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**ASPECTOS PETROGRÁFICOS E GEOQUÍMICOS  
DE CÔNDRULOS EM METEORITOS PRIMITIVOS:  
UM ESTUDO DE CASO A PARTIR DO METEORITO  
CAMPO SALES**

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Orientador: Dr. Herbet Conceição

Coorientadora: Dra. Débora Correia Rios

**DISSERTAÇÃO DE MESTRADO**

Programa de Pós-Graduação em Geociências e Análise de Bacias

São Cristóvão-SE  
2023

Cristine de Almeida Pereira

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Dissertação apresentada ao Programa de Pós-Graduação em Geociências e Análise de Bacias da Universidade Federal de Sergipe, como requisito para obtenção do título de Mestre em Geociências.

**Orientador:** Dr. Herbet Conceição

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CAMPO SALES**

por:

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(Geóloga, Universidade Federal da Bahia – 2019)

**DISSERTAÇÃO DE MESTRADO**

Submetida em satisfação parcial dos requisitos ao grau de:

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*Para a menininha de 10 anos que sonhava em ser cientista.*

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## **RESUMO**

Os meteoritos condrílicos representam fascinantes lembretes da história da evolução do Sistema Solar, desde o início da Nebula até a configuração vigente. Através do estudo dos côndrulos - pequenas partículas esféricas que caracterizam os meteoritos condríicos -, é possível conhecer a composição e os possíveis processos que predominavam nos primeiros estágios nebulares. Com base nisso, este estudo se propôs a ampliar a compreensão desses processos, mediante a observação dos côndrulos presentes no meteorito Campos Sales, um condrito ordinário. Este espécime apresenta côndrulos com dimensões máximas de 1 mm, cuja mineralogia é predominantemente: olivina ( $\text{Fo}_{75}$ ,  $\text{Fa}_{25}$ ), enstatita ( $\text{En}_{77}$ ,  $\text{Fs}_{23}$ ), augita ( $\text{En}_{51}$ ,  $\text{Fs}_8$ ,  $\text{Wo}_{41}$ ), e plagioclásio. Como inclusões nos côndrulos são encontrados cristais de troilita, cromita, cloroapatita e liga metálica (Fe-Ni). Em termos texturais, os côndrulos foram classificados três tipos: barrado, radial e granular. Os do tipo barrado e radial são formados, respectivamente, por cristais esqueléticos de olivina ou enstatita, com diâmetro de ~0,8 mm. Verifica-se que a associação do plagioclásio com a augita é recorrente em todos os tipos de côndrulos, formando texturas de intercrescimento. Associados ao plagioclásio também podem ser vistos cristais euédricos de cromita, enstatita e olivina. Mediante a obtenção de dados químicos dos minerais foi possível classificar o plagioclásio como oligoclásio ( $\text{Or}_6$ ,  $\text{Ab}_{84}$ ,  $\text{An}_{10}$ ), bem como constatar que muitos cristais de olivina e piroxênios têm pouca variação composicional centro-borda e estavam bem próximo ao equilíbrio com o líquido durante suas cristalizações. Sobre os processos que deram origem aos côndrulos é possível inferir que os diferentes tipos texturais foram originados, possivelmente, a partir de fontes distintas. O processo posterior de acresção destas partículas resultou na formação do corpo parental, onde os côndrulos – de natureza distintas foram - conectados pela matriz. A matriz do meteorito Campos Sales caracteriza-se principalmente pela presença de cristais subédricos de enstatita, além de cristais da liga metálica, sulfeto, merrillita, cromita, olivina e plagioclásio. A pouca variação composicional centro-borda dentro dos principais minerais que compõem os côndrulos, associada à ausência de vidro na matriz, sugerem a existência de um evento termal que devitrificou o vidro da matriz e permitiu esse reequilíbrio químico dentro dos côndrulos.

**PALAVRAS-CHAVE:** Condritos ordinários, texturas meteoríticas, processos nebulares.

## **ABSTRACT**

Chondritic meteorites represent fascinating reminders of the early history of the Solar System evolution, from the beginning of the Nebula to its current configuration. Through the study of the chondrules - small particles present in the chondrite - it is possible to learn how the composition and evolutionary processes that predominated in the first stages of nebular development. This study aimed to better understand these processes, through the mineral chemistry and petrography of the chondrules present in the Campos Sales meteorite. This meteorite shows small chondrules, with maximum dimensions of 1 mm, and a mineralogy predominantly constituted by: olivine ( $\text{Fa}_{25}$ ), enstatite ( $\text{En}_{77}$ ,  $\text{Fs}_{23}$ ), augite ( $\text{En}_{51}$ ,  $\text{Fs}_8$ ,  $\text{Wo}_{41}$ ), and plagioclase. Troilite, Fe-Ni metal alloy, chromite and chlorapatite crystals occur as inclusions. In textural terms, three types were classified: barred, radial and granular. The barred and radial chondrules display skeletal crystals of olivine or enstatite, respectively, and diameters of approximately ~0.8. It is verified that the association of plagioclase with augite is recurrent in all types of chondrules, with textures that are like intergrowth. Crystals of chromite, enstatite, and olivine were found in close association with the chondrules of plagioclase. The mineral chemistry allowed to classify this plagioclase as oligoclase ( $\text{Or}_6$ ,  $\text{Ab}_{84}$ ,  $\text{An}_{10}$ ), as well as to notice that most crystals of olivine and pyroxene have little core-border compositional variation and were very close to the equilibrium with the liquid during their crystallizations. The processes required to explain the origins of these chondrules evoke different sources areas in the nebula. Later, during the accretionary phase, these particles were combined to form Campos Sales meteorite's parental body and the groundmass that involves them. In view of the little compositional variation within the crystals and in the absence of glass in the matrix, we propose a thermal event, that devitrified the glass and allowed chondrules's chemical rebalancing.

**Keywords:** Ordinary Chondrites, meteoritic textures, nebular processes.

## **LISTA DE FIGURAS**

Figura 1. Mapa do Brasil e Rota do local do achado Campos Sales.....	14
Figura 2. Tipos texturais de côndrulos no meteorito Campos Sales .....	22
Figura 3. Imagens BSE de côndrulos barrados do meteorito Campos Sales.....	23
Figura 4. Imagens BSE de côndrulos radiais e granulares do MCS.....	24
Figura 5. Diagrama de Rhodes cristais de olivina do MCS.....	26
Figura 6. Diagrama de classificação dos piroxênios.....	26
Figura 7. Diagrama de Rhodes dos cristais de enstatita e augita.....	27
Figura 8. Diagrama de classificação para os dados dos feldspatos do MCS.....	27
Figura 9. Diagramas Binários .....	30
Figura 10. Diagrama binário de Na <sub>2</sub> O versus K <sub>2</sub> O.....	31
Figura 11. Esquema simplificado de classificação dos meteoritos.....	43
Figura 12. Imagens de fragmentos de condritos ordinários.....	46
Figura 13. Imagens de texturas em côndrulos obtidas na literatura.....	47

## **LISTA DE TABELAS**

Tabela 1. Comparação entre as composições de padrões internacionais e os dados obtidos com EDS-MEV neste estudo.....	20
Tabela 2. Variação das composições químicas dos minerais presentes nos côndrulos estudados do meteorito Campos Sales.....	25
Tabela 3. Variação dos óxidos no centro e na borda em cristais de olivina, enstatita e augita.....	25
Tabela 4. Composição química dos côndrulos do MCS .....	28
Tabela 5. Composição química dos côndrulos do MCS.....	28
Tabela 6. Dados de composição química para côndrulos de Olivina Granular (GO).....	29
Tabela 7. Dados de composição química para côndrulos de Olivina Barrada (BO).....	29
Tabela 8. Dados de composição química para côndrulos de Olivina Piroxênio Granular.....	29
Tabela 9. Classificação dos Côndrulos.....	48

## SUMÁRIO

Capítulo I: Introdução.....	13
Referências .....	16
Capítulo II: <b>Unraveling the Origins of the Solar System: A Comprehensive Petrological Investigation of Chondrules within the Campos Sales Meteorite.....</b>	<b>17</b>
<i>Introdução.....</i>	<i>18</i>
<i>Materiais e Métodos.....</i>	<i>19</i>
<i>Resultados.....</i>	<i>20</i>
<i>Discussões.....</i>	<i>31</i>
<i>Conclusões.....</i>	<i>34</i>
<i>Referências.....</i>	<i>36</i>
Capítulo III: Conclusões.....	39
Anexos.....	43
<i>Estado da Arte.....</i>	<i>43</i>
<i>Normas para Publicação.....</i>	<i>52</i>
<i>Tabelas de dados.....</i>	<i>66</i>

## **CAPÍTULO I: INTRODUÇÃO**

## I. INTRODUÇÃO

O meteorito Campos Sales (MCS), objeto de estudo deste trabalho, é um corpo cuja queda foi presenciada em 31 de janeiro de 1991, na área rural da cidade de Campos Sales, Ceará, Brazil. Os fragmentos de rocha coletados totalizaram em uma massa de aproximadamente 23 kg, e o meteorito foi classificado como um condrito ordinário L5 com baixo índice de choque (Scorzelli *et al.*, 1998).

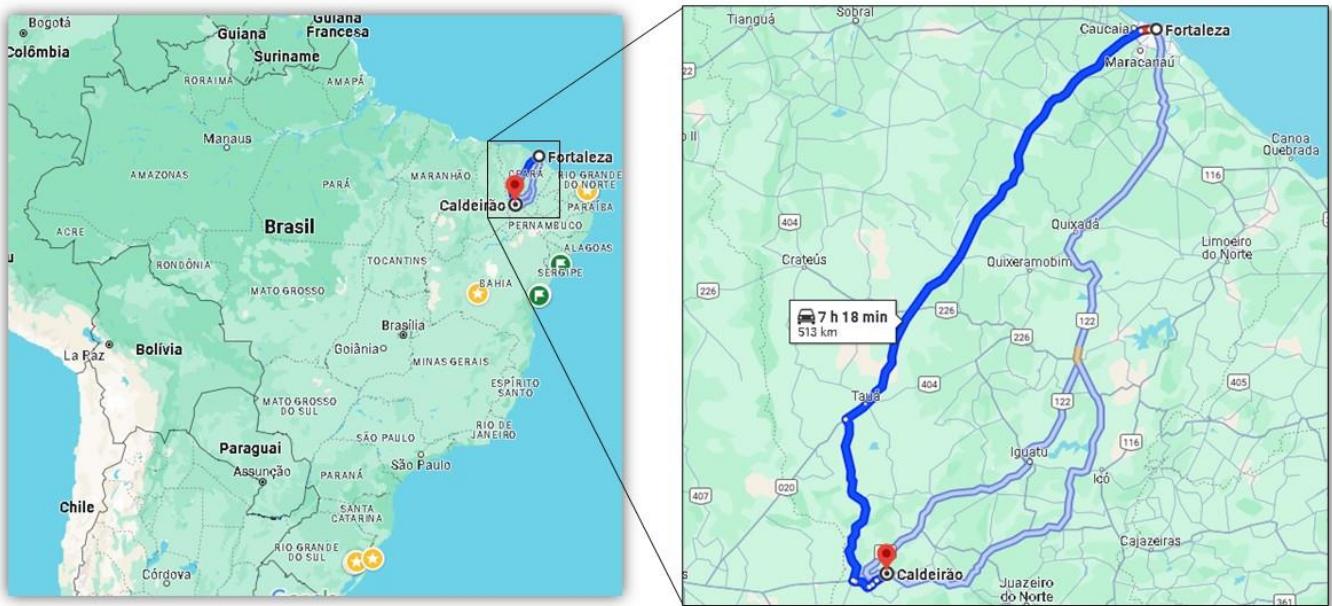


Figura1. Mapa do Brasil (a esquerda) e Rota do local do achado Campos Sales/ Caldeirão até Fortaleza- Ceará (a direita). Fonte: Google Maps.

Apesar de ser conhecida a localização de queda do MCS, não se conhece com precisão seu corpo originário. Segundo estudos de Meier et al. (2017) e de Jenniskens et al. (2019), condritos do tipo L são associados com corpos parentais asteroidais presentes no cinturão de asteroides de Júpiter. No caso específico dos condritos L5, associa-se a origem dessas rochas com a fragmentação de asteroides da família Gefion, cuja quebra do corpo original ocorreu a  $4497 \pm 6$  Ma atrás segundo idades obtidas pelos métodos de U-Pb e Pb-Pb(Jenniskens et al., 2019).

Mediante a essas informações, o presente estudo, visou a obtenção de dados petrográficos e mineraloquímicos dos côndrulos presentes na amostra do MCS disponível, a fim de estudar os côndrulos e os minerais que compõem a rocha de maneira mais detalhada.

As informações e conclusões obtidas pretendem ser publicadas na revista *Meteoritics and Planetary Science*, que atua como um dos principais expoentes na divulgação de informações da área meteorítica.

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**CAPÍTULO II: Unraveling the Origins of the Solar System: A Comprehensive Petrological Investigation of Chondrules within the Campos Sales Meteorite**

**Unraveling the Origins of the Solar System:  
A Comprehensive Petrological Investigation of Chondrules within the Campos Sales Meteorite**

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## ABSTRACT

This paper investigates chondrules, integral components of chondritic meteorites from the early Solar System. Focusing on 33 chondrules from the Campos Sales Meteorite, an L5 ordinary chondrite, we explore their compositions, mineral formation, and origin. Considering the hypothesis that chondrules may be "magmatic" droplets, we examine the compositions of these "primitive melts." Campo Sales' chondrules, mostly circular with some undefined shapes, contain olivine, enstatite, augite, chromite, troilite, Cl-apatite, and silicon dioxide. Varied textures, including barred, radial, and granular patterns, alongside skeletal crystals of olivine, enstatite, and augite, are observed, some featuring intergrowth textures. Chemical data reveal compositional homogeneity, indicating a chemical reequilibration event. Despite challenges in discerning elemental patterns, the study underscores rapid crystallization and preservation of skeletal shapes and volatile elements, suggesting accretion before complete solidification. These findings offer insights into early Solar System evolution, emphasizing chondrules as records of magmatic processes amid challenges in understanding their elemental patterns. The study provides comprehensive insights into type L chondrules, unraveling their composition, formation, and the intricate processes shaping the early Solar System.

## Keywords:

Chondrules,  
Campo Sales Meteorite,  
Petrography,  
Geochemical Compositions,  
Solar System Formation,  
Origins Processes.

## HIGHLIGHTS

1. The petrological aspects of Campo Sales meteorite sheds light on the enigmatic evolution of the early Solar System, providing glimpses into its formative processes.
2. Chondrules are key observatories providing valuable insights into the early Solar System's evolution. Chondrules within the Campos Sales Meteorite serve as critical windows into formative processes, sparking debates over planetary or nebular origins.
3. The diversity of chondrules within the Campo Sales meteorite contribute to unique mineralogical signatures. Petrographic scrutiny unveils irregular fractures, adding complexity to mineral composition. Classification identifies three main chondrule groups – barred olivine, radial enstatite, and granular – each characterized by distinctive characteristics.
4. L-type chondrules, despite exhibiting a spherical tendency, exhibit pronounced deformation, challenging assumptions of uniform pressure. This suggests dynamic interactions and resilience within dynamic environments.
5. Chemical data indicate minimal compositional variability within “balanced” chondrites. The prevalence of skeletal olivine and pyroxenes suggests rapid crystallization from magnesium and iron-rich materials during distinct magmatic events, offering insights into the chondrite’s geological history.
6. The “balanced” nature of some chondrites give valuable insights into the processes and conditions present in the early solar system. Deformation and agglutination dynamics provide clues to non-simultaneous crystallization, highlighting distinct occurrences during the early Solar System.
7. This investigation unravels complexities in type L chondrules, challenging existing paradigms. Chondrules emerge as records of magmatic processes, inviting a reevaluation of our understanding amid ongoing challenges in deciphering their elemental patterns.

## INTRODUCTION

Meteorites, remnants of extraterrestrial rocks penetrating Earth's atmosphere, primarily originate from asteroids and, to a lesser extent, Mars, the Moon, and comets (Rubin & Ma, 2020). Beyond their captivating luminous displays, meteorites have intrigued humanity for millennia, as evidenced by historical accounts such as the Egyptians using "metal from the sky" in artifacts like King Tutankhamun's dagger (Comelli et al., 2016, Wang & Korotev, 2019). Classified based on petrographic characteristics and geochemical compositions, meteorites encompass various groups, reflecting distinct formation processes like condensation around newly formed stars, crystallization from chondritic melts, aqueous alterations, and shock metamorphism (Rubin & Ma, 2020).

Among meteorites, chondrites, which are rich in chondrules, provide crucial insights into the early Solar System (Scott & Krot, 2005). These meteorites originated from the fusion and consolidation of their parent bodies, sparking increased study in the 19<sup>th</sup> century and subsequent debates on planetary versus nebular processes. In 1864, H. C. Sorby proposed a groundbreaking idea, suggesting that chondrites' material might have originated from fusion, subsequent fragmentation, and consolidation due to the mechanical and chemical actions of their parent body (Merrill, 1920). However, it wasn't until the 1960s that investigations took a more profound turn.

During this pivotal period, two prevailing perspectives emerged on the origin of chondrules: (i) formation through planetary processes proposed by Urey in 1954, or (ii) formation through nebular processes as suggested by Wood in 1963 and Larimer & Anders in 1967. By the 1970s, studies confirmed chondrites' nebular origin (Grossman and Larimer, 1974).

The current classification of chondrules considers their mineralogical-textural characteristics and FeO content, resulting in two primary groups: type I, characterized by low FeO (<10% wt.), and type II, with high FeO (>10% wt.). Subcategories within these groups are further defined based on the prevalence of olivine (A) or pyroxene (B), as well as observed textures such as barred, radial, granular, porphyritic, microcrystalline, among others (Gooding & Keil, 1981). Regarding shape, the prevailing notion, rooted in the belief that chondrules originate from solidified droplets, asserts that these particles should ideally exhibit a spherical form. However, in reality, chondrules manifest in both spherical and non-spherical forms, including fragments of spheres or shapes resembling droplets (Hewins, 1997).

