# PARSA ENSTATITE CHONDRITE: A MINERALOGIC AND TEXTURAL ANALYSIS

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### ABSTRACT

The mineralogy and petrology of Parsa, an EH4 enstatite chondrite (Bhandari et al., 1980), was analyzed with an emphasis on the rare mineral roedderite [(Na,K)<sub>2</sub>(Mg,Fe)<sub>5</sub>Si<sub>12</sub>O<sub>30</sub>)] using a scanning electron microscope, a JEOL Hyperprobe, and a Raman spectrometer. The dominant minerals in Parsa include enstatite (Mg<sub>2</sub>Si<sub>2</sub>O<sub>6</sub>), kamacite (Fe-Ni alloy, more than 90-95 wt% Fe), troilite (FeS), and taenite (Fe-Ni alloy, more than 20 wt% Ni), indicating formation under highly reducing conditions. Secondary minerals include albite (NaAlSi<sub>3</sub> $O_8$ ), quartz (SiO<sub>2</sub>), daubreelite (FeCr<sub>2</sub>S<sub>4</sub>), caswellsilverite (NaCrS<sub>2</sub>), roedderite, and a mystery Ca-Mg-silicate. The minerals are fragmented, creating a brecciated texture, with only the primary minerals forming crystals larger than 300 µm. All minerals are surrounded by FeO(OH), a weathering product of iron-containing minerals. Both kamacite and taenite contain up to 15 wt% Si, with more partitioned into taenite. Kamacite contains quartz inclusions, whereas taenite does not. The metallic minerals demonstrate partial melting, indicating that Parsa's parent body underwent a heating episode. Roedderite occurs as elongated euhedral crystals, commonly as inclusions in troilite. All crystals are less than 15 µm across. K and Na typically occur in a 1:1 atomic ratio with no apparent zoning. Roedderite contained within troilite typically forms euhedral to subhedral, unbrecciated prisms with aspect ratios of  $\sim$ 5, whereas roedderite crystals surrounded by brecciated silicates are typically anhedral. This difference in morphology may reflect differences in the physical properties of the troilite and other phases.

## **1. INTRODUCTION**

Meteorites provide a critical look into the solar system's past. The Earth's early history has been obliterated by tectonic processes and erosion, but many meteorites date back to the solar system's formation 4.5 billion years ago. Enstatite chondrites are a type of stony meteorite that contains chondrules and a higher percentage of enstatite relative to other chondrites. These rare and primitive meteorites are perhaps the best candidates to model the starting material of the earth (Javoy, 1995; Javoy et al., 2010; Smith, 1982), and thus information about them can lead to a more accurate understanding of the processes that shaped the present-day Earth.

The familiar iron meteorites represent the cores of planetary bodies and are relatively rare among meteorite falls. Chondrites, which greatly outnumber irons among falls, are stony meteorites. They are relatively unmodified material from the solar nebula, and isotopic ages of chondrites date back to formation of the solar system (McSween, 1987). <sup>87</sup>Rb-<sup>86</sup>Sr ages chondrites of  $4.50 \pm 0.015$  billion years (Minster et al., 1982) and the presence of <sup>129</sup>Xe, a decay product of short-lived <sup>129</sup>I, in chondrites indicates that they were witnesses to formation of the solar system (McSween, 1987).

Chondrites are also relatively unmodified solar nebula material: similar elemental composition ratios between chondrites and the Sun indicate that the meteorites are scarcely fractionated (McSween, 1987). Petrologic and mineralogical study of the typical characteristics of chemically unaltered chondrites can provide a comparison to altered chondrites; by studying the initial and final products, hypotheses of alteration processes can be made. This thesis is half of the equation: a study of the initial product, a relatively unaltered enstatite chondrite.

