Metamorphism & Electricity

Metamorphic Contributions to Electrical Phenomena in the Earth's Crust

By
Daniel S. Helman

Abstract:

Metamorphism generates electrical and magnetic phenomena, and is influenced by these forces. Information fundamental to their combined study is presented, including examples from microtectonics, crystal physics, geophysics, seismology, mineralogy and materials science. Applications for earthquake prediction, planetary science research, alternative energy and science education are included. Work on reported seismic electric signals is analyzed and summarized.

Ten hypotheses related to earthquake mechanisms and prediction are presented, as well as eighteen recommendations for further study. Eight microtectonic deformation mechanisms are explored. Two hundred seventeen descriptions of minerals exhibiting ferroelectricity, pyroelectricity or piezoelectricity are presented, with quantitative data where known. Fifty-three of these are centrosymmetric, and explanations are given for their apparent violations of crystal theory. A comprehensive list of thirty-two mechanisms that generate telluric currents is also presented, as are some novel or inexpensive experimental techniques in crystal physics.

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Metamorphism & Electricity

Metamorphic Contributions to Electrical Phenomena in the Earth's Crust

A THESIS

Presented to the Department of Geological Sciences
California State University, Long Beach

In Partial Fulfillment
of the Requirements for the Degree

MASTER OF SCIENCE IN GEOLOGY

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By Daniel S. Helman

August 2013

Selected Results, Hypotheses and Recommendations for Further Study

Chapter	Result
2*	List of 32 mechanisms that generate telluric currents
2	<u>Further study:</u> A global, permanent network of electrical measurement stations might be established, to correlate and contrast geomagnetic data
3	List of 24 mineral properties that generate electricity or magnetism or are related to them
4	Carbon tape can be used instead of thermoplastic to affix a sample to the jig for lapping
4*	EBSD can give crystal orientation reliably, and is quicker than XRD
4	A heat gun can be used safely to heat samples to high temperature
4*	<u>Further study:</u> Sample holders modified from Morgan et al. (1984) should be tested for their use in generating the directed loads or torques needed to measure piezoelectric phenomena
5	List of 44 minerals exhibiting ferroelectricity, with data for 24
5	List of 131 other minerals exhibiting pyroelectricity, with data for 11
5	List of 42 other minerals exhibiting piezoelectricity, with data for 18
5*	List of 53 centrosymmetric minerals that exhibit pyro- or piezoelectricity despite having a center of symmetry
5*	List of 10 mechanisms to account for pyro- or piezoelectricity in minerals that have a center of symmetry
5	<u>Further study:</u> Elastic moduli, conductance, capacitance, magnetic susceptibility and symmetry-based electrical and magnetic data should be gathered for more minerals at a range of temperatures and pressures
5	<u>Further study:</u> More data should be gathered to explain why the dielectric strengths of some minerals and rocks are sensitive to frequency
5	<u>Further study:</u> Geomagnetic data from the ionosphere should be gathered via satellite
6*	Examples for how each of eight different deformation mechanisms either produce electricity or magnetism, or are influenced by electricity or magnetism
6*	<u>Further study:</u> Electricity and magnetism generated by different deformation mechanisms should be measured for different minerals under various conditions
7*	<u>Hypothesis:</u> Wavelets with a twenty-four-hour period in purported SES are due to greater rock conductivity from increased strain, and the diurnal signal itself is due to solar radiation
7	<u>Hypothesis:</u> Groundwater fluctuations and the release of other volatiles at about the time of major seismic activity are caused by hydrous-anhydrous transitions in minerals
7*	<u>Hypothesis:</u> SES are caused by the release of radon gas into groundwater, and the subsequent ionization and motion of material
7	<u>Further study:</u> The seismic-dynamo effect and correlations with SES should be verified by other researchers
7	<u>Further study:</u> The VAN method of earthquake prediction should be verified by other researchers and at other locations
8	<u>Further study:</u> More electrical conductivity values of crustal rock should be measured, with data available online
8	<u>Further study:</u> More groundwater levels should be measured, with data available online
8*	<u>Hypothesis:</u> An applied electric field enhances presumed SES data collection
8*	<u>Hypothesis:</u> An applied magnetic field enhances presumed SES data collection
8*	<u>Further study:</u> Magnitudes of electric signals generated from various ions and volatiles in various rock types should be measured
8	<u>Further study:</u> The number of ground-based radon monitoring stations should be increased
8	<u>Hypothesis:</u> Electric and/or magnetic phenomena are the trigger mechanisms for earthquakes
8	<u>Hypothesis:</u> The controlled triggering of earthquakes can be used to manage earthquake damage as controlled burns manage wildfires, but only if the legal problems can be resolved
8*	<u>Hypothesis:</u> Electricity, magnetism and volatile liberation form a trigger mechanism for earthquakes
8*	<u>Hypothesis:</u> The time lag of several weeks to several months between purported SES and major seismic events are due to the time it takes for volatiles to be released from the rock and the interaction of electricity, magnetism and volatiles

Selected Results, Hypotheses and Recommendations for Further Study, Continued

Chapter	Result
8	<u>Hypothesis</u> : Groundwater fluctuations and the release of other volatiles at about the time of major seismic activity are caused by changes to the geometry of the fluid paths in rock
8*	<u>Hypothesis</u> : The formation of highly refractive minerals is favored in regions where heat flow is high
8	<u>Further study</u> : An online model of the Earth's electric field should be constructed
8	<u>Further study</u> : The Earth's intrinsic magnetic field and solar activity should be compared to look for long term patterns
8	<u>Further study</u> : The amount of electrical energy potentially generated by rock should be compared with the energy needed for generating organic molecules
8	<u>Further study</u> : Electrical properties of minerals should be studied to see whether any alternative energy projects are implied
8*	<u>Further study</u> : A test apparatus should be built to see whether ferroelectricity in ice could be used to generate significant electricity from diurnal freeze-thaw cycles
8*	<u>Further study</u> : A test apparatus should be built with suspended ions in porous media, to see whether the electrokinetic effect, electrochemistry, the geomagnetic field and the moon's gravity can be used to generate significant electricity

Notes: Entries with an asterisk are original to this thesis, to the best of the author's knowledge.

WE, THE UNDERSIGNED MEMBERS OF THE COMMITTEE,
HAVE APPROVED THIS THESIS

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August 2013

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Daniel S.Helman

Long Beach, California
Summer, 2013

Nota Bene

This is a revised version of the thesis. The text of the original (which is housed online in the PQDT database) is double spaced and has 12 point font throughout, weighing in at 527 pages. A few typographical, grammatical and (minor) stylistic revisions have been made to the copy you have before you, and, of course, the pagination is different. If one is moved to cite this work, please note that this is the self-published version, to avoid confusion.

