

# Laser-induced Breakdown Spectroscopy:

*A 21<sup>st</sup> Century Analytical  
Tool for the Geosciences*



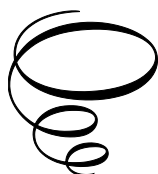
# Laser-induced Breakdown Spectroscopy:

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By

Russell S. Harmon and Giorgio S. Senesi

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To my twin sons, Brendan and Jonathan, of whom I am so proud, and to my wife Karen whose support over 55 years has made my research career possible.

**Russell S. Harmon**

To my daughters, Alessandra and Roberta, you are the light of my life and my greatest adventure bringing joy and inspiration to my life every day. To my wife, Erica whose patience and love made this book possible. To my mother, whose endless love and support has been my foundation and to my father, a champion of scientific inquiry and a beacon of intellectual rigor who taught me the value of hard work, perseverance and unwavering support.

This book is for all of you. Thank you!

**Giorgio S. Senesi**



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## FOREWORD

It is a great pleasure to introduce *Laser-Induced Breakdown Spectroscopy – A 21<sup>st</sup> Century Analytical Tool for the Geosciences*, a volume that blends decades of pioneering research, practical innovation, and foresight into a single, comprehensive resource. LIBS, the main focus of this book, is among the most versatile analytical methods available today, offering reliable, minimally destructive chemical analysis across both laboratory and field settings. It has been used to analyze a wide range of materials across numerous fields, from food and cultural heritage objects to forensic samples and hazardous substances. Its ability to provide fast, reliable, and minimally destructive chemical information is transforming how we study minerals, rocks, soils, sediments, and even extraterrestrial materials. Over the past 25 years, more than 1,000 peer-reviewed publications on LIBS and geomaterials have been published, underscoring its growing importance as a tool for geochemical analysis.

The journey to this point has been remarkable. Three decades ago, geological samples were first analyzed with LIBS, which was then primarily a tool for physicists and spectroscopists studying laser–matter interactions. Early challenges were significant: the complex behavior of laser-induced plasmas, crowded emission spectra, and ongoing concerns about reproducibility made LIBS seem promising yet impractical for routine geochemical analysis.

Persistence, creativity, and technological innovation gradually shifted this view. Advances in solid-state microchip lasers, miniaturized spectrometers, and sensitive light-detection devices enhanced accuracy and reliability. Meanwhile, developments in chemometrics and computational analysis allowed researchers to interpret complex spectral data. By overcoming these challenges, LIBS evolved from a physics experiment into a dependable geochemical tool, now widely used in academia, government, and industry.

This progress is shown by the variety of instrumentation available today, from benchtop laboratory devices to portable handheld analyzers and durable industrial systems. This flexibility has put LIBS in the hands of practicing geoscientists, enabling reliable and consistent results across many applications. Its biggest impact is likely in situations where traditional methods are not feasible or where LIBS provides clear advantages in cost, speed, or versatility.

The leadership of this volume's authors has been key to LIBS's success. I have had the privilege of working with both Dr. Russell Harmon and Dr. Giorgio S. Senesi on numerous projects, gaining direct insight into their rigor, creativity, and dedication. Dr. Harmon's career covers geochemistry, analytical science, and leadership within the U.S. Army research enterprise and international geochemical organizations, helping to establish LIBS as a recognized tool in Earth and planetary science. Dr. Senesi has expanded LIBS into studies of minerals, soils, plants, meteorites, and cultural heritage, fostering international collaborations that have helped spread the technology worldwide. Together, they bring authority and a broad vision of what LIBS can achieve.

This book builds on and significantly expands an important 2021 review paper by the authors, "Laser-Induced Breakdown Spectroscopy – A Geochemical Tool for the 21<sup>st</sup> Century." That article provided the community with an overview of LIBS development, achievements, and challenges. The current volume goes further by offering a deeper exploration of fundamentals, new applications, advanced methodologies, and future directions, making it a comprehensive reference in the geoscience field.

The chapters cover both the fundamentals and the latest advances of LIBS in geosciences. Readers will find clear explanations of plasma generation, spectral collection, and calibration, along with discussions of important topics such as chemometrics, compositional imaging, and mapping. These are based on real-world applications—soil characterization, meteorite analysis, mineral exploration, and environmental monitoring. Notably, there are sections showing how LIBS can be combined with complementary methods such as Raman spectroscopy, fluorescence, or mass spectrometry, expanding the geoscientist's analytical tools.