The processes governing chondrule formation remain incompletely understood. Some researchers propose that these particles underwent at least one melting event before being incorporated into the parent body (Desch et al., 2012; Johnson et al., 2015; Morris et al., 2016). Additionally, the enigmatic formation of chondrules involves not only melting events but also rapid cooling, leading to the development of skeletal crystals composed of olivine and pyroxenes (Hewins, 1997).

Expanding on our existing understanding of meteorite textures and mineralogy, and operating under the assumption that chondrules serve as the primary droplets of magmas in the Solar System, a fundamental inquiry arises: What constitutes the composition of the material that gave rise to these chondrules? Does a singular material underlie diverse chondrules through distinct formation processes, or do different sources contribute to their origins? To address these questions comprehensively, we conducted an extensive assessment of the petrography and mineral chemistry of submillimeter chondrules from the Campos Sales meteorite. The fall of the Campos Sales meteorite (MCS) was witnessed on January 31, 1991, in the town of Campos Sales, Ceará, Brazil (Scorzelli et al., 1998). Weighting 23.68 kg, the recovery mass of this meteorite was subsequently classified as an ordinary chondrite of the L5 type.

## MATERIALS AND METHODS

In this investigation, we employed a polished thin section obtained from a fragment of the Campos Sales meteorite, generously provided by Dr. Wilton Carvalho. The total analyzed area of this thin section approximates 8 cm<sup>2</sup>. Our examinations utilized both petrographic and scanning electron microscopes (SEM) at the Condomínio de Laboratórios Multiusuários das Geociências of the Universidade Federal de Sergipe, Brazil.

The SEM, a Tescan Veja 3 LMU model, was equipped with detectors for secondary electrons, backscattered electrons (BSE), cathodoluminescence, and energy dispersive spectroscopy (EDS). The thin section underwent an initial gold coating (8-10 nm thickness), followed by cleaning and carbon coating to enhance observations in the petrographic microscope.

### Microanalysis:

The SEM, utilizing the backscattered electron (BSE) detector for texture analysis, captured images of the sample. Chemical compositions of the minerals were acquired using EDS (Oxford Instrument X-Act model) with a resolution of 125 eV. Internal calibration of the EDS involved standards with precise measurements ( $2\sigma$ ), including albite albite (NaK $\alpha$ ,  $\pm 0.2$ ), corundum (AlK $\alpha$ ,  $\pm 0.2$ ), metallic chromium (CrK $\alpha$ ,  $\pm 0.4$ ), fluorite (FK $\alpha$ ,  $\pm 0.3$ ), metallic iron (FeK $\alpha$ ,  $\pm 0.4$ ), halite (ClK $\alpha$ ,  $\pm 0.3$ ), metallic manganese (MnK $\alpha$ ,  $\pm 0.2$ ), metallic nickel (NiK $\alpha$ ,  $\pm 0.3$ ), orthoclase (KK $\alpha$ ,  $\pm 0.2$ ), periclase (MgK $\alpha$ ,  $\pm 0.4$ ), quartz (SiK $\alpha$ ,  $\pm 0.4$ ), metallic titanium (TiK $\alpha$ ,  $\pm 0.2$ ), wollastonite (CaK $\alpha$ ,  $\pm 0.2$ ).

The analytical conditions for EDS-SEM were set at 20 kV voltage, 17 nA intensity, 0.4  $\mu$ m electron beam diameter, 60-240 s (average counting time), and 15 mm analysis distance. Analytical data were processed using AztecEnergy software (version 4.0, Oxford Instruments®), employing ZAF corrections for “Quant routine” analysis and accurate oxide percentage calculations. Rigorous correction procedures for false peaks, escape peaks, and coincident energy peaks were applied following Newbury's recommendations (2009). To ensure accuracy and reliability, the results underwent verification against mineral standards and oxides from Astimex Scientific Ltd®, Cameca, and internal standards of CLGeo (**Table 1**).

**Table 1:** Comparison between the compositions of international standards (AST, CAM) and the data acquired through Energy Dispersive Spectroscopy – Scanning Electron Microscope (EDS-SEM) in the current study. The abbreviations used are AST (Astimex standards), EM for EDS-SEM, CAM (Cameca Standards). The column labeled “ $2\Theta$ ” denotes the difference between the standards and the EDS-SEM data, providing a quantitative measure of the variance between the two datasets.

	Olivine			Cr-Diopside			Fosterite			Fayalite			Enstatite			Diopside			Cl-Apatite			Phosphate					
	AST	EM	2Θ	AST	EM	2Θ	CAM	EM	2Θ	CAM	EM	2Θ	CAM	EM	2Θ	CAM	EM	2Θ	CAM	EM	2Θ	CAM	EM	2Θ			
SiO <sub>2</sub>	41.85	41.08	0.26	55.13	55.43	0.27	43.63	43.94	0.27	29.48	29.75	0.24	59.85	59.21	0.31	55.49	55.89	0.27									
TiO <sub>2</sub>				0.05	0.09	0.08																					
FeO	6.51	6.68	0.14	1.21	1.21	0.10				70.52	70.25	0.25															
MgO	51.57	51.81	0.24	17.46	18.14	0.17	56.34	56.06	0.23				40.15	40.36	0.22	18.62	18.58	0.17									
MnO	0.12	0.12	0.07																								
CaO				25.55	24.60	0.16										25.90	25.54	0.16	53.30	53.83	0.21	43.94	44.79	0.20			
NiO	0.20	0.32	0.09																								
Cr <sub>2</sub> O <sub>3</sub>				0.58	0.53	0.08																39.90	39.45	0.28	53.98	54.06	0.30
P <sub>2</sub> O <sub>5</sub>																						6.80	6.73	0.09			
Cl																									1.21	1.16	0.11
V <sub>2</sub> O <sub>5</sub>																											
Total	100.30	100.00		99.98	100.00		100.00	100.00		100.00	100.00		100.00	99.57		100.00	100.00		100.00	100.00		99.13	100.00				

## Analysis and Classification:

Chemical analyses covered crystals of minerals within chondrules and the matrix. Structural formulas were computed for pyroxenes, olivine, and plagioclase, with analyses falling within an acceptable range of variation. The area calculation tool available in the AztecEnergy software was used. The 33 well-defined chondrules underwent total composition studies and correlation of composition versus area. Manual delimitation marked the boundaries of each chondrule, guided by texture observation, imaging, and chemical data, leading to their textural classification into three distinct groups: barred, radial, and granular.

Chemical data treatment employed GCDKit® software for graph generation, observing chemical correlations and affinities. Additionally, the MagMin\_PT® program (Gündüz and Asan, 2022) calculated crystallization pressures and temperatures using algorithms from various authors. Abbreviations for mineral names followed IMA-CNMNC approved mineral symbols (Warr, 2021).

## RESULTS

### Chondrule Diversity and Petrographic Insights:

The examination of the Campos Sales meteorite (MCS) provides a nuanced understanding of chondrule diversity and petrographic features. In this 8.14 cm<sup>2</sup> polished thin section, chondrules, ranging from millimeter to submillimeter sizes, compose a significant portion (~40%) of the specimen. They are subtle to the naked eye yet distinctly preserved in thin sections. Three distinct components emerge: well-defined chondrules, fragments with relic structures, and a crystalline matrix, contributing to a holistic petrographic landscape.

MCS unveils a rich mineralogy, including olivine (Fo<sub>74-78</sub>), orthopyroxene (En<sub>75-79</sub>, Fs<sub>25-21</sub>), clinopyroxene (En<sub>47-54</sub>, Fs<sub>8</sub>, Wo<sub>45-58</sub>), chromite (Sp<sub>15</sub>, Mt<sub>2</sub>, Usp<sub>6</sub>, Chr<sub>77</sub>), kamacite (90% < Fe < 93% and 5% < %Ni < 7%), taenite (79% < Fe < 87% and 11% < Ni < 18%), tetrataenite (68% < Fe < 40% and 27% < Ni < 55%), Cl-apatite (4% < Cl < 6%), troilite (32% < S < 40% and 54% < Fe < 65%), merrillite (Ca<sub>18</sub>Na<sub>2</sub>Mg<sub>2</sub>(PO<sub>4</sub>)<sub>14</sub>), plagioclase (Or<sub>6</sub>, Ab<sub>84</sub>, An<sub>10</sub>), silicon dioxide, and ilmenite. Noteworthy is the presence of irregular fractures, particularly visible in olivine and pyroxene crystals, while no shock veins are observed, and adding a layer of complexity to the mineral composition of this meteorite.

### Chondrule Characterization and Classification:

Chondrules within MCS exhibit diverse characteristics, with calculated diameters ranging from 0.8 mm to 2 mm and areas varying across a spectrum (from 0.078 mm<sup>2</sup> to 3.413 mm<sup>2</sup>). No distinct predominance in diameter or area is noted among different chondrules. Olivine, enstatite, augite, and oligoclase emerge as primary constituents of chondrules, accompanied by accessory minerals including troilite, Fe-Ni alloy, chromite, Cl-apatite, and silicon dioxide. A meticulous classification yields three main chondrule groups,

based on main mineral content (>80% olivine or pyroxene) and textural aspects: barred olivine, radial enstatite, and granular (**Figures 1, 2, 3**), each contributing distinctive mineralogical signatures.

#### *Barred Chondrules: A Microscopic Mosaic of Olivine Dominance*

Within the barred chondrules, depicted vividly in **Figures 1A and 2**, a captivating interplay of minerals unfolds. The dominant presence of skeletal olivine crystals, boasting a %Fo exceeding 80%, characterizes these chondrules. These crystals, ranging from fractured to intact, exhibit a parallel orientation and lengths of up to 1 mm. The interstices between the olivine crystals host a diverse assembly, including pyroxene crystals (enstatite and augite), chlorapatite, plagioclase, and chromite.

In certain chondrules with a barred texture, an additional layer of complexity emerges. Anhedral olivine crystals (<30 µm) intricately associate with plagioclase (<30 µm) and pyroxenes (<40 µm). **Figures 2B and 2C** unveils the presence of euhedral chromite crystals (4-6 µm), forming an intriguing intergrown appearance with plagioclase and augite crystals. Notably, twinning in plagioclase crystals remains absent in the thin section.

The microscopic landscape extends its richness with rare occurrences of microspheres of silicon dioxide, boasting diameters of up to 2.5 µm (**Figure 2D**). These microspheres, sporadic in occurrence, find association with olivine crystals and, at times, plagioclase. As the exploration moves toward the outer zone of the barred chondrules, dispersed anhedral troilite crystals and fragments of the metallic alloy make their presence known, contributing to the intricate mosaic of mineralogical diversity.

#### *Subtle Rhythms: Exploring the Enigmatic World of Radial Texture Chondrules*

In the radial texture chondrules (**Figures 1B and 3A**), enstatite takes center stage with skeletal crystals (%En > 60%) ranging from 0.07 to 0.7 mm, exhibiting fractures devoid of preferential directions. Within this intricate structure, subhedral olivine crystals coexist with plagioclase and augite crystals (<50 µm), showcasing a texture akin to intergrowth. This phenomenon may stem from exsolution or eutectoid formation processes. The presence of fractures, lacking a distinct directionality and potentially filled with plagioclase crystals, adds to the complexity of this captivating microscopic world.

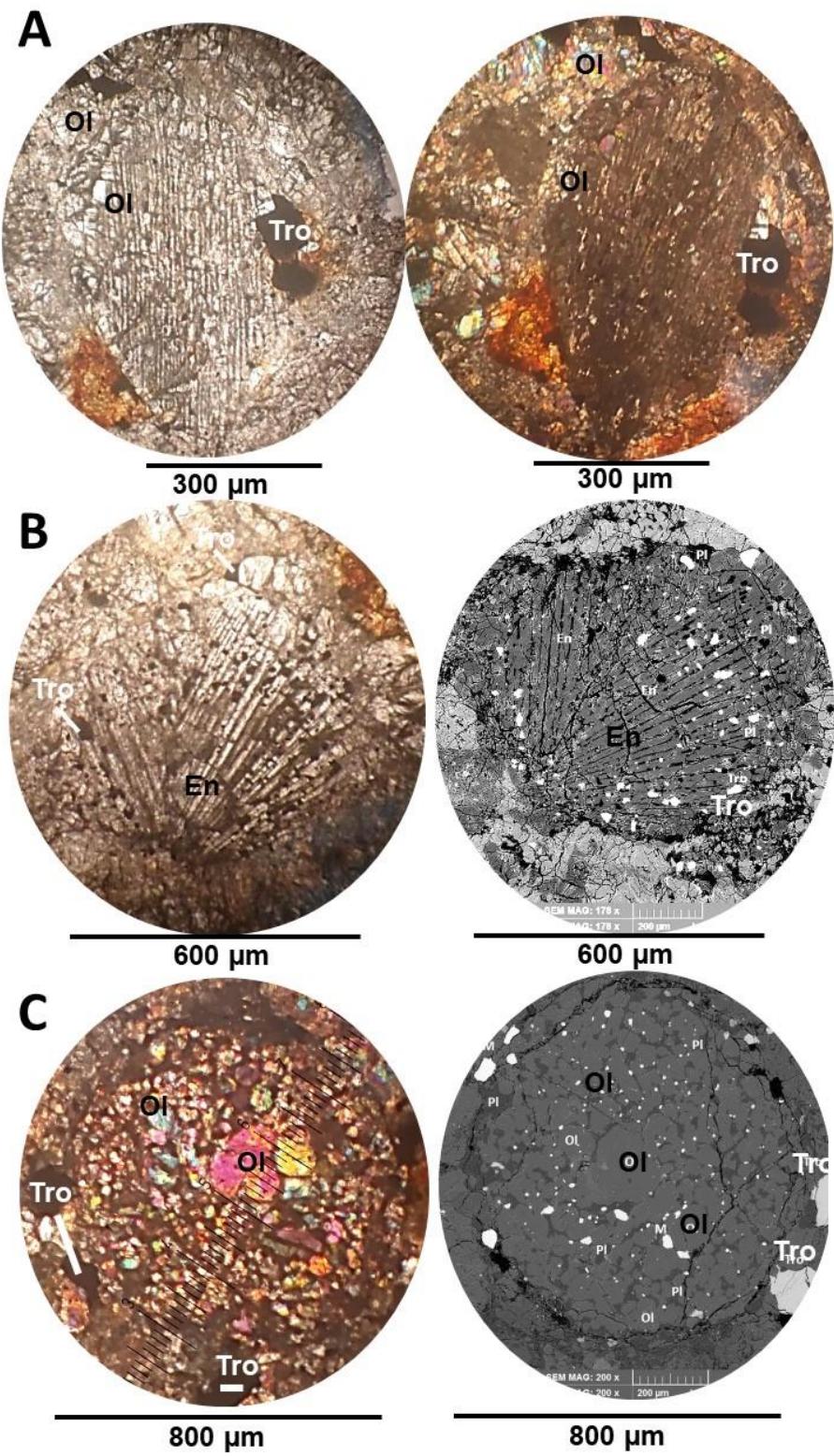
Diverging from their barred counterparts, radial chondrules boast a heightened abundance of sulfide crystals dispersed throughout their interior, allowing to explore the nuanced details of their formations as we unravel the distinctive characteristics within this radial texture.

#### *The Mosaic: Unraveling the Chondrules of Granular Texture*

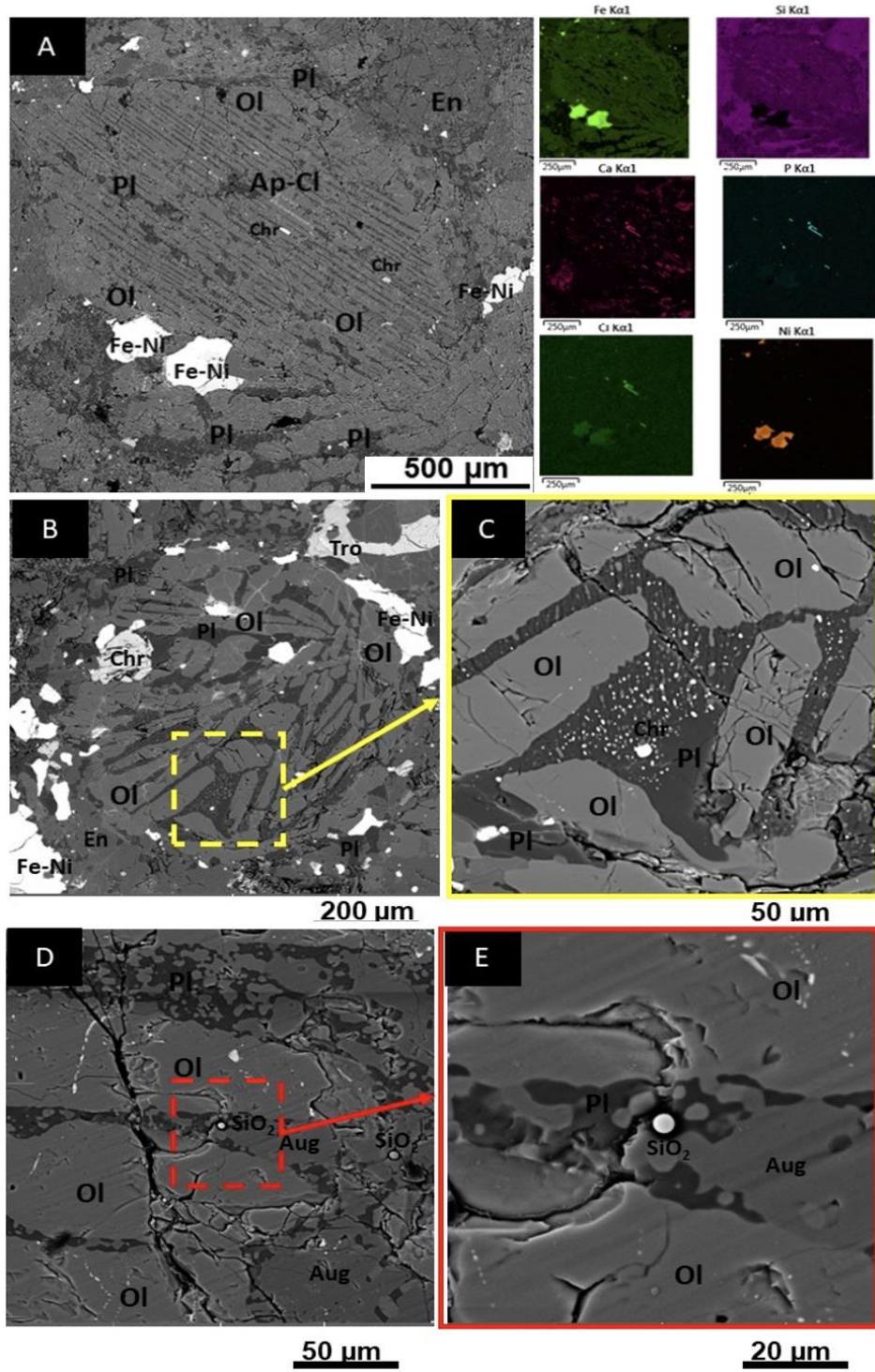
The granular texture (**Figures 1C and 3C**) unfolds as distinct segments within chondrules, diverging from the mineralogical patterns observed in barred olivine or radial pyroxene textures. This textural type reveals an intriguing interplay, showcasing the coexistence of plagioclase with augite and enstatite, reminiscent of the associations observed in the other two chondrule types.