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LIST OF ABBREVIATIONS

$\pm$	Plus or Minus
$\approx$	Approximately Equal to
$<$	Less Than
$\leq$	Less Than or Equal to
$>$	Greater Than
$\geq$	Greater Than or Equal to
$!$	Factorial
$\propto$	Is Proportional to
∞	Infinity
$^{\circ}$	Degrees
$^{\circ}\text{C}$	Degrees Celsius
$^{\circ}\text{F}$	Degrees Fahrenheit
$\perp$	Perpendicular
1	The x Axis in Voigt Notation
$\mathbf{1}$	A 360° Rotational Symmetry Axis
$\underline{\mathbf{1}}$	A 360° Rotoinversion
2	The y Axis in Voigt Notation
$\mathbf{2}$	A Two-Fold Rotational Symmetry Axis
3	The z Axis in Voigt Notation
$\mathbf{3}$	A Three-Fold Rotational Symmetry Axis
$\underline{\mathbf{3}}$	A Three-Fold Rotoinversion
4	The yz Plane in Voigt Notation
$\mathbf{4}$	A Four-Fold Rotational Symmetry Axis
$\underline{\mathbf{4}}$	A Four-Fold Rotoinversion
5	The xz Plane in Voigt Notation
6	The xy Plane in Voigt Notation

6	A Six-Fold Rotational Symmetry Axis
<u>6</u>	A Six-Fold Rotoinversion
$\square^{-1}$	Divided by the Quantity $\square$
$\square^{-2}$	Divided by the Square of the Quantity $\square$
$\square^{-3}$	Divided by the Cube of the Quantity $\square$
$\square^{-x}$	Divided by the Quantity $\square$ Raised to X
$\square^{2+}$	With a Positive Charge of Two
$\square^{3+}$	With a Positive Charge of Three
$\square\square.\square\square.\square\square$	Nickel-Strunz Category
$[\square]$	Coordinated with Other Atoms by the Number $\square$
$[\square\square\square]$	Crystallographic Plane $\square\square\square$
$[\]$	Lattice-Site Void
Δ	Change in
∂	Partial Derivative
η	Strain
θ	Angle Variable
κ_1	Variance in Natural Time Analysis
μ_X	Chemical Potential Energy of Phase X
$\Pi(v)$	Power Spectrum
$\Pi(v)_{\text{ideal}}$	Ideal Power Spectrum
π	Ratio of Circumference to Diameter of a Circle
ρ	Electrical Resistivity
Σ	Sum of
σ	Stress
Φ	Number of Phases
χ	Magnetic Susceptibility
χ_i	Natural Time Coefficient of the i-th event
Ω	Ohm

A	Ampere
a	Variation Indicator Variable
a	Primary Crystallographic Direction
Ab	Albite
AC	Alternating Current
ACWI	Advisory Committee on Water Information, USGS
AT	Shear Vibration Mode Thickness A
B	Magnetic Field Strength
B	Magnetic Field Tensor
b	y Intercept
b	Secondary Crystallographic Direction
BLG	Bulging Recrystallization
C	Coulomb
c	Tertiary Crystallographic Direction
c (ij)	Stiffness
c_0 (ij)	Original Stiffness Value for Calculations
c^S (ij)	Adiabatic Stiffness
c^T (ij)	Isothermal Stiffness
<i>Ccmm</i>	Crystallographic Space Group with an Additional Lattice Point on the c Axis, plus Three Mirror Planes, and Translation Along the c Plane at the Primary Symmetry Axis
<i>Cmcm</i>	Crystallographic Space Group with an Additional Lattice Point on the c Axis, plus Three Mirror Planes, and Translation Along the c Plane at the Secondary Symmetry Axis
CSAMT	Controlled Source Audio Magnetotelluric Survey
D	Critical Exponent
D''	Highly Conductive Region of the Earth's Deep Mantle
d	Day
d (ij)	Piezoelectric (Electric Charge) Strain Rate
DC	Direct Current

DD	Dilatency Diffusion Model
DFA	Detrended Fluctuation Analysis
DNA	Deoxyribonucleic Acid
E-	East Longitude [prefix]
E	Electric Field Tensor
e^-	Electron
e	The Euler Number, Approximately 2.71828
e (ij)	Piezoelectric (Electric Charge) Stress Rate
EBSD	Electron Backscatter Diffraction
ECLAT	European Cluster Assimilation Technology, Department of Physics & Astronomy, University of Leicester
EDS	Energy Dispersive X-Ray Spectroscopy
ELF	Extremely Low Frequency Radio Signal
EM	Electromagnetic
EURISGIC	European Risk from Geomagnetically Induced Currents, Seventh Framework Programme (F7), European Union
eV	Electron Volt
f	Frequency
FEG	Field Emission Gun
FIB	Focused Ion Beam
G-	Giga- [prefix]
g	Gram
g (ij)	Piezoelectric (Electric Field) Strain Rate
GBM	Grain Boundary Migration
GIC	Geomagnetically Induced Current
GVEF	Gradual Variation in the Electric Field of the Earth
H	Magnetic Field Strength, Divided by Vacuum Permeability
h (ij)	Piezoelectric (Electric Field) Stress Rate
HAARP	High Frequency Active Auroral Research Program

hr	Hour
Hz	Hertz
<i>i</i>	Index Number
<i>i</i>	Square Root of Negative One
IGRAC	International Groundwater Resources Assessment Centre, UNESCO
IMA	International Mineralogical Association
IRIS	Incorporated Research Institutions for Seismology
ISTP SB RAS	Institute of Solar-Terrestrial Physics, Russian Academy of Sciences, Siberian Branch
IUGS	International Union of Geological Sciences
<i>j</i>	Index Number
K	Degrees Kelvin
<i>K</i> (i)	Relative Dielectric Strength
k-	Kilo- [prefix]
k	Constant Number
<i>k</i> (ij)	Electromechanical Coupling Factor
<i>k</i> (p)	Poled Electromechanical Coupling Factor
<i>k</i> (t)	Thickness Compressional Coupling Factor
L	Length
LBD	Landolt-Börnstein Database
ln	Natural Logarithm
log	Logarithm Base 10
M-	Mega- [prefix]
M	Metal
M_0	Spontaneous Magnetization
M_L	Local Earthquake Magnitude on the Richter Scale
M_S	Saturation Magnetization
M	Magnetization Tensor
m-	Milli- [prefix]

m	Meter
$\underline{m}$	Slope
m_o	Observed Magnitude
m_t	True Magnitude
$\boldsymbol{m}$	Mirror Plane
MAD	Mean Angular Deviation
MICRESS	Microstructure Evolution Simulation Software
min	Minute
MMSP	Mesoscale Microstructure Simulation Project
N-	North Latitude [prefix]
N	Newtons
N_f	Number of Degrees of Freedom
N_v	Number of Independent Variables
N_X	Number of Particles of Phase X
n-	Nano- [prefix]
n	Number of Events
n_c	Number of Controlling Conditions in a System
n_m	Number of Moles of a Gas
n_v	Number of Variables in a System
NIED	National Research Institute for Earth Science and Disaster Prevention, Japan
OH	Hydroxide
Or	Orthoclase
P	Pressure
P_T	Transition Pressure
p-	Pico- [prefix]
p	Electric Polarization
p	Pyroelectric Polarization Rate
$\mathbf{p}$	Electric Polarization Tensor

p_i	Fractional Quantity of Energy of the i-th Event
Pa	Pascal
<i>P</i>	Primitive Lattice Type
<i>Pbma</i>	Crystallographic Space Group with a Primitive Unit Cell, plus Three Mirror Planes, Translation Along the b Plane at the Primary Axis and Along the a Plane at the Tertiary Symmetry Axis
Pc (ij)	Pressure Stiffness Slope
Pc^S (ij)	Adiabatic Pressure Stiffness Slope
Pc^T (ij)	Isothermal Pressure Stiffness Slope
PeakE	Peak Value Across a Range of Electric Field Strengths
PeakP	Peak Value Across a Range of Pressures
PeakT	Peak Value Across a Range of Temperatures
PFM	Phase Field Model
PGE	Platinum Group Elements
pH	Power of Hydrogen Concentration
<i>Pnmn</i>	Crystallographic Space Group with a Primitive Unit Cell, plus Three Mirror Planes, with an Additional Translation Half-way Along the Diagonal of the Face Perpendicular to the Secondary Symmetry Axis
<i>Pnmm</i>	Crystallographic Space Group with a Primitive Unit Cell, plus Three Mirror Planes, with an Additional Translation Half-way Along the Diagonal of the Face Perpendicular to the Primary Symmetry Axis
ppm	Parts per Million
Q_i	Quantity of Energy Released in the i-th Event
Q_{tot}	Total Energy Released
q	Spontaneous Polarization
Qz	Quartz
R	Ideal Gas Constant
<i>R<u>3</u>c</i>	Crystallography Space Group with a Rhombohedral Unit Cell, a Three-Fold Symmetry Axis with a Rotoinversion at the Primary Symmetry Axis, and a Mirror Plane plus Translation along the c Plane at the Secondary Symmetry Axis
<i>R<u>3</u>m</i>	Crystallography Space Group with a Rhombohedral Unit Cell, a Three-Fold Symmetry Axis with a Rotoinversion at the Primary Symmetry Axis, and a Mirror Plane at the Secondary Symmetry Axis