Equally important is how the book situates LIBS within the broader scope of geoscience. Geological research requires tools that work across different scales—from tiny crystal structures to planetary phenomena. LIBS has shown its versatility in this area. In the field, handheld devices allow real-time mineral identification, helping geologists differentiate ore-related pegmatites or evaluate exploration prospects. In the laboratory, LIBS provides detailed elemental maps at micrometer resolution, revealing heterogeneities that previously required lengthy, costly analysis. In planetary exploration, LIBS has achieved notable success with NASA's ChemCam and SuperCam systems on the Curiosity and Perseverance rovers, supplying chemical data from the Martian surface to scientists on Earth. These examples emphasize LIBS's unique ability to deliver fast, contactless, and even stand-off measurements where no other method can operate.

The future of LIBS remains very promising. Research is advancing in several key areas, such as analyzing light elements that are difficult for other methods, enabling quick in situ analysis under normal or extreme conditions, and providing high-speed, spatially resolved multi-element mapping for compositional imaging. High-rate megapixel LIBS systems are already allowing rapid drill core scanning and detailed mapping, while portable analyzers connected to GPS support real-time geochemical surveys. Combining LIBS with other portable techniques—such as portable XRF, Raman, or laser-induced fluorescence—creates a powerful all-in-one field toolkit for mineral exploration and environmental monitoring.

Another frontier involves integrating artificial intelligence and machine learning. These techniques manage the large spectral datasets LIBS produces, identifying key features, enhancing classification, and reducing processing time. When applied correctly and validated, such algorithms can accelerate mineral identification, improve quantitative analysis, and enable near-instant decisions. Although not a universal solution, combining LIBS with machine learning marks a significant step toward automated, intelligent geochemical analysis.

LIBS also offers a new way to classify minerals and rocks. Traditional methods depend heavily on microscopic examination and laboratory tests, which are both time-consuming and require specialized skills. By delivering elemental data within seconds—even from a single laser shot—LIBS allows field geologists to make more confident identifications and supports the development of new classification systems based on detailed, high-resolution compositional data.

*Laser-Induced Breakdown Spectroscopy – A 21<sup>st</sup> Century Analytical Tool for the Geosciences* is more than just a technical manual. It is a comprehensive, forward-looking resource that highlights the latest advancements while clearly pointing to future directions. Thorough yet accessible, rigorous yet practical, it is equally valuable for students new to LIBS and for experienced researchers looking for the most recent developments. I am confident it will soon become a standard reference, inspiring both current and future generations of geoscientists to explore new frontiers in the field.

**Richard Hark**  
Institute for the Preservation of Cultural Heritage  
Yale University

# INTRODUCTION

Knowledge about the chemical composition of minerals, rocks and soils is fundamental to the geosciences and today geochemistry is of such importance that facilities for chemical analysis are widespread within government agencies, universities, and industry. One of the enduring needs within the geosciences community since the systematic chemical analysis of rocks and minerals began in the United States Geological Survey in the late 19<sup>th</sup> century has been a capability for in situ chemical analysis for routine use outside the traditional analytical laboratory. Such instrumentation must be readily portable and lightweight to facilitate use by an individual as well as robust and ruggedized for use in the remote and harsh environments in which geological materials often need to be analyzed. Laser-induced breakdown spectroscopy (LIBS) is one of the few current technologies that meets this need, having a capability to detect and measure every element in the periodic table above its intrinsic material specific LOD. Although initially developed over 50 years ago (Brech and Cross, 1962), the common application of LIBS within the geosciences began about two decades ago. This has been facilitated first through the development of mobile and soLIBS systems for use outside of the conventional laboratory setting for in situ analysis in the ambient environment by both close-in or stand-off approaches and then strongly accelerated over the last decade by the development of commercial hLIBS analyzers. As noted by (Crocombe, 2018), the five general use cases for spectroscopic analysis as applied to geology are:

Detection: Is something present?

Identification: What is this?

Confirmation: Is this what I think it is?

Classification: What class does this belong to?

Quantification: How much of this is present?