#### **Insights into Chondrule Shape and Deformation:**

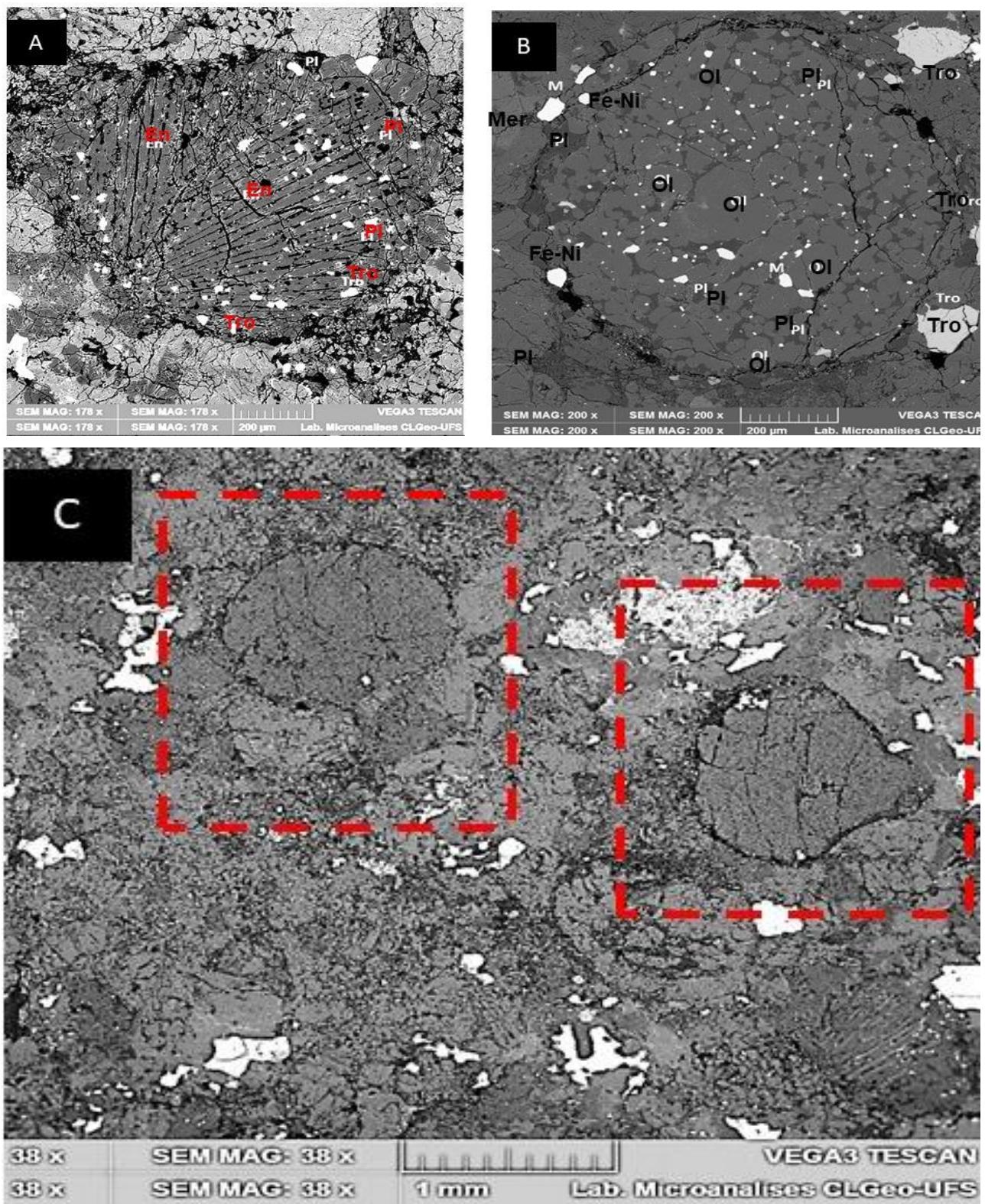
Moreover, upon closer scrutiny, a consistent tendency emerges among chondrules, transcending their textural classifications, to assume a spherical morphology. Despite this prevailing spherical inclination in numerous chondrules, the visual landscape is punctuated by indications of deformation (**Figure 3C**), causing alterations in their shapes. In certain instances, this deformation is so pronounced that it results in the disintegration of the chondritic structure itself. Within this intricate pattern, glimpses into the fundamental nature of the material become discernible only when traces of residual structures endure, underscoring the impact of substantial deformation on their morphology and offering insights into the resilience of chondrules within dynamic environments.



**Figure 1:** Textural Varieties of Chondrules within the Campo Sales Meteorite (MCS). Detailed visual representations using various microscopy techniques: (A) Barred Olivine: Displaying an image captured with polarized light on the left and plain light on the right. (B) Radial Pyroxene (Enstatite): Featuring a backscattered electron (BSE) image on the left and a plain light image on the right. (C) Granular: Showcasing a BSE image on the left and a polarized light image on the right.



**Figure 2:** Backscattered Electron (BSE) Images, accompanied by elemental distribution maps, of Barred Chondrules in the Campos Sales Meteorite. (A) On the left, a barred olivine chondrule exhibiting skeletal olivine (Ol) crystals, plagioclase (Pl) crystals, interstitial chromite (Chr), and chlorapatite (Ap-Cl) crystal. Surrounding the chondrule are Fe-Ni and enstatite (En) crystals. On the right, false-color elemental maps depict the distribution of Fe, Si, Ca, P, Cl, and Ni. (B) Barred chondrule featuring a more randomly arranged configuration of skeletal olivine crystals. Notable are the plagioclase crystals interspersed between olivine crystals and the presence of a chromite crystal. (C) Detail of image B (bottom center - highlighted in yellow) emphasizing plagioclase and micrometer-sized chromite crystals positioned between the skeletal olivine crystals. Light gray crystals correspond to augite, and white dots represent chromite crystals. (D) Detail of a barred chondrule highlighting the presence of silicon dioxide spheres in conjunction with plagioclase and augite (Au) crystals nestled among the skeletal olivine crystals. (E) Detail of image D (highlighted in red) focusing on the area with silicon dioxide sphere presence.



**Figure 3:** Backscattered Electron (BSE) Imaging providing insights into the structural features of radial and granular chondrules within the Campos Sales Meteorite, enhancing our understanding of their internal composition and shape variations. (A) Radial chondrule featuring skeletal enstatite (En) crystals with interstitial plagioclase (Pl) crystals. The chondrule exhibits the presence of troilite (Tro) crystals within. (B) Granular chondrule predominantly composed of olivine (Ol) and plagioclase (Pl) crystals. Peripheral zones of the crystal contain Fe-Ni and troilite crystals, while an outer portion of the chondrule displays a merrillite (Mer) crystal. (C) Chondrules presented with preserved shapes, along with one chondrule highlighted in red, showcasing a distinctly deformed shape.

## Unlocking Elemental Chronicles: Analyzing Mineral Compositions and Chondrule Equilibria

The chemical analysis focused on unraveling the intricacies of both mineral and chondrule compositions, offering a comprehensive view of the Campos Sales meteorite's elemental makeup. **Table 2** provides a detailed overview of the chemical variations within the analyzed minerals, excluding metallic alloy and sulfide. Observations reveal a consistent composition for ferromagnesian silicate crystals in both the matrix and chondrules of MCS (**Table 3**).

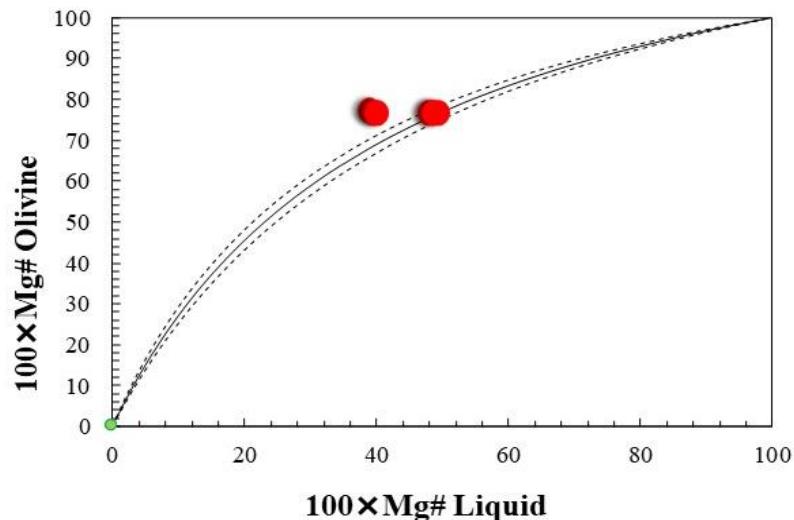
**Table 2:** Chemical Composition Variation of Minerals in Studied Chondrules from the Campos Sales Meteorite.

Mineral / Oxide (% wt)	Olivine		Enstatite		Augite		Chromite		Merrillite		Cl-Apatite		Plagioclase	
SiO <sub>2</sub>	37.73	40.77	55.50	56.20	52.80	54.80	0.94	4.89	0.30	2.31	0.60	2.04	61.26	66.14
TiO <sub>2</sub>		0.02	0.40	0.30	0.60	0.20	2.47	1.71	0.01	0.21	0.02	0.20	0.09	
Al <sub>2</sub> O <sub>3</sub>		1.32	0.20	0.20	3.60	0.40	2.89	6.61		13.94	0.22	0.71	17.02	21.55
Cr <sub>2</sub> O <sub>3</sub>	0.08	0.01	0.40	0.10	2.60	0.50	59.91	40.63		0.02			0.09	
FeO	22.52	19.75	12.70	11.70	5.10	5.20	30.17	41.09	0.53	1.72	0.76	11.82	4.35	0.53
MnO	0.43	0.43	0.50	0.40	0.30	0.30	0.54	0.66		0.04	0.04	0.02	0.08	
MgO	39.11	37.00	29.40	30.40	14.50	18.10	1.01	1.85	4.17	5.56	0.06	0.43	5.43	
CaO	0.06	0.46	0.80	0.80	18.50	19.70	0.07	0.15	45.98	37.34	50.50	38.60	1.78	2.51
Na <sub>2</sub> O		0.25			2.00	0.50	0.23	0.95	3.15	2.04	0.59	0.69	8.96	7.27
K <sub>2</sub> O		0.08		0.10		0.10	0.01	0.06		0.08		0.04	0.54	1.49
P <sub>2</sub> O <sub>5</sub>	0.01						0.23		45.56	36.58	40.56	30.72		
CO <sub>2</sub>												9.41		
Cl									0.08		5.12	4.15		
<b>Total</b>	<b>99.94</b>	<b>99.95</b>	<b>100.00</b>	<b>100.00</b>	<b>99.90</b>	<b>99.80</b>	<b>98.47</b>	<b>98.60</b>	<b>99.78</b>	<b>99.84</b>	<b>98.83</b>	<b>98.47</b>	<b>100.00</b>	<b>99.55</b>

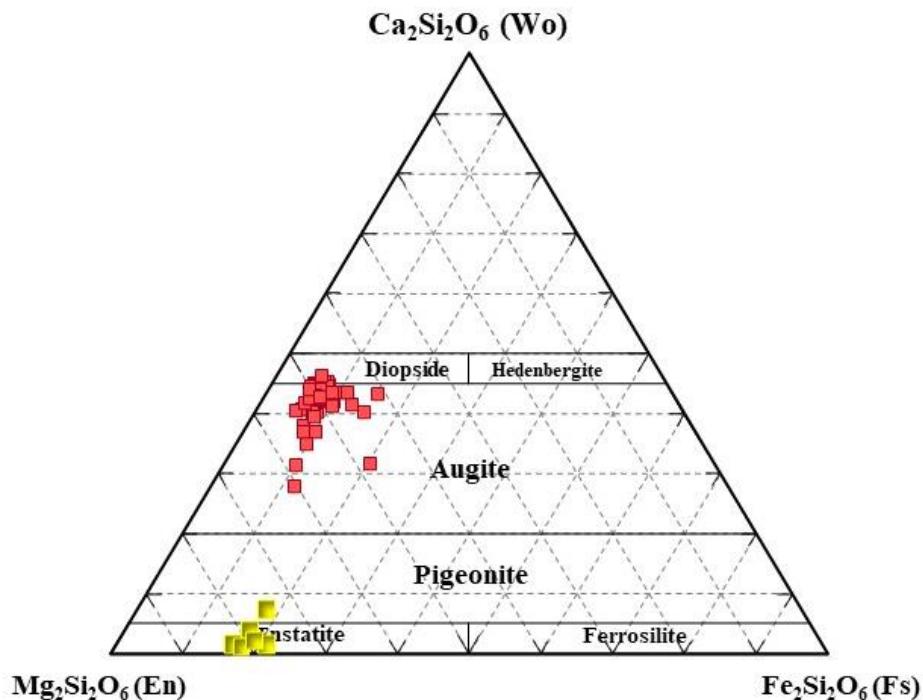
**Table 3:** Variation in Chemical Compositions (%wt. = weight percent) of Olivine, Enstatite, and Augite Crystals at the Center and Edge. The data provides insights into the elemental variations within these crystals at distinct structural locations.

Mineral / Oxide (% wt)	Olivine		Enstatite		Augite	
	Center	Edge	Center	Edge	Center	Edge
SiO <sub>2</sub>	38.13	37.21	56.46	56.14	55.99	55.49
TiO <sub>2</sub>		0.20	0.24	0.10	0.37	0.37
Al <sub>2</sub> O <sub>3</sub>	0.01		0.06	0.34	0.44	0.30
FeO	22.04	23.10	11.20	11.23	3.71	4.16
MnO		0.48	0.31	0.34	0.16	0.22
MgO		38.74	30.94	30.54	18.69	17.88
CaO			0.55	0.84	19.55	20.78
Na <sub>2</sub> O			0.04	0.06	0.59	0.28
K <sub>2</sub> O			0.05			0.02
<b>Total</b>	<b>60.18</b>	<b>99.73</b>	<b>99.85</b>	<b>99.59</b>	<b>99.50</b>	<b>99.50</b>

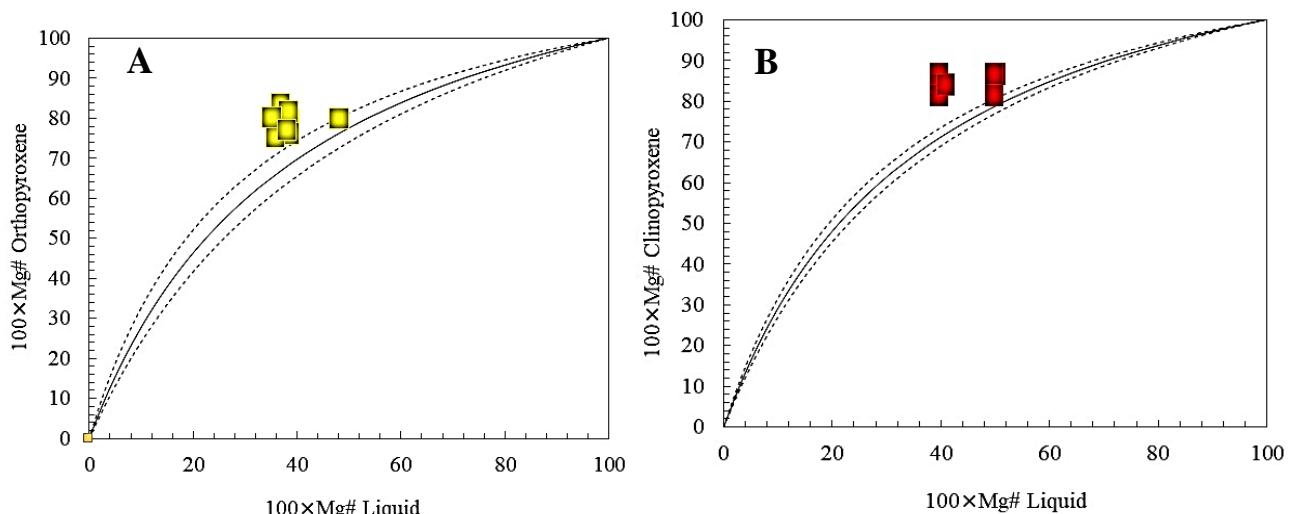
Further examination of olivine crystals ( $n=18$ ) using the Rhodes diagram (Rhodes 1970, **Figure 4**) indicates equilibrium with the liquid during crystallization, showcasing a dynamic interplay between elements. Orthopyroxene crystals ( $n=20$ ) predominantly fall within the enstatite field, while clinopyroxene crystals ( $n=25$ ) correspond to augite, with some bordering augite and diopside (**Figure 5**). Equilibrium analysis between orthopyroxene crystals and the liquid (**Figure 6**) illustrates a distinct trend, emphasizing non-equilibrium conditions. Augite crystals, on the other hand, exhibit a closer alignment with the equilibrium line. Plagioclase crystals ( $n=28$ ) predominantly display albite composition, with some exhibiting oligoclase composition and a lone crystal at the oligoclase-andesine boundary (**Figure 7**). No clear correlation emerges between petrographic and chemical data.



