---	---	---	---	---	---	---

[a][23], [b][27], [c][16]; [d][24], [e][25], [f][3]; [g][10]; [h][26]

Table 1 (Contunied). Raman peak positions (cm^{-1}) of silicate minerals for LAR 12095, Yamato 984028, MIL 03346, NWA 2975, NWA 10628, NWA 10720, RBT 04262 and SaU 060 Martian achondrites, respectively (CMRS: Confocal micro-Raman Spectrometer, MRI: microRaman Instrument, RLS: Raman Laser Spectrometer)

Minerals	**[a]LAR 12095 (532 *nm*)**	**[b]Yamato 984028 (532 *nm*)**		**[c]MIL 03346 (532 *nm*)**	**[d]NWA 2975 (532 *nm*)**			**[e]NWA 10628 (532 and 785 *nm*)**			**[f]NWA 10720 (532 *nm*)**	**[g]RBT 04262 (532 *nm*)**			**[h]SaU 060 (532 *nm*)**
		Interior Grain (IG)	**Exterior Grain (EG)**		**CMRS**	**MRI**	**RLS**	**532 nm**	**785 nm**						
Pyroxene	---		---	---	---	---	---	---	318	---	---		---		327
	332		---	---	---	---	---	---	---	---	---		---		---
	398		---	---	---	---	---	---	394	---	---		---		393
	538		---	---	---	---	---	---	---	---	---		---		---
	658		---	---	---	---	---	---	666	657	---		---		---
	672		---	---	---	---	---	---	---	---	---		---		670
	940		---	---	---	---	---	---	---	---	---		---		---
	---		---	---	---	---	---	---	---	992	---		---		---
	1003		---	---	---	---	---	---	1003	---	---		---		1002
Pyroxene with calcite grain	---		---	---	---	---	---	---	---	---	---		---		327
	---		---	---	---	---	---	---	---	---	---		---		395
	---		---	---	---	---	---	---	---	---	---		---		670
	---		---	---	---	---	---	---	---	---	---		---		1002
Orthopyroxene	---	236	---	---	---	---	---	---	---	---	---	---	---		---
	---	334	---	---	---	---	---	---	---	---	323	330	---		---
	---	410	---	---	---	---	---	---	---	---	---	395	---		---
	---	661	---	---	---	---	---	---	---	---	640	656	---		---
	---	682	---	---	---	---	---	---	---	---	663	674	---		---
	---	1007	---	---	---	---	---	---	---	---	---	1002	---		---
Clinopyroxene	---	---	228	---	---	---	---	---	---	---	---	---	---		---
	---	---	326	---	---	---	---	---	---	---	---	---	---		---
	---	---	360	---	---	---	---	---	---	---	---	---	---		---
	---	---	393	---	---	---	---	---	---	---	---	---	---		---
	---	---	532	---	---	---	---	---	---	---	---	---	---		---
	---	---	667	---	---	---	---	---	---	---	---	---	---		---
	---	---	1013	---	---	---	---	---	---	---	---	---	---		---
Fe-bearing pyroxene	---		---	---	---	---	---	---	---	---	319		---		---
	---		---	---	---	---	---	---	---	---	663		---		---
Olivine	819	---	821	---	---	---	---	---	---	---	---	820	818	818	---
	848	---	852	---	---	---	---	---	---	---	---	849	848	846	---
	---	---	917	---	---	---	---	---	---	---	---	915	---	910	---
	---	---	953	---	---	---	---	---	---	---	---	---	---	948	---

[a][23], [b][27], [c][16]; [d][24], [e][25], [f][3]; [g][10]; [h][26]

Table 1 (Contuined). Raman peak positions (cm^{-1}) of silicate minerals for LAR 12095, Yamato 984028, MIL 03346, NWA 2975, NWA 10628, NWA 10720, RBT 04262 and SaU 060 Martian achondrites, respectively (CMRS: Confocal micro-Raman Spectrometer, MRI: microRaman Instrument, RLS: Raman Laser Spectrometer)