Chondritic meteorites are typically divided into three types: ordinary,

carbonaceous, and enstatite (McSween, 1987). Enstatite chondrites may provide a good model for the solar nebula material that accreted to form Earth (Javoy, 1995; Javoy et. el. 2010; Smith, 1982). Enstatite chondrites are highly reduced and have a higher percentage of essentially Fe-free enstatite and a higher proportion of metallic Fe than other chondrites (McSween, 1987). Their low oxidation state is similar to Earth's (Javoy 1995), suggesting that the chondrite's parent body and the Earth formed at a comparable distance from the Sun (McSween, 1987). Further, oxygen isotope ratios in enstatite chondrites are nearly identical to Earth's (Javoy 1995). These similarities support the hypothesis that enstatite chondrites can be a valid model of a primordial Earth (Javoy, 1995).

I examined a fragment of the Parsa enstatite chondrite, an EH4 meteorite that fell in India in 1942. The EH4 classification implies a high percentage of metallic Fe and a relatively unmodified state (Van Schmus and Wood, 1967). Dr. Tim McCoy from the Smithsonian Institution for Natural History provided a  $\sim 1 \text{ cm}^2$  polished thin section of the meteorite (Figure 1).



Figure 1. Mosaic of 16 backscattered electron SEM images of the Parsa thin section.

In this thesis I discuss the general mineralogy and texture of this meteorite fragment, with emphasis on roedderite  $[(Na, K)_2(Mg,Fe)_5Si_{12}O_{30}]$ . Roedderite was originally thought to form exclusively in extraterrestrial material, but subsequent research has found it in volcanic ejecta in Eifel, Germany (Hentschel et al., 1980). I emphasized analysis of roedderite due to the lack of literature on its occurrence and formation. This information is necessary to understand its alkali-rich presence in extraterrestrial material.

Roedderite is a member of the osumilite  $[(K,Na)(Fe^{2+},Mg)_2(Al,Fe^{3+})_3(Si,Al)_{12}O_{30}]$ mineral group (Olsen, 1967). It has a complex hexagonal crystallographic structure, with double hexagonal rings composed of (Si, Al)-tetrahedra (Hentschel et al., 1980). This structure allows for a cavity in between the rings (Hentschel et al., 1980). In osumilite, which lacks one of roedderite's 12-fold cations, water may reside in this cavity (Hentschel et al., 1980). The extra cation in roedderite could supplant molecular water within the rings (Schreyer and Schairer, 1962), but later research suggested that the complex hexagonal structure could potentially accommodate two 12-fold cations without filling the inner-ring cavity (Seifert and Schreyer, 1969).

The terrestrial occurrence of roedderite in volcanic ejecta in Eifel, Germany, most likely formed via contact metamorphism of gneiss by tephritic magma (Hentschel et al., 1980). Extraterrestrial roedderite occurrences are thought to form in the presence of a fluid phase during post-accretion processes on their parent body (Rambaldi et al., 1986).

### 2. METHODS

This study utilized a variety of imaging and quantitative instruments to determine the mineralogy and petrology of Parsa. A scanning electron microscope, electron microprobe, and Raman spectrometer were the major analytical instruments, with minor imaging contributions from an FEI Helios 600 Nanolab Dual Beam System in the Chapel Hill Analytical and Nanofabrication Laboratory (CHANL) on UNC Chapel Hill's campus with the aid of Dr. Carrie Donley.

### 2.1 Scanning Electron Microscope Analysis

The Tescan Vega 5130 SEM in UNC Chapel Hill's Department of Geological Sciences was used for imaging and energy-dispersive X-ray (EDX) analysis. The SEM has a thermionic W filament, and the X-ray analysis system uses a Sirius silicon drift detector with a 4pi spectral analyzer and software. Imaging modes include secondary electron, backscattered electron, and cathodoluminescence. The instrument was typically run with a 15 kV accelerating voltage.