REE	Rare Earth Elements
RPM	Rotations per Minute
RRUFF	The Name of a Scientist's Cat
RT	Ambient Room Temperature
S	Siemens
S_n	Entropy in Natural Time Analysis
S	Entropy
s	Segment Size
s (ij)	Compliance
SGR	Subgrain Rotation
SEM	Scanning Electron Microscope
SES	Seismic Electric Signal
SI	International System of Units
SP	Self Potential
T	Tesla
T	Temperature
t	Seebeck Coefficient
Tc (ij)	Temperature Stiffness Slope
$Tc^{(n)}$ (ij)	Polynomial Temperature Stiffness Factor
TM	Transition Metal
T - P - X	Temperature-Pressure-Chemistry
U	Internal Energy
UNESCO	United Nations Educational, Scientific and Cultural Organization
U.S.	United States
USGS	United States Geological Survey
V	Volt
V	Volume
v	Angle

VAN	Varotsos-Alexopoulos-Nomicos
Var(x)	Variation Measure Function
VLf	Very Low Frequency Radio Signal
X	Chemical Composition Variable
x	Number Variable
XI	Crystal
XRD	X-Ray Diffraction
y	Number Variable

LIST OF NOMENCLATURE

α -particle	A helium nucleus formed through radioactive decay
a Axis	The primary crystallographic axis of a crystal (and that is not the axis of six-, four-, or three-fold rotation for hexagonal, tetragonal and trigonal crystals, respectively)
Acicular	Needle-like in form
Activation Energy	The energy required to initiate a process
Acute Angle	An angle measuring less than 90°
Adiabatic	A system at constant entropy
Adsorb	To attach to a surface
Aesthenosphere	The part of a planetary body immediately below its lithosphere, and that is subject to ductile deformation
Albite	The sodium-rich member of the plagioclase mineral group
Albitite	A rock composed primarily of albite, generally formed in a dike
Albitization	The transformation of plagioclase minerals within a rock to albite
Alkali	A substance containing either alkali metal or alkali earth elements
Alkali Earth	An element from the second group on the periodic table, namely beryllium, magnesium, calcium, strontium, barium or radium
Alkali Metal	An element from the first group on the periodic table, namely lithium, sodium, potassium, rubidium, cesium or francium
Alloy	A solid solution of two or more metals
Alluvium	A deposit of unconsolidated sediment that has been transported by water, not of marine origin
Alpine	A hydrothermal classification, describing processes typically affecting subducted ophiolite rock, at high pressure and a range of low to high temperature
Alteration	A chemical change to a rock or mineral
Alumina	Al ₂ O ₃ (corundum) used as an abrasive
Aluminous Rock	A rock that contains minerals with high aluminum content
Amphibole	A common silicate mineral group, typically rich in iron and magnesium, with aluminum sometimes substituting for the silicon atom

Amphibolite	A metamorphic rock composed mainly of minerals from the amphibole group, especially hornblende or actinolite
Amygdaloid	A feature found in extrusive igneous rocks in which vesicles have been filled with a secondary mineral
Andesite	An extrusive igneous rock with intermediate chemical composition (in terms of silica, iron, magnesium, calcium and sodium content); the extrusive equivalent of diorite
Angle Gauge	A device for measuring angles
Anion	A negatively charged ion
Anisotropic	A material with properties that vary by direction
Annealing	A process of heating and cooling a metal, to remove internal stress and increase ductility
Anoxic	Without oxygen
Antiferroelectric	An electrical phenomenon found in a ferroelectric material whose switchable sublattice orientations are orthogonal, and whose electrical response is asymmetrical, expressing more electricity under one orientation than another
Antimonide	A chemical substance containing antimony, oxidation state three minus, Sb^{3-} , as a major constituent
Antimonite	A chemical substance containing antimony, oxidation state three plus, Sb^{3+} , as a major constituent
Arsenide	A chemical substance containing arsenic, oxidation state three minus, As^{3-} , as a major constituent
Arsenite	A chemical substance containing arsenic, oxidation state three plus, As^{3+} , as a major constituent
Arsenate	A chemical substance containing an ion with arsenic and four oxygen atoms, valence three minus, $[\text{AsO}_4]^{3-}$, as a major constituent
Ash	A combustion product, with particle size $< 4\text{mm}$
Astrobiology	The study of life in the cosmos, especially related to its origin, distribution and evolution
AT Cut	A quartz plate cut with its thickness proportional to a frequency (1.661 MHz-mm), so that the overtones produced during vibrations are whole number odd multiples of the fundamental frequency of vibration
Augite	A common rock-forming mineral of the pyroxene group
Authigenic	A substance or thing generated <i>in situ</i>
Avogadro's Number	A number that defines one mole of a substance, approximately 6.022×10^{23} particles

b Axis	The secondary crystallographic axis of a crystal (and that is not the axis of six-, four-, or three-fold rotation for hexagonal, tetragonal and trigonal crystals, respectively)
b Plane	A plane perpendicular to the b axis
Banded Iron Formation	A typically Precambrian rock composed of alternating layers of iron oxides (often magnetite or hematite) and shale or chert
Bar	A pressure unit equal to 100,000 pascals, and approximately equal to the atmospheric pressure of Earth at the equator
Basalt	A common extrusive igneous rock, rich in iron and magnesium minerals and calcium-rich plagioclase, and poor in silica
Base Metal	A metal that oxidizes or corrodes easily, such as iron, nickel, lead, zinc or copper
Bedded Deposit	A formation that contains secondary minerals along the bedding of sedimentary rock
Benioff-Gutenberg Low Velocity Zone	A region of the upper mantle between the lithosphere and aesthenosphere that is characterized by low seismic shear wave velocities
Biogenic	A process involving the metabolism of living organisms or a material created by such a process
Birefringent	A material with two different (orthogonal) refractive indices that refract electromagnetic radiation in different frequencies depending on orientation
Bismuthide	A chemical substance containing bismuth, oxidation state three minus, Bi^{3-} , as a major constituent
Bismuthite	A chemical substance containing bismuth, oxidation state three plus, Bi^{3+} , as a major constituent
Bitumen	A semi-solid or highly viscous liquid form of petroleum, synonymous with asphalt
Bolide	Any large crater-forming meteorite whose chemical composition is unknown
Boltzmann Constant	A physical constant that relates the energy of an ideal gas to temperature
Bond Energy	The energy in chemical bonds, formed by the interactions of electric charges or electrons
Boro-	A chemical substance containing boron
Boson	A fundamental class of particles distinguished from fermions (the other fundamental class) as follows: there is no limit to the number of bosons that can occupy the same quantum state simultaneously, whereas fermions are limited to a single particle per quantum state at any one time