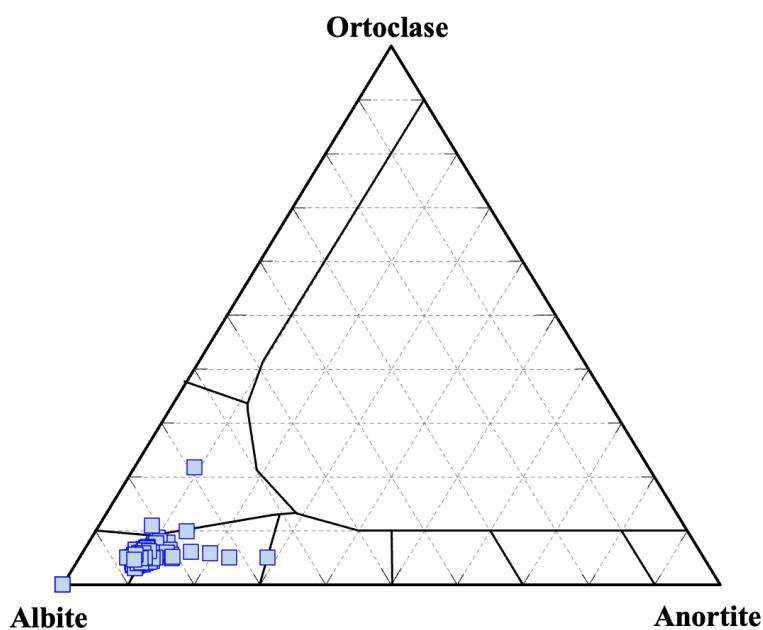
**Figure 4:** Rhodes Diagram for Assessing Equilibrium with Liquid during Olivine Crystallization applied to MCS Chondrules (Rhodes, 1970).



**Figure 5:** Ca-Fe-Mg Pyroxenes Classification Diagram by Morimoto et al. (1988). Data points highlighted in red represent clinopyroxene crystals, while those in yellow denote orthopyroxene crystals. The diagram aids in the systematic classification and differentiation of MCS' pyroxene compositions based on their Ca, Fe, and Mg content.



**Figure 6:** Rhodes Diagram for (A) Enstatite and (B) Augite Crystal Composition Data in MCS. The diagram aids in visualizing and comparing the equilibrium with the liquid during the crystallization process for these distinct mineral compositions.



**Figure 7:** Ab-Or-An Classification Diagram Applied to Plagioclase Crystals in the Campos Sales Meteorite. The diagram facilitates the systematic classification of plagioclase compositions based on the abundance of albite (Ab), orthoclase (Or), and anorthite (An), providing valuable insights into the mineralogical characteristics of the meteorite.

Representative samples of 33 chemical compositions from different chondrules are presented in **table 4**. All chondrules, characterized by FeO content exceeding 10%, fall under type II, further subclassified into types A ( $\text{Ol} > 80\%$ ), B ( $\text{Px} > 80\%$ ), or type AB, aligning with observed textural groups (**Tables 5, 6, 7**).

**Table 4:** Chemical Composition of Analyzed Chondrules from the Campos Sales Meteorite, offering comprehensive insights into the elemental makeup of these essential components.

Sample/ Oxide (% wt.)	C21	C23	C22	C28	C32	C26	C17	C8	C25	C16	C18	C6	C5	C4	C20	C1	C2	C11	C12	C3	C31	C9	C10	C30	C33	C19	C7	C24	C29	C13	C15	C27	C14
SiO <sub>2</sub>	40.21	42.81	43.62	43.72	43.75	44.85	44.97	45.72	45.89	45.98	46.39	46.96	47.79	48.05	48.60	48.88	49.08	49.59	50.10	50.65	51.33	51.42	52.87	52.38	53.17	53.38	53.49	53.76	54.21	54.55	54.93	55.42	56.71
TiO <sub>2</sub>	0.05	0.09	0.07	0.07	0.06	0.03	0.04	0.08	0.05	0.06	0.12	0.13	0.09	0.08	0.01	0.17	0.11	0.04	0.14	0.16	0.08	0.13	0.13	0.13	0.13	0.14	0.15	0.14	0.22	0.17	0.19	0.07	0.09
Al <sub>2</sub> O <sub>3</sub>	1.71	4.55	5.05	5.25	3.85	4.97	4.85	5.65	4.20	5.23	11.87	4.40	6.34	6.21	4.99	6.33	6.43	9.08	10.85	5.07	4.75	11.44	3.67	5.36	5.15	7.19	5.36	4.52	5.65	3.60	5.56	4.51	0.12
FeO	18.56	16.66	15.75	16.27	16.09	15.28	14.75	14.50	15.37	14.13	13.65	14.87	13.20	12.98	13.36	13.69	13.50	10.72	10.44	12.94	13.37	9.87	11.45	11.98	11.03	10.27	10.34	11.51	9.00	9.65	10.09	10.07	10.95
MnO	0.39	0.19	0.29	0.35	0.35	0.25	0.32	0.38	0.38	0.29	0.28	0.27	0.28	0.33	0.35	0.28	0.30	0.24	0.26	0.31	0.31	0.19	0.35	0.34	0.34	0.20	0.36	0.30	0.32	0.31	0.28	0.43	0.43
MgO	37.78	27.12	31.90	31.02	32.99	27.72	29.66	29.29	28.69	26.97	19.60	25.44	24.50	28.42	28.16	26.02	26.00	22.05	19.71	26.81	25.25	19.86	27.07	24.75	25.20	16.34	25.42	24.38	20.60	23.92	22.97	23.45	30.83
CaO	0.75	1.52	1.22	0.53	1.26	2.62	3.06	1.36	2.33	4.30	1.29	3.29	2.13	1.25	1.36	1.49	1.45	3.42	1.85	0.94	1.06	1.26	2.55	2.39	2.23	8.32	2.24	1.14	6.64	4.97	2.92	3.82	0.65
Na <sub>2</sub> O	0.43	1.73	1.78	1.99	1.46	2.00	2.01	2.18	1.62	2.32	5.24	1.63	2.47	2.31	2.09	2.34	2.39	4.00	4.68	2.17	1.87	5.09	1.50	2.08	2.11	3.51	1.97	1.71	2.13	1.56	2.33	1.85	0.11
K <sub>2</sub> O	0.05	0.10	0.14	0.18	0.14	0.14	0.16	0.16	0.11	0.17	0.37	0.12	0.19	0.17	0.21	0.19	0.32	0.41	0.16	0.18	0.34	0.09	0.16	0.21	0.26	0.15	0.19	0.19	0.11	0.19	0.15	0.06	
P <sub>2</sub> O <sub>5</sub>		0.08			0.05	0.03	0.33		0.09	0.12		0.06		0.35			0.06				0.28								0.02				
SO <sub>3</sub>	0.04	5.10	0.13	0.56		2.05	0.16	0.26	1.32	0.46	0.97	2.81	2.89	0.15	0.48	0.55	0.50	0.47	1.53	0.79	1.80	0.02	0.24	0.38	0.38	0.39	0.53	2.36	1.05	1.13	0.43	0.23	
Cl	0.03	0.06	0.04	0.05	0.05	0.04		0.07	0.04		0.08	0.07	0.05	0.04	0.04	0.03	0.04		0.03			0.10	0.08	0.04	0.04					0.03	0.05		0.04
<b>Total</b>	100.00	99.99	100.00	100.00	100.00	100.00	100.00	99.99	100.00	100.00	99.98	100.00	99.99	99.99	100.00	100.00	100.00	100.00	100.00	100.00	99.99	99.99	100.00	100.00	100.00	100.00	100.00	99.99	100.00	100.00	100.00		

**Table 5:** Chemical Composition Data for All Type IIA Olivine Chondrules categorized as Granular Olivine (GO) in the Campos Sales meteorite. The data offers detailed insights into the elemental makeup of these specific chondrule types.

Sample/ Oxide (% wt.)	C22	C32	C17	C16	C6	C5	C1	C2	C3	C30	C19	C24	C15	C14
SiO <sub>2</sub>	43.62	43.75	44.97	45.98	46.96	47.79	48.88	49.08	50.65	52.38	53.38	53.76	54.93	56.71
TiO <sub>2</sub>	0.07	0.06	0.04	0.06	0.13	0.09	0.17	0.11	0.16	0.13	0.14	0.14	0.19	0.09
Al <sub>2</sub> O <sub>3</sub>	5.05	3.85	4.85	5.23	4.40	6.34	6.33	6.43	5.07	5.36	7.19	4.52	5.56	0.12
FeO	15.75	16.09	14.75	14.13	14.87	13.20	13.69	13.50	12.94	11.98	10.27	11.51	10.09	10.95
MnO	0.29	0.35	0.32	0.29	0.27	0.28	0.28	0.30	0.31	0.34	0.20	0.30	0.28	0.43
MgO	31.90	32.99	29.66	26.97	25.44	24.50	26.02	26.00	26.81	24.75	16.34	24.38	22.97	30.83
CaO	1.22	1.26	3.06	4.30	3.29	2.13	1.49	1.45	0.94	2.39	8.32	1.14	2.92	0.65
Na <sub>2</sub> O	1.78	1.46	2.01	2.32	1.63	2.47	2.34	2.39	2.17	2.08	3.51	1.71	2.33	0.11
K <sub>2</sub> O	0.14	0.14	0.16	0.17	0.12	0.19	0.21	0.19	0.16	0.26	0.19	0.19	0.06	
P <sub>2</sub> O <sub>5</sub>			0.03	0.09		0.06							0.02	
SO <sub>3</sub>	0.13		0.16	0.46	2.81	2.89	0.55	0.50	0.79	0.38	0.39	2.36	0.43	
Cl	0.04	0.05			0.07	0.05	0.03	0.04		0.04			0.05	0.04
<b>Total</b>	100.00	100.00	100.00	100.00	100.00	99.99	100.00	100.00	100.00	100.00	100.00	100.00	99.99	100.00

**Table 6:** Chemical Composition Data for All Type IIA Olivine Chondrules categorized as Barred Olivine (BO) in the Campos Sales meteorite. The data offers detailed insights into the elemental makeup of these specific chondrule types.

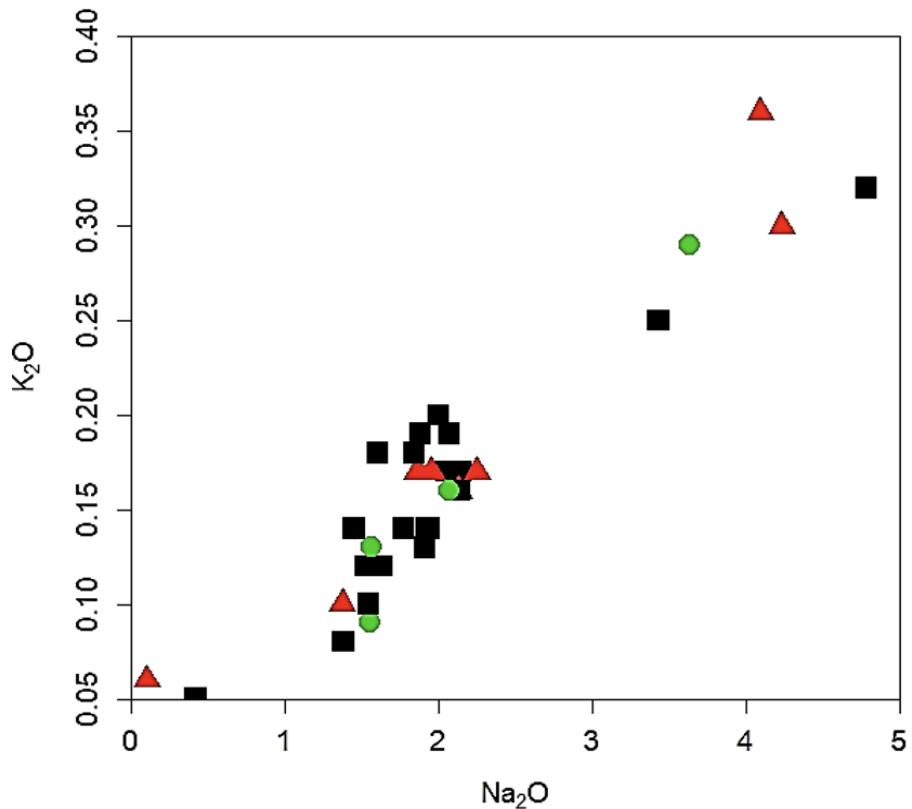
Sample/ Oxide (% wt.)	C21	C28	C26	C4	C12	C9	C10	C33	C7
SiO <sub>2</sub>	40.21	43.72	44.85	48.05	50.10	51.42	52.87	53.17	53.49
TiO <sub>2</sub>	0.05	0.07	0.03	0.08	0.14	0.13	0.13	0.13	0.15
Al <sub>2</sub> O <sub>3</sub>	1.71	5.25	4.97	6.21	10.85	11.44	3.67	5.15	5.36
FeO	18.56	16.27	15.28	12.98	10.44	9.87	11.45	11.03	10.34
MnO	0.39	0.35	0.25	0.33	0.26	0.19	0.35	0.34	0.36
MgO	37.78	31.02	27.72	28.42	19.71	19.86	27.07	25.20	25.42
CaO	0.75	0.53	2.62	1.25	1.85	1.26	2.55	2.23	2.24
Na <sub>2</sub> O	0.43	1.99	2.00	2.31	4.68	5.09	1.50	2.11	1.97
K <sub>2</sub> O	0.05	0.18	0.14	0.17	0.41	0.34	0.09	0.21	0.15
P <sub>2</sub> O <sub>5</sub>			0.05			0.28			
SO <sub>3</sub>	0.04	0.56	2.05	0.15	1.53	0.02	0.24	0.38	0.53
Cl	0.03	0.05	0.04	0.04	0.03	0.10	0.08	0.04	
<b>Total</b>	<b>100.00</b>	<b>100.00</b>	<b>100.00</b>	<b>99.99</b>	<b>100.00</b>	<b>99.99</b>	<b>99.99</b>	<b>100.00</b>	<b>100.00</b>

**Table 7:** Chemical Composition Data for Type IIA Pyroxene Chondrules, specifically categorized as Granular Olivine Pyroxene (GOP), Granular Pyroxene (GP), and Radial Pyroxene (RP) in the Campos Sales meteorite. The data offers comprehensive insights into the elemental makeup of these specific chondrule types.

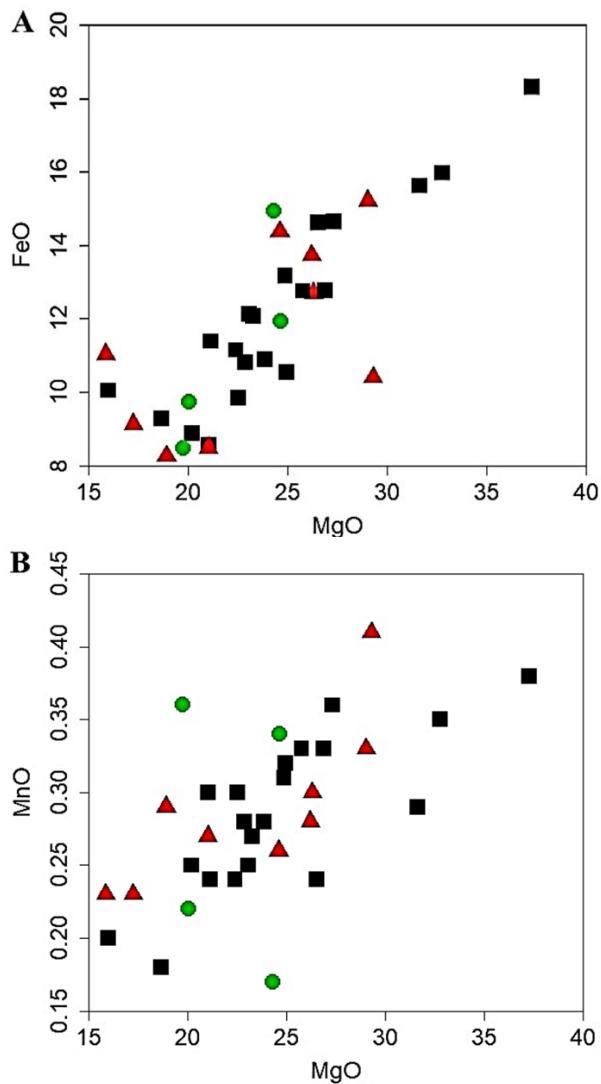
Type	IIAB - GOP			IIB - GP			IIB - RP		
	Sample/Oxide (% wt.)	C25	C31	C27	C11	C29	C23	C8	C18
SiO <sub>2</sub>	45.89	51.33	55.42	49.59	54.21	42.81	45.72	46.39	48.60
TiO <sub>2</sub>	0.05	0.08	0.07	0.04	0.22	0.09	0.08	0.12	0.01
Al <sub>2</sub> O <sub>3</sub>	4.20	4.75	4.51	9.08	5.65	4.55	5.65	11.87	4.99
FeO	15.37	13.37	10.07	10.72	9.00	16.66	14.50	13.65	13.36
MnO	0.38	0.31	0.43	0.24	0.32	0.19	0.38	0.28	0.35
MgO	28.69	25.25	23.45	22.05	20.60	27.12	29.29	19.60	28.16
CaO	2.33	1.06	3.82	3.42	6.64	1.52	1.36	1.29	1.36
Na <sub>2</sub> O	1.62	1.87	1.85	4.00	2.13	1.73	2.18	5.24	2.09
K <sub>2</sub> O	0.11	0.18	0.15	0.32	0.19	0.10	0.16	0.37	0.21
P <sub>2</sub> O <sub>5</sub>				0.06		0.08	0.33	0.12	0.35
SO <sub>3</sub>	1.32	1.80	0.23	0.47	1.05	5.10	0.26	0.97	0.48
Cl	0.04					0.06	0.07	0.08	0.04
<b>Total</b>	<b>100.00</b>	<b>100.00</b>	<b>100.00</b>	<b>100.00</b>	<b>100.00</b>	<b>99.99</b>	<b>99.99</b>	<b>99.98</b>	<b>100.00</b>

Despite petrographic variations and diverse chemical compositions, attempts to differentiate groups using binary diagrams proved challenging. A positive correlation between sodium and potassium (**Figure 8**) highlights their substitution within plagioclase. Additionally, three main groups, rich in alkalis, intermediate, and low content, are observed independently of textural types, providing further insights into the chemical intricacies of the meteorite.