The SEM was mainly used to find possible roedderite occurrences by utilizing its EDX capabilities. Roedderite crystals in Parsa are both rare and small; they are recognized by their high abundance of K. X-ray maps, typically at a magnification of 180x-220x, were used to find hotspots of K (Figures 2A-B). If the K frame exhibited an area of high concentration, point analyses gave semiquantitative compositional data for the region (Figure 3). The maps were also used in the program ENVI (see section **2.4 ENVI**) to estimate modal abundances of the primary minerals in Parsa. The SEM was set for an 8-oxygen mineral.



Figure 2A (left). X-ray map of Mg. Figure 2B (right). X-ray map of K.



Figure 3. Semiquantitative elemental data for a roedderite grain using the SEM's point analysis tool.

Five different areas of the thin section were X-ray mapped at magnifications ranging from 180x-220x. The time constant was set to 0.8  $\mu$ s in order to maximize the count rate, at the expense of detector resolution. All maps have a resolution of 1280x960 pixels and consist of averages of 75 frames, with dwell times ranging from 45 to 75  $\mu$ s, requiring 1-2 hours per map. There is little difference between the products of a 45 and 75  $\mu$ s dwell time.

The SEM provided semiquantitative data on Parsa's minerals. Generally, the probe current for point analyses was kept low in order to keep the absorption current high (1-5 nA). When analyzing a possible roedderite crystal, all elements that are not included in its formula were excluded from analysis.

# 2.2 Electron Microprobe Analysis

The majority of quantitative compositional data and high-resolution images in this study resulted from electron microprobe analysis (EMPA) with a JEOL JXA-8530F Hyperprobe at the Southeastern North Carolina Regional Microanalytical and Imaging Consortium (SENCR-MIC) at Fayetteville State University, under the direction of lab technician Nicholas Foster. Table 1 shows the standards used for each analyzed element and the crystal they were loaded on (LIF, PET, or TAP).

TABLE 1. STANDARDS FOR THE JEOL HYPERPROBE								
Element	Mineral Standard	Mineral Locale	Crystal					
Al	Grossular Garnet		TAP					
Ca	Diopside	Wakefield, Quebec	PET					
Со	Pure Metal		LIF					
Cr	Pure Metal		LIF					
Cu	Cuprite	Synthetic	LIF					
Fe	Fayalite/Pyrite <sup>1</sup>	/Locality unknown	LIF					
K	Sanidine		PET					
Mg	Olivine	San Carlos	TAP					
Na	Albite	Strickland Quarry, Haddam, CT, USA	TAP					
Ni	Ni Silicide/Pure Metal <sup>1</sup>	Synthetic/	LIF					
S	Pyrite		PET					
Si	Grossular Garnet		TAP					

<sup>1</sup>X/Y: X was used for silicate minerals, Y for sulphides.

#### 2.3 Raman Spectroscopy

Raman spectroscopy was used to differentiate between phases of a mineral (e.g., quartz and tridymite). I used the Raman spectrometer in UNC Chapel Hill's Department of Physics and Astronomy, with the help of Dr. Laurie McNeil. Raman analysis uses a high magnification optical microscope and a Genesis CX SLM 4W optically-pumped, solid-state laser with a spot size of 2  $\mu$ m, operating at 532 nanometers. Fluorescent lights are extinguished during analysis and the analysis is performed twice for 2 to 4 minutes each to average out false peaks caused by cosmic rays. The resulting spectrum can be cross-referenced with the RRUFF online database. Phases can only be determined if a previous study posted the Raman pattern for the crystalline phase.

#### 2.4 Image Analysis

The geospatial analysis program ENVI was used to make phase maps from electron and X-ray images, using a method developed by Stephen Challener, a senior undergraduate in the UNC Chapel Hill Geological Sciences department. The step-by-step process for one element's X-ray map from the Revolution software is described below and continues into the stacking and classification of maps. Before step 1, the user must extract the X-ray maps for each element from Revolution and save them as image files.