Minerals	**[a]LAR 12095 (532 *nm*)**	**[b]Yamato 984028 (532 *nm*)**		**[c]MIL 03346 (532 *nm*)**	**[d]NWA 2975 (532 *nm*)**			**[e]NWA 10628 (532 and 785 *nm*)**			**[f]NWA 10720 (532 *nm*)**	**[g]RBT 04262 (532 *nm*)**	**[h]SaU 060 (532 *nm*)**
		Interior Grain (IG)	**Exterior Grain (EG)**		**CMRS**	**MRI**	**RLS**	**532 nm**		**785 nm**			
Olivine with Fe-oxide	---	---	---	---	---	---	---	---		---	816	---	---
	---	---	---	---	---	---	---	---		---	847	---	---
	---	---	---	---	---	---	---	---		---	---	---	---
	---	---	---	---	---	---	---	---		---	---	---	---
Fayalite	---	---		---	---	---	---	156	---	---	---	---	---
	---	---		---	---	---	---	172	---	---	---	---	---
	---	---		---	---	---	---	243	---	---	---	---	---
	---	---		---	---	---	---	292	---	---	---	---	---
	---	---		---	---	---	---	313	---	---	---	---	---
	---	---		---	---	---	---	384	---	---	---	---	---
	---	---		---	---	---	---	508	---	---	---	---	---
	---	---		---	---	---	---	574	---	---	---	---	---
	---	---		---	---	---	---	814	---	---	---	---	---
	---	---		---	---	---	---	839	---	---	---	---	---
	---	---		---	---	---	---	902	---	---	---	---	---
Iddingsite	---	---		185	---	---	---	---	---	---	185	---	---
	---	---		299	---	---	---	---	---	---	---	---	---
	---	---		---	---	---	---	---	---	---	406	---	---
	---	---		---	---	---	---	---	---	---	575	---	---
	---	---		603	---	---	---	---	---	---	---	---	---
	---	---		692	---	---	---	---	---	---	685	---	---
	---	---		---	---	---	---	---	---	---	964	---	---
	---	---		983	---	---	---	---	---	---	---	---	---
	---	---		1135	---	---	---	---	---	---	---	---	---
	---	---		---	---	---	---	---	---	---	1313	---	---
	---	---		---	---	---	---	---	---	---	1430	---	---
Feldspar	---	---		---	---	---	---	---	---	163	---	---	---
	---	---		---	---	---	---	---	183	---	---	---	---
	---	---		---	---	289	---	---	---	---	---	---	---
	---	---		---	---	---	---	---	---	---	---	---	---
	---	---		---	---	479	---	---	483	478	---	---	---
	---	---		---	---	506	---	---	511	509	---	---	---
K-feldspar	---	---		---	---	---	---	---	---	---	475	---	---
	---	---		---	---	---	---	---	---	---	513	---	---

[a][23], [b][27], [c][16]; [d][24], [e][25], [f][3]; [g][10]; [h][26]

Table 1 (Contuined). Raman peak positions (cm^{-1}) of silicate minerals for LAR 12095, Yamato 984028, MIL 03346, NWA 2975, NWA 10628, NWA 10720, RBT 04262 and SaU 060 Martian achondrites, respectively (CMRS: Confocal micro-Raman Spectrometer, MRI: microRaman Instrument, RLS: Raman Laser Spectrometer)