Botryoidal	A mineral form that has a globular aspect; named for a "bunch of grapes" from the Greek
Brazil Twin	A quartz twin along the plane $[11\bar{2}0]$ with the left- and right-handed structures combined (penetrating) in a single crystal
Breccia	A sedimentary rock composed of broken fragments of other rock in a fine-grained matrix
Brittle Fracturing	Brittle deformation (fracturing) at low temperature or high strain rate
Bulging Recrystallization	A dynamic recrystallization process in which one grain bulges into a neighboring grain, thereby capturing material and reducing the overall dislocation density of the aggregate
c Axis	The axis of six-, four-, or three-fold rotation for hexagonal, tetragonal and trigonal crystals, respectively
c Plane	A plane perpendicular to the c axis
Calcareous	A rock or substance containing a significant amount of calcium carbonate
Calcitic	A rock that contains a significant amount of the mineral calcite
Caliper	A device to measure the thickness of a material to a specified precision
Capillarity	The ability to use surface tension to create fluid flow, based on very small channel size
Carbide	A chemical substance containing carbon and another, less electronegative element
Carbon Tape	Sticky tape made from the element carbon and available commercially for electron microscope work
Carbonate	A chemical substance containing an ion with carbon and three oxygen atoms, valence two minus, $[\text{CO}_3]^{2-}$, as a major constituent
Carbonatite	An intrusive or extrusive igneous rock composed of more than 50% carbonate minerals
Cartesian Coordinate System	Three-dimensional data graphic representation with orthogonal axes and a sign convention that follows the right-hand rule
Cation	A positively-charged ion
Cavitation	The formation and subsequent collapse of small cavities in a substance
Centrosymmetric	A crystal lattice whose inverse lattice is identical
Charge	(1) A powdered sample, enclosed for heating at high or low pressures; (2) an electric charge
Charge Carrier	The local host of an electric charge, such as an ion, electron, or crystal lattice vacancy

Charge Dislocation	The displacement of an electric charge carrier
Charge Transmission	The transmission of electric charge through direct contact
Charge-Vacancy Coupling	A process involving the interaction of charged particles and charged structural vacancies in a material
Chemical Potential	Potential energy from chemical bonds that can be released during a chemical reaction
Chiral	A substance that is characterized by left-handed and right-handed forms
Chlorite	A chemical substance containing an ion with chlorine and two oxygen atoms, valence one minus, $[\text{ClO}_2]^-$, as a major constituent
Chondrite	A class of stony (non-metallic) meteorites that have not undergone melting or chemical differentiation
Chromate	A chemical substance containing an ion with chromium and four oxygen atoms, valence two minus, $[\text{CrO}_4]^{2-}$, as a major constituent
Clastic	A previously fractured material, from the Greek verb “to cleave”
Coal	A carbon-rich sedimentary or metamorphic rock formed from plant matter
Coble Creep	A deformation mechanism in which lattice vacancies diffuse along grain boundaries
Coercive Field	The strength of the electric field needed to reverse the polarity of a ferroelectric material
Colloid	A particle fine enough to remain indefinitely suspended in water
Complexing Agent	A chemical compound (usually organic) that attaches to a metal ion with two or more separate coordinating bonds
Compliance	(1) The capacity of an elastic material to allow deformation; (2) the elastic modulus that one may use to convert stress data into strain data
Compression	Elastic or permanent deformation from being pressed together
Concretion	A typically spherical or ovoid mass in sedimentary rock formed by the precipitation of chemical cement
Conductance	The ability of a material to conduct electricity, measured in units of S, which is the inverse of resistance, that is, Ω^{-1}
Conductivity	The ability of a material to conduct electricity over a distance, measured in units of S m^{-1} , for example, and which is the inverse of resistivity
Contact Metamorphism	A metamorphic process in which an igneous intrusion alters the surrounding rock mainly by heat

Converse Piezoelectric Effect	The ability of a material to deform when subjected to an electric field because of the field's effect on the crystal lattice
Converse Piezomagnetic Effect	The ability of a material to deform when subjected to a magnetic field because of the field's effect on the crystal lattice
Country Rock	A rock native to a region, as, for example, the basement rock underlying newer sedimentary rock may be termed the country rock
Critical Exponent	An exponent in an empirical power law whose value determines the criticality of the system
Cross-Polarized Light	Light transmitted through two polarizing plates at 90° angles to each other, generally with another medium (e.g. a crystal) between the two plates that may cause refraction
Crystal	A solid material whose atomic arrangement repeats with a definite period
Crystal Class	Any of 32 distinct groups of crystals organized by the symmetries of the placement of atoms in their unit cells
Crystal Face	A flat surface on a crystal, created by natural crystal growth
Crystal Lattice	The arrangement of atoms in a crystal
Crystal Plastic Deformation	A deformation mechanism that occurs through the movement of lattice defects within crystals
Cubic Crystal System	A category of crystals in which the walls of the unit cell are perpendicular, and of equal length
Curie Transition	A phase transition in which a material changes from a permanent magnetic state, whether ferro-, ferri- or antiferromagnetic, to an induced (paramagnetic) magnetic state
Cyanoacrylate	A glue, also known as Super Glue [®]
Cyclosilicate	A silicate mineral whose framework is composed of rings of silicate tetrahedra
Cyclotron Frequency	The frequency of vibration of a charged particle moving perpendicular to a magnetic field
d-Orbital	An electron orbital characteristic of transition metals, containing ten electrons when full
Dauphiné Twin	A quartz twin rotated by 60° about the c axis
Decibel	In electrical applications, a logarithmic (base 10) unit of change in power or intensity determined by comparison with a given or reference value
Defect Charging	The electric charging of defects in a crystal lattice
Deformation	A change in shape

Deformation Band	A region in a crystal with a high concentration of lattice dislocations that have migrated there during recovery, an early stage of annealing processes
Deformation Mechanism	A distinct process whereby rocks, metals or other materials accommodate strain
Deformation Twinning	A deformation mechanism in which stress is accommodated by the growth of (often microscopic) crystal twins
Degrees of Freedom	The difference between the number of variables in a system and number of constraints upon them
Denominator	The number written below the line, for a fraction
Dependent Variable	A property which depends upon another property
Depleted Soil	A soil lacking in one or more of the following: major minerals (nitrogen, phosphorus or potassium), trace minerals, organic matter, neutral or close to neutral pH, and a range of microorganisms
Derivative	A measure of the rate of change of a variable
Detrital Mineral	A mineral that remains after other rock constituents have been weathered and transported away
Deuteric	A mineral that has been formed by alteration of original material during a late stage of igneous processes
Deviatoric	A process causing (or tending to cause) a displacement
Devitrification	A process in which an amorphous (glass) phase is replaced by crystalline material
Diabase	An intrusive igneous rock akin to basalt, forming dikes or sills
Diagenesis	A process of alteration to sediment or sedimentary rock at temperatures and pressures lower than those required for metamorphism or melting
Diamagnetic	A material that dampens a magnetic field
Diborate	A chemical substance containing an ion with two boron atoms as a major constituent
Dichromate	A chemical substance containing an ion with two chromium and seven oxygen atoms, valence two minus, $[\text{Cr}_2\text{O}_7]^{2-}$, as a major constituent
Dielectric	An electrical insulator that can be polarized to store electric charge
Dielectric Permittivity	The ability of a substance to store electrical energy supplied by an externally applied electric field
Differential Equation	An equation with derivatives as some of its terms

Diffusion Creep	A deformation mechanism that accomodates strain at high temperature by the random migration of lattice vacancies either along grain boundaries (Coble Creep) or within crystals (Nabarro-Herring Creep)
Dike	An igneous intrusion that forms a vertical or nearly vertical sheet
Dilatency Diffusion Model	A model for earthquake nucleation, characterized by microcracking during a dilatency phase, and the migration of water and ions during a diffusion phase, with both processes acting together to overcome rock strength
Dimer	A structure formed of two chemical units
Diopside	A common mineral of the pyroxene group
Dislocation Climb	The migration (caused via movement of vacancies) of a glide plane to another part of a crystal lattice during crystal plastic deformation
Dislocation Creep	The combination of dislocation glide and dislocation climb active at the same time
Dislocation Glide	The motion of defects along a slip plane over time, causing deformation to a crystal's shape
Dislocation Loop	A combination of line defects forming a circle or loop in a crystal lattice
Dissolution-Precipitation	A deformation mechanism occuring by pressure solution at grain boundaries, with the material precipitating elsewhere within the system
Diurnal	An event that occurs daily
Dodecaborate	A chemical substance containing an ion with twelve boron atoms as a major constituent
Dolostone	A sedimentary rock with a high (> 50%) concentration of the mineral dolomite
Dopant	A trace impurity added to a chemical substance to alter its electrical properties
Druse	A coating of usually small crystals that has grown on a rock surface
Ductile	Deformation without fracture
Dunite	An ultramafic igneous rock, composed primarily of olivine
Dynamic Recrystallization	A deformation mechanism in which the shapes, sizes and orientations of crystals and grain boundaries are altered to minimize defects and dislocations
Eclogite	A dense metamorphic rock resulting from high-pressure processes acting on mafic igneous parent rock
Edge Dislocation	A line defect formed at the edge of an extra half-lattice plane within a crystal lattice

