

Analysis of Minerals Using Handheld Laser-Induced Breakdown Spectroscopy Technology

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Abstract: Laser-induced breakdown spectroscopy (LIBS), a rapid and versatile analytical technique, is becoming increasingly widespread within the geoscience community. Suitable for fieldwork analyses using handheld analyzers, the elemental composition of a sample is revealed by generating plasma using a high-energy laser, providing a practical solution to numerous geological challenges, including identifying and discriminating between different mineral phases. This data paper presents over 12,000 reference mineral spectra acquired using a handheld LIBS analyzer (© SciAps), including those of silicates (e.g., beryl, quartz, micas, spodumene, vesuvianite, etc.), carbonates (e.g., dolomite, magnesite, aragonite), phosphates (e.g., amblygonite, apatite, topaz), oxides (e.g., hematite, magnetite, rutile, chromite, wolframite), sulfates (e.g., baryte, gypsum), sulfides (e.g., chalcopyrite, pyrite, pyrrhotite), halides (e.g., fluorite), and native elements (e.g., sulfur and copper). The datasets were collected from 170 pure mineral samples in the form of crystals, powders, and rock specimens, during three research projects: NEXT, Labex Ressources 21, and ARTeMIS. The extensive spectral range covered by the analyzer spectrometers (190–950 nm) allowed for the detection of both major (>1 wt.%) and trace (<1 wt.%) elements, recording a unique spectral signature for each mineral. Mineral spectra can serve as reference data to (i) identify relevant emission lines and spectral ranges for specific minerals, (ii) be compared to unknown LIBS spectra for mineral identification, or (iii) constitute input data for machine learning algorithms.

Dataset: <https://doi.org/10.24396/ORDAR-165>.

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Keywords: laser-induced breakdown spectroscopy; handheld LIBS; minerals; spectra; database



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1. Summary

The laser-induced breakdown spectroscopy (LIBS) technique is a rapid and versatile analytical solution for analyzing various geological materials: rocks [1–3], powders [4–6], and minerals [7,8]. Additionally, by overcoming the limitations of laboratory-based systems through the development of handheld analyzers [9–12], the LIBS technique has significantly increased its potential and attractiveness to the geoscience community. The ability to access geochemical information onsite during field investigations is particularly valuable in geology as the spatial scale of the studied objects ranges from microns (minerals) to hundreds of kilometers (geological structures). Handheld LIBS has successfully

been used to address several challenges in geology, including determining the proportion of targeted elements in mining operations [6,13–15] and the spatial distribution of chemical elements [16,17], identifying geological samples [1,18], and exploring extraterrestrial rocks and soils during space missions [19–21]. Furthermore, by processing LIBS analysis using chemometric algorithms [22], the spectra of known samples can be used as references to identify rock species [18,23], highlight chemical variation within a specific mineral phase [24–27], and discriminate between minerals presenting similar physical characteristics that might complicate onsite identification [28,29].

The presence or absence of minerals, as well as the chemical variations observed in different minerals or within a specific mineral phase, can reveal the genesis conditions and the geological processes leading to the deposit formation. Mineral phase identification can be performed in the field based on physical characteristics (i.e., color, crystal form) but might be challenging, especially with small-sized textures (e.g., phaneritic and microgranular matrices) or if different minerals are visually similar (e.g., spodumene, petalite, Li micas). The idea is to apply LIBS to automate mineral identification in rock samples based on the fact that an LIBS spectrum obtained from a mineral sample reflects the nature, structure, and proportions of the elements it contains, generating a unique spectral fingerprint for each mineral. While these types of approaches are powerful tools [3,28–30], their implementation depends on the availability of comprehensive and high-quality reference data. Accurate recognition, classification, and clustering depend on reliable and representative input variables, highlighting the critical importance of LIBS spectral libraries.

This study provides access to more than 12,000 reference LIBS spectra for several mineral species, including silicates, carbonates, sulfides, sulfates, oxides, and native elements (Table 1). Multiple samples of the same mineral species were analyzed to portray the geochemical diversity observed in a mineral phase across different deposits. The number of analyses per sample was maximized to generate large datasets compatible with advanced chemometric techniques. Ultimately, this spectral library is a foundational step meant to be expanded and enriched by future research contributions, such as those focused on lithium-rich minerals [8] and other relevant studies, to support the future application of the LIBS technique in mineral discrimination and automatic mineral identification.

Table 1. Summary of the mineral samples analyzed: the mineral species, chemical formulas, number of samples analyzed, and total spectra acquired. Detailed metadata are available in the database.