Minerals	**[a]LAR 12095 (532 *nm*)**	**[b]Yamato 984028 (532 *nm*)**	**[c]MIL 03346 (532 *nm*)**	**[d]NWA 2975 (532 *nm*)**			**[e]NWA 10628 (532 and 785 *nm*)**			**[f]NWA 10720 (532 *nm*)**	**[g]RBT 04262 (532 *nm*)**	**[h]SaU 060 (532 *nm*)**
		Interior Grain (IG) / **Exterior Grain (EG)**		**CMRS**	**MRI**	**RLS**	**532 nm**	**785 nm**				
Plagioclase	---	---	---	---	---	---	---	---	---	481	---	---
	---	---	---	---	---	---	---	---	---	509	---	---
Kanoite	---	---	---	---	---	---	---	322	---	---	---	---
	---	---	---	---	---	---	---	542	---	---	---	---
	---	---	---	---	---	---	---	665	---	---	---	---
	---	---	---	---	---	---	---	1000	---	---	---	---
Pyroxferroite	---	---	---	---	314	316	---	---	---	---	---	---
	---	---	---	---	385	390	---	---	---	---	---	---
	---	---	---	---	670	668	---	---	---	---	---	---
	---	---	---	---	990	995	---	---	---	---	---	---
	---		---	---	1007	1005	---	---	---	---	---	---

[a][23], [b][27], [c][16]; [d][24], [e][25], [f][3]; [g][10]; [h][26]

Table 2. Raman peak positions (cm^{-1}) of sulfate and sulfide minerals for LAR 12095, MIL 03346, NWA 2975, NWA 10628, NWA 10720, RBT 04262 and SaU 060 Martian achondrites, respectively (CMRS: Confocal micro-Raman Spectrometer, MRI: microRaman Instrument, RLS: Raman Laser Spectrometer)

Minerals	**[a]LAR 12095 (532 *nm*)**	**[b]MIL 03346 (532 *nm*)**	**[c]NWA 2975 (532 *nm*)**			**[d]NWA 10628 (532 and 785 *nm*)**	**[e]NWA 10720 (532 *nm*)**		**[f]RBT 04262 (532 *nm*)**	**[g]SaU 060 (532 *nm*)**
			CMRS	**MRI**	**RLS**	**785 nm**				
Gypsum	138	---	---	---	---	---	---	183	---	---
	183	---	---	---	---	---	---	---	---	---
	224	---	---	---	---	---	---	---	---	---
	328	---	---	---	---	---	---	---	---	---
	416	412	---	---	---	---	---	415	---	---
	435	---	---	---	---	---	---	---	---	---
	495	492	---	---	---	---	---	492	494	---
	620	618	---	---	---	---	---	620	---	---
	674	---	---	---	---	---	---	671	---	---
	1009	1008	---	---	---	1008	---	1009	1008	---
	1103	---	---	---	---	---	---	---	---	---
	1138	1141	---	---	---	---	---	1136	1136	---
	1454	---	---	---	---	---	---	---	---	---
Anhydrite	---	---	---	---	---	1018	---	---	---	---
Epsomite	---	---	---	---	---	---	---	252	---	---
	---	---	---	---	---	---	---	366	---	---
	---	---	---	---	---	---	---	446	---	---
	---	---	---	---	---	---	---	459	---	---
	---	---	---	---	---	---	---	612	---	---
	984	---	---	---	---	---	---	984	---	---
	---	---	---	---	---	---	---	1060	---	---
Jarosite	139	---	---	---	---	---	---		---	---
	224	227	---	---	---	---	---		---	---
	300	300	---	---	---	---	---		---	---
	355	360	---	---	---	---	---		---	---
	434	440	---	---	---	---	---		---	---
	454	---	---	---	---	---	---		---	---
	573	574	---	---	---	---	---		---	---
	---	626	---	---	---	---	---		---	---
	---	1010	---	---	---	---	---		---	---
	---	1107	---	---	---	---	---		---	---
	---	1157	---	---	---	---	---		---	---
Mackinawite	---	---	217	---	---	---	---		---	---
	---	---	280	---	---	---	---		---	---
	---	---	390	---	---	---	---		---	---
	---	---	476	---	---	---	---		---	---
	---	---	589	---	---	---	---		---	---
	---	---	646	---	---	---	---		---	---
	---	---	1282	---	---	---	---		---	---
Oxidized mackinawite	216	---	---	---	---	---	---		---	---
	276	---	---	---	---	---	---		---	---
Oxidized mackinawite with iron oxides	214	---	---	---	---	---	---		---	---
	274	---	---	---	---	---	---		---	---
	385	---	---	---	---	---	---		---	---
	582	---	---	---	---	---	---		---	---
Oxidized mackinawite with iron oxides and pyrrhotite	216	---	---	---	---	---	---		---	---
	282	---	---	---	---	---	---		---	---
	329	---	---	---	---	---	---		---	---
	363	---	---	---	---	---	---		---	---
	396	---	---	---	---	---	---		---	---
	583	---	---	---	---	---	---		---	---

a[23], b[27], c[16]; d[24], e[25], f[3]; g[10]; h[26]