Efflorescence	A crystalline deposit that results from the dehydration of an earlier hydrated crystal
Ejecta	The debris or particles that are expelled during a volcanic or impact process
Elastic	An interaction with no permanent deformation or loss of energy
Elastic Moduli	The stiffness (c) and compliance (s) coefficients
Electric Dipole	A configuration of a material in which a pair of electric charges are separated by a small distance
Electric Dipole Moment	A measure of the polarization of a system of charges or polar molecules, measured in coulomb meters, for example
Electrical Impedence	A measure of the total opposition to alternating electric current flow in a material, with resistance, inductance and capacitance making contributions
Electrical Polarization	The development of electric charge in a material or on a surface
Electrocaloric Effect	A change in temperature due to the application of an external electric field
Electrochemical Effect	An electric current caused by the motion of ions in an ion-rich fluid
Electrogyration	An applied electric field that changes the direction of photons being transmitted in a medium
Electrokinetic Effect	Electrostatic charging of a porous rock as a fluid carrying ions moves through it
Electrolyte	A chemical compound that contributes dissolved ions when added to a solvent
Electromagnetic Force	A force caused by interactions of electric charge or magnetic polarization
Electromagnetic Induction	A process whereby a change in a magnetic field induces an electric current in a nearby conducting material, or a change in an electric field induces a change in a nearby magnetic field, without relying on any physical contact of the materials involved
Electromagnetic Radiation	A form of energy characterized by frequency and wavelength, and carried by photons, which, in turn, mediate the electromagnetic force
Electromechanical Coupling Factor	A calculated generalization of the piezoelectric stress and strain rates into a single coefficient
Electromigration	A process in which an applied electric field recrystallizes a material and thereby produces desirable properties, useful in metals or thin film fabrication

Electron Backscatter Diffraction	A technique which uses a phosphor screen to detect the scattering interference of electrons from the bottom of a sample in a scanning electron microscope
Electron Volt	The amount of energy needed to move one electron across an electric potential of one volt
Electronegativity	A measure of the ability of atoms, ions or other groups of elements to attract and retain electrons
Electrooptic Effect	An applied electric field that changes the frequency of photons being transmitted in a medium
Electroremediation	The application of an electric potential to the ground to attract metal (contaminant) ions to a well for removal.
Electrostatic Induction	A process whereby the presence of an electric charge induces an equal and opposite charge to appear in a nearby material, to maintain the electric neutrality of a system
Electrostriction	A process whereby materials constrict under an electric field, caused by surface charging
Empirical	Data or a law based on observation only, without any theoretical support
Enantiomorphic	A substance characterized by left-handed and right-handed forms
Energy Dispersive X-Ray Spectroscopy	A system that uses X-rays generated in an electron microscope to identify materials, based on characteristic inner-shell electron energies
Enriched Zone	A region of an ore or mineral deposit that is enriched in metals or minerals of interest
Entropy	A measure of the disorder of a system
Epithermal	A hydrothermal category characterized by low temperature (25 to 300°C) and low pressure
Euclidean Space	A real coordinate space without curvature
Euler Angles	Three rotations that are used to describe the orientation of a solid in Euclidean space
Evaporite	A sedimentary mineral formed by evaporation and crystallization
Exo-Electron Emission	The release of low-energy electrons from a material during stress relaxation, or the addition of heat or photons, after an initial priming
Exsolution	A process whereby a mineral in solid solution becomes unstable, and two separate mineral phases form, typically in lamellae
Extensive Parameter	A parameter that does not depend on the amount of material present (in a thermodynamic system)

Extremely Low Frequency Radio Signal	A radio signal with a frequency from ten hertz to three thousand hertz (10 Hz to 3 kHz)
Extrusive	A mode of igneous rock formation in which magma reaches the surface, flowing out as lava or explosive forms, whether subaerial or submarine
Facies	A suite of rock types formed under specific conditions; for metamorphic facies, these are defined by the minerals that develop at different pressures and temperatures; for sedimentary facies, these are defined by rock features derived from the original depositional environments
Factorial	The multiplication of a number with all of the natural numbers that are less than that number
Feldspar	A group of common rock-forming minerals that contain potassium, sodium or calcium in an aluminous silicate framework
Feldspathoid	A group of minerals similar to feldspars, but with a lower silica content and different lattice symmetry
Felsic	A rock that is rich in feldspar and quartz; the "fel-" refers to feldspar, and the "-si-" to silicate
Fenite	A type of alkalic syenite that is formed by metasomatism
Ferrimagnetic	A material that displays a spontaneous (permanent) magnetic field based on its magnetic domain orientation
Ferroan	A compound or material containing iron
Ferroelectric	A material that can generate an electric response under pressure, a response whose sign is switchable with an external electric field, which reorients two competing crystal sublattices
Ferromagnetic	A material that displays a spontaneous (switchable) magnetic field based on its magnetic domain orientation
Ferrous	A substance containing iron in a two plus oxidation state, Fe^{2+}
Finite Element Modeling	A mathematical process that breaks a partial differential problem into related discrete functions that are solvable
First Order Phase Transition	A description of a transition process in which both forms coexist for part of the transition
Flux	The change in magnitude or direction of a field
Foliation	A layered form in metamorphic rock due to a preferred orientation of minerals
Four-Fold Symmetry	The quality that allows a shape to be rotated equally four times in 360° , whose form with each rotation is the same as the original form

Fourier Transform	A mathematical procedure that creates a new function showing how values in the original repeat with a definite period
Fractoemission	The emission of electrons in a fracture as electrons are distributed unevenly during fracture processes
Fractoluminescence	A process of electromagnetic emission in the visible light frequency range caused by the fracture of material and the subsequent release of electronic bond energy
Fracture-charging	The build-up of electric charge in a fracture as electrons are distributed unevenly during fracture processes
Fumarole	A landform feature (e.g. a fissure) on the surface of a planet where volcanic gases are emitted
Fundamental Frequency	A pitch upon which overtones are built in harmony
Gabbro	An intrusive igneous rock rich in iron- and magnesium-bearing minerals and lacking quartz, chemically equivalent to basalt
Gangue	A mass of unwanted material surrounding or closely mixed with ore minerals
Gauge Boson	An elementary particle that mediates one of the fundamental forces of nature
Geomagnetic Field	Earth's magnetic field
Geomagnetic Jerk	Short-term changes to the second derivative of the geomagnetic field
Geomagnetically Induced Current	Earth electric currents caused by solar wind or space weather, whose impact in the ionosphere creates changes in the geomagnetic field, which, in turn, cause electrical induction in the ground
Germanate	A mineral that contains the germanium tetrahedron, (O_2GeO_2), as a primary constituent of the crystal lattice, or a rock composed of a high percentage of germanium-rich minerals
Glaucophane	A common rock-forming mineral of the amphibole group
Gneiss	A common metamorphic rock with alternating dark and light bands, formed at high temperatures and pressures
Grain Boundary Migration	A dynamic recrystallization process in which grain shapes become interlocked (like a puzzle) from motion of the grain boundaries
Granitic	A rock with a chemical composition similar to granite
Granular Flow	A deformation mechanism in a fine-grained aggregate wherein the grains slide past one another to accommodate strain and develop a lattice-preferred orientation
Gravity Wave	Wave transmission of energy at a fluid interface or within a fluid where gravity and buoyancy act to oppose the displacement