A notable diversity in composition exists both within and among the studied chondrule groups, featuring ranges of  $\text{SiO}_2 = 33.95\% - 53.86\%$ ,  $\text{MgO} = 15.84\% - 37.28\%$ ,  $\text{FeO} = 8.26\% - 18.31\%$  and  $\text{CaO} = 0.5\% - 8.14\%$ . This compositional variability aligns with expectations when considering the distinct types of chondrules and their mineralogical compositions. In contrast, other assessed chemical elements exhibit percentages within the ranges of  $0.01 < \text{TiO}_2 < 0.2\%$ ,  $0.11 < \text{Al}_2\text{O}_3 < 10.75\%$ , and  $0.17 < \text{MnO} < 0.41\%$ . Consequently, it proved challenging to establish a specific compositional range for these elements based on their association with the identified textural types. Alkali elements, especially  $\text{Na}_2\text{O}$  ( $0.1\% - 4.78\%$ ) and  $\text{K}_2\text{O}$  ( $0.05\% - 0.36\%$ ), vary significantly, they primarily signify the presence of plagioclase in chondrules. Diagrams incorporating  $\text{MgO}$  as a distinguishing agent (**Figure 9**) likely capture the substitution of  $\text{MgO}$  by  $\text{FeO}$  and  $\text{MnO}$  within the olivine and enstatite structures.



**Figure 8:** Binary Diagram of  $\text{Na}_2\text{O}$  versus  $\text{K}_2\text{O}$  applied to MCS' chondrule compositions obtained in this study. The data points for radial pyroxene chondrules are highlighted in green, barred olivine chondrules in red, and granular chondrules in black. The diagram provides a visual representation of the variations in sodium and potassium oxide content across different chondrule types.



**Figure 9:** MgO versus FeO (A) and MgO versus MnO (B) variation diagrams applied to the compositions of MCS' chondrules. Data points for radial pyroxene chondrules are depicted in green, barred olivine chondrules in red, and granular chondrules in black. The diagrams offer insights into the variations in magnesium, iron, and manganese oxide content across different chondrule types in the study.

## DISCUSSIONS: MINERALOGICAL AND TEXTURAL INSIGHTS IN TYPE L CHONDRULES

### Chondrules Characteristics in Campos Sales Meteorite: Comparisons and Patterns

The mineral chemistry data derived from the Campos Sales meteorite (MSC) sheds light on the homogeneity in the chemical composition of the chondrules examined. A comparative analysis involving olivine ( $\text{Fo}_{75}\text{Fa}_{25}$ ) and orthopyroxene ( $\text{Fs}_{22}$ ) compositions reveals analogous trends with Varre-Sai ( $\text{Fo}_{75}\text{Fa}_{25}$ , VS, Zucolotto et al., 2012) and Lavras do Sul ( $\text{Fo}_{75.1}\text{Fa}_{24.9}$ , LS, Zucolotto et al., 2010) meteorites, both categorized as L5 ordinary chondrites.

Non-porphyritic chondrules in the MCS primarily fall into the categories of barred olivine, radial pyroxene, and granular, aligning with Rubin's (1989a) textural classifications. Similar observations exist in Varre-Sai and Lavras do Sul meteorites, suggesting consistent patterns in L5

ordinary chondrites. No discernible correlation is observed between the size, textural type, and shape of chondrules in MCS. This variability, consistent with previous studies on L-type chondrites (Gooding and Keil, 1981, Gooding, 1983), challenges the notion of strict relationships between these parameters.

Despite some flattened or deformed areas, chondrules' shapes in MCS predominantly exhibit a spherical tendency (**Figure 2C**), especially in radial and barred categories. Gooding and Keil (1981) note that non-porphyritic chondrules often display enhanced sphericity, facilitating their identification during microscopy, and indicative of uniform pressure during their formation. Beyond the presence of rounded chondrules, the MCS exhibits a variety of chondrules with diverse shapes. These include representations of chondrule fragments and granular chondrules. Zucolotto et al. (2012) have previously noted that numerous types of non-porphyritic chondrules and fragments within meteorites, such as the MCS, demonstrate deviations from the expected sphericity pattern.

#### *Deformation and Agglutination Dynamics*

Microscopic examination reveals deformed areas, especially at chondrule boundaries in contact zones, been it is noticeable that chondrules are partially to completely deformed, and even broken at their edges. Ductile deformation of chondrules throughout various types suggests a non-simultaneous crystallization process during agglutination. This evidence aligns with the concept of plastic deformation during the interaction of chondrules in different stages of solidification.

In the MCS context, the observation of ductile deformation across various chondrule types implies that their crystallization did not occur simultaneously during the agglutination phase. Essentially, some chondrules were already in a more solid state, while others exhibited more plastic behavior. The interaction between these chondrules likely led to the deformation of the more plastic ones as they were "pressed" against the more solid ones. As per the findings of Gooding and Keil (1981), the presence of these areas suggests a process of plastic deformation occurring on surfaces that were not entirely solidified, especially when in contact with chondrules in a more advanced stage of solidification.

Deformed areas, as those observed in MCS' chondrules, may also signify shock metamorphism events, evidenced by broken chondrule boundaries. However, determining the timing of these shock events remains challenging, leaving open the question of when these metamorphic events occurred.

#### *Skeletal Olivine and Pyroxenes: Insights into Solar System Origins*

The chondrules examined in the MCS exhibit a notable abundance of skeletal olivine and pyroxenes. This prevalence of specific mineral textures suggests that during the early stages of the Solar System, there were distinct occurrences when materials rich in magnesium and iron formed. Subsequently, these materials underwent rapid crystallization, albeit not necessarily simultaneously. This hypothesis finds support in the work of Blander (1983), which proposes that the origin of chondrules is rooted in the condensation of drops from a metastable silicate liquid, followed by processes of crystallization and accretion. However, it is essential to clarify that these observations do not imply that the chondrules originated from the fractional crystallization of the same magma. Rather, they highlight moments when drops of liquids with specific compositions formed, cooled, and eventually became integral components of the same parental body.

#### **Mineralogical Aspects of Chondrules in L-type Meteorites**

The chemical data for each mineral in MCS reveal minimal compositional variability (**Tables 2 and 3**), implying the classification of this meteorite as a balanced chondrite. Nevertheless, individual chondrules within the meteorite exhibit distinct chemical compositions. Considering these observations, it is plausible to infer the occurrence of a thermal event that prompted chemical reequilibration and suggests diverse sources for the origin of these chondrules.

As elucidated by Blander (1983), variations in composition may arise from kinetic factors such as nucleation constraints during the condensation and crystallization phases, slow chemical reactions, and sluggish ion diffusion rates. Moreover, the possibility of chondrules "inheriting" materials from pre-existing chondrules cannot be discounted. The proposition by Blander (1983) gains support from studies conducted by Ushikubo et al. (2013), particularly those involving oxygen isotopes. These studies indicate discernible differences in nebular compositions during chondrule formation processes for certain types of chondrites.

#### *Unraveling the Significance of Metastable Phases in Chondrules*

In all investigated chondrules within the MCS, a distinctive metastable phase is discernible, characterized by elevated levels of alkalis, silicon, magnesium, iron, and calcium. This phase exhibits compositional similarities to plagioclase and augite, alternating between the two compositions. Primarily occupying interstitial spaces between olivine and enstatite crystals, occasional euhedral inclusions of chromite may be present. Petrographic scrutiny reveals diffuse contacts between plagioclase and augite crystals within this phase, alongside small anhedral crystals of enstatite and olivine interspersed within the interstitial material.

This particular association is not exclusive to the MCS meteorite but is also observed in the Lavras do Sul meteorite (Zucolotto et al., 2010). The metastable phase exhibits various possibilities, including:

- (i) Representing a metastable phase evolving through the exsolution of plagioclase and augite, culminating in a mesh texture. However, the crystals are of such small size that obtaining individual analyses with the SEM beam was unattainable; or
- (ii) Arising from the eutectoid co-crystallization of plagioclase and augite.

In either case, several crystals analyzed within this phase exhibited plagioclase composition. The plagioclase in MCS comprises submillimeter-sized crystals with minimal compositional variation, primarily classified as albite-oligoclase based on chemical data in this study.

The presence of oligoclase is further substantiated by the alkali content in the comprehensive chemical analyses of the chondrules. Alexander et al. (2008) conducted a study on the occurrence of volatile elements, including sodium, in chondrites. According to these authors, the abundance of volatiles remained relatively constant even during the formation of chondrules. To prevent evaporation, the chondrules that preserved these volatile elements would need to originate in regions characterized by high dust/gas ratios. An alternative proposition by Yurimoto and Wasson (2002) suggests that the ratios of sodium and other volatile elements could have been preserved through processes involving rapid fusion and crystallization of the chondrules.

Chen and Goresy (2000) propose in their research that the plagioclase-like material may be maskelynite. Maskelynite, as defined by Chen and Goresy (2000), is a glass with a composition closely resembling that of plagioclase and results from melting caused by a high-pressure episode. Alternatively, the plagioclase might be the high-pressure polymorph of feldspar, known as lingunite, which occurs under conditions of 22 GPa pressure and 2200°C temperature (Liu, 2006).

Among these possibilities, the first aligns most consistently with the textural and chemical data, given the holocrystalline nature of the MCS and the absence of significant indications of shock events in other crystalline phases, such as olivine.

#### *Polymorphs of Chromium*

The euhedral chromium-rich crystals, primarily located within the metastable phase, were initially identified as chromite crystals. Another potential mineral phase, as proposed by Chen et al. (2008) and Xie et al. (2011), suggests that these Cr-crystals may be xieite. Xieite is recognized

as a high-pressure and high-temperature polymorph of chromite, forming under conditions of 20–23 GPa pressure and temperatures between 1800°C and 2000°C.

While the possibility of these crystals being xieite is intriguing, a comprehensive assessment reveals the absence of other minerals exhibiting textures indicative of a high-intensity shock event. According to the criteria established by Stöffler et al. (1991), the shock levels in MCS are classified as S1-S2, denoting a very weak shock experience with impact pressures ranging from 4 to 10 GPa and a post-shock temperature increase between 10 and 50°C. Given these considerations, it is presently more appropriate to assert that the crystals within the metastable phase are, indeed, chromite.

#### *Geothermometry*

Utilizing olivine crystals as a basis, the geothermometer proposed by Putirka (2008) yields temperatures ranging from 1076.78°C to 1125.38°C. Similarly, when the geothermometer developed by Putirka et al. (1996) is applied to enstatite crystals, it indicates a temperature range akin to that of olivine, with values spanning from 973.65°C to 1126.94°C. The geothermometer values for olivine align closely with those suggested by Murata et al. (2007) for the crystallization temperatures of this mineral. Furthermore, in the context of L-type chondrites, where thermal events are concerned, Slater-Reynolds & McSween (2005) propose a maximum temperature of 950°C.

Notably, no discernible textural features indicative of a significant thermal metamorphic event was identified in the MCS. Consequently, it is inferred that the calculated values aptly represent the crystallization temperatures of the examined minerals.

## CONCLUSIONS

Grounded in the premise that chondrules might embody droplets derived from distinct magmas formed during the early phases of the Solar System, our study delves into 33 chondrules from the Campos Sales meteorite, an L5 ordinary chondrite.

Chondrules within the MCS showcase a composition dominated by skeletal crystals of olivine, enstatite, and augite, accompanied by varying proportions of metal, troilite, plagioclase, chromite, and Cl-apatite. The predominant textural variations include barred, radial, and granular structures.

Analysis of mineral chemical composition data reveals minimal variation within individual crystals. Nevertheless, each chondrule exhibits a distinct composition, suggesting diverse progenitors for these particles. Our interpretation posits that the minerals in MCS chondrules underwent formation via a multitude of processes in their nebular origin region. Differences in these processes and compositions within the nebular zone likely influenced the observed chondrule compositions. Contemporary features affirm the rapid formation of chondrules. During accretion for parental body formation, not all chondrules were fully solidified, resulting in varied chondrule shapes.

The presence of skeletal crystals implies rapid chondrule crystallization, preserving volatile elements, notably within the meta-stable phase rich in olivine crystals. Subsequently, MCS chondrules experienced accretion, forming a larger body. A subsequent thermal event, possibly shock-induced disaggregation, occurred with temperatures and pressures adequate for mineral re-equilibration but insufficient for differentiation or obliteration of most chondrules.

While the homogeneity in crystal composition strongly indicates the occurrence of this thermal event, geothermometric data suggest crystallization temperatures rather than subsequent events. In summary, our comprehensive investigation into the mineralogical and textural facets of type L meteorite chondrules unveils crucial insights into their composition, formation

dynamics, and the potential influence of diverse processes during the early stages of the Solar System.

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## CONFLICT OF INTEREST DECLARATION

We, the undersigned authors of this paper declare that we have no conflicts of interest to disclose regarding this research. We have not received any financial support or funding, and we have no financial interests, personal relationships, or affiliations with organizations that could be perceived as affecting the research, analysis, or conclusions presented in this paper. We also affirm that we have no competing professional or personal interests that could impact the integrity or impartiality of the research conducted or the findings reported.

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## **CAPÍTULO III: CONCLUSÕES**

## CONCLUSÕES

A partir das evidências e discussões aqui apresentadas fica claro que os meteoritos representam parte fundamental da história do Sistema Solar, que ainda não é completamente conhecida pela humanidade. O que se pode argumentar, até aqui, é que o conhecimento sobre os materiais primordiais formados nos primeiros estágios evolutivos do Sistema Solar, é essencial para avançar na compreensão dos processos que culminaram em sua atual configuração, os quais permanecem intrigantemente desconhecidos. Ademais, é a partir do estudo de meteoritos condrícticos que é possível entender uma das primeiras estruturas geradas com o resfriamento da nebulosa solar: os côndrulos.

Os côndrulos são partículas submilimétricas a milimétricas, com formas arredondadas e compostas por silicatos ferromagnesianos. É a partir do estudo desses minerais máficos e das relações entre eles, que é possível vislumbrar os processos, o tempo, e as condições vigentes e que resultaram nas rochas extraterrestres de onde os côndrulos são encontrados hoje.

A partir da proposição da hipótese investigativa em que se considera os côndrulos como possíveis gotas de “magmas” nebulares, buscou-se conhecer aspectos peculiares a essas partículas. A base deste estudo foi a investigação textural, mineral e química dos côndrulos presentes no meteorito Campos Sales (MCS).

Os tipos texturais majoritários de côndrulos do MCS são: barrado, radial e granular. Esses côndrulos costumam ter formas que tendem a esfera, podendo ou não apresentar áreas deformadas quando em contato com outros. Além disso, essas feições texturais são as mais distinguíveis e preservadas em comparação com a matriz do meteorito.

Os côndrulos do MCS são compostos predominantemente por cristais esqueléticos de olivina ( $\text{Fa}_{25}\text{Fo}_{75}$ ) e enstatita ( $\text{En}_{75-79}, \text{Fs}_{25-21}$ ), e secundariamente por cristais de augita e plagioclásio os quais apresentam texturas que sugerem processos de ex-solução. Adicionalmente, foi possível identificar cristais submilimétricos euedrais de cromita/xieita, dispersos entre os cristais de plagioclásio e augita, bem como cristais de Cl-apatita.

Chama a atenção a existência de microesferas de dióxido de silício, também associadas com os cristais de plagioclásio dentro dos côndrulos de olivina barrada. Tais esferas são

raras e, na amostra estudada do MCS, foi possível observar apenas 3 destas esferas, com tamanho sempre inferior a 0,005 mm.

Salienta-se aqui o fato de que cristais de troilita e liga Fe-Ni são encontrados, por vezes, inclusos em côndrulos granulares e radiais, mas não é tão corriqueiro encontrá-los em côndrulos barrados. Dessa maneira, sua maior presença é na matriz do meteorito, principalmente nas adjacências dos côndrulos.

Tendo em vista os aspectos compositionais, os minerais que compõem os côndrulos do MCS apresentam pouca variação centro-borda. Esse aspecto confirma a classificação da amostra como um condrito ordinário reequilibrado, além de indicar a existência de um evento termal que tenha propiciado o reequilíbrio composicional.

Os dados químicos permitiram não apenas a classificação dos cristais de olivina, enstatita e augita, mas também foram utilizados para classificar o plagioclásio. Apesar dos cristais de plagioclásio serem muito pequenos ( $<30\mu\text{m}$ ), os teores de sódio associados aos baixos conteúdos de potássio e cálcio permitem determinar sua composição como de oligoclásio.

Mediante aos aspectos interpretadas a partir do desafio proposto pelo estudo dos côndrulos do MCS, apresenta-se as etapas relacionadas à sua história de formação, desde suas origens até a sua chegada à superfície da Terra. Estas fases podem ser sumariadas como:

- (1) Formação dos côndrulos a partir do resfriamento rápido do material nebular precursor;
- (2) Acresção dos côndrulos em diferentes estágios de resfriamento e formação do corpo parental;
- (3) Ocorrência do evento termal e reequilíbrio químico;
- (4) Chegada a Terra.

Apesar dessas etapas parecerem óbvias, muito ainda se desconhece sobre os mecanismos que desencadearam essas fases. Alguns autores apontam que a formação dos diferentes côndrulos indica a variabilidade de composição entre as regiões nebulares. Mediante à variação de composição química e as diferentes texturas encontradas acredita-se que a ideia sobre a formação esteja correta e seja representativa para o conjunto amostral estudado. Sugere-se, pois, a continuidade das pesquisas com a integração de dados isotópicos.

## **ANEXOS**

## Estado da Arte

Os meteoritos são a principal fonte de informação sobre a composição dos materiais extraterrestres (Palme & Zipfel, 2017). Esses fragmentos de rocha – ou metal – são originados principalmente a partir de colisões dos corpos asteroidais ou planetesimais presentes no cinturão de asteroides, e, secundariamente, da superfície da Lua e de Marte (Engrand, 2011; Palme & Zipfel, 2017). Eles, também são compostos de assembleias complexas de minerais anidros e hidratados, podendo ter ou não algum composto orgânico (Engrand, 2011).