Mineral	Formula	Sample	Spectra
Albite	$\text{Na}(\text{AlSi}_3\text{O}_8)$	5	356
Amblygonite	$(\text{Li},\text{Na})\text{Al}(\text{PO}_4)(\text{F},\text{OH})$	1	96
Apatite	$\text{Ca}_5(\text{PO}_4)_3(\text{Cl}/\text{F}/\text{OH})$	5	368
Apophyllite	$\text{KCa}_4(\text{Si}_4\text{O}_{10})_2\text{F}_8(\text{H}_2\text{O})$	1	46
Aragonite	CaCO_3	1	49
Arsenopyrite	FeAsS	4	304
Baryte	BaSO_4	1	60
Beryl	$\text{Be}_3\text{Al}_2(\text{Si}_6\text{O}_{18})$	2	192
Biotite	$\text{K}(\text{Fe}^{2+}/\text{Mg})_2(\text{Al}/\text{Fe}^{3+}/\text{Mg}/\text{Ti})([\text{Si}/\text{Al}/\text{Fe}]_2\text{Si}_2\text{O}_{10})(\text{OH}/\text{F})_2$	4	207
Calcite	CaCO_3	2	97
Cassiterite	SnO_2	6	486
Chalcopyrite	CuFeS_2	5	363
Chlorite	$\text{A}_{5-6}\text{T}_4\text{Z}_{18}/\text{A} = \text{Al}, \text{Fe}, \text{Li}, \text{Mg}, \text{Mn}, \text{Ni}/\text{T} = \text{Al}, \text{Fe}, \text{S}/\text{Z} = \text{O}, \text{OH}$	3	223
Chromite	FeCr_2O_4	1	40
Columbite	$(\text{Fe},\text{Mn})\text{Nb}_2\text{O}_6$	1	96
Copper	Cu	1	30
Dolomite	$\text{CaMg}(\text{CO}_3)_2$	1	40
Fluorite	CaF_2	11	731
Galena	PbS	1	29
Garnet	$\text{X}_3\text{Z}_2(\text{SiO}_4)_3/\text{X} = \text{Mg}, \text{Ca}, \text{Fe}, \text{Mn}/\text{Z} = \text{Al}, \text{Fe}, \text{Cr}, \text{V}$	4	160
Gypsum	$\text{Ca}(\text{SO}_4)_2(\text{H}_2\text{O})$	1	50
Hematite	Fe_2O_3	5	317

Table 1. Cont.

Mineral	Formula	Sample	Spectra
Illite	$(K,H_3O)Al_2Si_4O_{10}(OH)_2$	1	80
Ilmenite	$FeTiO_3$	1	109
Kaolinite	$Al_2Si_2O_5(OH)_4$	1	40
K-feldspars	$KAlSi_3O_8$	7	592
Kyanite	Al_2SiO_5	1	40
Li micas	$KLi_2Al(Si_4O_{10})(F,OH)_2$ to $K(Li_{1.5}Al_{1.5})(AlSi_3O_{10})(F,OH)_2$	22	2550
Magnesite	$MgCO_3$	1	40
Magnetite	$Fe^{2+}Fe^{3+}_2O_4$	1	10
Malachite	$Cu_2(CO_3)(OH)_2$	1	20
Molybdenite	MoS_2	3	145
Muscovite	$KAl_2(AlSi_3O_{10})(OH)_2$	5	272
Pyrite	FeS_2	4	248
Pyrrholite	Fe_7S_8	1	50
Quartz	SiO_2	8	349
Rhodochrosite	$MnCO_3$	1	40
Rutile	TiO_2	4	266
Serpentinite	$(Mg,Fe)_3Si_2O_5(OH)_4$	1	40
Sphalerite	$(Zn,Fe)S$	8	534
Spodumene	$LiAlSi_2O_6$	1	125
Stannite	$(Mn,Fe)(Ta,Nb)_2O_6$	1	96
Sulfur	S	1	10
Talc	$Mg_3Si_4O_{10}(OH)_2$	1	40
Tantalite	$(Fe, Mg, Mn)Ta_2O_6$	1	96
Topaz	$Al_2SiO_4(F,OH)_2$	1	44
Tourmaline	$AD_3G_6(T_6O_{18})(BO_3)_3X_3Z$ A = Ca, Na, K, Pb D = Al, Fe, Li, Mg, Mn, Ti/G = Al, Cr, Fe, V T = Si, Al/X = O, OH/Z = F, O, OH	11	709
Vermiculite	$(Mg,Fe,Al)_3(Al,Si)_4O_{10}(OH)_2 \cdot 4H_2O$	1	40
Vesuvianite	$Ca_{10}Al_4(SiO_4)_5(OH)_4$	1	40
Wolframite	$(Mn, Fe)WO_4$	6	429
Wollastonite	$CaSiO_3$	1	40
Zinnwaldite	$KFe_2Al(Al_2Si_2O_{10})(OH)_2$ to $KLi_2Al(Si_4O_{10})(F,OH)_2$	4	128
Zircon	$ZrSiO_4$	1	96