Greenstone	A sequence of volcanic rock with a green aspect, for example, altered basalts
Greisen	An alteration product of granitic rock, formed by contact with late stage gas- and water-rich fluids during granite emplacement
Greywacke	A sedimentary rock composed of poorly sorted angular sand grains in a clay matrix, formed by turbidity currents
Groundmass	The small-grained portion of an igneous rock that supports the larger crystals
Geothermometer	Minerals or structures whose properties indicate the temperature of rock formation or deformation
Guano	The excrement waste of bats, birds and seals
Gutenberg-Richter Law	An expression for the relationship between the magnitudes and number of earthquakes in a region, with frequency decreasing exponentially as magnitude increases
Halide	A mineral with fluorine, chlorine, bromine or iodine anions as a major constituent
Hardpan	A dense waterproof layer of some soil horizons below the upper topsoil layer, typically calcareous
Harzburgite	An ultramafic igneous rock containing mostly olivine and pyroxene
Heat Gun	A tool that looks and works like a hair-dryer, sold for heating old paint to make it easier to strip
Heckmann Diagram	A schematic diagram showing how mechanical and other physical effects are coupled together
Heptaborate	A chemical substance containing an ion with seven boron atoms as a major constituent
Hexaborate	A chemical substance containing an ion with six boron atoms as a major constituent
Hexagonal	A form exhibiting six-fold symmetry
Hexagonal Crystal System	A category of crystals in which the unit cell displays six-fold symmetry and is prismatic along the <i>c</i> axis
High-Frequency Electromagnetic Effects	Electric, magnetic or electromagnetic phenomena of microwave or higher frequencies that can influence the orientation or energy state of materials
High-Grade Metamorphism	A metamorphic process occurring at about 800°C or higher and at pressures found at 10 km depth or deeper
Hornblende	A common rock-forming mineral series of the amphibole group
Humus	A stable mass of organic material in soil

Hydrostatic Pressure	Pressure that is equal in all directions
Hydrothermal	A geologic process involving the circulation of heated water
Hydroxide	A chemical substance containing an ion with one oxygen and one hydrogen atom, valence one minus, $[\text{OH}]^-$, as a major constituent
Hydroxy-	A term denoting the presence of an hydroxide ion
Hypabyssal	A rock that is formed at medium to shallow depths in the Earth's crust
Hysteresis Loop	A trace of the electric field caused by the interaction of an externally applied field and a ferroelectric material, that shows different paths depending on whether the external field is increasing or decreasing
Ideal Gas	A gas in which the molecules are perfectly elastic in their collisions
Impingement Microcrack	A discontinuity (plus some dilation) at a grain contact, radiating in from the edge of the contact
Inclusion	A substance trapped inside a mineral during formation
Independent Variable	A property that does not depend on another property, used in equations
Index	A unique number with which to identify a variable, and also a synonym for “subscript”
Infrared	Electromagnetic radiation whose wavelength is longer than that of visible light, but shorter than microwaves or radio waves
Ino-	A crystal lattice in a framework structure composed of chains of the form that follows this prefix
Inosilicate	A silicate mineral whose framework is composed of chains of silicate tetrahedra
Intensive Parameter	A parameter that depends on the amount of material present (in a thermodynamic system)
Intergranular Fracture	A discontinuity (plus some dilation) between grains
Intermediate Igneous Rock	An igneous rock whose chemistry lies between felsic and mafic compositions
Internal Energy	The ability of a system to do work
Internal Wave	A wave that propagates through a medium but does not reach the surface or its other boundaries
Interstitial	An extra site within a crystal lattice
Intrusive	An igneous rock or process that was formed or occurs within the Earth
Inverse Lattice	A mathematical model created by reflecting the coordinates of a crystal lattice through a point, creating a set of inverse coordinates

Iodate	A chemical substance containing an ion with iodine and three oxygen atoms, valence one minus, $[\text{IO}_3]^-$, as a major constituent
Ion	An atom with electric charge from either extra or fewer electrons compared to the number of protons in its nucleus
Ionosphere	The part of the Earth's atmosphere from about 85 to 600 km, consisting of charged particles
Ironstone	A sedimentary rock with iron-rich minerals as a major constituent, and typically considered distinct from the rock of banded iron formations
Isothermal	A process conducted at constant temperature
Isotropic	A substance that is characterized by equal properties in all directions
Jahn-Teller Effect	A process whereby molecules become distorted so as not to maintain two or more electron configurations with equivalent energies
Jig	A holder used during drilling or sawing
Kaolinitization	A hydrothermal alteration process whereby feldspars and other clay minerals change to kaolinite
Kelvin	A scale for measuring temperature based on absolute zero, sharing the size of the degree with the Celsius scale
Kerf	The thickness of a saw blade
Kikuchi Lines	Bands of electrons diffracted by the crystal lattice planes of a sample during electron microscopy
Kimberlite	An ultramafic igneous rock that typically forms pipes, dikes and sills, and that may contain mantle xenoliths and minerals
Kinetics	The rate at which chemical reactions occur
Kinking	A deformation mechanism in which stress causes kinks to develop in a crystal grain
Laccolith	A dome-shaped sheet intrusion of igneous rock, formed by emplacement between layers of sedimentary rock
Lacustrine	Pertaining to lakes
Lamella	A plate-like structure occurring in a mineral
Lapping	The process of making the thickness uniform for a cut crystal plate
Lateritic	A soil rich in iron and aluminum hydroxides, typically formed by long-term chemical weathering in wet, hot tropical regions
Lattice	The orderly arrangement of atoms in a crystal
Lattice Defect	A flaw in the arrangement of atoms that make up a crystal

Lattice-Preferred Orientation	The shared alignment of crystallographic axes in an aggregate of crystals
Leucite	A rock-forming mineral of the feldspathoid group
Leucosome	The light-colored part of a migmatite, which itself is a mixture of high-grade metamorphic and igneous rock types, formed by partial melting
Lignite	The lowest-ranked grade of coal
Limestone	A sedimentary rock composed primarily of calcite
Line Defect	A defect in a crystal lattice occurring as a line (rather than as an isolated point)
Linear	An expression which varies proportionally, as in the equation: $x = ky$, where x and y are variables, and k is a constant
Low-Frequency Electromagnetic Effects	Electric, magnetic or electromagnetic phenomena of radio or lower frequencies
Low-Grade Metamorphism	A metamorphic process occurring at about 500°C or lower and at pressures found at 30 km depth or shallower
MacLaurin Series	A mathematical expression that represents a function as the sum of the values of its derivatives around the origin
MAD Number	The mean angular deviation (in degrees) when fitting Kikuchi lines from a sample with computer-generated Kikuchi lines
Mafic	A rock that is rich in magnesium and iron; the "ma-" refers to magnesium, and the "-fi-" to iron
Magmatic Segregation	A process during rock formation or volcanism in which minerals are segregated in a magma chamber
Magnetic Domain	A region in a magnetic material with uniform magnetic properties
Magnetic Fabric	A spatial and geometric configuration of the grains in rock that displays a magnetic anisotropy
Magnetic Susceptibility	The volume magnetic susceptibility, a measure of the magnetization of a material in response to a magnetic field
Magnetization	The development of magnetic polarization in a material or on a surface
Magnetogyration	An applied magnetic field process that changes the direction of photons being transmitted in a medium
Magneto optic Effect	An applied magnetic field process that changes the frequency of photons being transmitted in a medium
Magnetostriction	The constriction of materials under the influence of a magnetic field, caused by surface polarization
Magnetotail	The distal part of an oblong magnetic field