A classificação dos meteoritos agrupa de amostras que experimentaram processos similares na formação de seus corpos parentais de origem, contudo esse aspecto não quer dizer diretamente que amostras de um mesmo grupo pertençam a apenas um único corpo parental. (Engrand, 2011). Existem dois grandes grupos de meteoritos: (i) diferenciados – rochosos acondríticos, férreos magnéticos e mistos – e (ii) não diferenciados – rochosos condrílicos (Figura 11), os quais se subdividem em diversos outros subgrupos (Zanda, 2004; Engrand, 2011; Jacquet, 2022), sistematizados na figura abaixo.

## Grupos de Meteoritos

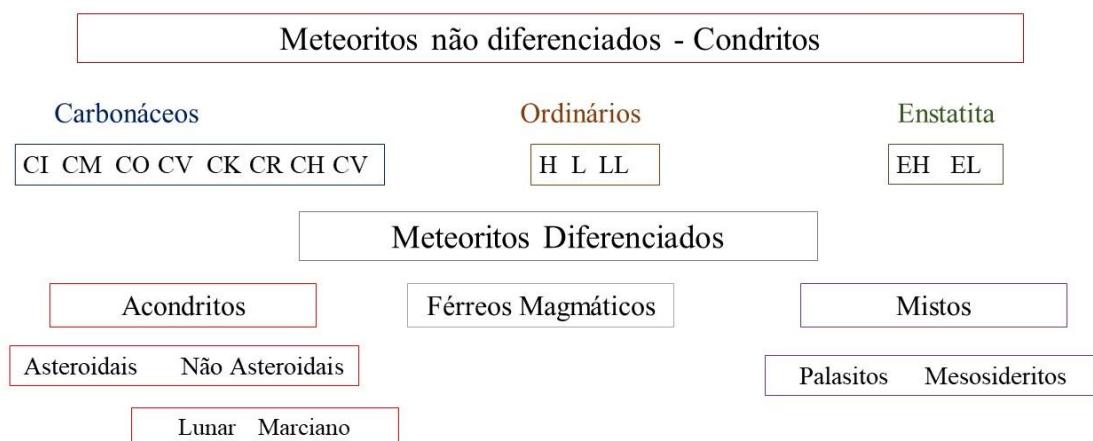


Figura 11. Esquema simplificado de classificação dos meteoritos. Tradução da autora a partir da imagem disposta no trabalho de Jacquet (2022). Carbonáceos: meteorito de Ivuna (CI); meteorito de Mighei (CM); meteorito de Ornans (CO); meteorito de Vigarano (CV); meteorito de Karoonda (CK); meteorito de Renazzo (CR); meteorito carbonáceo com >50% de FeNi. Ordinários: meteoritos com 25 - 30% de teor de ferro (H); meteoritos com 20 – 25% de teor de ferro (L); meteoritos com teor de ferro <20% (LL). Enstatita: alto teor de ferro (EH); baixo teor de ferro (EL).

A classificação simplificada apresentada na Figura 1 evidencia que os meteoritos diferenciados são originados a partir de corpos parentais que sofreram diferenciação química, que experimentaram fusão, e tiveram seus constituintes químicos dispostos em uma estrutura acamada – núcleo, manto e crosta (Palme & Zipfel, 2017) – como é o caso do planeta Terra. É por isso que essas rochas constituem amostras essenciais para o entendimento dos processos de formação planetária (Engrand, 2011).

Os acondritos, por exemplo, apresentam composições bastante diferentes da composição média do sistema solar, em função dos processos de diferenciação ocorridos nos corpos parentais (Palme & Zipfel, 2017), sendo correlacionáveis às camadas mais externas da litosfera dos planetas rochosos.

Em se tratando dos meteoritos não diferenciados, essas rochas são oriundas de corpos que não experimentaram processos de diferenciação, pois não alcançaram temperaturas altas o suficiente para se fundirem totalmente. Nesse grupo, encontram-se as rochas chamadas de condritos (Palme & Zipfel, 2017).

Desta forma, as amostras condríticas podem ser consideradas as mais primitivas em termos de composição, uma vez que apresentam teores elementais próximos à média do sistema solar. Contudo, mesmo os corpos parentais condrícticos experimentaram posteriormente vários graus de metamorfismo termal, correlacionáveis aos impactos que fragmentaram estes planetesimais (Engrand, 2011; Palme & Zipfel, 2017).

Importante citar, no caso do condrito primitivo, a classe dos condritos carbonáceos. Os meteoritos dessa classe experimentaram episódios de alteração aquosa, mas suas composições continuam similares às razões elementares da fotosfera solar, o que indica uma preservação da composição do momento em que tais rochas foram geradas (Lodders, 2010).

Seguindo-se a classificação apresentada na Figura 11, existem três categorias principais para de condritos: os enstatita condritos (EC), os condritos carbonáceos (CC), e os condritos ordinários (OC). Sobre eles seguem-se algumas explicações, respectivamente.

Os EC foram formados em ambientes tão reduzidos que elementos litófilos como manganês e cálcio são presentes em sulfetos. Nessa classe, também existem variações no teor de ferro permitindo uma subclassificação como ELL (muito baixo conteúdo de Fe), EL (baixo conteúdo de Fe) e EH (alto conteúdo de ferro).

Em contrapartida, o grupo dos CC representam os condritos que apresentam algum conteúdo de material orgânico, além de a magnetita, um óxido de Fe, ser

encontrada ao invés da liga metálica (Fe-Ni), comum em meteoritos. Essa categoria apresenta diversos subgrupos que são, em geral, denominados de acordo com o meteorito tipo do grupo, por exemplo: CI – Condrito Ivuna, CM – Condrito Murray, CV – Condrito Vigarano, entre outros.

Por fim, os condritos ordinários (OC = Ordinary Chondrites) integram o grupo dos condritos mais comuns, podendo ser subdivididos de acordo com os teores de ferro em: H (alto teor de Fe – 25 a 30 wt%); L (baixo teor de Fe – 20 a 25 wt%) e LL (baixíssimo teor de Fe <20%) (Zanda, 2004; Oliveira, 2020). A classificação dos OC leva também em consideração a definição física (limites) dos côndrulos presentes, cujo valor varia de 3-6, com o tipo 3 representando condritos com côndrulos muito bem definidos (Figura 12A), e o tipo 6 representando condritos cujos côndrulos são pouco definidos (Figura 12B). Os tipos 1 e 2 são utilizados apenas para a classificação de meteoritos que experimentaram alteração aquosa.

Um dado relevante a acrescentar é de que os condritos, de forma geral, são formados por uma matriz na qual estão presentes côndrulos e outras inclusões refratárias.

Estas inclusões refratárias são compostas de minerais de altas temperaturas (1773-1883°C), sendo os dois tipos principais de inclusões os: silicatos e óxidos ricos em Ca-Al (CAIs) e os agregados de olivina ameboidais (AOA) (Scott e Krot, 2005).

A matriz condríctica se refere a todo o material de granulometria fina que envolve os côndrulos. Os cristais da matriz são compostos de minerais anidros e/ou hidratados com cerca de 10 nm até 5 µm (Brearley, 2005).

Os côndrulos são esferas milimétricas a submilimétricas que correspondem às primeiras gotas de produtos nebulares cristalizadas na forma esférica, e que constituem de 20% – 80% da massa dos condritos (Hewins, 1997; Zanda, 2004; Alexander *et al.*, 2008; Engrand, 2011; Palme & Zipfel, 2017).

Por sua importância para os estudos sobre condritos destaca-se que os côndrulos são predominantemente compostos por silicatos ferromagnesianos (olivina e piroxênios) que experimentaram fusão a partir de um mesmo e desconhecido processo, antes de serem incorporados, por acresção, aos corpos parentais (Hewins, 1997). Por isto mesmo se considera de grande importância avaliar a composição e as texturas presentes nessas partículas para entender quais processos poderiam ser comuns durante os primeiros estágios de formação do Sistema Solar.

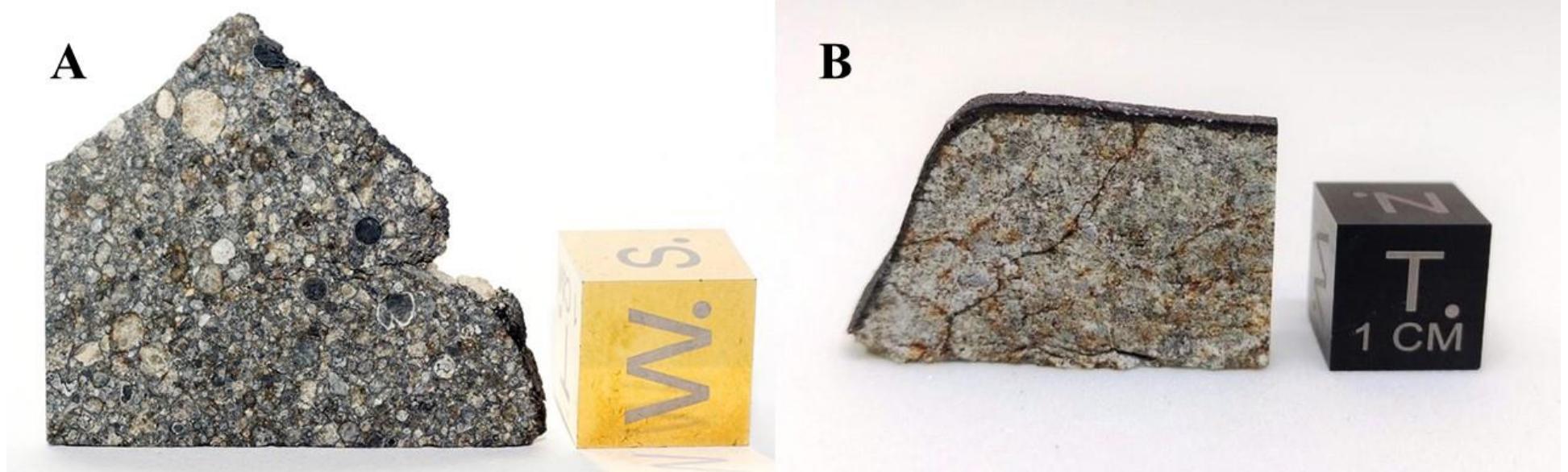


Figura 12. Imagens de fragmentos de condritos ordinários. A- Amostra do condrito ordinário Vicência com as estruturas arredondadas - côndrulos - bastante definidas. Imagem por Anna Morris, disponível em: [https://www.lpi.usra.edu/meteor/get\\_original\\_photo.php?recno=5759274](https://www.lpi.usra.edu/meteor/get_original_photo.php?recno=5759274) visitado no dia 20/03/2023. B- Amostra do condrito Três Irmãos cujos côndrulos não estão distinguíveis a olho nu. Imagem por Rodrigo Guerra, disponível em: [https://www.lpi.usra.edu/meteor/get\\_original\\_photo.php?recno=5760140](https://www.lpi.usra.edu/meteor/get_original_photo.php?recno=5760140) acessado em 20/03/2023.

McSween (1977) reconheceu, dois grupos principais de côndrulos:

- (i) pobres em FeO (tipo I)
- (ii) ricos em FeO (tipo II).

Nessa classificação de McSween (1977), além dos côndrulos, os minerais mais importantes eram a troilita, a liga Fe-Ni e o vidro. Para os côndrulos do tipo I, verificou-se um menor teor de ferro nos silicatos, com a presença do Fe na liga metálica Fe-Ni e no sulfeto. Esse comportamento foi associado com a formação em condições mais reduzidas. Os côndrulos do tipo II que contêm teores mais elevados de Fe nas estruturas da olivina e dos piroxênios, tiveram suas origens associadas a ambientes com condições mais oxidantes.

Posteriormente, Gooding & Keil (1981) tomando como referência os parâmetros de observação para rochas ígneas, sugeriram uma classificação para os côndrulos correlacionando as texturas observadas (barrada, radial, porfirítica, microporfirítica e granular) com o mineral predominante (olivina e/ou piroxênio) (Figura 13).

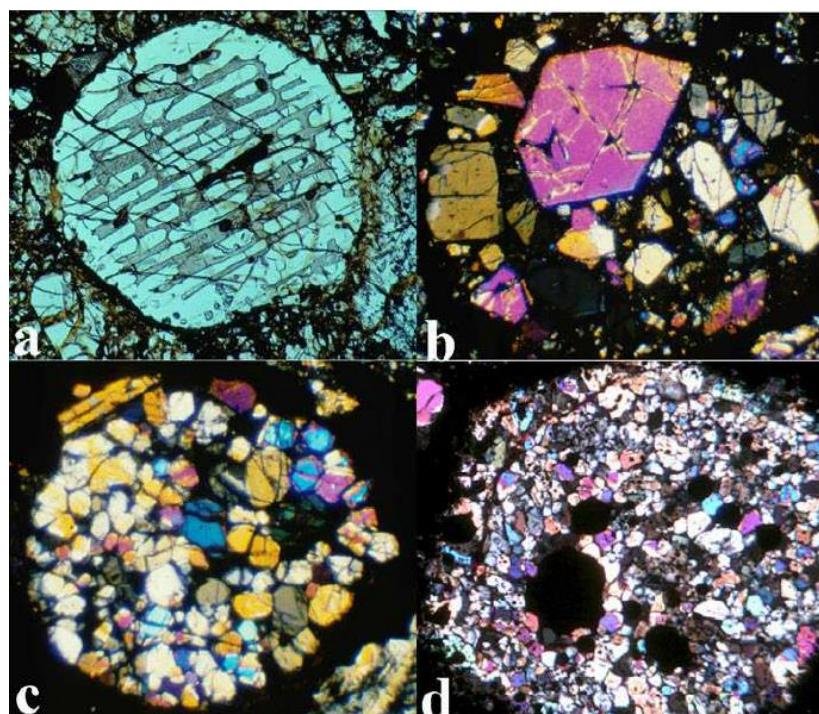


Figura 13. Imagens de texturas em côndrulos obtidas na literatura. A- Côndrulo de olivina barrada; B- Côndrulo de olivina porfirítica; C- Côndrulo de olivina microporfirítica; D- Côndrulo de olivina microporfirítica.. (Hewins, Connolly, Libourel, 2005)

Foi a partir dos trabalhos de McSween (1977), Gooding & Keil (1981) e Jones (1994) que Hewins (1997) associou e resumiu as classificações sugeridas anteriormente na tabela 1, que pode ser vista abaixo.

Tabela 9. Classificação de Côndrulos segundo Hewins (1997). Abreviações: Faialita (Fa), Olivina (Ol), Intermediário (Int.), Piroxênio (Px), Olivina (Ol), Olivina Microporfírica (MPO), Olivina Granular (GO), Olivina Barrada (OB), Olivina Porfirítica (OP), Piroxênio Radial (RP), Piroxênio Porfirítico (PP), Piroxênio Granular (GP), Olivina Piroxênio Radial (POR), Olivina Piroxênio Porfirítica (POP) e Olivina Piroxênio Granular (GOP).

<b>Tipo</b>	<b>Subtipo</b>	<b>Variedades Texturais</b>	
I (pobre em FeO) Olivina Fa<10.	IA	Ol> 80%	MPO, GO, (BO, PO)
	IAB	Int.	POR, POP, GOP
	IB	Px>80%	RP, PP, GP
II (rico em FeO) Olivina Fa>10.	IIA	Ol> 80%	OB, OP, (MPO, GO)
	IIAB	Int.	POR, POP, GOP
	IIB	Px>80%	RP, PP, GP

Baseando-se nos aspectos texturais, Hewins (1988) e Lofgren (1996) inferiram as feições presentes nos côndrulos para inferência dos principais processos ocorridos em sua gênese. Mediante isso, indicou-se que na formação dos cristais esqueléticos de olivina e piroxênio (BO e RP) ocorreu uma fase de crescimento rápido dos cristais. Essa etapa se desenvolveria enquanto os côndrulos ainda estavam totalmente fundidos e começaram a resfriar.

Tratando do tema, Hewins (1997) acrescenta ainda que as relações entre os côndrulos podem esclarecer, ou complicar ainda mais o entendimento sobre os mecanismos que originaram tais partículas. Por exemplo, a existência de côndrulos inclusos nas estruturas de outros, bem como a presença de anéis ígneos, indicam que a formação de tais estruturas condriticas não foi coetânea.

É necessário ter em mente que os estudos sobre a origem dos côndrulos começaram a ocorrer muito antes do século XX. De acordo com Merrill (1920), em 1864 o pesquisador H. C. Sorby, na Inglaterra, indicou que o material de um condrito poderia

ter se originado a partir da fusão, ruptura em partes menores e posterior consolidação a partir de ações mecânicas e químicas do seu corpo parental.

A proposição de Sorby foi validada com a pesquisa de Paque & Bunch (1997). Os dados obtidos por estes autores indicaram que as feições presentes nos côndrulos exigem um evento de aquecimento muito rápido ( $<1600^{\circ}\text{C}$ ), seguido de um evento de resfriamento mais rápido do que o resfriamento nebular. De igual modo, segundo os mesmos autores, após a formação de cada côndrulo, mediante a um mecanismo de acumulação de massa que concentra os côndrulos e os separa por tamanho, inicia-se a acresção que culminaria na formação dos corpos parentais.

Essa discussão avançou muito mais com o trabalho de Connolly *et al.* (1998), cujos dados associam os processos com os tipos texturais dos côndrulos. Para estes autores, as texturas condrícticas poderiam ser formadas como produtos de fusões incompletas (olivina porfirítica e microporfirítica) a completas (olivina barrada). Além disso, a temperatura máxima do aquecimento rápido alcançaria até  $2100^{\circ}\text{C}$  com um mínimo de  $1750^{\circ}\text{C}$  para formação dos côndrulos.

Em contraponto, Alexander *et al.* (2008), apresentam dados que discordam da temperatura proposta por Connolly *et al.* (1998). De acordo com estes autores, a temperatura de formação dos côndrulos variaria entre  $1973$  e  $2273^{\circ}\text{C}$ , assim como também demonstram que, durante o processo de fusão, os côndrulos funcionam essencialmente como um sistema fechado, pelo menos para os elementos com volatilidade igual ou menor que a do sódio (Na).

Palme *et al.* (2015) ressaltam que apesar dos côndrulos serem os elementos de maior destaque no estudo dos meteoritos não diferenciados, não se deve desconsiderar as relações com a matriz. Uma vez que se infere que existe uma complementariedade entre as razões elementais de Si/Mg e Fe/Mg da matriz com os côndrulos.