Atomic emission spectroscopy is a technique for chemical analysis that measures the intensity of light emitted from a flame, spark, arc or plasma to determine the presence or mass fraction of an element in a sample. LIBS is a specific form of atomic emission spectroscopy that offers rapid, multi-element analysis in real-time with minimal sample preparation. In LIBS, a rapidly-pulsed low energy laser beam is tightly focused on a sample to

create a plasma in which constituent elements can be detected and identified through spectral analysis of emitted light. LIBS can detect most elements, particularly light elements, in the periodic table at high sensitivity with a single laser shot. Quantitative analysis by LIBS is readily achieved using calibration curves generated from matrix-matched standards or through calibration-free methodologies and, when used in conjunction with chemometric techniques and pre-established databases, LIBS spectral analysis is capable of identifying and discriminating unknown materials. LIBS can also be used for rapid microscale compositional imaging at high spatial resolution.

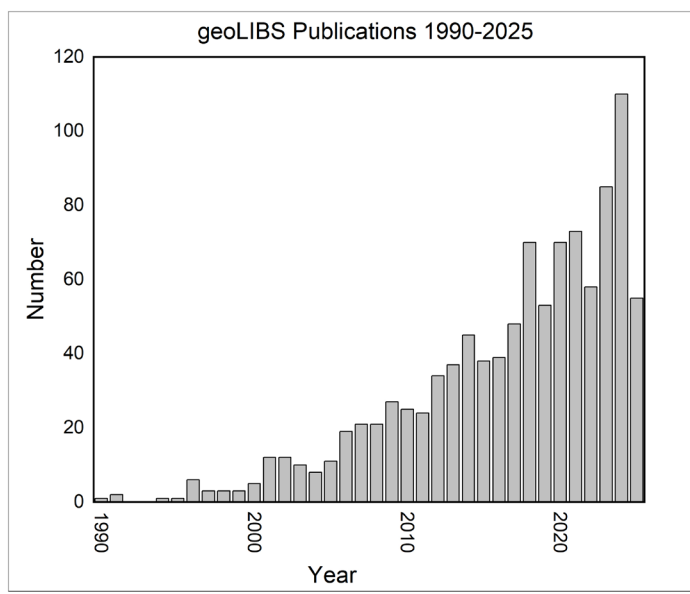
As every element in the periodic table has one or more optical emission lines in the broadband spectral regions between 190 to 900 nm, LIBS is ideally suited for the multi-element analysis of all types of geological media, because offers with a single laser pulse simultaneous detection of all chemical elements in solids, liquids and gases with little to no sample preparation. It is notable and important that LIBS is particularly sensitive to the elements of low atomic number – H, Li, Be, B and C, that cannot be readily determined by many other analytical methods and to first-row transition elements of the periodic table that together comprise the bulk of the Earth's silicate crust and mantle. Thus, as shown in Figure 1, these elements have the lowest LODs. Most elements of the periodic table have been observed in LIBS spectra of geological media, and although LIBS LODs have been steadily improving over the past two decades concomitant with technological progress in LIBS instrumentation, it is important to understand that they are highly dependent on sample matrix and the operational capabilities of the LIBS system used for an analysis.



- A capability to analyze ultra-thin biofilms, alteration layers, coatings, and contamination on a sample surface or to use the LIBS plasma shock wave to remove such allochthonous materials prior to analysis;
- A capability to analyze fluid or solid inclusions in minerals;
- Rapid compositional imaging and analysis of rock and mineral surfaces with sub-millimeter spatial resolution and megapixel 2-D compositional mapping of compositionally complex samples at the 10s of mm spatial scale at kHz rates;
- Stratigraphic compositional profiling to >100 mm depth and in situ analysis of individual particles, mineral grains, and both liquid and solid inclusions;
- Deployment in extreme environments that is not possible for many conventional analytical techniques;
- Easily combined in the same benchtop analytical setup in the laboratory with other analytical techniques such as LIF, RS, IR,  $\mu$ XRF, or LA-ICP-MS for simultaneous multi-element and molecular analysis.
- Collectively, this broad suite of capabilities makes LIBS a simple and extremely versatile analytical technique that can be applied to a broad spectrum of geological investigations because there are many different types of geological media that can be readily analyzed, either in the laboratory or outside in the field.