2. Data Description

The spectral database is available open access (license CC-BY-NC-SA) on the ORDaR platform (OTELo Research Data Repository), managed by the Observatory Earth Environment of Lorraine (OTELo), via the following doi: <https://doi.org/10.24396/ORDAR-165>. The database, titled “Mineral spectra acquired using handheld LIBS”, includes a metadata file summarizing essential information: the sample ID, mineral type, chemical formula, sample type, matrix type, number of data points, spectra per sample, and spectra per mineral. To simplify data manipulation, the spectra are organized into individual zip files corresponding to the 55 mineral species analyzed, including albite, amblygonite, apophyllite, aragonite, apatite, arsenopyrite, baryte, beryl, cassiterite, calcite, chalcopyrite, chlorite, chromite, columbite, copper, kyanite, dolomite, fluorite, galena, garnet, gypsum, hematite, illite, ilmenite, kaolinite, k-feldspars, magnetite, magnesite, malachite, muscovite, pyrite, pyrrhotite, quartz, rhodochrosite, rutile, serpentinite, sulfur, sphalerite, spodumene, stannite, talc, tantalite, topaz, tourmaline, vermiculite, vesuvianite, wolframite, wollastonite, and zircon.

2.1. Spectra Files

The spectra files are organized as follows: Individual spectra (e.g., spectrum1, spectrum2, spectrum3) represent the average signal obtained by multiple laser shots in each zone, with two to four laser pulses. The labeled “Average” spectra are the mean spectra for each analysis grid. As detailed in the “Data acquisition” Section, one analysis point represents a grid of multiple analyzed zones, with each zone analyzed using successive laser shots. Further details on data acquisition are available in the Methodology Section.

LIBS data were exported from the LIBS analyzer in CSV format. A spectrum corresponds to a file containing 23,432 rows recording the signal intensity as a function of the wavelength. The downloaded files were wavelength-normalized by resampling the spectral data to a consistent wavelength scale, correcting for variations in the pixel-to-wavelength mapping due to detector inconsistencies or calibration shifts. The high spectral resolution (0.033 nm) is particularly valuable for accurately analyzing complex matrices such as geological materials. In minerals composed of various elements, this degree of precision minimizes emission line overlap and enhances the ability to detect weak signals from trace elements even next to the stronger emission lines of major components. However, the large number of variables per spectrum can increase processing times, especially for large-scale datasets. To optimize the computational time, targeted strategies can be implemented: (i) focusing on relevant spectral regions based on emission line selection, (ii) reducing the data dimensionality using PCA, SOM, etc., and (iii) spectral binning.

2.2. LIBS Signal

The baseline of LIBS spectra varies significantly depending on the elemental composition of the mineral analyzed (Figure 1a). A flat baseline is observed in minerals such as quartz, Li micas, albite, calcite, etc. Meanwhile, minerals rich in metallic elements (e.g., Fe, Cu, Cr, Zn, etc.), including pyrite, chromite, and arsenopyrite, exhibit an elevated background signal across the visible and ultra-violet wavelength range due to the high thermal conductivity of these elements affecting the plasma density and temperature [30,31]. In minerals containing higher-atomic-mass elements (e.g., Nb, Ta, Zr), such as columbite, tantalite, and zircon, a higher signal results from increased Bremsstrahlung radiation. These differences emphasize the need for custom spectral processing when involving multiminerall LIBS data. Baseline correction and normalization should be specifically adapted to the mineral species targeted. Additionally, the physical nature of the analyzed samples is reflected in the signal intensity. As shown in Figure 1b, the LIBS signal intensity of quartz differs between powdered and crystalline samples. The signal intensities recorded from powdered samples are substantially higher than those obtained in crystals. Intensity gaps caused by textural variations are attributed to higher ablation rates in unconsolidated powders and reduced scattering, which enhances the laser interaction with powder particles [14,32,33].

2.3. Element Detection

For each mineral, characteristic emission lines at specific wavelengths and varying intensities define a unique and distinctive spectral signature. In this sense, the distribution of emission lines across the entire spectral range of an LIBS spectrum differs significantly from one mineral to another (Figure 1a). For instance, minerals rich in transition metals (e.g., Fe), characterized by complex atomic structures and numerous energy level transitions, lead to a higher density of emission lines, generating spectra with densely packed lines. A higher emission density increases the potential for spectral interference, and the signal of less abundant trace elements may be concealed (Figures 1a and 2c).

Even if the presence of known emission lines reveals the chemical composition of the mineral, the signal intensities recorded of these lines do not correlate directly with the absolute abundance of the elements in the mineral. The signal intensity of an element is the result of various factors besides its concentration. Elements with lower ionization energies (e.g., Li ~ 5.39 eV, Na ~ 5.14 eV) produce stronger emission signals (Figure 2a), while elements with moderate ionization energies (e.g., Si ~ 8.15 eV) yield comparatively weaker signals even at higher concentrations (Figure 2b).