Table 2 (Continued). Raman peak positions (cm^{-1}) of sulfate and sulfide minerals for LAR 12095, MIL 03346, NWA 2975, NWA 10628, NWA 10720, RBT 04262 and SaU 060 Martian achondrites, respectively (CMRS: Confocal micro-Raman Spectrometer, MRI: microRaman Instrument, RLS: Raman Laser Spectrometer)

Minerals	[a]LAR 12095 (532 *nm*)	[b]MIL 03346 (532 *nm*)	[c]NWA 2975 (532 *nm*)			[d]NWA 10628 (532 and 785 *nm*)	[e]NWA 10720 (532 *nm*)		[f]RBT 04262 (532 *nm*)	[g]SaU 060 (532 *nm*)
			CMRS	**MRI**	**RLS**	**785 nm**				
Pyrrhotite	---	---	213	209	---	---	---		---	---
	---	---	276	276	---	---	---		---	---
	---	---	---	---	---	---	322		---	---
	---	---	---	---	---	---	342		---	---
	---	---	---	378	---	---	380		---	---
	---	---	390	---	---	---	---		---	---
	---	---	---	---	---	---	428		---	---
	---	---	488	---	---	---	---		---	---
	---	---	589	---	---	---	---		---	---
	---	---	645	---	---	---	---		---	---
	---	---	---	---	---	---	710		---	---
	---	---	1291	---	---	---	---		---	---
Pyrite	---	---	---	---	---	---	341		---	---
	---	---	---	---	---	---	380		---	---
	---	---	---	---	---	---	428		---	---
FeS	---	---	---	---	---	---	---	216	---	---
	---	---	---	---	---	---	---	278	---	---
	---	---	---	---	---	---	---	390	---	---
Elemental sulfur	149	---	---	---	---	---	---	154	---	---
	219	---	---	---	---	---	---	221	---	---
	244	---	---	---	---	---	---	---	---	---
	---	---	---	---	---	---	---	437	---	---
	471	---	---	---	---	---	---	474	---	---
Marcasite	319	---	---	---	---	---	---		---	---
	381	---	---	---	---	---	---		---	---
Rozenite	---	---	---	---	---	990	---		---	---

[a][23], [b][27], [c][16]; [d][24], [e][25], [f][3]; [g][10]; [h][26]

Table 3. Raman peak positions (cm^{-1}) of other minerals (e.g., phosphates, carbonates, oxides) for LAR 12095, MIL 03346, NWA 2975, NWA 10628, NWA 10720, RBT 04262 and SaU 060 Martian achondrites, respectively (CMRS: Confocal micro-Raman Spectrometer, MRI: microRaman Instrument, RLS: Raman Laser Spectrometer)