As a consequence of the continual refinement and miniaturization of lasers, spectrometers, and optoelectronic detectors that has occurred over the past two decades, LIBS instrumentation has progressed from bespoke laboratory systems to commercial laboratory instruments, to industrial systems for analysis during on-line processing, to portable and then handheld analyzers for in situ analysis in the field, and even to analyzers for undersea and extraterrestrial analysis. There has been a continuously growing LIBS literature related to geological media over the past 35 years since the publication by Grant et al. (1990) on the LIBS analysis of iron ore that now exceeds 1030 peer-reviewed publications (Figure 2). Prior to 2015, the large majority of these papers were published in the physics, chemistry, and spectroscopic literature because the LIBS community was initially focused on the advancing and maturing the analytical technology, with significant efforts directed toward the development of instrumentation, measurement protocols, and data processing methodologies to improve analytical performance. The use of LIBS for problem solving within the geosciences, which has only arisen during the past decade, has produced a concomitant rise of LIBS publications in the geosciences literature. Among the most exciting recent

technological advances in LIBS have been the demonstration of LIBS for isotopic analysis, the appearance of commercial hLIBS analyzers for rapid chemical analysis in the field under ambient environmental conditions, the development of LIBS techniques for rapid megapixel microchemical mapping, and the introduction of tandem LIBS/LA-ICP-MS laboratory instruments that can provide a comprehensive chemical and isotopic analysis that typically would require three to five separate analytical instruments. This book describes the LIBS technique and illustrates how LIBS has been applied across the full breadth of the geosciences, which we define here as the geoLIBS domain that includes geological, pedological, environmental, archaeological, paleoclimatological, and forensic applications in which natural materials are analyzed.



**Fig. 2** GeoLIBS publications over the 35 years period from 1990-2025.

This book begins by briefly reviewing summarizing the principles of plasma generation and the fundamentals of plasma emission spectroscopy (Chapter 1) as it applies to LIBS and then moves through a discussion of LIBS instrumentation, sample analysis, and spectral data acquisition and processing before discussing how LIBS is used in the geosciences. Chapter 2 describes the variety of LIBS instrumentation used to analyze natural materials. The data from each LIBS measurement is the emission spectrum recorded from

the plasma generated by a single laser shot that atomizes a small amount of the sample and generates a plasma that emits light as energized elements ions, and molecules decay to their ground state. Chapter 3 first considers how different kinds of geologic media (i.e., minerals, rocks, and soils; natural waters, brines, and hydrothermal fluids; and the ambient atmosphere and geogenic emissions) are analyzed by LIBS and then discusses different approaches to their analysis. The capability of LIBS to rapidly provide chemical analyses of natural materials outside the laboratory setting is one of its primary attributes. After spectral data processing, the recorded LIBS spectrum is then used either for qualitative or quantitative analysis as discussed in Chapter 4. Chemometrics is the use of mathematical and multivariate statistical methods to obtain relevant information on chemical systems and, as discussed in Chapter 5, has been used in LIBS in data processing and in the development of calibration models for quantification and for geomaterial classification and discrimination. The area of LIBS microimaging and compositional mapping of geomedia is discussed in Chapter 6. Then, the two Chapters 7 and 8, respectively, discuss the analysis of different kinds of geological media and describe eight domains of practical geoLIBS application. The increasing popular approach of combining LIBS with other analytical techniques is examined in Chapter 9. The scope of this book is by choice limited to LIBS for analysis of terrestrial geomedia. However, it would be remiss to totally exclude LIBS analysis as a tool in extra-terrestrial exploration, so Chapter 10 presents a brief overview of this exciting and rapidly moving area of LIBS application. We conclude with a summary and consideration of future prospects of LIBS as regards its application within the geosciences. Essential reference books, book chapters, and review articles published in the last 20 years dealing with LIBS, and more specifically with geoLIBS are listed at the end of the text after the References.