- 1. Load image into Adobe Photoshop and grayscale (Image $\rightarrow$ Mode $\rightarrow$ Grayscale)
- 2. Crop image to 1280 x 960 pixels
  - a. Keep all X-ray data; only crop the information band (with scale and magnification) out

- Load image into ENVI and georeference (Map→Registration→Select GCPs: Image to Image)
  - a. Note: must have a previously-georeferenced, 1280 x 960 pixel image as a reference to select GCPs; download an ASTER GLOBAL DEM image from earthexplorer.usgs.gov and load this image into ENVI as the base image (the location of the DEM does not matter); use this to georeference all X-ray images
  - b. These should be the only two images in windows
  - c. Select one point, such as the top-left corner, on the base image and its corresponding point on the X-ray image. Repeat for at least three corners.
- 4. Repeat steps 1-3 for all desired elements and save separately
- 5. Stack each element's image (Basic Tools $\rightarrow$ Layer Stacking $\rightarrow$ Import File)
  - a. This step allows each image to be a band in the stacked image
  - b. The imported files are the saved images from Step 4
- 6. Apply 9x9 Gaussian blur on stacked image (Filter→Convolutions and Morphology→Convolutions→Gaussian Low Pass) to smooth the image
  - a. The size of the smoothing kernel controls the amount of smoothing
- 7. Load stacked and blurred image into a window
- Overlay regions of interest (ROIs) on unique minerals identified by their spectra
- 9. Classify the image (Classification→Supervised→Maximum Likelihood)
  - a. Use the ROIs from step 8

b. Steps 8 and 9 may need to be repeated for a satisfactory result

In step 8, I distinguished minerals by color: each sub-image in the stacked image can be loaded into the red, green, or blue (RGB) color bands. These produce a colorcoded map that is dependent on the element that is in each band. As an example, with Fe in the red band, Ni in the green, and S in the blue, kamacite appears orange, troilite purple, and taenite green (Figure 4). Regions of interest are overlain on these identified minerals. Step 9 classifies all pixels in the image according to the denoted ROIs. Using various RGB combinations, all major minerals are classified (Figure 5).

ENVI software can calculate the area of each classified area, which is synonymous to approximate modal percent for that mineral. Modal percentages for three X-ray areas were individually calculated and averaged to estimate area percentages of the phases. To determine the area percentage of a single element, the Decision Tree Classification tool in ENVI was applied to that element's image. Pixels in ENVI are given a value from 0-255. To estimate the noise cut-off pixel value of 25, I used the Ni X-ray image to determine a value that left the silicate minerals predominantly black, assuming that silicates have little Ni in them and those points were noise. The X-ray images have noise that should not contribute to the area percentage of the element. Using Classification  $\rightarrow$  Decision Tree  $\rightarrow$  Build New Decision Tree and inputting the equation {variable name: [band number]} GT 25 (Figure 6), ENVI assigned all pixels less than 25 to '0' and all pixels greater than 25 to '1.' Zero-valued pixels are black and one-valued pixels are white. The 'Basic Stats' tool contained the percentage of pixels in the image that were '1,' which is analogous to element percent. This method was repeated for any map of that element and the results were averaged.



Figure 4. ENVI image with Fe in the R band, Ni in the G band, and S in the B band. Regions of interest (ROI) are overlain on the minerals; the green ROI (denoted in figure) is kamacite, the red ROI is troilite, and the blue ROI is taenite.



Figure 5. Classified ENVI image using the Maximum Likelihood supervised method.

000	X ENVI Decision Tree
File Options Help	
Aluminum_	OOOX Edit Decision Properties   Name Aluminum_I   Expression:   {Warp (Image (Al.jpg):[1]) GT 25   OK Cancel   Execute
Node 1: "" [0 (0.00%)]	

Figure 6. Screen capture of the ENVI Decision Tree method. Clicking on the 'Aluminum\_1' button brings up the equation box.