Magnetotelluric	A term referring to both magnetic and electrical constituents in the ground, whether artificially induced or natural
Malter Effect	The pulling of electrons to the surface of a material from deep inside during fractoemission
Manganite	An hydroxide of manganese oxide
Manganoan	A substance containing manganese
Marble	A metamorphic rock formed from limestone or dolostone
Marl	A mud or mudstone rich in calcium carbonate
Massif	A group of mountains formed by faulting of a large section of the Earth's crust
Matrix	The small-grained portion of soil, sediment, or sedimentary rock that supports larger rock fragments
Medium	A substance that transmits some physical property, wave, or wave-like particle
Megaborate	A chemical substance containing an ion with seven or more boron atoms as a major constituent
Melamine	A white material used to coat some press- and particle board
Melanite	A black, titanium-rich variety of andradite garnet
Melanosome	The dark-colored part of a migmatite, which itself is a mixture of high-grade metamorphic and igneous rock types, formed by partial melting
Mesitylene	A benzene derivative with three methyl groups substituting symmetrically on the benzene ring
Mesothermal	A hydrothermal category characterized by moderate temperature (250 to 450°C) and low to moderate pressure
Meta-	A metamorphic rock that formed from the rock type listed after this prefix, e.g. metaconglomerate
Metal	A material that is a good conductor of heat and electricity because of its electron configuration
Metalloid	A material that has properties in between those of metals and non-metals, also called a semi-metal: boron, silicon, germanium, arsenic, antimony, selenium or tellurium, for example
Metamorphic Facies	An assemblage of metamorphic minerals formed under similar pressure and temperature conditions
Metamorphism	A solid-state change in the chemistry of earth materials, associated with the parameters of pressure, temperature, chemical composition and time

Metasomatism	A solid-state change in the chemistry of earth materials, similar to metamorphism, but at near-surface temperatures and pressures, and often involving fluid
Miarolitic	A rock containing irregular-shaped cavities lined with crystals
Micaceous	A rock with abundant mica
Micron	A micrometer, with 1,000 micrometers equal to 1 mm
Microtectonics	The study of small deformation structures using microscopes
Migmatite	A mixture of high-grade metamorphic and igneous rock types, formed by partial melting
Mineral	A natural, solid, crystalline material with a distinct chemical formula formed by geologic processes
Mineral Group	A set of minerals whose crystal lattices are similar, but with different atoms occupying some lattice sites
Mineral Supergroup	A set of mineral groups, whose members share lattice similarities
Mineralogical	Topics relating to minerals
Mirror Plane	A symmetry element that rotoinverts points as a mirror does, with two-fold symmetry
Mole	The amount of material in 12 grams of carbon-12
Molybdate	A chemical substance containing an ion with molybdenum and four oxygen atoms, with valence two minus, as a major constituent
Moment Magnitude	A measure of earthquake magnitude based on the area of rupture, the length of the dislocation, and the stiffness of the ruptured earth materials
Monoborate	A chemical substance containing an ion with one boron atom as a major constituent
Monoclinic Crystal System	A category of crystals in which the unit cell walls are not orthogonal, but two of the walls are parallel
Nabarro-Herring Creep	A deformation mechanism in which lattice vacancies diffuse through crystal lattices
Natural Fission Reactor	A rock that contains radionuclides and hosts naturally-occurring fission reactions
Natural Log	A logarithm with the Euler number (e) as its base
Natural Number	A digital number and member of the set $\{1,2,3,4,\dots,\infty\}$
Néel Temperature	A magnetic phase transition temperature above which ferri- or antiferromagnetic materials change to an induced (paramagnetic) state

Neso-	A crystal lattice in a framework structure composed of the form that follows this prefix, connected indirectly via other atoms or ions
Nesosilicate	A silicate mineral whose framework is composed of silicate tetrahedra connected to each other indirectly via other atoms or ions
Newton	The amount of force needed to accelerate one gram at one meter per second per second
Nickel-Strunz	A mineral classification system
Niobate	A chemical substance containing an ion with niobium atoms as a major constituent
Nitrate	A chemical substance containing an ion with nitrogen and three oxygen atoms, valence one minus, $[\text{NO}_3]^-$, as a major constituent
Nitride	A chemical substance containing nitrogen in an oxidation state of three minus, N^{3-}
Non-Centrosymmetric	A crystal lattice whose inverse lattice can be rotated to match the original lattice
Nonmetal	Any of the following elements, sharing common properties such as low density, high electronegativity, and poor conductance of heat and electricity when compared to metals: hydrogen, carbon, nitrogen, phosphorus, oxygen, sulfur, fluorine, chlorine, bromine, iodine, astatine and the noble gasses
Norite	A mafic intrusive igneous rock similar to gabbro, but containing orthopyroxene instead of clinopyroxene
Normal	Forms that intersect at a right angle
Numerator	The number written above the line, for a fraction
Oblique	An angle that is not 90°
Obsidian	A glassy extrusive igneous rock of felsic composition
Octahedron	An eight-pointed solid composed of two square-based pyramids stacked base to base
Oolitic	A sedimentary rock composed of spherical grains with concentric layers in the grains
Open System	In thermodynamics, a system that can receive inputs from outside itself
Ophiolite	A group of rock types formed via mid-ocean ridge volcanism into ultramafic crust, including, in sequence, muds and cherts, greenstone, gabbro, serpentinite, and peridotite
Optic Axis	An orientation based on variation in the transmission of light through a crystal

Order of Magnitude	An approximation of the size of a number, specifying the power of 10 to which the number is closest
Ordinal	That which can be put in order
Ore	Rock with enough metallic minerals in it to be mined commercially
Organic	A category including most chemical compounds containing carbon, typically those that form from biological rather than geological processes
Orthoclase Feldspar	A common rock-forming group of potassic aluminosilicate minerals that cleave at a 90° angle
Orthogonal	Forms that intersect at a right angle
Orthorhombic Crystal System	A category of crystals in which the walls of the unit cell are perpendicular and of unequal length
Overtone	A tone whose frequency is some simple function of a fundamental frequency, and whose sound is higher in pitch
Oxidation	A chemical reaction wherein electrons are lost
Oxide	A chemical substance containing oxygen bonded with at least one other element
Oxy-	A chemical substance containing oxygen
Peraelectric	A material that strengthens an electric field and increases it more than linearly
Paramagnetic	A material that strengthens a magnetic field and increases it more than linearly
Partial Derivative	A measure of the rate of change of a variable while holding other variables constant
Partial Differential Equation	An equation with partial derivatives as some of its terms
Pascal	A unit of pressure equal to one newton per square meter
Pauli Paramagnetism	A weak form of paramagnetism caused by the difference in magnetic potential energy between spin-up and spin-down electron states
Peat	A stable mass of partially decomposed vegetation
Pegmatite	An intrusive igneous rock with large (> 2.5 cm) crystals, often of granitic composition
Pelitic	A fine-grained rock or sediment
Peltier Effect	The generation of heat at an electrified junction of two dissimilar conductors

Penrose Tiles	A set of tile shapes that will cover a flat surface without any repeating pattern
Pentaborate	A chemical substance containing an ion with five boron atoms as a major constituent
Periclase	A magnesium oxide mineral, typically occurring in contact metamorphic zones
Peridotite	An ultramafic intrusive igneous rock consisting mainly of olivine and pyroxene
Period	A unit of time
Peroxy	A chemical bond in which two oxygen atoms are present where only one is normally found
Perpendicular	Forms that intersect at a right angle
Petrologic	A descriptive term relating to rocks
Phase	A distinctive chemical or physical state of a substance
Phase Field Model	A mathematical system that describes boundary interfaces with partial differential equations
Phonolite	An extrusive igneous rock of intermediate composition and low silica content, typically containing feldspathoid minerals
Phosphate	A chemical substance containing an ion with phosphorus and four oxygen atoms, valence three minus, $[\text{PO}_4]^{3-}$, as a major constituent
Phosphide	A chemical substance with phosphorus as the more electronegative constituent
Phosphorite	A sedimentary rock rich in phosphorus, not formed by weathering or erosion of pre-existing rock
Photon	A particle of light or other electromagnetic phenomenon
Phyllo-	A crystal lattice in a framework structure composed of the form that follows this prefix, connected directly in sheets
Phyllosilicate	A silicate mineral whose framework is composed of silicate tetrahedra connected to each other in sheets
Piezoelectric Strain Rate	A measure of the rate at which a material transforms strain into electricity, observed either as an electric charge (d) or as an electric field (g)
Piezoelectric Stress Rate	A measure of the rate at which a material transforms stress into electricity, observed either as an electric charge (e) or as an electric field (h)
Piezoelectricity	An electric field or charge caused during the application of pressure, due to distortion of a crystal lattice