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# LIST OF SYMBOLS, ACRONYMS, AND DEFINITIONS

AAS	Atomic absorption spectroscopy
AD	Array detector
ALH	Adaptive local hyperplane (chemometric technique)
andesite	Igneous volcanic rock with 52 to 63 % SiO <sub>2</sub>
ANN	Artificial neural network (chemometric technique)
basalt	Igneous volcanic rock with < 52 % SiO <sub>2</sub>
BMA	Bayesian model averaging (chemometric technique)
BSA	Binary search algorithm (chemometric technique)
CART	Classification and regression tree
CCD	Charge-coupled device
CF-LIBS	Calibration free LIBS
chemometrics	The use of mathematical and statistical methods to obtain information on chemical systems
CMOS	Complementary Metal Oxide Semiconductor
CNN	Convolutional neural network (chemometric technique)
CRM	Certified reference material
CWT	Continuous wavelet transform (chemometric technique)
dacite	Igneous volcanic rock with 63 to 77 % SiO <sub>2</sub>
DFA	Discriminant factor analysis (chemometric technique)
DP-LIBS	Double-pulse LIBS
DP- $\mu$ LIBS	Double pulse micro-LIBS
DPSS	Diode-pumped solid state
$e$	Electron charge
ECIS	External calibration/internal standardization
EDS	Energy dispersive X-ray spectroscopy
EDXRF	Energy dispersive X-ray fluorescence
$\mu$ -EDXRF	Micro-energy dispersive X-ray fluorescence
EMPA	Electron microprobe analysis

EMPA-WDS	Electron microprobe analysis-wavelength dispersive spectrometry
EN	Elastic net regression (chemometric technique)
EPA	United States Environmental Protection Agency
eV	Electron volt
$\varepsilon(\lambda)$	Emissivity as a function of wavelength
FOC	Fiber optic cable
FOM	Figures-of-merit
fpLIBS	Field-portable LIBS system
fs-LIBS	Femtosecond LIBS
FTIRS	Fourier transform infrared spectroscopy
FTIR-ATR	Fourier transform infrared total attenuated reflectance spectroscopy
FTIR-PAS	Fourier transform mid-infrared photoacoustic spectroscopy
FWHM	Full-width at half maximum
GA	Genetic algorithm (chemometric technique)
geogenic	Having a geological origin
geoLIBS	LIBS as applied to geological materials
GPR	Gaussian process regression (chemometric technique)
granite	Intrusive igneous rock composed mostly of quartz and feldspar
GT	Graph theory (chemometric technique)
$h$	Planck constant
hLIBS	Handheld LIBS
hXRF	Handheld XRF
hRS	Handheld Raman
HCA	Hierarchical cluster analysis (chemometric technique)
H-CF	Hybrid calibration free/ANN
HSI	Hyperspectral imaging
ICCD	Intensified CCD
ICA	Independent component analysis (chemometric technique)
ICP	Inductively coupled plasma
ICP-AES	Inductively coupled plasma-atomic emission spectrometry
ICP-OES	Inductively coupled plasma-optical emission spectroscopy
ICP-MS	Inductively coupled plasma-mass spectroscopy

IFALS	Image features assisted line selection
INAA	Instrumental neutron activation analysis
IR	Infra-red (spectral region of $\lambda > 700$ nm)
ISM	Internal standard method
$k$	Boltzmann constant
kelyphite	A petrographical textural term referring to a fine-grained, fibrous intergrowth of multiple phases such as pyroxene, spinel and amphibole typically forming a rim surrounding garnet
kHz	Kilohertz (i.e., 1000 cycles per second)
KMC	K-means clustering
KNN	K-nearest neighbors (chemometric technique)
LA-ICP-MS	Laser ablation inductively coupled plasma mass spectrometry
LA-ICP-OES	Laser ablation inductively coupled plasma optical emission spectrometry
LA-ICP-QMS	Laser ablation inductively coupled plasma quadrupole mass spectrometry
LA-LIBS	Laser ablation laser-induced breakdown spectroscopy
LA-TOF-MS	Laser ablation time of flight mass spectrometry
LAMIS	Laser ablation molecular isotopic spectrometry
LASSO	Least absolute shrinkage and selection operator (chemometric technique)
LCT	A class of granite pegmatites enriched in Li, Cs, and Ta
LDA	Linear discriminant analysis (chemometric technique)
LIBS	Laser-induced breakdown spectroscopy
LIF	Laser-induced fluorescence
LIPAc	Laser-induced plasma acoustics
LMA	Levenberg-Marquardt algorithm
LOD	Limit of detection
LOQ	Limit of quantification
LOSO	Leave-one-sample-out (common chemometric cross-validation model)
LSSVM	Least squares support vector machine
LTE	Local thermodynamic equilibrium
$\lambda$	Wavelength
$m$	Electron rest mass
$\mu\text{m}$	Micrometer, $1 \mu\text{m} = 1000 \text{ nm} = 10\,000 \text{ \AA}$