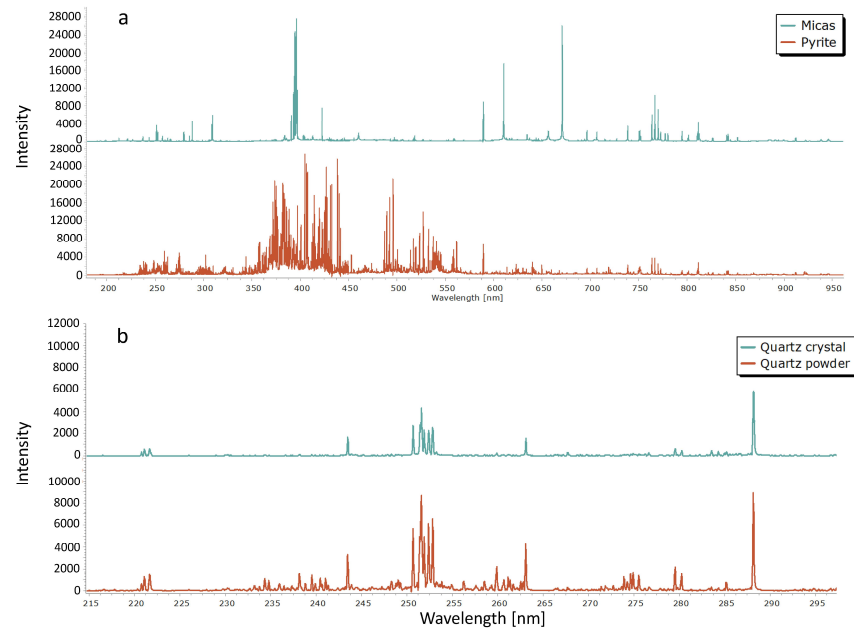


Figure 1. Mineral LIBS spectra: (a) the baseline variation based on the mineral composition, showing higher density plasma for pyrite due to metallic elements' presence, compared to a flat baseline for Li-rich micas; (b) the signal intensity variation for quartz analyzed as powder samples, exhibiting stronger signals compared to those of crystal phases.

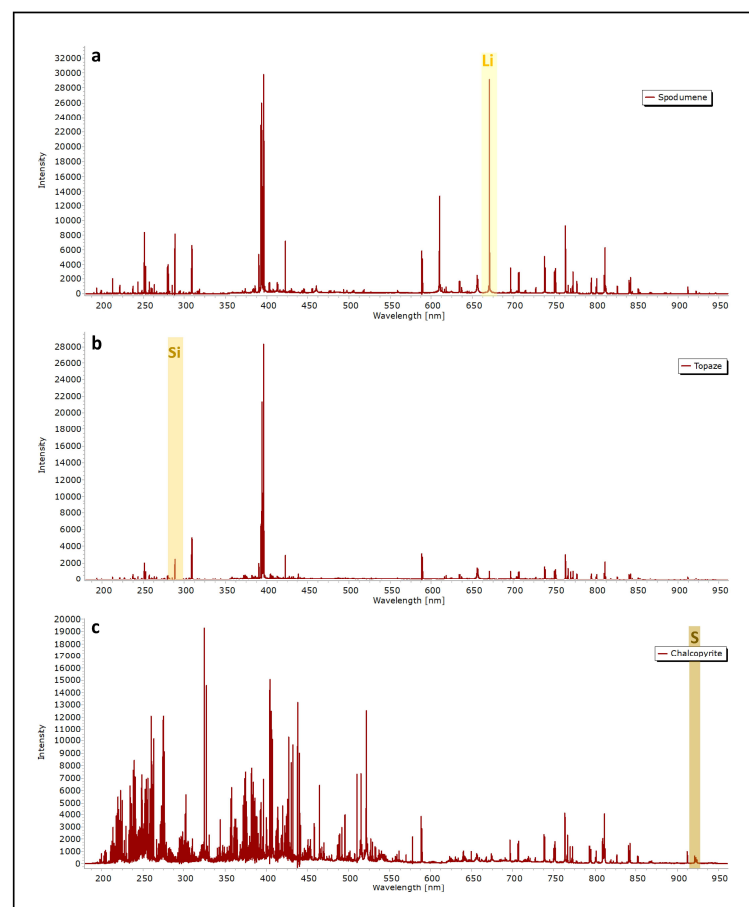


Figure 2. Variation in the LIBS signal intensity for different elements: (a) Li, an element with low ionization energy, is a major component of spodumene; (b) Si, an element with moderate ionization energy, is a primary constituent of topaz; and (c) S, an element with high ionization energy, is a key component of chalcopyrite.

