Unveiling Mineral Phase Distribution In The Chelyabinsk LL Chondrite Using LIBS Mapping And Cluster Analysis

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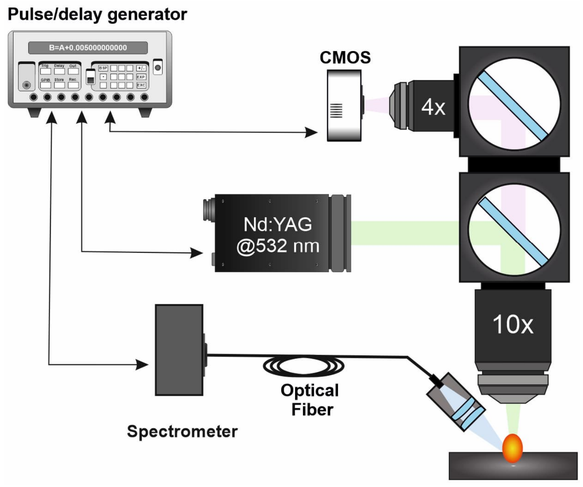
Abstract

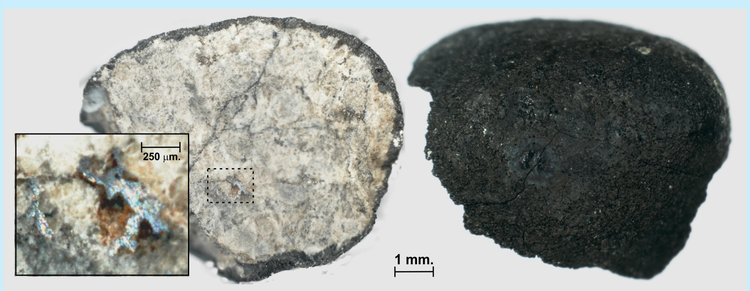
The **Chelyabinsk meteorite** was analyzed using **Laser-Induced Breakdown Spectroscopy (LIBS)** combined with **Raman spectroscopy** to characterize chemical and **mineralogical heterogeneity** across its **inner matrix, fusion crust, and metallic inclusions**. LIBS spectra acquired at selected points revealed major elements including Fe, Mg, Si, Al, Ca, Cr, Mn, Na, and Ni. Relative intensity ratios normalized to Fe confirmed a higher abundance of rock-forming silicates in the inner matrix, Fe-rich metallic inclusions, and intermediate compositions in the fusion crust. High-resolution **LIBS mapping** (100 µm) visualized the **spatial distribution of mineral phases**, with **Na + Ca** highlighting **plagioclase**, **Fe + Mg olivine and pyroxene**, **Cr chromite**, and **Fe + Ni metallic phases**. **K-means** clustering integrated the elemental maps into a **single classification**, clearly distinguishing five mineral phases. **Calibration-Free LIBS (CF-LIBS)** was applied at strategically selected points to determine semi-quantitative elemental compositions. A ternary diagram based on the CF-LIBS-derived oxide percentages ($FeO–MgO–SiO_2$) confirmed the classification of Chelyabinsk as an **LL-type ordinary chondrite**. This workflow demonstrates that LIBS mapping combined with clustering and CF-LIBS allows rapid, minimally invasive assessment of meteorite heterogeneity, mineral distribution, and classification, providing detailed microscale compositional information while preserving the integrity of rare samples.

Experimental Set-up



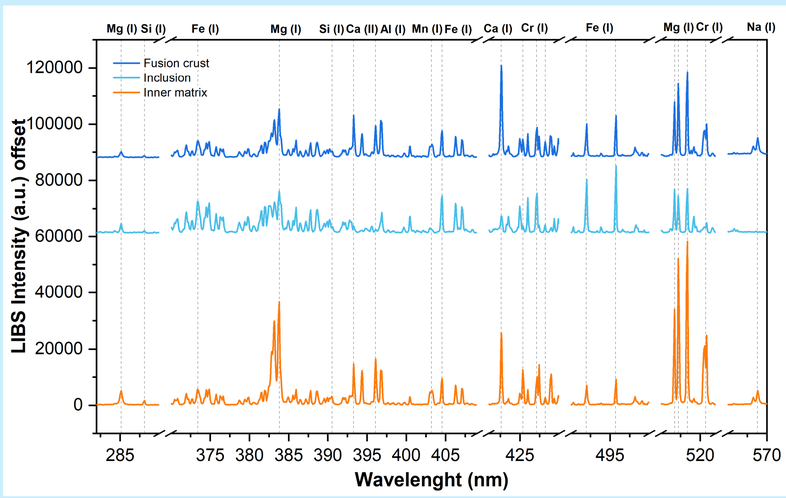
- For LIBS analysis, the sampling position was adjusted using an **XY stage** and monitored with an USB CMOS camera.
- **Fluence**= 145 J/cm²
- **Resolution**= 100 µm
- 5 shots/position