$\mu$ EDXRF	Micro X-ray fluorescence analysis
MC	Monte Carlo method
MD	Minimum distance
ME-LIBS	Microwave-enhanced LIBS
MFA	Model free algorithm
MLR	Multiple linear regression
MSD	Minimum standard deviation
NASA	United States National Aeronautics and Space Administration
Nd:YAG	Neodymium:Yttrium Aluminium Garnet laser
$N_e$	Plasma electron density
NE-LIBS	Nanoparticle enhanced-LIBS
NIR	Near-Infra-red (spectral region $>700<3000$ nm)
NMR	Nuclear magnetic resonance
NN	Nearest neighbors (chemometric technique)
NP	Nanoparticle
ns-LIBS	Nanosecond LIBS
NYF	A class of granite pegmatites enriched in Nb, Y, and F
OPC-LIBS	One point calibration-LIBS
OES	Optical emission spectroscopy
PC	Principal component (chemometric feature)
PCA	Principal components analysis (chemometric technique)
PDA	Photodiode array
PGE	Platinum group elements (Ru, Rh, Pd, Os, Ir, and Pt)
PLS	Partial least squares analysis (chemometric technique)
PLSDA	Partial least squares discriminant analysis (chemometric technique)
PLSR	Partial least squares regression (chemometric technique)
PMT	Photomultiplier tube
ppb	Parts per billion (i.e., micrograms per liter)
ppm	Parts-per-million (i.e., milligrams/liter)
QMS	Quadrupole mass spectrometry
$\nu$	Frequency
$r^2$	Coefficient of determination value
REE	Rare earth elements (the lanthanide element series with $Z = 57$ to $71$ )
RE-LIBS	Resonance-enhanced LIBS

RF	Random forest (chemometric technique)
rhyolite	Igneous volcanic rock with > 77 % SiO <sub>2</sub>
RMSD	Root mean square deviation
RMSE	Root mean square error
ROC	Receiver operating characteristic
ROV	Remotely operated vehicle
RR	Ridge regression (chemometric technique)
RS	Raman spectroscopy
RSD	Relative standard deviation
RVM	Relevance vector machine (chemometric technique)
Saha equation	Relationship expressing the ionization state of a gas in thermal equilibrium to its pressure and temperature
$\sigma$	Wavenumber
sd	Standard deviation
SBR	Signal-to-background
SD-LIBS	Spark discharge assisted LIBS
SEM-EDS	Scanning electron microscopy-energy-dispersive X-ray spectroscopy
SIMCA	Soft independent modeling of class analogies (chemometric technique)
SIMS	Secondary ion mass spectrometry
SM	Similarity maps
S/N	Signal to noise ratio
SOC	Soil organic carbon
SOM	Self-organizing maps
soLIBS	Stand-off LIBS analysis where the sample being analyzed is located some distance from the LIBS system
SP-LIBS	Single-pulse LIBS
spectral line	The optical manifestation of an electronic transition between energy levels of atoms or ions, denoted by the symbol I for atomic transitions and II for ionic transitions
STM	Standard calibration method
SVD	Single value decomposition (chemometric technique)
SVM	Support vector machine (chemometric technique)
SVR or SVMR	Support vector machine regression (chemometric technique)

SWT	Stationary wavelet transform
$T_e$	Plasma electron temperature
TL	Transfer learning
TIMS	Thermal ionization mass spectrometry
TMA	Thermo-mechanical analysis
UV	Ultraviolet (spectral region of $200 < \lambda < 400$ nm)
VCA	Vertex component analysis
VIS	Visible (spectral region of $400 < \lambda < 700$ nm)
VIS-NIR	Visible near-infrared spectroscopy
VIS-NIR-SWIR	Visible near-infrared spectroscopy short wave infrared spectroscopy
wavenumber	$= 1/\lambda$
WD	Weibull distribution
WNN	Wavelet neural network
WT	Wavelet transform
WTD	Wavelet threshold denoising
WTS	Wavelet transform smoothing
XRD	X-ray diffraction analysis
XRF	X-ray fluorescence analysis
Z	Atomic number