Os côndrulos são assim relíquias dos processos que deram origem ao Sistema Solar. Conhecê-los e os compreender é aprender uma parte da nossa história. A melhor compreensão destes processos evolutivos nos estágios primitivos do Sistema Solar se torna possível mediante o estudo das texturas e composições dos minerais presentes em cada um deles. Todavia, é primordial entender que, apesar de em um condrito existirem muitos côndrulos, cada um deles com uma composição diferente e, provavelmente, os mecanismos que incorreram na sua formação podem ter ocorrido em momentos e de formas significativamente distintas, ou seja, cada côndrulo é representante de um momento singular nesta história.

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Abstract	This paper investigates chondrules, integral components of chondritic meteorites from the early Solar System. Focusing on 33 chondrules from the Campos Sales Meteorite, an L5		

ordinary chondrite, we explore their compositions, mineral formation, and origin. Considering the hypothesis that chondrules may be "magmatic" droplets, we examine the compositions of these "primitive melts." Campo Sales' chondrules, mostly circular with some undefined shapes, contain olivine, enstatite, augite, chromite, troilite, Cl-apatite, and silicon dioxide. Varied textures, including barred, radial, and granular patterns, alongside skeletal crystals of olivine, enstatite, and augite, are observed, some featuring intergrowth textures. Chemical data reveal compositional homogeneity, indicating a chemical reequilibration event. Despite challenges in discerning elemental patterns, the study underscores rapid crystallization and preservation of skeletal shapes and volatile elements, suggesting accretion before complete solidification. These findings offer insights into early Solar System evolution, emphasizing chondrules as records of magmatic processes amid challenges in understanding their elemental patterns. The study provides comprehensive insights into type L chondrules, unraveling their composition, formation, and the intricate processes shaping the early Solar System.

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No, this is not for a special issue

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No, it wasn't submitted previously

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Dear Cristine Pereira,

Your manuscript "Unraveling the Origins of the Solar System: A Comprehensive Petrological Investigation of Chondrules within the Campos Sales Meteorite" has been successfully submitted and is being delivered to the Editorial Office of *Meteoritics & Planetary Science* for consideration.

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Tabela 5.1 Dados químicos obtidos a partir das análises de cristais de olivina presentes no meteorito Campos Sales. Dados da fórmula estrutural obtidos a partir do cálculo para 4 átomos de oxigênio. Fo= Forsterita, Fa= Fayalita, Mo=Monticellita. C = centro, b = borda

Cristal	117	131	28	29	47	48	20	23	34	57	66	43	139	52	90	91	1	106
Posição	c	b	c	c	c	b	c	b	b	b	c	c	c	c	c	c	c	c
SiO <sub>2</sub>	38,33	38,99	38,61	38,71	38,98	38,66	39,11	39,32	38,95	38,15	38,96	39,42	39,2	37,99	37,87	37,77	38,13	37,73
TiO <sub>2</sub>	0,11		0,1	0,07			0,02			0,07	0,07	0,04		0,03				
Al <sub>2</sub> O <sub>3</sub>	1,72	0,36	0,05						0,09		0,18	0,31		0,09		0,52	0,01	
Cr <sub>2</sub> O <sub>3</sub>	0,11		0,08		0,04	0,08			0,04		0,05		0,07	0,13	0,05	0,13	0,08	0,08
FeO	20,72	20,97	21,23	20,86	21,7	21,48	21,45	20,3	20,82	21,96	20,68	19,66	19,04	21,99	22,02	22,01	22,04	22,52
MnO	0,47	0,46	0,44	0,55	0,4	0,44	0,48	0,41	0,53	0,58	0,42	0,35	0,36	0,39	0,46	0,44	0,39	0,43
MgO	38,39	38,74	39,44	39,8	38,84	39,21	38,9	39,65	39,52	38,93	39,11	40,33	41,04	39,52	39,47	39,11	39,31	39,11
CaO	0,14	0,08	0,04			0,04	0,04	0,06		0,03	0,09	0,04	0,06	0,01	0,01	0,03		0,06
Na <sub>2</sub> O		0,01															0,05	
K <sub>2</sub> O		0,06	0,02								0,07	0,04	0,03			0,02	0,01	
Total	99,99	99,67	100,01	99,99	99,96	99,91	100	99,87	99,82	99,95	99,71	99,95	99,95	99,98	99,96	99,98	99,98	99,94
Si	0,994	1,011	1,001	1,003	1,010	1,002	1,014	1,019	1,010	0,989	1,010	1,022	1,016	0,985	0,982	0,979	0,988	0,978
Al	0,053	0,011	0,002					0,003		0,005	0,009		0,003				0,016	
Fe	0,449	0,455	0,460	0,452	0,470	0,466	0,465	0,440	0,451	0,476	0,448	0,426	0,413	0,477	0,477	0,477	0,478	0,488
Mg	1,484	1,497	1,524	1,538	1,501	1,515	1,503	1,532	1,527	1,504	1,511	1,558	1,586	1,527	1,525	1,511	1,519	1,511
Total cations	2,998	2,992	3,001	3,007	2,992	2,997	2,994	3,008	3,004	2,992	2,999	3,019	3,031	2,999	2,998	2,996	2,996	2,991
End members																		
Fo	76,106	75,996	76,320	76,815	75,747	75,948	75,928	77,151	76,587	75,378	76,396	78,051	78,833	75,825	75,650	75,534	75,667	75,088
Fa	23,039	23,073	23,042	22,582	23,737	23,336	23,483	22,155	22,631	23,849	22,658	21,341	20,514	23,665	23,672	23,843	23,795	24,251
Mo	0,199	0,113	0,056	0,000	0,000	0,056	0,056	0,084	0,000	0,042	0,126	0,056	0,083	0,014	0,014	0,042	0,000	0,083

Tabela 5.2 Dados químicos obtidos a partir das análises de cristais de enstatita presentes no meteorito Campos Sales. Dados da fórmula estrutural obtidos a partir do cálculo para 3 átomos de oxigênio. En= Enstatita, Fs= Ferrossilita, Wo= Wolastonita. C = centro, b = borda

Cristal Posição	111 c	70 b	82 c	106 c	27 c	30 c	34 c	36 c	4 c	15 c	20 c	101 c	104 c	127 c	128 c	130 c	131 c	1 c	5 c	6 b
SiO <sub>2</sub>	55,7	55,5	55,9	55,5	56,0	55,7	55,9	55,9	56,0	56,1	56,0	55,8	56,0	56,2	56,2	55,9	56,3	56,5	56,5	56,1
FeO	13,3	13,0	13,2	12,7	13,2	13,6	13,1	13,3	13,3	13,1	12,7	12,8	12,4	12,0	11,7	11,5	10,9	11,2	11,1	11,2
MnO	0,5	0,5	0,5	0,5	0,5	0,4	0,5	0,6	0,6	0,5	0,5	0,4	0,4	0,4	0,4	0,3	0,3	0,3	0,5	0,3
MgO	28,3	29,4	29,3	29,4	29,4	28,9	29,7	29,2	29,3	29,4	29,9	29,4	29,9	30,3	30,4	30,3	31,1	30,9	30,8	30,5
CaO	0,6	0,6	0,8	0,8	0,5	0,6	0,5	0,7	0,5	0,7	0,6	0,9	0,9	0,7	0,8	0,8	0,7	0,6	0,8	0,8
Total	99,9	99,9	100,0	100,0	100,0	99,9	100,0	100,0	99,9	100,0	99,9	99,9	100,0	100,0	100,0	99,9	100,0	99,9	99,9	99,8
Si	1,988	1,982	1,994	1,979	1,996	1,993	1,992	1,993	1,998	1,998	1,994	1,987	1,991	1,991	1,989	1,978	1,987	1,994	1,996	1,988
Fe <sup>++</sup>	0,398	0,388	0,394	0,379	0,393	0,407	0,389	0,398	0,397	0,392	0,377	0,380	0,368	0,354	0,346	0,341	0,323	0,331	0,327	0,333
Mn	0,014	0,015	0,015	0,014	0,016	0,012	0,014	0,017	0,017	0,016	0,014	0,013	0,011	0,011	0,013	0,010	0,010	0,009	0,016	0,010
Mg	1,506	1,564	1,560	1,564	1,562	1,540	1,577	1,554	1,561	1,563	1,587	1,560	1,584	1,602	1,604	1,599	1,633	1,629	1,623	1,612
Ca	0,021	0,024	0,030	0,032	0,020	0,024	0,017	0,027	0,018	0,025	0,024	0,034	0,034	0,027	0,028	0,030	0,026	0,021	0,028	0,032
Total	3,999	3,998	3,999	3,999	3,997	3,998	4,000	4,000	3,998	3,999	4,001	4,000	4,000	4,000	3,998	4,000	4,001	3,998	3,997	4,001
En	0,78	0,79	0,79	0,79	0,79	0,78	0,80	0,79	0,79	0,79	0,80	0,79	0,80	0,81	0,81	0,81	0,83	0,82	0,82	0,82
Fs	0,21	0,19	0,20	0,19	0,20	0,21	0,20	0,20	0,20	0,20	0,19	0,19	0,18	0,18	0,18	0,17	0,16	0,17	0,17	0,17
Wo	0,01	0,01	0,02	0,02	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,02	0,02	0,01	0,01	0,02	0,01	0,01	0,01	0,02

Tabela 5.3 Dados químicos obtidos a partir das análises de cristais de augita presentes no meteorito Campos Sales. Dados da fórmula estrutural obtidos a partir do cálculo para 3 átomos de oxigênio. En= Enstatita, Fs= Ferrossilita, Wo= Wolastonita. C = centro, b = borda

Cristal	67	68	69	74	79	93	98	99	41	86	61	6	8	28	29	31	16	49	55	70	71	92	94	99	37
Posição	c	c	c	c	c	b	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c
SiO <sub>2</sub>	53,9	54,7	54,3	54,1	53,8	54,1	53,7	54,1	53,9	54,2	54,6	54,5	54,6	54,5	54,1	54,2	54,0	52,8	54,3	54,6	54,2	54,3	54,1	54,0	54,8
Cr <sub>2</sub> O <sub>3</sub>	0,8	0,8	0,9	1,1	0,9	1,0	0,6	0,8	1,2	1,0	0,6	0,7	0,7	0,7	0,9	0,9	0,8	2,6	0,7	0,5	0,6	0,9	0,9	0,5	0,5
FeO	5,1	5,5	4,9	5,1	5,0	4,7	5,2	5,0	4,8	5,2	5,2	4,7	4,8	4,8	5,3	5,2	4,9	5,1	3,8	3,9	4,1	4,5	4,7	3,8	5,2
MgO	16,7	17,7	17,2	17,2	16,3	17,3	17,3	16,8	17,2	17,0	19,0	17,6	17,2	17,4	16,8	16,4	17,8	14,5	17,7	17,3	17,4	17,4	17,1	15,4	18,1
CaO	21,0	19,4	20,6	20,7	21,9	20,9	20,7	21,4	20,8	20,6	18,5	20,7	20,7	20,7	21,0	21,4	20,8	18,5	22,1	22,2	22,0	21,0	21,5	21,0	19,7
Na <sub>2</sub> O	0,7	0,7	0,6	0,6	0,4	0,7	0,6	0,5	0,6	0,5	0,7	0,6	0,7	0,7	0,6	0,7	0,5	2,0	0,4	0,5	0,4	0,6	0,5	1,3	0,5
Total	99,5	99,9	99,9	99,8	99,8	99,8	99,7	99,5	99,9	100,0	99,9	100,0	100,0	100,0	99,8	100,0	100,0	99,9	99,9	100,0	99,9	99,9	100,0	99,9	99,8
Si	1,985	1,996	1,987	1,984	1,975	1,979	1,968	1,992	1,973	1,983	1,983	1,989	1,993	1,991	1,983	1,986	1,973	1,935	1,984	1,990	1,980	1,985	1,979	1,964	1,999
Fe <sup>++</sup>	0,158	0,168	0,151	0,156	0,153	0,142	0,160	0,153	0,147	0,158	0,157	0,143	0,145	0,148	0,162	0,158	0,149	0,157	0,117	0,119	0,124	0,137	0,143	0,115	0,158
Mg	0,915	0,963	0,940	0,941	0,894	0,945	0,946	0,923	0,936	0,930	1,027	0,955	0,938	0,948	0,917	0,895	0,970	0,789	0,959	0,941	0,948	0,946	0,933	0,834	0,983
Ca	0,828	0,757	0,808	0,813	0,862	0,819	0,812	0,842	0,816	0,807	0,721	0,810	0,808	0,809	0,824	0,840	0,813	0,726	0,865	0,867	0,862	0,823	0,842	0,818	0,769
Na	0,049	0,048	0,044	0,041	0,029	0,046	0,041	0,037	0,040	0,038	0,048	0,045	0,047	0,047	0,043	0,050	0,038	0,141	0,031	0,037	0,031	0,042	0,035	0,089	0,038
Total	4,002	3,997	3,998	4,000	3,996	4,001	4,007	4,002	4,000	3,994	4,003	4,001	3,995	4,001	4,000	4,001	4,007	4,003	4,005	4,001	4,003	3,999	4,000	3,990	3,995
En	0,48	0,51	0,49	0,49	0,47	0,50	0,50	0,48	0,49	0,49	0,54	0,50	0,49	0,50	0,48	0,47	0,51	0,47	0,50	0,49	0,49	0,50	0,49	0,47	0,52
Fs	0,08	0,10	0,08	0,08	0,09	0,07	0,07	0,07	0,08	0,09	0,08	0,07	0,08	0,07	0,08	0,08	0,06	0,09	0,05	0,06	0,06	0,07	0,07	0,07	0,08
Wo	0,44	0,40	0,42	0,43	0,45	0,43	0,43	0,44	0,43	0,42	0,38	0,43	0,43	0,43	0,43	0,44	0,43	0,44	0,45	0,45	0,45	0,43	0,44	0,46	0,40

Tabela 5.4 Dados químicos obtidos a partir das análises de cristais de plagioclásio presentes no meteorito Campos Sales. Dados da fórmula estrutural obtidos a partir do cálculo para 5 átomos de oxigênio. Or= Ortoclásio, Ab= Albita, An= Anortita. C = centro, b = borda

Espectro	14	15	16	17	56	57	59	33	37	38	40	41	15	55	56
Posição	b	c	c	c	c	c	c	c	c	c	c	c	c	c	c
SiO <sub>2</sub>	65,44	65,05	65,19	65,17	64,48	65,05	64,01	65,29	64,99	65,29	65,28	64,04	65,31	65,24	64,93
TiO <sub>2</sub>	0	0,07			0,06	0,08	0,01						0,05		0,12
Al <sub>2</sub> O <sub>3</sub>	21,22	21,45	21,4	21,27	20,54	21,29	20,95	21,17	21,27	21,12	20,99	21,11	18,86	21,29	21,33
FeO	0,75	0,43	0,66	0,63	1,39	0,73	1,39	0,66	0,96	0,75	0,56	1,38	1,56	0,78	0,74
CaO	1,87	2	1,95	2,02	2,02	2,08	2,15	1,93	2,04	1,99	1,74	2,14	2,07	2	2,22
Na <sub>2</sub> O	10,08	10,1	9,98	10,18	8,86	9,29	8,96	10,06	9,92	9,87	9,49	9,5	8,83	9,93	9,61
K <sub>2</sub> O	0,64	0,88	0,81	0,73	1,43	1,3	1,35	0,9	0,82	0,98	1,94	1	0,67	0,61	0,98
Total	100	100	99,99	100	99,83	99,88	99,47	100,01	100	100	100	99,17	99,82	99,85	99,95
Si	2,89	2,88	2,88	2,88	2,87	2,88	2,86	2,89	2,88	2,89	2,89	2,87	2,90	2,88	2,87
Al	1,10	1,12	1,11	1,11	1,08	1,11	1,10	1,10	1,11	1,10	1,10	1,11	0,99	1,11	1,11
Total	3,99	3,99	4,00	3,99	3,95	3,99	3,96	3,99	3,99	3,99	3,99	3,98	3,89	3,99	3,99
Fe	0,03	0,02	0,02	0,02	0,05	0,03	0,05	0,02	0,04	0,03	0,02	0,05	0,06	0,03	0,03
Ca	0,09	0,09	0,09	0,10	0,10	0,10	0,10	0,09	0,10	0,09	0,08	0,10	0,10	0,09	0,11
Na	0,86	0,87	0,86	0,87	0,76	0,80	0,78	0,86	0,85	0,85	0,82	0,82	0,76	0,85	0,82
K	0,04	0,05	0,05	0,04	0,08	0,07	0,08	0,05	0,05	0,06	0,11	0,06	0,04	0,03	0,06
Total	5,01	5,02	5,01	5,02	5,01	5,00	5,01	5,02	5,02	5,01	5,02	5,02	5,00	5,00	5,01
Or	3,65	4,91	4,60	4,08	8,62	7,57	8,05	5,05	4,66	5,55	10,88	5,80	4,23	3,51	5,61
Ab	87,39	85,71	86,11	86,44	81,16	82,25	81,19	85,85	85,62	84,98	80,92	83,77	84,78	86,83	83,70
An	8,96	9,38	9,30	9,48	10,23	10,18	10,77	9,10	9,73	9,47	8,20	10,43	10,98	9,66	10,68

Tabela 5.4 Dados químicos obtidos a partir das análises de cristais de plagioclásio presentes no meteorito Campos Sales. Dados da fórmula estrutural obtidos a partir do cálculo para 5 átomos de oxigênio. Or= Ortoclásio, Ab= Albita, An= Anortita. C = centro, b = borda