Chelyabinsk meteorite



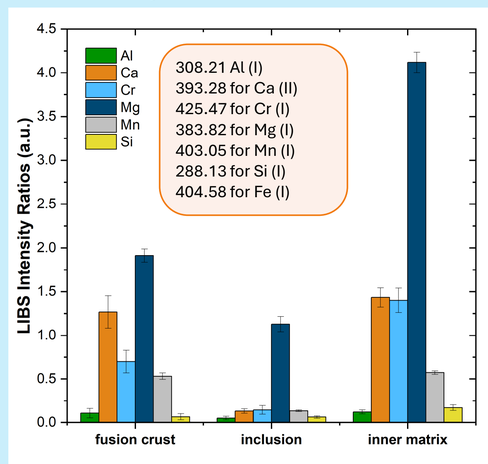
- **Date fell**: February 15, 2013
- **Location**: Chebarkul, Chelyabinsk Oblast, Russia
- **Lithology**: light-colored
- **Type**: LL ordinary chondrite
- **Weight and fragment size:** 0,405 g, 10 x 6 x 4 mm

LIBS identification



Average spectra provide differences in elemental composition between three regions. **Fe** is dominant in all regions, especially in the **metallic inclusions**. **Magnesium and silicon** exhibit stronger emission in the **light-colored matrix**, reflecting mineral phases such as **olivine and pyroxene**.

Ratios of major elements relative to iron

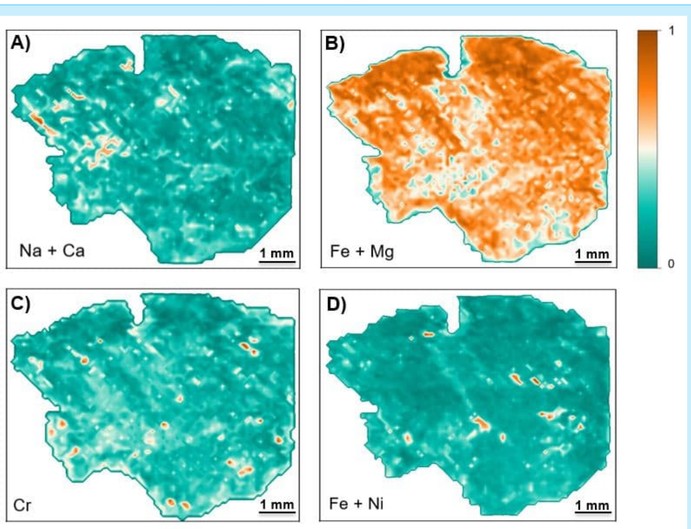


LIBS spectra were recorded in **three selected regions** of the Chelyabinsk meteorite:

- **fusion crust**
- **metallic inclusions**
- **light-colored matrix.**

Al/Fe, Ca/Fe, and Mn/Fe ratios in the inclusions differ significantly, reflecting **the Fe-rich metallic nature of the inclusions**. **Mg/Fe** and **Si/Fe** ratios are significantly higher in the matrix compared to the inclusions and fusion crust, consistent with the **enrichment of silicate minerals in the matrix**.

LIBS mapping



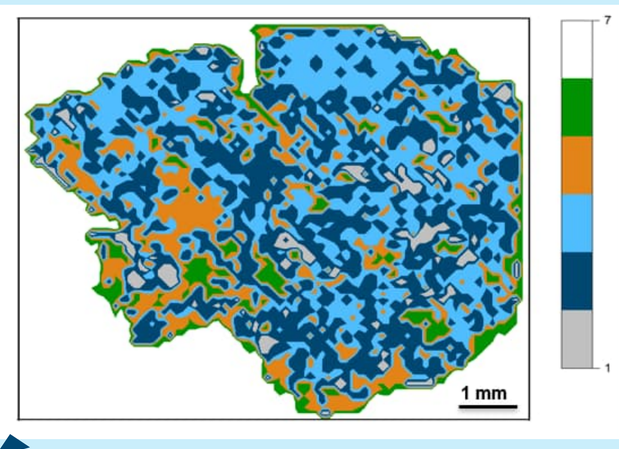
A) Na + Ca (plagioclase)
B) Fe + Mg (olivine and pyroxene)
C) Cr (chromite)
D) Fe + Ni (metallic inclusions)

These maps represent the **sum** of the most relevant **elemental signals** associated with **each mineral phase**.