Minerals	**[a]LAR 12095 (532 *nm*)**	**[b]MIL 03346 (532 *nm*)**	**[c]NWA 2975 (532 *nm*)**			**[d]NWA 10628 (532 and 785 *nm*)**			**[e]NWA 10720 (532 *nm*)**	**[f]RBT 04262 (532 *nm*)**	**[g]SaU 060 (532 *nm*)**
			CMRS	**MRI**	**RLS**		**785 nm**				
Hematite	220	---	---	222	---	---	227	224	---	---	---
	---	---	---	---	---	---	246	241	---	---	---
	288	---	---	292	---	---	295	291	---	---	---
	---	---	---	---	---	---	327	---	---	---	---
	---	---	---	---	---	---	390	---	---	---	---
	400	---	---	408	---	---	412	406	---	---	---
	493	---	---	507	---	---	500	---	---	---	---
	---	---	---	---	---	---	549	---	---	---	---
	601	---	---	605	---	---	610	609	607	---	---
	665	---	---	659	---	---	---	---	657	---	---
	---	---	---	1318	---	---	---	1311	---	---	---
Magnetite	---	---	---	---	---	---	---	543	---	---	---
	---	---	---	658	---	---	---	663	---	---	---
Ti-magnetite	---	---	---	---	---	---	---		305	---	---
	---	---	---	---	---	---	---		547	---	---
	---	---	---	---	---	---	---		674	---	---
Ilmenite	---	---	---	---	---	---	---	223	---	---	---
	---	---	---	---	---	---	---	---	334	---	---
	---	---	---	---	---	---	---	369	367	---	---
	---	---	---	---	---	---	---	677	677	---	---
Goethite	---	---	---	---	---	---	301	---	---	---	---
	---	---	---	---	---	---	394	---	---	---	---
	---	---	---	---	---	---	476	---	---	---	---
	---	---	---	---	---	---	553	---	---	---	---
Maghemite	---	---	---	---	---	---	---		185	---	---
	---	---	---	---	---	---	---		340	---	---
	---	---	---	---	---	---	---		494	---	---
	---	---	---	---	---	---	---		650	---	---
	---	---	---	---	---	---	---		720	---	---
	---	---	---	---	---	---	---		1314	---	---
	---	---	---	---	---	---	---		1430	---	---
Titanomagnetite	---	---	---	---	---	---	---		---	302	---
		---	---	---	---	---	---		---	406	---
		---	---	---	---	---	---		---	526	---
		---	---	---	---	---	---		---	672	---
Anatase	---	---	---	---	---	---	---		143	---	---
	---	---	---	---	---	193	---		---	---	---
	---	---	---	---	---	392	---		397	---	393
	---	---	---	---	---	516	---		515	---	512
	---	---	---	---	---	639	---		638	---	632
Apatite	---	---	591	---	---	---	---		---	---	---
	---	---	---	956	---	---	---		962	---	---
	---	---	1047	---	---	---	---		---	---	---
Merrillite	---	---	132	---	---	---	---	---	---	---	---
	---	---	289	---	---	---	---	290	---	---	---
	---	---	---	---	---	---	---	---	---	356	---
	---	---	408	---	---	---	---	408	---	410	---
	---	---	447	---	---	---	---	449	---	448	---
	---	---	552	---	---	---	---	556	---	547	---
	---	---	---	---	---	---	---	---	---	595	---
	---	---	606	---	---	---	---	606	---	---	---
	---	---	626	---	620	---	---	628	---	622	---
	---	---	957	---	962	---	958	---	---	958	---
	---	---	972	---	976	---	977	---	---	974	---
	---	---	---	---	---	---	---	---	---	1046	---
	---	---	1084	---	---	---	---	---	---	1082	---

[a][23], [b][27], [c][16]; [d][24], [e][25], [f][3]; [g][10]; [h][26]

Table 3 (Continued). Raman peak positions (cm^{-1}) of other minerals (e.g., phosphates, carbonates, oxides) for LAR 12095, MIL 03346, NWA 2975, NWA 10628, NWA 10720, RBT 04262 and SaU 060 Martian achondrites, respectively (CMRS: Confocal micro-Raman Spectrometer, MRI: microRaman Instrument, RLS: Raman Laser Spectrometer)