Cristal	89	90	92	93	101	103	104	114	14	16	17	18	13
Posição	c	c	c	c	c	c	c	c	c	c	c	c	c
SiO <sub>2</sub>	64,99	65,18	65,02	65,02	65,67	65,41	64,24	65,51	64,77	65,1	65,14	64,73	64,72
TiO <sub>2</sub>									0,02	0,01		0,12	0,09
Al <sub>2</sub> O <sub>3</sub>	21,25	21,31	21,01	21,23	21,21	20,83	19,05	21,19	18,86	19,52	21,07	19,83	19,57
FeO	0,77	0,7	1	0,9	0,49	0,58	2,27	0,52	0,72	1,11	0,58	0,78	1,6
CaO	2,17	2,14	2,08	1,96	2,2	2,34	1,83	1,96	4,11	2,66	2,15	3,46	2,02
Na <sub>2</sub> O	9,75	9,84	9,88	9,9	9,68	9,81	9,26	9,98	8,66	8,99	9,63	8,98	9,12
K <sub>2</sub> O	1,07	0,83	1,01	0,99	0,75	1,02	0,95	0,84	1,02	1,09	1,28	1,07	0,79
Total	100	100	100	100	100	99,99	97,6	100	99,73	99,88	100,01	100,01	99,64
Si	2,88	2,88	2,88	2,88	2,90	2,89	2,93	2,89	2,89	2,89	2,88	2,88	2,88
Al	1,11	1,11	1,10	1,11	1,10	1,09	1,02	1,10	0,99	1,02	1,10	1,04	1,03
	3,99	3,99	3,98	3,99	4,00	3,98	3,95	3,99	3,88	3,92	3,98	3,92	3,91
Fe	0,03	0,03	0,04	0,03	0,02	0,02	0,09	0,02	0,03	0,04	0,02	0,03	0,06
Ca	0,10	0,10	0,10	0,09	0,10	0,11	0,09	0,09	0,20	0,13	0,10	0,16	0,10
Na	0,84	0,84	0,85	0,85	0,83	0,84	0,82	0,85	0,75	0,77	0,83	0,77	0,79
K	0,06	0,05	0,06	0,06	0,04	0,06	0,06	0,05	0,06	0,06	0,07	0,06	0,04
Total	5,02	5,01	5,02	5,02	4,99	5,01	5,00	5,01	5,02	5,01	5,02	5,02	5,02
Or	6,04	4,72	5,68	5,60	4,33	5,70	5,74	4,76	5,78	6,42	7,22	6,07	4,83
Ab	83,67	85,06	84,49	85,09	84,99	83,32	84,98	85,92	74,64	80,43	82,59	77,44	84,79
An	10,29	10,22	9,83	9,31	10,67	10,98	9,28	9,32	19,58	13,15	10,19	16,49	10,38

Tabela 5.5 Dados químicos obtidos a partir das análises de cristais de espinélio presentes no meteorito Campos Sales. Dados da fórmula estrutural obtidos a partir do cálculo para 4 átomos de oxigênio. C = centro, b = borda

Cristal	57	58	59	60	61	62	63	64	65	66	67	68	45	41	42	43	44	52
Posição	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c
TiO <sub>2</sub>	2,53	2,43	2,4	2,3	2,39	2,38	2,27	2,49	2,34	2,66	1,88	2,45	2,44	2,66	2,4	2,62	2,28	2,47
Al <sub>2</sub> O <sub>3</sub>	7,1	7,09	6,61	6,41	7,49	7,14	7,03	6,67	6,41	6,36	6,47	6,55	5,61	6,41	5,86	6,38	6,33	2,89
Cr <sub>2</sub> O <sub>3</sub>	54,96	55,78	55,79	55,66	55,05	55,41	54,99	55,78	55,58	54,59	46,24	53,31	55,56	54,61	55,77	55,09	55,86	59,91
FeO	30,75	30,74	30,9	31,34	30,58	30,78	30,95	30,95	31,01	32,43	29,85	31,37	29,73	31,13	30,89	30,99	30,86	30,17
MnO	0,52	0,4	0,56	0,49	0,23	0,38	0,54	0,27	0,64				0,28	0,59	0,47	0,33	0,21	0,54
MgO	2,62	2,73	2,36	2,24	2,75	2,47	2,2	2,35	2,41	2,59	7,27	3,64	3,72	2,52	2,6	2,59	2,37	1,01
Total	98,48	99,17	98,62	98,44	98,49	98,56	97,98	98,51	98,39	98,63	91,71	97,32	97,47	98,48	98,44	98,56	98,65	97,35
Ti	0,068	0,065	0,065	0,062	0,064	0,064	0,062	0,067	0,064	0,072	0,054	0,067	0,067	0,072	0,065	0,071	0,062	0,069
Al	0,300	0,297	0,280	0,273	0,315	0,301	0,299	0,283	0,273	0,270	0,291	0,280	0,240	0,273	0,250	0,271	0,269	0,127
Cr	1,557	1,569	1,585	1,589	1,555	1,569	1,571	1,585	1,586	1,556	1,394	1,531	1,594	1,559	1,595	1,569	1,592	1,765
Fe <sup>++</sup>	0,922	0,914	0,929	0,946	0,913	0,922	0,935	0,930	0,936	0,978	0,952	0,953	0,902	0,940	0,935	0,934	0,930	0,940
Mn	0,016	0,012	0,017	0,015	0,007	0,012	0,017	0,008	0,020					0,018	0,014	0,010	0,006	0,017
Mg	0,140	0,145	0,126	0,121	0,146	0,132	0,119	0,126	0,130	0,139	0,413	0,197	0,201	0,136	0,140	0,139	0,127	0,056
Total	3,003	3,002	3,002	3,007	3,001	3,000	3,003	2,999	3,007	3,015	3,104	3,028	3,016	3,012	3,012	3,009	3,008	2,985

Tabela 5.5 Dados químicos obtidos a partir das análises de cristais de espinélio presentes no meteorito Campos Sales. Dados da fórmula estrutural obtidos a partir do cálculo para 4 átomos de oxigênio. C = centro, b = borda

Cristal	26	29	110	118	119	120	121	18	22
Posição	c	c	c	c	c	c	c	c	c
TiO <sub>2</sub>	2,2	2,05	2,76	2,73	2,88	2,98	2,97	2,41	2,08
Al <sub>2</sub> O <sub>3</sub>	6,61	6,47	6,2	6,27	6,27	6,04	6,21	8,38	8,58
Cr <sub>2</sub> O <sub>3</sub>	56,14	55,9	56,01	56,38	55,84	56,39	55,52	54,92	54,85
FeO	30,14	31,52	30,08	29,94	29,72	30,41	30,28	28,96	29,71
MnO	0,68	0,56	0,55	0,7	0,67	0,7	0,83	0,63	0,55
MgO	2,34	2,15	2,67	2,72	2,54	2,44	2,75	3,19	2,9
Total	98,96	98,65	98,35	98,8	98,55	98,96	98,66	98,91	98,91
Ti	0,059	0,056	0,075	0,073	0,078	0,080	0,080	0,064	0,055
Al	0,280	0,275	0,263	0,264	0,266	0,255	0,263	0,348	0,357
Cr	1,593	1,595	1,593	1,595	1,586	1,597	1,575	1,532	1,533
Fe <sup>++</sup>	0,904	0,951	0,905	0,896	0,893	0,911	0,908	0,854	0,878
Mn	0,021	0,017	0,017	0,021	0,020	0,021	0,025	0,019	0,016
Mg	0,125	0,116	0,143	0,145	0,136	0,130	0,147	0,168	0,153
Total	3,005	3,009	2,997	2,997	2,996	2,994	3,001	2,996	3,000

Tabela 5.6 Dados químicos obtidos a partir das análises de cristais de cloroapatita presentes no meteorito Campos Sales. C = centro, b = borda

Cristal	110	111	113	114	115	116	117	118	119	120	121	122	123	124	83	85	107	109	110
Posição	c	b	c	c	c	c	c	b	c	c	c	c	c	b	c	b	c	c	c
Na <sub>2</sub> O	0,67	0,51	0,53	0,45	0,51	0,66	0,42	0,71	0,48	0,59	0,54	0,62	0,64	0,92	0,41	0,57	0,77	0,29	0,33
MgO	0,13	0,39	0,12	0,14	0,04	0,11	0,26	0,09	0,23	0,06	0,04	0,1	0,2	0,11	0,18	0,34	0,54	0,2	0,19
SiO <sub>2</sub>	0,62	0,81	0,61	0,53	0,73	0,72	0,7	0,84	0,74	0,6	0,67	0,97	0,85	1,16	0,31	0,46	1,16	0,47	0,74
P <sub>2</sub> O <sub>5</sub>	40,41	38,07	40,06	36,3	37,76	39,04	39,06	39,83	37,31	40,56	37,76	37,2	34,49	37,17	36,7	36,97	36,58	37,24	30,99
CaO	50,64	47,68	50,55	46,36	46,55	49,76	49,37	47,53	46,39	50,5	48,17	46,63	42,03	46,12	51,43	46,76	46,65	50,25	57,45
Cl	5	4,8	5,16	4,67	4,69	4,94	4,95	5,1	4,52	5,12	4,68	4,58	4,37	4,56	4,74	4,78	4,69	4,96	4,18
F	1,11	0,81	0,43	0,65	0,76	0,63	0,45	1,47	0,49	1,07	0,08	0,77	1,95	0,62	1	0,75	1,07	0,58	0,27
CO <sub>2</sub>		1,35		9,32	5,51	2,04	2,76	2,8	5,44		3,52	5,32	11,73	5,34		6,86	2,5	0,94	
Al <sub>2</sub> O <sub>3</sub>	0,23	0,71	0,17	0,21	0,27	0,13	0,12	0,55	0,16	0,22	0,27	0,85	0,93	0,61	4,55	1,98	4,89	4,38	5,08
TiO <sub>2</sub>	0,13		0,04	0,06		0,05				0,02	0,07	0,02	0,07	0,07	0,17		0,03	0,01	
MnO	0,1		0,14	0,07		0,1	0,04		0,2	0,04	0,04	0,09	0,08	0,06	0,07	0,02	0,04	0,15	
FeO	0,44	4,22	1,49	0,85	2,53	1,11	1,34	0,54	3,64	0,76	3,65	2,47	2,18	2,73	0,4	0,45	1,01	0,45	0,69
Total	99,48	99,35	99,3	99,61	99,35	99,24	99,52	99,46	99,6	99,54	99,49	99,62	99,52	99,47	99,96	99,94	99,93	99,92	99,92

Tabela 5.7 Dados químicos obtidos a partir das análises de cristais de troilita presentes no meteorito Campos Sales. C = centro, b = borda

Cristal	19	20	21	22	23	24	1	2	117	39	40	22	23	24	25	26	42	43	44	45
Posição	c	c	c	c	c	b	c	b	c	c	c	c	c	c	c	c	c	c	c	b
S	37,64	37,41	37,91	37,84	37,62	38,23	36,52	32,84	36,63	36,78	37,49	37,57	32,43	35,2	37,08	35,16	36,23	36,9	37,13	37,21
Ti							0,01					0,1	0,07	0,06	0,11					0,03
V	0,07	0,04	0,01		0,03	0,1	0,09	0,01	0,03											0,09
Cr	0,09	0,02		0,04				0,04			0,16		0,16			0,03				
Mn	0,07	0,08		0,03	0,17		0,18	0,03	0,04			0,07		0,02		0,03	0,11	0,03		
Fe	61,81	61,55	61,72	62,06	60,51	61	60,13	62,84	61,22	59,56	59,04	58,48	65,31	60,37	59,36	57,99	59,18	53,89	60,08	60,09
Co		0,11	0,02		0,15	0,26		0,03		0,1	0,07									
Ni	0,17	0,24	0,06	0,03	1,16	0,27	0,04	0,02	0,25		0,08	0,02			0,09	0,14		1,58		
Cu		0,18				0,23			0,06	0,04	0,04									
Zn	0,15	0,36			0,14	0,22	0,01		0,14											
Si			0,28		0,36		0,35	0,46		0,24	0,25	0,34	0,25	0,41	0,52	1,22	0,23	0,69	0,3	0,26
O						2,23	2,83	1,74	2,8	2,65	2,98	1,51	3,28	2,29	4,57	2,22	6,34	2,14	2,01	
Total	100	99,99	100	100	100	100	100	99,11	99,97	99,66	99,78	99,56	99,73	99,34	99,45	99,11	97,89	99,51	99,71	99,66

Tabela 5.7 Dados químicos obtidos a partir das análises de cristais de troilita presentes no meteorito Campos Sales. C = centro, b = borda

Cristal	19	20	21	22	23	24	25	26	27	28	66	67	68	71	72	73	74	76
Posição	c	c	c	c	c	c	c	c	b	c	c	c	c	c	c	c	c	b
S	38,54	38,42	38,35	37,22	38,5	37,85	39,1	36,81	38,24	38,56	35,28	31,69	38,73	38,05	38,34	38,76	38,95	34,84
Ti		0,12	0,04		0,05	0,06	0,07	0,04		0,06	0,75	0,79	0,04					0,04
V		0,02	0,08	0,05			0,1	0,06		0,03								
Cr	0,09	0,04		0,07	0,14	0,05				0,06	0,15	0,13	0,06	0,08				0,16 0,04
Mn			0,05	0,13	0,04			0,13		0,03		0	0	0,02		0,01	0,1	
Fe	60,6	60,21	60,72	61,34	60,62	61,36	60,02	62,2	60,95	57,86	57,45	60,2	60,69	61,49	60,92	60,5	60,28	61,89
Co	0,54	0,4	0,32	0,4	0,1	0,09	0,3	0,23	0,38	0,17	0,09							
Ni	0,2	0,29	0,19	0,36	0,22	0,48	0	0,2	0,12		0,07	0,34			0,14	0,04	0,02	
Cu	0,03	0,01	0,14	0,06		0,12	0,14	0,03	0,04	0,28	0,35							
Zn		0,23	0,11							0,1								
Si		0,26		0,34	0,33		0,27	0,3	0,27	0,27	0,48	0,76	0,27	0,26	0,29	0,3	0,27	0,36
O										2,7	4,4	4,77						2,51
Total	100	100	100	99,97	100	100,01	100	100	100	100,02	99,12	98,68	99,79	99,9	99,69	99,61	99,82	99,64

Tabela 5.8 Dados químicos obtidos a partir das análises de cristais de liga metálica Fe-Ni presentes no meteorito Campos Sales. C = centro, b = borda

Cristal	44	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	32	75	76
Posição	b	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c
Fe	79,85	81,34	81,83	82,48	81,69	80,09	80,74	82,48	82,12	81,64	82,19	81,28	82,74	80,95	85,14	81,11	79,15	80,32	85,15	82,35	84,18
Ni	16,6	14,26	14,52	14,73	14,16	16,38	14,12	14,33	14,71	13,93	14,18	13,76	13,85	14,89	11,53	15,72	16,76	16,45	10,97	15,49	13,31
Al	0,67	0,8	0,46	0,3	0,57	0,41	1,57	0,46	0,35	0,75	0,54	0,83	0,38	0,62	0,52	0,52	0,42	0,37	0,63	0,44	0,5
Co		0,86	0,96	0,52	0,49	0,65	0,77	0,65	0,73	0,74	0,82	0,75	0,55	0,68	0,68	0,82	0,83	0,96	0,81	1,27	1,13
Si	0,29	0,35	0,35	0,4	0,37	0,38		0,25	0,43	0,31	0,42	0,43	0,42	0,39			0,4	0,38	0,24		
Cu		0,06		0,1	0,13	0,26	0,3	0,16	0,13	0,2	0,11	0,17	0,17	0,13	0,08	0,19	0,4	0,2	0,07	0,01	0,08
Sc																					
Mn	0,05	0,14		0,01	0,04	0,04	0,15		0,06	0,11	0,01	0,07	0,12	0,14	0,11	0,04	0,1		0,02		0,04
Cr	0,06	0,02	0,03	0,08	0,11	0,09		0,11		0,08	0,09	0,18	0,19	0,02	0,03	0,02	0,01		0,1	0,05	0,03
Zn		0,1	0,07		0,14					0,02			0,06		0,08		0,12	0,07			0,02
V		0,08	0,05	0,04				0,03		0,01		0,08		0,02					0,02	0,05	
Ti	0,02		0,09		0,07	0,07	0,11			0,02	0,05	0,05	0,06					0,06	0,03		0,05
Total	97,54	98,01	98,36	98,66	97,7	98,37	97,72	98,55	98,56	97,78	98,39	97,52	98,61	97,88	98,19	98,42	98,19	98,81	98,02	99,63	99,39

Tabela 5.8 Dados químicos obtidos a partir das análises de cristais de liga metálica Fe-Ni presentes no meteorito Campos Sales. C = centro, b = borda

Cristal	77	78	88	104	90	87	116	38	29	30	31	29	30	31	32	33	34	35	36	37	38	
Posição	c	b	c	c	b	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	c	
Fe	83,87	81,14	84,14	86,67	78,84	81,58	66,22	62,56	45,94	46,07	46,53	58,31	61,57	61,68	63,56	64,52	64,87	64,76	64,36	64,47	61,82	
Ni	13,24	16,15	13,56	12,55	18,31	16,75	29	34,24	52,42	52,61	52,68	37,23	36,89	35,09	34,53	34,13	33,8	33,57	33,33	33,77	36,78	
Al	0,39	0,58	0,52	0,36	0,43	0,39	0,96	0,29	0,45	0,78	0,34	0,64	0,54	0,64	0,67	0,41		0,66	0,58	0,49	0,28	
Co	0,99	1,1	1,22		1,08		0,21	0,29	0,04		0,37	0,7	0,55	0,66	0,33	0,62	0,58	0,45	0,54	0,57		
Si				0,03	0,31	0,48	0,32	0,18	0,31	0,33	0,3	0,32		0,29	0,31	0,34		0,37	0,39	0,34		
Cu		0,06			0,19		0,33	0,41	0,4		0,25	0,07	0,05	0,21	0,08	0,26	0,15	0,31	0,23	0,22		
Sc										0,02												
Mn				0,07		0,05	0,08		0,07	0,13		0,05		0,07		0,15	0,02					
Cr	0,04	0,04	0,14	0,05		0,07	0,05	0,01	0,05			0,02		0,01		0	0,11	0,05	0,01	0,03		
Zn		0,07									0,02				0,03	0,16		0,39	0,03			
V	0,15		0,01			0,09					0,02	0,01		0,05	0,02	0,11	0,01		0,04			
Ti		0,19	0,05	0,07						0,06	0,06	0,08	0,06	0,03								
Total	98,68	99,33	99,64	99,8	99,16	99,32	97,26	97,98	99,7	99,98	99,91	97,31	99,84	98,41	99,99	100,01	99,95	99,78	99,8	99,99	100,01	