3. Methods

3.1. Samples

Table 1 summarizes the samples analyzed to obtain the mineral spectra contained in the database. In total, 171 mineral samples were analyzed using a handheld LIBS analyzer: 127 were crystal hand specimens, 25 were phenocrysts included in rock matrices, and 19 were compressed powder pellets (<50 µm) shaped using a 13 mm diameter, 2 mm thick cylindrical mold and a 10-ton hydraulic press [34]. The pellets were formed using a pressure of 7 tons for approximately 2 minutes to ensure the cohesion of the mineral powders. The solid samples were unprocessed and selected for their flat surface to ensure proper adhesion to the analysis window, ensuring good plasma quality.

Most samples were sourced from the teaching and research collections of the École Nationale Supérieure de Géologie (ENSG, University of Lorraine, Nancy, France) and the GeoRessources laboratory (University of Lorraine, Nancy, France). Additional contributions came from the San Finx mine (Spain) and the University of Thessaloniki (Greece).

3.2. LIBS Techniques

The fundamental principles of LIBS have been detailed in numerous publications [35–37]. In summary, plasma is generated on the surface of a sample using a high-power pulsed laser. The excited chemical components of the plasma (atoms, ions, and molecules) emit light to release excess energy and return to stable energy states. The spectral signal is collected and analyzed using optical collectors and spectrometers to produce a spectrum, illustrating the signal intensity (a.u.) as a function of the wavelength (nm). Emission lines at specific positions reveal the elemental composition, while the signal intensity depends on several factors (i.e., the element concentration, ionization potential, acquisition parameters, etc.).

3.3. Handheld LIBS Analyzer

The handheld LIBS analyzer used in this study was the SciAps Z300 model (MA, USA), composed of a Nd:YAG laser with an output energy of 5–6 mJ per pulse, operating at a wavelength of 1064 nm, a pulse duration of 1 nanosecond, and a pulse repetition rate of up to 50 Hz. Characterized by 4 hours of autonomy per battery and a compact design (weight: 2 kg), the device is user-friendly and convenient for field missions. An integrated camera allows for the precise visualization of the sample surface before an analysis, facilitating the accurate targeting of specific minerals in rock samples. A constant argon flush is used during measurements to enhance the signal-to-noise ratio and improve signal intensity, particularly in the UV range [36,37]. The combination of spectrometers enables the coverage of a large spectral band (190–950 nm), detecting elements from light (H) to heavy (U) with a spectral resolution of 0.03 nm. The detection limits vary from a few ppm (Li = 5 ppm) to hundreds of ppm (C = 400 ppm). The instrument includes automated drift correction, performed when starting the device and approximately every hour using an onboard reference material, ensuring result consistency over time. Two data acquisition modes are available. In the “standalone mode”, the analyzer operates independently of external devices, providing flexibility during field operations. The “connected mode”, accessed via ProfileBuilder software, allows for more control over the acquisition parameters for detailed spectra visualization and emission line identification using an integrated spectral database. The first mode is ideal for onsite analysis, while the connected mode is better suited for comprehensive data inspection during data acquisition.

3.4. Data Acquisition

Four averaged analysis points were measured for each sample. An analysis point consisted of multiple zones arranged in a grid (e.g., 3×3 , 5×5 , 6×6). At least two laser shots were averaged per zone, following an initial cleaning shot to remove any surface contaminants. Increasing the number of laser shots per location, minimizing variations caused by plasma instability and maximizing the number of analysis points across the sample surface, ensured a representative signal, accounting for chemical variations and inhomogeneous element distribution within the crystal (e.g., zoning, inclusions). The distance between two zones ranged from 100 to 200 μm , ensuring independent plasma formation and no interference from prior shots. A flat surface was a key point when selecting samples, as topographic irregularities can affect the signal by altering the laser absorption, ablation efficiency, and plasma formation [38]. An onboard sensor prevented the laser from firing when the sample was not correctly aligned with the analysis window, guaranteeing safe operation under laser class 1M conditions. However, this mechanism complicated the analysis of clear crystals (e.g., quartz, fluorite), potentially not detected due to their transparency or high reflectivity, hindering laser interaction. The analysis was aborted in such cases, and no spectra were recorded.

3.5. Spectra Visualization

The CSV files can be imported into a similar handheld LIBS analyzer via the analyzer software (ProfileBuilder) for detailed visualization and emission peak identification using the integrated spectral database. External software, like SpectraGryph [39], offer a user-friendly interface for visualizing and processing LIBS spectra. Multiple spectra can be processed simultaneously, including baseline correction, normalization, and feature extraction.

3.6. Applications

LIBS spectra obtained from mineral samples can be used to build custom spectral datasets, providing input data for training mathematical models to generate qualitative, quantitative, and mineralogical information for unknown rock and mineral samples. In this sense, numerous studies have demonstrated the potential of the LIBS technique, when combined with chemometric methods, as a tool for automatic mineral identification [29,40,41]. Machine learning algorithms have been designed to identify patterns to make predictions based on the data features.