# **3. RESULTS AND DISCUSSION**

# **3.1 General Mineralogy**

The primary minerals in Parsa include enstatite, kamacite, troilite, FeO(OH), and taenite. The majority of the matrix is FeO(OH) (Dr. Tim McCoy, personal communication), a weathering product of Fe-containing minerals. FIB CHANL semiquantitative data confirmed an Fe:O ratio of 1:2. Raman spectroscopy could not determine the FeO(OH) phase; the spectrum from Parsa did not overlap with a spectrum from the RRUFF database (Figure 7A and 7B). The database only has spectrum for lepidocrocite and goethite phases; the Parsa FeO(OH) phase is a different mineral.





Figures 7A (top) and 7B (bottom). Comparison of the Parsa FeO(OH) Raman spectrum (blue) to the goethite (top, black) and lepidocrocite (bottom, black) Raman spectra. Goethite locale is Alexander mine, Czech Republic, analyzed by Michael Scott. Lepidocrocite locale is Malvern, PA, USA, analyzed by the University of Arizona Mineral Museum.

Secondary minerals include albite, quartz, roedderite, daubreelite,

caswellsilverite, and a mystery Ca-Mg-silicate (Figure 8). Table 2 depicts modal percentages for the primary minerals and their weathered, matrix byproduct using the ENVI method. They are normalized to 100%, ignoring secondary minerals classified in the ENVI image. Figure 9 visually shows the normative modal percentages of minerals. Albite and the mystery Ca-Mg-silicate are commonly located in or near enstatite, while

quartz is commonly an inclusion in kamacite (Figure 10). The identity of quartz was verified by Raman spectroscopy (Figure 11) after co-referencing with the RRUFF online database. Daubreelite and caswellsilverite are rare and occur as 10-20 µm crystals in the matrix.

![](_page_14_Figure_2.jpeg)

Figure 8. Semiquantitative elemental data for the mystery Ca-Mg-silicate grain using the SEM's point analysis tool.

WEATHERED BYPRODUCT IN PARSA. NUMBERS 1-3 REFER TO THE THREE CLASSIFIED X- RAY AREAS.							
Mineral	1	2	3	Average			
Enstatite	45.9	39.2	37.4	40.8			
Kamacite	6.9	7.2	6.5	6.9			
Troilite	5.4	8.3	9.1	7.6			
Taenite	2.5	4.0	3.8	3.4			
FeO(OH)	29.3	41.2	43.3	41.3			
Total	100	100	100	100			
Other	19.0	10.5	12.8	14.4			

TABLE 2. NORMALIZED MODAL PERCENTAGES FOR THE PRIMARY MINERALS AND

![](_page_15_Figure_1.jpeg)

Figure 9. Bar graph depicting the normative modal percentages of minerals in each X-ray area from Table 2.

![](_page_15_Picture_3.jpeg)

Figure 10. Kamacite grain with quartz inclusions outlined in red. JEOL Hyperprobe imaging.

![](_page_16_Figure_1.jpeg)

Figure 11. Raman spectrum for an SiO<sub>2</sub> inclusion in kamacite (blue). The black spectrum is a quartz Raman pattern for comparison from the RRUFF database; the quartz locale is Spruce Claim, King County, Washington, USA, analyzed by Bob Downs. Characteristic peak heights occur at the same wave numbers.

Table 3 shows compositions of kamacite, taenite, and troilite. The Fe:Ni ratio is

approximately 0.94 in kamacite and 0.20 in taenite. Si is present in both kamacite and

taenite, but is ~5 times more abundant in the latter. Other trace metal data depict partition