Minerals	**[a]LAR 12095 (532 *nm*)**	**[b]MIL 03346 (532 *nm*)**	**[c]NWA 2975 (532 *nm*)**			**[d]NWA 10628 (532 and 785 *nm*)**			**[e]NWA 10720 (532 *nm*)**	**[f]RBT 04262 (532 *nm*)**	**[g]SaU 060 (532 *nm*)**
			CMRS	**MRI**	**RLS**		**785 nm**				
Calcite	---	---	---	---	---	---	---	154	---	---	---
	---	---	---	281	---	282	---	281	---	---	---
	---	---	---	711	---	714	---	713	---	---	---
	---	---	---	1087	---	1088	---	1086	1086	---	---
Carbon	---	---	---	---	---	---	---	1577	---	---	---
Carbonate	---	---	---	---	---	---	---		---	---	280
	---	---	---	---	---	---	---		---	---	1083
Glassy inclusions	---	---	---	---	---	---	---		364	---	---
	---	---	---	---	---	---	---		691	---	---

[a][23], [b][27], [c][16]; [d][24], [e][25], [f][3]; [g][10]; [h][26]

IV. CONCLUSIONS

In this study, a brief review of previous Raman analysis studies of silicate (e.g., olivine, fayalite, orthopyroxene, clinopyroxene, pyroxene, augite, enstatite), sulfate (e.g., gypsum, anhydrite, epsomite, rozenite, and jarosite), and sulfide (e.g., mackinawite, marcasite, pyrite, and pyrrhotite) minerals selected from Martian achondrites, which are very important for understanding the origin of the planet Mars, was made. Data obtained from Raman peak positions of silicate, sulfate, and sulfide minerals commonly found in Martian meteorites provide multi-layered information about the planet's magmatic, hydrothermal, and surface alteration processes. The mineral contents of different meteorite types (shergottite, nakhlite, chassignite) allow interpretation of the environments in which they were formed. The presence of some minerals only in certain meteorites indicates the existence of regional differences in the Martian crust. In all three tables, the meteorites in which the minerals are observed, the spectroscopy wavelengths in which they are detected, and the characteristic peaks are presented in detail. In this way, the compilation becomes not only qualitative but also quantitative. The tables can serve as a basic reference for the scientific community for future spectroscopic comparisons, analysis of SHERLOC data, and mineralogical mapping of Mars [28-31].

It was difficult to make a comparative analysis due to the scattered Raman spectroscopy data in the literature; this study fills this gap. There were very few sources that both defined the mineral phases and systematically showed which meteorites they were found. Therefore, it is obvious that it is necessary to organize the spectra published within the scope of Raman analyses in order to create a database based on the studies carried out on selected silicate, sulfate and sulfide minerals within the scope of the study. Therefore, the importance of summarizing such minerals within a study cannot be denied in terms of a database useful for researchers in the field. This study also has the potential to identify possible past habitability based on silicates (e.g. phyllosilicates) and sulfates on Mars, and it has also made a significant contribution to the lack of spectral references required for data interpretation of SHERLOC and similar Mars missions.

It is hoped that this literature overview will be a starting point in constructing a database of silicate, sulfate, and sulfide minerals found in Martian achondritic meteorites. Detailed examination of the presence of silicate, sulfate, and sulfide minerals in SNC-type Martian achondrites allows us to understand the geologic evolution of Mars, including its aqueous alterations and the past environmental conditions. A consolidated database will be a useful library for verification of Raman spectra currently carried out by SHERLOC onboard Perseverance (Mars 2020)

[28-31]. Therefore, published Raman spectra compiled by combining silicate, sulfate, and sulfide minerals in selected Martian achondrite samples may be useful and guiding for readers and researchers in this field. Additionally, integrated analyses of complementary techniques such as XRD and EDS together with Raman data will provide more precise determination of mineral phases. More detailed environmental modeling of Mars' surface conditions can be done by statistical modeling based on quantitative analysis of Raman spectra (e.g., bandwidth, intensity). Such systematic data tables can be used as a basic reference for the calibration of next-generation spectrometers to be sent to Mars.