The performance of these models highly depends on the quality of input data points and their ability to emphasize relevant characteristics, as the equations and rules implemented are calibrated using these attributes. The ability to determine the mineralogical composition of rocks by associating LIBS spectra with specific minerals based on spectral features represents a rapid and practical solution for resource optimization during field operations. This highlights the importance of generating extensive and high-quality mineral spectral libraries to support advanced mathematical approaches for LIBS applications in geology. In order to enable use by any type of processing method already available or to be developed, the database is provided without any postprocessing of the spectra.

4. User Note

The samples, as well as the methodology followed during this study, are described in the metafile and the present article, respectively. Various Li-rich mica samples, grouped under the keyword “calibration”, are associated with additional geochemical quantitative data, which are not included in the paper or metafile but can be made accessible upon request.

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References

1. El-Saeid, R.H.; Abdel-Salam, Z.; Pagnotta, S.; Palleschi, V.; Harith, M.A. Classification of sedimentary and igneous rocks by laser induced breakdown spectroscopy and nanoparticle-enhanced laser induced breakdown spectroscopy combined with principal component analysis and graph theory. *Spectrochim. Acta Part B At. Spectrosc.* **2019**, *158*, 105622. [CrossRef]
2. Syvilay, D.; Bousquet, B.; Chapoulie, R.; Orange, M.; Bourdonnec, F.X.L. Advanced statistical analysis of LIBS spectra for the sourcing of obsidian samples. *J. Anal. At. Spectrom.* **2019**, *34*, 867–873. [CrossRef]
3. Alvarez-Llamas, C.; Tercier, A.; Ballouard, C.; Fabre, C.; Hermelin, S.; Margueritat, J.; Duponchel, L.; Dujardin, C.; Motto-Ros, V. Ultrafast μ LIBS imaging for the multiscale mineralogical characterization of pegmatite rocks. *J. Anal. At. Spectrom.* **2024**, *39*, 1077–1086. [CrossRef]
4. Fabre, C.; Ourti, N.E.; Ballouard, C.; Mercadier, J.; Cauzid, J. Handheld LIBS analysis for in situ quantification of Li and detection of the trace elements (Be, Rb and Cs). *J. Geochem. Explor.* **2022**, *236*, 106979. [CrossRef]
5. Foucaud, Y.; Fabre, C.; Demeusy, B.; Filippova, I.V.; Filippov, L.O. Optimisation of fast quantification of fluorine content using handheld laser induced breakdown spectroscopy. *Spectrochim. Acta Part B At. Spectrosc.* **2019**, *158*, 105628. [CrossRef]
6. Korbel, C.; Mezoued, N.; Demeusy, B.; Fabre, C.; Cauzid, J.; Filippova, I.V.; Filippov, L.O. Quantification of lithium using handheld instruments: Application of LIBS and XRF spectroscopy to assay the lithium content of mineral processing products. *J. Anal. At. Spectrom.* **2024**, *39*, 1838–1853. [CrossRef]
7. Fabre, C.; Marulier, L.; Monfaredi, B.; Motto-Ros, V.; Bousquet, B.; Eglinger, A.; Tarantola, A. Exploring rare earth elements in complex microscopic mineral phases: Inputs from μ LIBS imaging. *Spectrochim. Acta Part B At. Spectrosc.* **2024**, *216*, 106954. [CrossRef]
8. Fabre, C.; Ourti, N.E.; Mercadier, J.; Cardoso-Fernandes, J.; Dias, F.; Perrotta, M.; Koerting, F.; Lima, A.; Kaestner, F.; Koellner, N.; et al. Analyses of Li-Rich Minerals Using Handheld LIBS Tool. *Data* **2021**, *6*, 68. [CrossRef]
9. Harmon, R.S.; De Lucia, F.C.; Miziolek, A.W.; McNesby, K.L.; Walters, R.A.; French, P.D. Laser-induced breakdown spectroscopy (LIBS)—an emerging field-portable sensor technology for real-time, in-situ geochemical and environmental analysis. *Geochem. Explor. Environ. Anal.* **2005**, *5*, 21–28. [CrossRef]
10. Lemiere, R.; Harmon, R.H. XRF and LIBS for Field Geology. In *In Portable Spectroscopy and Spectrometry*, 1st ed.; Crocombe, R., Leary, P., Kammrath, B., Eds.; Wiley: Hoboken, NJ, USA, 2021; pp. 455–497. [CrossRef]