TABLE 3 ELEMENT WEIGHT PERCENTAGES IN KAMACITE TAENITE AND TROUTE AND

differences between kanacite, taefine, and troffile as well (Table 5).
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COMPARATIVE RATIOS.									
Crystal	Са	Со	Cu	Cr	Fe	Ni	S	Si	Total
Kamacite									
1	0.01	0.48	0.05	0.01	93.77	2.38	0.04	2.04	98.77
2	0.03	0.47	0.04	0.00	93.69	2.75	0.00	2.24	99.23
3	0.01	0.49	0.00	0.08	94.02	2.62	0.05	2.03	99.29
4	0.03	0.46	0.05	0.02	93.68	2.91	0.02	2.06	99.22
5	0.03	0.46	0.00	0.04	94.77	2.81	0.00	2.04	100.16
Average	0.02	0.47	0.03	0.03	93.99	2.69	0.02	2.08	99.33
SD1	0.01	0.01	0.03	0.03	0.46	0.21	0.02	0.09	
Taenite									
1	0.01	0.02	0.42	0.01	6.04	79.98	0.12	11.46	98.06
2	0.03	0.02	0.30	0.00	6.27	80.28	0.07	11.82	98.88

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3	0.04	0.00	0.31	0.00	6.16	80.35	0.11	11.47	98.43
4	0.03	0.03	0.39	0.02	6.56	80.66	0.04	11.51	99.24
5	0.02	0.01	0.29	0.01	7.56	80.34	0.02	11.49	99.74
Average	0.03	0.02	0.34	0.01	6.52	80.34	0.07	11.55	98.87
SD1	0.01	0.01	0.06	0.01	0.61	0.24	0.04	0.15	
Troilite									
1	0.00	0.07	0.15	0.60	60.96	0.40	35.00	0.00	97.18
2	0.00	0.07	0.10	0.70	60.78	0.05	36.17	0.00	97.87
3	0.00	0.09	0.10	0.77	60.73	0.00	36.43	0.03	98.15
4	0.04	0.08	0.04	0.82	60.92	0.00	36.26	0.01	98.16
5	0.06	0.05	0.14	0.82	60.71	0.00	36.40	0.01	98.18
Average	0.02	0.07	0.11	0.74	60.82	0.09	36.05	0.01	97.91
SD1	0.03	0.01	0.04	0.09	0.11	0.18	0.60	0.01	
Ratios									
$C_{kam}/C_{tae}$	0.79	27.76	0.08	3.87	14.42	0.03	0.30	0.18	
$C_{kam}/C_{tro}$	1.02	6.76	0.26	0.04	1.55	29.72	0.00	208.38	
$C_{tae}/C_{tro}$	1.29	0.24	3.26	0.01	0.11	886.76	0.00	1154.92	

<sup>1</sup>Standard Deviation

# **3.2 General Petrology**

Like many meteorites, Parsa is severely brecciated (Figure 12). The majority of the unbroken grains are subhedral to anhedral. Many of the primary minerals that are at least 300  $\mu$ m in greatest dimension have fractures running through them. The matrix is composed of small, 10-50  $\mu$ m, brecciated grains of primary and secondary minerals (Figure 12). All minerals are surrounded by FeO(OH).

![](_page_18_Picture_1.jpeg)

# Figure 12. JEOL image depicting the brecciated matrix of Parsa with larger primary minerals.

FeO(OH) has no distinguishable grains, but surrounds all mineral grains (Figure 13). It formed by oxidation of the reduced-Fe meteorite in Earth's highly oxygenated atmosphere. It surrounds all minerals and commonly fills the fractures of larger mineral grains.

Figure 13. JEOL image depicting the crystal-poor texture of FeO(OH), outlined in red. Blue outlines the FeO(OH)-filled fractures in enstatite and troilite crystals.

![](_page_18_Picture_5.jpeg)

The taenite is always observed adjacent to kamacite, typically at the rims of the crystals (Figure 14). The size of the kamacite grain has an inverse relationship with the total taenite presence; the smaller the kamacite crystal, the higher the kamacite:taenite ratio.

![](_page_19_Figure_2.jpeg)

Figure 14. JEOL image depicting the preferential crystallization of taenite at the rims of kamacite grains; taenite is outlined in red.