REFERENCES

1. Norton OR, Chitwood LA (2008) Field guide to meteors and meteorites. Springer, London. https://doi.org/10.1007/978-1-84800-157-2
2. Kamil C, Unsalan O (2022) A short review on enstatite and pyroxene in L6 chondrites studied by Raman Spectroscopy. Journal of Spec. and Mol. Sci 4(1):163-170.
3. Cao H, Chen J, Fu X, Xin Y, Qi X, Shi E, Ling Z (2022) Raman spectroscopic and geochemical studies of primary and secondary minerals in Martian meteorite Northwest Africa 10720. J Raman Spectrosc 53(3):420. https://doi.org/10.1002/jrs.6254
4. McSween HY, Stolper EM (1980) Basaltic meteorites and their parent planets. Scientific American 242(6):54-63. https://doi.org/10.1038/scientificamerican0680-54
5. Cassidy WA (2003) Meteorites, ice, and Antarctica. Cambridge University Press, New York.
6. MetBull. Meteoritical Bulletin Database. https://www.lpi.usra.edu/meteor/metbull.php, Accessed 3 March 2025
7. Treiman, AH (2005) The nakhlite meteorites: Augite-rich igneous rocks from Mars. Chem. der Erde Geochem 65(3):203-270. https://doi.org/10.1016/j.chemer.2005.01.004
8. Papike JJ, Karner JM, Spilde MN, Shearer CK, Burger PV (2009) Silicate mineralogy of Martian meteorites. Geochim. Cosmochim. Acta 73(24):7443-7485. https://doi.org/10.1016/j.gca.2009.09.008
9. Prinz M, Hlava PH, Keil K (1974) The Chassigny meteorite: A relatively iron-rich cumulate dunite. Meteoritics 9:393-394.
10. Huidobro J, Aramendia J, García-Florentino C, Ruiz-Galende P, Torre-Fdez I, Castro K, Arana G, Madariaga JM (2021) Mineralogy of the RBT 04262 Martian meteorite as determined by micro-Raman and micro-X-ray fluorescence spectroscopies. J Raman Spectrosc 53(3):450-462. https://doi.org/10.1002/jrs.6291
11. Takenouchi A, Mikouchi T, Yamaguchi A (2018) Shock veins and brown olivine in Martian meteorites: Implications for their shock pressure–temperature histories. Meteorit. Planet. Sci 53(11):2259-2284. https://doi.org/10.1111/maps.13120
12. Hu J, Sharp TG (2022) Formation, preservation and extinction of high-pressure minerals in meteorites: Temperature effects in shock metamorphism and shock classification. Prog. Earth Planet. Sci 9:6. https://doi.org/10.1186/s40645-021-00463-2
13. Lancelot E (2010) Raman spectroscopy for geological materials analysis. Technical Report.
14. Caporali S, Moggi-Cecchi V, Muniz-Miranda M, Pagliai M, Pratesi G, Schettino V (2012) SERS investigation of possible extraterrestrial life traces: Experimental adsorption of adenine on a Martian meteorite. Meteorit. Planet. Sci 47(5):853-860. https://doi.org/10.1111/j.1945-5100.2012.01361.x
15. Chen M, Xie X, El Goresy A (2004) A shock-produced (Mg, Fe)SiO3 glass in the Suizhou meteorite. Meteorit. Planet. Sci 39(11):1797-1808. https://doi.org/10.1111/j.1945-5100.2004.tb00076.x
16. Hallis LJ (2013) Alteration assemblages in the Miller Range and Elephant Moraine regions of Antarctica: Comparisons between terrestrial igneous rocks and Martian meteorites. Meteorit. Planet. Sci 48(2):165-179. https://doi.org/10.1111/maps.12049
17. Alpers CN, Jambor JL, Nordstrom DK (2000) Sulfate minerals: Crystallography, geochemistry, and environmental significance. Ribbe, PH, eds. Mineral. Society of America 40:608.
18. Vaughan DJ (2005) Minerals/Sulphides. Selley RC, Cocks LRM, Plimer IR, eds. Encyc. of Geol 574-586. https://doi.org/10.1016/B0-12-369396-9/00276-8
19. Treiman, AH (2006) Sulfate-Bearing minerals in the Martian meteorites. Martian Sulfates as Recorders of Atmospheric-Fluid-Rock Interactions Workshop, Houston, Texas, Oct. 22-24.
20. King PL, McLennan SM (2010) Sulfur on Mars. Elements 6(2):107-112. https://doi.org/10.2113/gselements.6.2.107