# MINERAL CHEMICAL COMPOSITIONS

## Oxide Minerals

alexandrite	$\text{BeAl}_2\text{O}_4$
cassiterite	$\text{SnO}_2$
chrysoberyl	$\text{BeAl}_2\text{O}$
columbite	$(\text{Mn}, \text{Fe}^{2+})(\text{Nb}, \text{Ta})_2\text{O}_6$
corundum	$\text{Al}_2\text{O}_3$
hematite	$\text{Fe}_2\text{O}_3$
limonite	$\text{FeO}(\text{OH}) \cdot n\text{H}_2\text{O}$
maghemite	magnetic $\text{Fe}_2\text{O}_3$ with the structure of $\text{Fe}_3\text{O}_4$
magnetite	$\text{Fe}_3\text{O}_4$
tantalite	$(\text{Fe}^{2+}, \text{Mn})(\text{Ta}, \text{Nb})_2\text{O}_6$

## Silicate Minerals

actinolite	$\text{Ca}_2(\text{Mg}_{4.5-2.5}\text{Fe}_{0.5-2.5})\text{Si}_8\text{O}_{22}(\text{OH})_2$
aegirine	$\text{NaFe}^{3+}\text{Si}_2\text{O}_6$
albite feldspar	$\text{NaAlSi}_3\text{O}_8$
almandine	$\text{Fe}_3\text{Al}_2(\text{SiO}_4)_3$
andradite	$\text{Ca}_3\text{Fe}_2(\text{SiO}_4)_3$
beryl	$\text{Be}_3\text{Al}_2(\text{SiO}_3)_6$
biotite	$\text{K}(\text{Mg}, \text{Fe})_3\text{AlSi}_3\text{O}_{10}(\text{F}, \text{OH})_2$
bytownite feldspar	$(\text{Ca}_{0.7-0.9}\text{Na}_{0.3-0.1})(\text{Al}(\text{Al}, \text{Si})\text{Si}_2\text{O}_8)$
catapleiite	$\text{Na}_2\text{Zr}(\text{Si}_3\text{O}_9) \cdot 2\text{H}_2\text{O}$
cerite	$(\text{Ce}, \text{La}, \text{Ca})_9(\text{Mg}, \text{Fe})(\text{SiO}_4)_6(\text{SiO}_3\text{OH})(\text{OH})_3$
chlorite	$(\text{Mg}, \text{Fe})_3(\text{Si}, \text{Al})_4\text{O}_{10}(\text{OH}_2 \cdot (\text{Mg}, \text{Fe})_3(\text{OH})_6)$
elbaite	$\text{Na}(\text{Li}, \text{Al})_3\text{Al}_6(\text{BO}_3)_3\text{Si}_6\text{O}_{18}(\text{OH})_4$
eucryptite	$\text{LiAlSiO}_4$
eudialyte	$(\text{Na}_{15}\text{Ca}_6(\text{Fe}, \text{Mn})_3\text{Zr}_3\text{Si}(\text{Si}_{25}\text{O}_{73})(\text{O}, \text{OH}, \text{H}_2\text{O})_3(\text{OH}, \text{Cl})_2$
garnet	$\text{X}_3\text{Y}_2\text{Si}_3\text{O}_{12}$ , where $\text{X} = 2^+$ , $\text{Ca}^{2+}$ , $\text{Mn}^{2+}$ , $\text{Fe}^{2+}$ and $\text{Y} = \text{Al}^{3+}$ , $\text{Cr}^{3+}$ , $\text{Fe}^{3+}$
grossular	$\text{Ca}_3\text{Al}_2(\text{SiO}_4)_3$
hectorite	$\text{Na}_{0.4}\text{Mg}_{2.7}\text{Li}_{0.3}\text{Si}_4\text{O}_{10}(\text{OH})_2$
hiddenite	$\text{LiAlSi}_2\text{O}_6$
homilite	$\text{Ca}_2(\text{Fe}, \text{Mg})\text{B}_2\text{Si}_2\text{O}_{10}$