Parsa minerals show evidence of partial melting at a moderate number of locations (Figure 15, Dr. Emma Bullock pers. comm.). Typically, the Fe-containing minerals--troilite in particular--portray this pattern. This suggests the meteorite's parent body underwent a heating episode after initial accretion, but it lacked the necessary amount of heat to completely equilibrate the meteorite (Parsa is still a petrologic class 4).

![](_page_20_Picture_1.jpeg)

Figure 15. JEOL image showing the texture of many Fecontaining minerals; many grains have evidence of melting at their outer edges.

# **3.4 Roedderite**

Using the ENVI method, 21 roedderite grains were found in Parsa. They are typically accessory minerals to troilite and grow in fractures. Albite is a common accessory mineral. The largest located grains are  $\sim 18 \ \mu m$  in greatest dimension. When euhedral, roedderite is an elongated crystal with an aspect ratio of  $\sim 5$  (Figure 16). It is commonly euhedral in the presence of troilite, but subhedral to anhedral in the presence of silicates. The grains show no apparent K-Na zoning, most likely due either to the slow cooling history of the meteorite or the small size of the grains.

![](_page_21_Picture_1.jpeg)

Figure 16. JEOL image of a euhedral roedderite grain surrounded by troilite.

Table 4 shows compositional data for six Parsa grains compared to roedderite crystals found in two other meteorites and the synthetic, K-Mg end member of roedderite. Parsa's roedderites have a moderately decreased Na/(Na+K) ratio compared to the Witchita County and Indarch meteorites. Several possible explanations for this include a heightened K-presence in Parsa's crystallization atmosphere or the Na being incorporated into a more stable mineral. The dominant presence of K suggests the roedderite structure has ample room to incorporate the larger 12-fold cation. It does not preferentially capture Na. The euhedral nature next to troilite suggests the roedderite morphology is more harmonious with troilite's structures as opposed to other silicate structures. Often, if the roedderite is subhedral, it touches both troilite and silicate minerals. The edge touching troilite is planar, while the edge touching a silicate mineral is anhedral (Figure 17).

TABLE 4: ELEMENTAL WEIGHT PERCENTAGES FOR ROEDDERITE GRAINS.									
Oxide	1 <sup>1</sup>	2	3	4	5	6	7 <sup>2</sup>	<b>8</b> <sup>3</sup>	94
SiO <sub>2</sub>	71.28	70.36	73.50	72.34	72.89	72.35	68.0	70.8	70.7
$AI_2O_3$	1.07	0.71	0.50	0.72	0.62	0.57	2.5	0.4	
FeO	2.44	2.86	0.96	0.51	0.84	1.35	0.4	1.0	
MgO	17.90	19.04	18.20	19.11	19.11	18.70	19.0	19.6	19.8
Na <sub>2</sub> O	2.82	2.85	2.71	2.60	2.50	2.74	5.3	4.2	
K <sub>2</sub> O	4.15	4.12	4.34	4.44	4.26	4.35	3.8	3.4	9.3
Total	99.67	99.92	100.21	99.72	100.22	100.06	99.0	99.4	99.8
Cation Ratios									
Na/(Na+K)	0.40	0.41	0.39	0.37	0.37	0.39	0.58	0.55	
Mg/(Mg+Fe)	0.88	0.87	0.95	0.97	0.96	0.93	0.98	0.95	
Si/(Si+Al)	0.99	0.99	0.99	0.99	0.99	0.99	0.96	0.99	

<sup>1</sup>Numbers 1-6 are Parsa roedderites, analyzed on the JEOL Hyperprobe

<sup>2</sup>Witchita County meteorite (Olsen, 1967)

<sup>3</sup>Indarch meteorite (Olsen, 1967)

<sup>4</sup>Synthetic K<sub>2</sub>O:5MgO:12SiO<sub>2</sub>: K<sub>2</sub>Mg<sub>5</sub>S<sub>12</sub>O<sub>30</sub> (Olsen, 1967)

![](_page_22_Picture_6.jpeg)

![](_page_22_Figure_7.jpeg)

Raman spectroscopy was performed on one roedderite grain. The RRUFF

database lacks any roedderite patterns for comparison. The pattern is relatively rough, but distinguishable peaks are found at wavenumbers 185, 275, 465, and 565 cm<sup>-1</sup> (Figure 18).