21. Dehoucka E, Chevrierb V, Gaudina A, Mangolda N, Matheć PE, Rochette P (2012) Evaluating the role of sulfide-weathering in the formationof sulfates or carbonates on Mars. Geochim. Cosmochim. Acta 90:47-63. https://doi.org/10.1016/j.gca.2012.04.057
22. Stawski TM, Van Driessche AES (2022) Formation of Sulfate Minerals in Natural and Industrial Environments. Minerals 12(3):299. https://doi.org/10.3390/min12030299
23. Huidobro J, Aramendia J, García-Florentino C, Poblacíon I, Castro K, Arana G, Madariaga JM (2023) Mineralogy of the LAR 12095 Martian shergottite as determined by micro-Raman and micro-X-ray fluorescence spectroscopies. J Raman Spectrosc 54(1):1248-1257. https://doi.org/10.1002/jrs.6558
24. Población I, Torre-Fdez I, Aramendia J, López-Reyes G, Cabalín LM, Madariaga JM, Rull F, Laserna JJ, Carrizo D, Martínez-Frías J, Belenguer T, Taravillo M, Dell'Aglio M, De Giacomo A, Huidobro J, Manrique JA, Delgado T, Arana G, Castro K, Veneranda M, Sanz-Arranz JA, Fortes FJ, García-Gómez L, the SIGUE-Mars team (2023) Raman spectroscopy, assisted by X-ray fluorescence and laser-induced breakdown spectroscopy, to characterise original and altered mineral phases in the NWA 2975 Martian shergottite. J Raman Spectrosc 54(11):1233-1247. https://doi.org/10.1002/jrs.6560
25. Prieto-delaVega I, García-Florentino C, Torre-Fdez I, Huidobro J, Aramendia J, Arana G, Castro K, Madariaga JM (2022) Original and alteration mineral phases in the NWA 10628 Martian shergottite determined by micro-Raman spectroscopy assisted with micro-energy dispersive X-ray fluorescence imaging. J Raman Spectrosc 53(3):435-449. https://doi.org/10.1002/jrs.6305
26. Hochleitner R, Tarcea N, Simon G, Kiefer W, Popp J (2004) Micro-Raman spectroscopy: a valuable tool for the investigation of extraterrestrial material. J Raman Spectrosc 35(6):515-518. https://doi.org/10.1002/jrs.1190
27. Dyar MD, Glotch TD, Lane MD, Wopenka B, Tucker JM, Seaman SJ, Marchand GJ, Klima R, Hiroi T, Bishop JL, Pieters C, Sunshine J (2011) Spectroscopy of Yamato 984028. Polar Sci 4:530-549.
28. Haney NC, Morris RV, Jakubek RS, Lapen T, Fries MD, Graff TG (2023) Effects of Mars Analogue Dust Deposition on DUV Raman Spectra: Implications for the Mars2020 Perserverance Rover SHERLOC Instrument. 54th Lunar and Planetary Science Conference (LPSC 2023), The Woodlands, Texas, March 13-17.
29. Jakubek RS, Fries MD (2023) Laser Raman Induced Degradation of Macromolecular Carbon in Coals and Meteorites. Earth Space Sci 10(6):1-17. https://doi.org/10.1029/2022EA002724
30. Sharma S, Roppel RD, Murphy AE et al (2023) Diverse organic-mineral associations in Jezero crater Mars. Nature 619:724-732. https://doi.org/10.1038/s41586-023-06143-z
31. Jakubek RS, Bhartia R, Uckert K et al (2024) Calibration of Raman Bandwidths on the Scanning Habitable Environments with Raman and Luminescence for Organics and Chemicals (SHERLOC) Deep Ultraviolet Raman and Fluorescence Instrument Aboard the Perseverance Rover. Appl. Spec 78(9):993-1008. https://doi.org/10.1177/00037028231210885