11. Lemi re, B.; Uvarova, Y.A. New developments in field-portable geochemical techniques and on-site technologies and their place in mineral exploration. *Geochem. Explor. Environ. Anal.* **2019**, *20*, 205–216. [[CrossRef](#)]
12. Harmon, R.S. Laser-Induced Breakdown Spectroscopy in Mineral Exploration and Ore Processing. *Minerals* **2024**, *14*, 731. [[CrossRef](#)]
13. Fontana, F.F.; van der Hoek, B.; Tassios, S.; Tiddy, C.; Stromberg, J.; Francis, N.; Uvarova, Y.A.; Lancaster, D.G. Laser Induced Breakdown Spectroscopy (LIBS) for whole rock geochemistry. *J. Geochem. Explor.* **2023**, *246*, 107160. [[CrossRef](#)]
14. Wise, M.A.; Harmon, R.S.; Curry, A.; Jennings, M.; Grima , Z.; Khashchevskaya, D. Handheld LIBS for Li Exploration: An Example from the Carolina Tin-Spodumene Belt, USA. *Minerals* **2022**, *12*, 77. [[CrossRef](#)]
15. Harmon, R.S.; Wise, M.A.; Curry, A.C.; Mistele, J.S.; Mason, M.S.; Grima , Z. Rapid Analysis of Muscovites on a Lithium Pegmatite Prospect by Handheld LIBS. *Minerals* **2023**, *13*, 697. [[CrossRef](#)]
16. Sweetapple, M.T.; Tassios, S. Laser-induced breakdown spectroscopy (LIBS) as a tool for in situ mapping and textural interpretation of lithium in pegmatite minerals. *Am. Mineral.* **2015**, *100*, 2141–2151. [[CrossRef](#)]
17. Pochon, A.; Desauty, A.M.; Bailly, L. Handheld laser-induced breakdown spectroscopy (LIBS) as a fast and easy method to trace gold. *J. Anal. At. Spectrom.* **2020**, *35*, 254–264. [[CrossRef](#)]
18. Jin, X.; Yang, G.; Sun, X.; Qu, D.; Li, S.; Chen, G.; Li, C.; Tian, D.; Yao, L. Discrimination of rocks by laser-induced breakdown spectroscopy combined with Random Forest (RF). *J. Anal. At. Spectrom.* **2022**, *38*, 243–252. [[CrossRef](#)]
19. Maurice, S.; Wiens, R.C.; Saccoccio, M.; Barraclough, B.; Gasnault, O.; Forni, O.; Mangold, N.; Baratoux, D.; Bender, S.; Berger, G.; et al. The ChemCam Instrument Suite on the Mars Science Laboratory (MSL) Rover: Science Objectives and Mast Unit Description. *Space Sci. Rev.* **2012**, *170*, 95–166. [[CrossRef](#)]
20. Maurice, S.; Wiens, R.C.; Bernardi, P.; Ca s, P.; Robinson, S.; Nelson, T.; Gasnault, O.; Reess, J.-M.; Deleuze, M.; Rull, F.; et al. The SuperCam Instrument Suite on the Mars 2020 Rover: Science Objectives and Mast-Unit Description. *Space Sci. Rev.* **2021**, *217*, 47. [[CrossRef](#)]
21. Xu, W.; Liu, X.; Yan, Z.; Li, L.; Zhang, Z.; Kuang, Y.; Jiang, H.; Yu, H.; Yang, F.; Liu, C.; et al. The MarSCoDe Instrument Suite on the Mars Rover of China’s Tianwen-1 Mission. *Space Sci. Rev.* **2021**, *217*, 64. [[CrossRef](#)]
22. Brunnbauer, L.; Gajarska, Z.; Lohninger, H.; Limbeck, A. A critical review of recent trends in sample classification using Laser-Induced Breakdown Spectroscopy (LIBS). *TrAC Trends Anal. Chem.* **2023**, *159*, 116859. [[CrossRef](#)]
23. Senesi, G.S.; Allegr ta, I.; Marangoni, B.S.; Ribeiro, M.C.; Porfido, C.; Terzano, R.; De Pascale, O.; Eramo, G. Geochemical identification and classification of cherts using handheld laser induced breakdown spectroscopy (LIBS) supported by supervised machine learning algorithms. *Appl. Geochem.* **2023**, *151*, 105625. [[CrossRef](#)]
24. Dutrow, B.L.; McMillan, N.J.; Henry, D.J. A multivariate statistical approach for mineral geographic provenance determination using laser-induced breakdown spectroscopy and electron microprobe chemical data: A case study of copper-bearing tourmalines. *Am. Mineral.* **2024**, *109*, 1085–1095. [[CrossRef](#)]
25. Shih, M.; Yuan, Y.; Shi, G.-H. Comparative analysis of LDA, PLS-DA, SVM, RF, and voting ensemble for discrimination origin in greenish-white to white nephrites using LIBS. *J. Anal. At. Spectrom.* **2024**, *39*, 1560–1570. [[CrossRef](#)]
26. Defnet, P.A.; Wise, M.A.; Harmon, R.S.; Hark, R.R.; Hilferding, K. Analysis of Garnet by Laser-Induced Breakdown Spectroscopy—Two Practical Applications. *Minerals* **2021**, *11*, 705. [[CrossRef](#)]
27. Ali, A.; Khan, M.Z.; Rehan, I.; Rehan, K.; Muhammad, R. Quantitative Classification of Quartz by Laser Induced Breakdown Spectroscopy in Conjunction with Discriminant Function Analysis. *J. Spectrosc.* **2016**, *2016*, 1835027. [[CrossRef](#)]
28. Capela, D.; Lopes, T.; Dias, F.; Ferreira, M.F.S.; Teixeira, J.; Lima, A.; Jorge, P.A.; Silva, N.A.; Guimar es, D. Advancing automated mineral identification through LIBS imaging for lithium-bearing mineral species. *Spectrochim. Acta Part B At. Spectrosc.* **2025**, *223*, 107085. [[CrossRef](#)]
29. Capela, D.; Ferreira, M.F.S.; Lima, A.; Dias, F.; Lopes, T.; Guimar es, D.; Jorge, P.A.; Silva, N.A. Robust and interpretable mineral identification using laser-induced breakdown spectroscopy mapping. *Spectrochim. Acta Part B At. Spectrosc.* **2023**, *206*, 106733. [[CrossRef](#)]
30. El Haddad, J.; de Lima Filho, E.S.; Vanier, F.; Harhira, A.; Padioleau, C.; Sabsabi, M.; Wilkie, G.; Blouin, A. Multiphase mineral identification and quantification by laser-induced breakdown spectroscopy. *Miner. Eng.* **2019**, *134*, 281–290. [[CrossRef](#)]
31. Ismail, A.M.; Imam, H.; Elhassan, A.; Youniss, T.W.; Harith, A.M. LIBS limit of detection and plasma parameters of some elements in two different metallic matrices. *J. Anal. At. Spectrom.* **2004**, *19*, 489–494. [[CrossRef](#)]
32. Cousin, A.; Sautter, V.; Fabre, C.; Dromart, G.; Montagnac, G.; Drouet, C.; Meslin, P.-Y.; Gasnault, O.; Beyssac, O.; Bernard, S.; et al. SuperCam calibration targets on board the Perseverance rover: Fabrication and quantitative characterization. *Spectrochim. Acta Part B At. Spectrosc.* **2022**, *188*, 106341. [[CrossRef](#)]
33. Kim, Y.; Fabre, C.; Cauzid, J. Access to quantitative analysis of carbonates using a portable LIBS instrument: First applications to single minerals and mineral mixtures. *Spectrochim. Acta Part B At. Spectrosc.* **2022**, *191*, 106397. [[CrossRef](#)]
34. Harmon, R.H.; Senesi, G.S. Laser-Induced Breakdown Spectroscopy—A geochemical tool for the 21st century. *Appl. Geochem.* **2021**, *128*, 104929. [[CrossRef](#)]