Although **LIBS provides elemental information**, a reliable **mineralogical interpretation** can be achieved by **combining** these results with **Raman spectroscopy**.

the data represented in the LIBS maps were subsequently used as input **variables for *K*-means clustering**

K-MEANS CLUSTERING MAP (K=6)



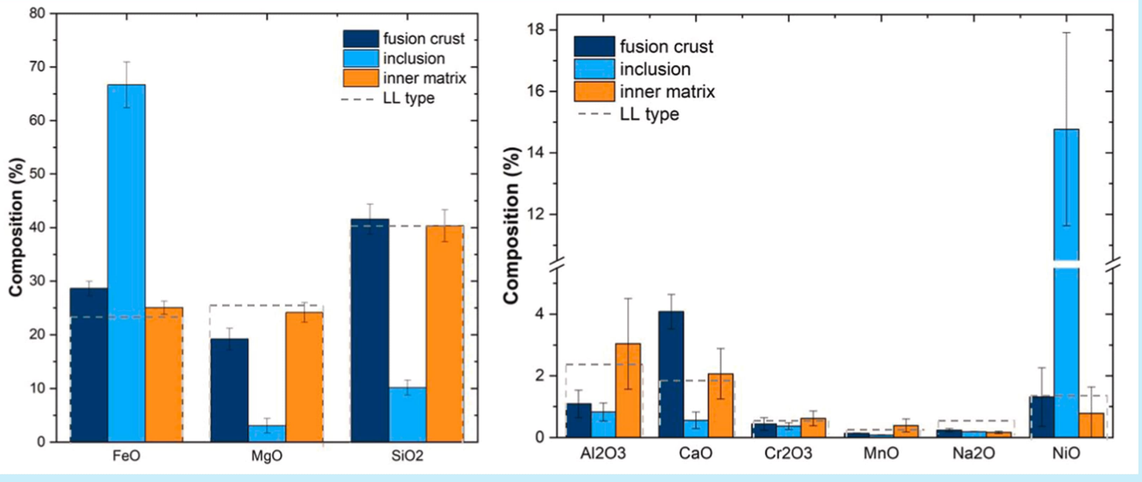
- **background**
- **chromite**
- **plagioclase**
- **Olivine and pyroxene**

Mineral phases detected by Raman spectroscopy

- **Fe-Ni metallic phase**

K-means integrated spatial and compositional information, improving **mineral phase classification** and revealing sample **heterogeneity** while enabling the selection of representative points for **quantitative analysis**.

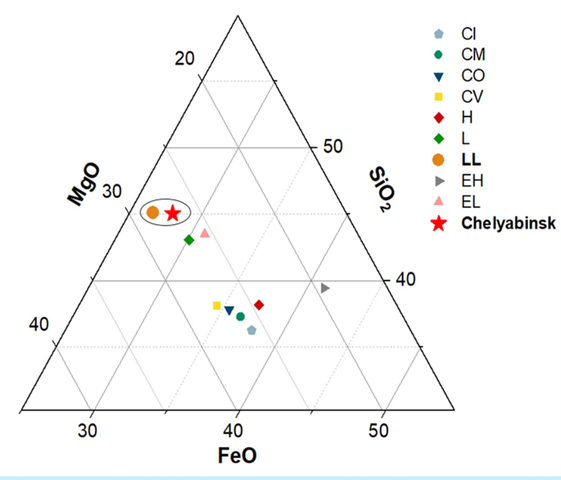
Quantitative LIBS analysis



The averaged results obtained for the **inner matrix** of the sample show good consistency with values reported in the **literature.**

For the **metallic inclusions**, four positions were selected based on the LIBS map obtained for Fe+Ni. Their average composition were 66.67% for Fe and 14.77% for Ni.

A **ternary diagram** has been constructed based on the typical distribution of **FeO, MgO, and SiO_2** for each class of **chondrite**. The Chelyabinsk is correctly classified as a chondrite **LL type**.



Conclusions

✓**LIBS** in combination with **Raman spectroscopy** is effective for the **minimally invasive characterization** of the chemical and mineralogical composition of **meteorites.**

✓The identification of major elements such as Fe, Mg, Si, Al, Ca, Mn, and Cr indicated a higher abundance of **rock-forming silicates** in the **matrix**. In contrast, the **metallic inclusions** are dominated by **iron** and **nickel**.

✓**LIBS mapping**, combined with **K-means clustering**, enabled a clear visualization of the **spatial distribution of mineral phases** including plagioclase, olivine, pyroxene, chromite, and Fe–Ni metallic inclusions.

✓**CF-LIBS** proved to be a powerful approach for **semi-quantitative analysis**.The results obtained showed good agreement with literature values for **LL-type** ordinary chondrites.

References

C. Burgos-Palop, L. García-Gómez, F.J. Fortes, J.M. Vadillo, M.R. López-Ramírez, M. Gritsevich, J.J. Laserna, *Mineral phase discrimination of the Chelyabinsk meteorite by LIBS mapping/cluster analysis*, Talanta, (2026).
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