kaolinite	$\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})$
kunzite	$\text{LiAlSi}_2\text{O}_6$
lepidolite	$\text{K}(\text{Li},\text{Al})_3(\text{Al},\text{Si},\text{Rb})_4\text{O}_{10}(\text{F},\text{OH})_2$
montmorillonite	$\text{Na}_{0.2}\text{Ca}_{0.1}\text{Al}_2\text{Si}_4\text{O}_{10}(\text{OH})_2(\text{H}_2\text{O})_{10}$
muscovite	$\text{Al}_2(\text{AlSi}_3\text{O}_{10})(\text{F},\text{OH})_2$
nepheline	$\text{Na}_3\text{K}(\text{Al}_4\text{Si}_4\text{O}_{16})$
nephrite	$\text{Ca}_2(\text{Mg},\text{Fe})_5\text{Si}_8\text{O}_{22}(\text{OH})_2$
nontronite	$\text{Ca}_{0.5}(\text{Si}_7\text{Al}_{0.8}\text{Fe}_{0.2})(\text{Fe}_{3.5}\text{Al}_{0.4}\text{Mg}_{0.1})\text{O}_{20}(\text{OH})_4$
olivine	$(\text{Mg},\text{Fe})_2\text{SiO}_4$
petalite	$\text{LiAlSi}_4\text{O}_{10}$
pezzottaite	$\text{Cs}(\text{Be}_2\text{Li})\text{Al}_2\text{Si}_6\text{O}_{18}$
pigeonite pyroxene	$(\text{Ca},\text{Mg},\text{Fe})(\text{Mg},\text{Fe})\text{Si}_2\text{O}_6$
plagioclase feldspar	$(\text{Ca},\text{Na})\text{Al}(\text{Al},\text{Si})\text{Si}_2\text{O}_8$
potassium feldspar	$\text{KAlSi}_3\text{O}_8$
pyrope	$\text{Mg}_3\text{Al}_2(\text{SiO}_4)_3$
pyrophyllite	$\text{Al}_2\text{Si}_4\text{O}_{10}(\text{OH})_2$
quartz	$\text{SiO}_2$
sericite	$\text{KAl}_2(\text{AlSi}_3\text{O}_{10})(\text{OH})_2$
spessartine	$\text{Mn}^{2+}_3\text{Al}_2(\text{SiO}_4)_3$
spodumene	$\text{LiAlSi}_2\text{O}_6$
talc	$\text{Mg}_3\text{Si}_4\text{O}_{10}(\text{OH})_2$
topaz	$\text{Al}_2\text{SiO}_4(\text{F},\text{OH})_2$
tourmaline	$\text{AW}_3\text{X}_6(\text{Si}_6\text{O}_{18})(\text{BO}_3)_3\text{Y}_3\text{Z}$ , where A = Ca, Na, K, Pb or is vacant; W = Al, $\text{Fe}^{2+}$ , $\text{Fe}^{3+}$ , $\text{Li}^+$ , $\text{Mg}^{2+}$ , $\text{Mn}^{2+}$ , or Ti, X = Al, $\text{Cr}^{3+}$ , $\text{Fe}^{3+}$ , or $\text{V}^{3+}$ ; Y = O and/or OH, and Z = F, O and/or OH
tremolite	$\text{Ca}_2\text{Mg}_5\text{Si}_8\text{O}_{22}(\text{OH})_2$
uvarovite	$\text{Ca}_3\text{Cr}_2(\text{SiO}_4)_3$
zircon	$\text{ZrSiO}_4$

### Carbonate Minerals

ankerite	$\text{Ca}(\text{Fe}^{2+},\text{Mg})(\text{CO}_3)_2$
aragonite	$\text{CaCO}_3$
azurite	$\text{Cu}_3(\text{CO}_3)_2(\text{OH})_2$
calcite	$\text{CaCO}_3$
cerrusite	$\text{PbCO}_3$
dolomite	$\text{CaMg}(\text{CO}_3)_2$
magnesite	$\text{MgCO}_3$
malachite	$\text{Cu}_2\text{CO}_3(\text{OH})_2$
rhodochrosite	$\text{MnCO}_3$
siderite	$\text{FeCO}_3$