35. Radziemski, L.; Cremers, D. A brief history of laser-induced breakdown spectroscopy: From the concept of atoms to LIBS 2012. *Spectrochim. Acta Part B At. Spectrosc.* **2013**, *87*, 3–10. [[CrossRef](#)]
36. Aguilera, J.A.; Bengoechea, J.; Aragón, C. Spatial characterization of laser induced plasmas obtained in air and argon with different laser focusing distances. *Spectrochim. Acta Part B At. Spectrosc.* **2004**, *59*, 461–469. [[CrossRef](#)]
37. Ya-xiong, H.; Wen-qi, Z.; Bin, Z.; Yong-sheng, Z.; Chuan, K.; Tao, X.; Yong, Z. Study on Time-Resolved Characteristics of Laser-Induced Argon Plasma. *Spectrosc Spectr Anal.* **2022**, *42*, 1049–1057.
38. Xu, W.; Sun, C.; Tan, Y.; Gao, L.; Zhang, Y.; Yue, Z.; Shabbir, S.; Wu, M.; Zou, L.; Chen, F.; et al. Total alkali silica classification of rocks with LIBS: Influences of the chemical and physical matrix effects. *J. Anal. At. Spectrom.* **2020**, *35*, 1641–1653. [[CrossRef](#)]
39. Menges, F. Spectroscopy. Spectroscopy Ninja—Optical Spectroscopy Software and Services. Available online: <http://spectroscopy.ninja/> (accessed on 15 January 2025).
40. Rifai, K.; Michaud Paradis, M.C.; Swierczek, Z.; Doucet, F.; Özcan, L.; Fayad, A.; Li, J.; Vidal, F. Emergences of New Technology for Ultrafast Automated Mineral Phase Identification and Quantitative Analysis Using the CORIOSITY Laser-Induced Breakdown Spec-troscopy (LIBS) System. *Minerals* **2020**, *10*, 918. [[CrossRef](#)]
41. Janovszky, P.; Jancsek, K.; Palásti, J.D.; Kopniczky, J.; Hopp, B.; Tóth, T.M.; Galbács, G. Classification of minerals and the assessment of lithium and beryllium content in granitoid rocks by laser-induced breakdown spectroscopy. *J. Anal. At. Spectrom.* **2021**, *36*, 813–823. [[CrossRef](#)]

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