![](_page_23_Figure_1.jpeg)

# Figure 18. Raman pattern for a Parsa roedderite crystal.

Krot and Wasson (1994) suggested that roedderite forms in an Al-deficient (peralkaline) environment; the alkali elements preferentially form feldspars in the presence of Al, Si, and O, but will revert to roedderite if Al<(K, Na). However, grains of either an aluminum oxide or aluminum hydroxide were found throughout the whole thin section and as an accessory mineral to roedderite (Figures 19A and 19B). This challenges the hypothesis of an Al-deficient environment. Local coexistence of albite, aluminum oxide/hydroxide, quartz, and enstatite suggest that roedderite could be formed by either one of these reactions:

 $5(Mg,Fe)SiO_3 + 2(Na,K)AlSi_3O_8 + SiO_2 \rightarrow (K,Na)_2(Mg,Fe)_5Si_{12}O_{30} + Al_2O_3$  $5(Mg,Fe)SiO_3 + 2(Na,K)AlSi_3O_8 + SiO_2 + H_2O \rightarrow (K,Na)_2(Mg,Fe)_5Si_{12}O_{30} + 2AlO(OH)$ 

Although quartz is not reliably an accessory mineral, roedderite typically forms near troilite, which is found near the quartz-included kamacite.

![](_page_24_Picture_1.jpeg)

Figures 19A (left). JEOL image of roedderite grain. Figure 19B (right). Al, Si, and Mg X-ray maps of the JEOL image in 19A overlain in Photoshop. The Al is yellow, Si is pink, and Mg is green. This shows the presence of an aluminum oxide or hydroxide in direct contact with the roedderite grain. Albite and quartz are present to the left of the roedderite grain.

# 4. CONCLUSIONS

Parsa is dominated by enstatite, troilite, kamacite, taenite, and FeO(OH). Minor minerals include albite, quartz, Al<sub>2</sub>O<sub>3</sub> (or AlO(OH)), daubreelite, caswellsilverite, roedderite, and a mystery Ca-Mg-silicate. Both Si and Cu are preferentially partitioned into taenite, whereas Co prefers kamacite. Parsa has a severely brecciated texture, with only primary minerals demonstrating larger than 300 µm. The matrix is a combination of small, brecciated mineral grains and a weathered byproduct of Fe-containing minerals, FeO(OH), that shows no clearly distinguishable crystals. The evidence of partial melting on the rims of troilite crystals suggests a post-accretion heating episode of the Parsa parent body, albeit not hot enough to completely equilibrate the meteorite.

Parsa roedderite crystals are K-dominated; accessory minerals include albite, quartz, and  $Al_2O_3$  (or AlO(OH)). The largest grain was ~18 µm in longest dimension. The crystals are euhedral to subhedral when adjacent to troilite, but anhedral when adjacent to silicate minerals. This suggests roedderite morphology is more compatible with troilite's structure.

The presence of a moderate number of aluminum oxide or aluminum hydroxide grains near roedderite contradict the theory that roedderite forms in an alkali-rich, Aldeficient environment. The local coexistence of albite, enstatite, quartz, and aluminum oxide/hydroxide suggest that roedderite is formed via one of these pathways:

 $5(Mg,Fe)SiO_3 + 2(Na,K)AlSi_3O_8 + SiO_2 \rightarrow (K,Na)_2(Mg,Fe)_5Si_{12}O_{30} + Al_2O_3$  $5(Mg,Fe)SiO_3 + 2(Na,K)AlSi_3O_8 + SiO_2 + H_2O \rightarrow (K,Na)_2(Mg,Fe)_5Si_{12}O_{30} + 2AlO(OH)$ 

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