Piezomagnetism	A magnetic field or polarization caused during the application of pressure, due to distortion of a crystal lattice
Piezooptic Effect	A change in the frequency of photons being transmitted within a medium due to pressure
Pinning Wall	The boundary separating magnetic domains
Pipe	A large, carrotiform igneous structure formed through deep volcanic eruptions
Placer Deposit	A clastic mineral deposit formed by separation due to gravity during transport
Plagioclase Feldspar	A common rock-forming group of aluminosilicate minerals that cleave at an inclined angle
Plane	A flat surface defined by three (nonlinear) points
Plasma	A state of matter where both fluid flow and the local action of electric charge influence its dynamic behavior, generally thought of as a charged gas
Plastic	Viscous flow in a medium without fracture
Plate	A thin material sample with parallel sides
Platinum Group Elements	Ruthenium, rhodium, palladium, osmium, iridium and platinum
Playa	A dry, alkaline lake with surficial evaporite deposits, usually found in desert regions
Pleat Dislocation	A combination of screw and edge dislocations that looks like a pleat in a crystal lattice
Plume	The cloud arising from a volcanic eruption
Plutonic	A rock forming at depth within the Earth
Pneumatolytic	An igneous alteration process caused by the presence of volcanic gasses
Point Defect	A defect in a crystal lattice occurring as an isolated point (rather than as a line)
Point Group	An organization of geometry based on taking one point as fixed and performing symmetry operations (such as rotation, translation and rotoinversion) to generate the other points, with symmetry properties distinguishing the different groups
Polar	A molecule or complex ion that displays positive and negative electric charges separated by a distance
Polar Chorus	Radio signals at high latitudes caused by the motions of charged particles in the ionosphere

Poled Electromechanical Coupling Factor	A value calculated from a thin disk of a crystal cut normal to the c axis taken while under an externally applied electric field
Polygon	A two-dimensional figure with regular sides and angles
Polyhedron	A three-dimensional figure with regular sides and angles
Polymetallic	A substance containing several types of metal
Polynomial	An expression with variables in powers (or which has terms that cannot be added for other reasons), as in the expression $x^4 + 2x$
Polytetrafluoroethylene	A non-reactive insulating material commonly sold under the commercial name Teflon [®]
Pore Pressure	Pressure caused by the presence of fluid within the pore space of a rock
Porphyry	An igneous rock containing large crystals set in a fine-grained groundmass
Potash	A salt with potassium as a major constituent
Potassic	A material that is high in potassium
Potential	Electric potential, synonymous with voltage
Power of Hydrogen (pH)	A measure of the hydrogen concentration of a liquid, indicating its acidity or alkalinity
Power Spectrum	The characterization of a signal according to variation in its frequency compared to some other quantity
Precipitate	A process whereby a chemical compound separates out via phase transition, e.g. a solid precipitating from a liquid solution; or, the (solid) chemical product of this process
Pressure Slope	A measure of the rate of change in some parameter across a range of pressures
Pressure Solution	The dissolution of material caused by pressure
Pressure Stiffness Slope	A measure of the rate of change in elastic moduli across a range of pressures
Primary Mineral	A mineral that formed during the formation of a rock
Primary Pyroelectric Effect	Pyroelectricity caused by the electric polarity of the crystal lattice
Prime Number	A number divisible only by itself and by one
Primitive Lattice	A unit cell with lattice sites on the corners, but without sites at the centers of the walls of the cell or at the center of the unit cell itself
Prism	An elongated solid form similar to a cylinder, but with a polygon in cross section instead of a circle

Projection	A mathematical procedure for making an image from an original, comparable to light casting a shadow
Pulaskite	A variety of syenite composed primarily of orthoclase, sodium-rich pyroxene, arfvedsonite (an amphibole-group mineral) and nepheline
Pyroclastic	A rock composed chiefly of angular fragments of volcanic rock, with or without clasts of country rock
Pyroelectricity	The expression of electric charge, voltage or current at the ends of the polar axis of a crystal due to its lattice symmetry
Pyroxene	A common silicate mineral group, typically rich in iron and magnesium
Pyroxenite	An ultramafic igneous rock composed mainly of pyroxene
Radionuclides	Atoms that give off radiation as the result of radioactive decay or nuclear fission
Raman Spectroscopy	A non-invasive technique to identify a crystal by shining a laser on it and correlating the unique resulting emission spectrum with a catalog of spectra for known crystals
Rare Earth Element	Any of the fifteen lanthanides, plus scandium and yttrium
Reciprocal Space	A space created by performing a Fourier transform on a set of coordinates or a function
Recovery Mechanism	A deformation mechanism that lowers the internal strain of a crystal by segregating lattice dislocations
Reduction	A chemical reaction wherein electrons are gained
Reflector	Any material that reflects neutrons during neutron diffraction analysis
Refractive	The ability to refract electromagnetic radiation
Regional Metamorphism	A class of metamorphic processes that occur over large areas and typically involve mountain formation
Relative Dielectric Strength	The ability of a material to hold electric charge, measured in proportion to the dielectric strength of a vacuum
Remanent Field	(1) The magnetization that remains in magnetic materials after a magnetizing field has been removed; (2) for ferroelectric materials, the strength of the electric field remaining when no applied electric field is present
Resistance	The ability of a material to resist the flow of electric current, measured in units of Ω , for example
Resistivity	Resistance to the flow of electric current over a distance, measured in units of Ω m, for example
Retrograde Alteration	A change to a material at lower temperatures and pressures than previously attained

Rhyolite	A felsic extrusive igneous rock, equivalent to granite in composition
Right Angle	90°
Rotation	A symmetry operation of moving every point to a new position that makes the same angle with respect to the origin and the old position
Rotoinversion	A symmetry operation wherein all points are rotated about an axis and reflected with a plane perpendicular to the rotation axis, as in a mirror, for example, which creates a rotation of 180°
Rotooptic Effect	A change in the direction of photons being transmitted in a medium by the application of pressure
Sandstone	A sedimentary rock formed primarily from sand-sized (1/16 to 2 mm) sediment grains
Sanidinite Facies	A high-temperature, low-pressure metamorphic regime, generally restricted to some contact metamorphic environments
Sapwood	The part of a tree where sap flows, outside the heartwood
Saturation Magnetization	The magnetic field strength needed to reverse the magnetic polarity of a ferromagnetic material
Scanning Electron Microscope	A microscope used to image samples via a beam of electrons striking a sample with detectors placed above the sample
Schist	A medium-grade foliated metamorphic rock
Screw Dislocation	A line defect formed by a twist about an axis in order to accommodate three-dimensional lattice defects
Second Derivative	The change in the slope of a function
Second Order Phase Transition	A description of a transition process in which both forms do not coexist for any part of the transition
Second Order Term	In crystallographic notation, a term with two indices
Secondary Mineral	A mineral that formed after the original formation of a rock
Secondary Pyroelectric Effect	The expression of electric charge in a pyroelectric material caused by piezoelectricity as heat deforms the crystal lattice
Seebeck Effect	An electromotive force and electric current that occur in a conducting material as it is subjected to a temperature gradient
Seebeck Coefficient	A measure of the field strength of the thermoelectric effect, in volts per degree
Seismic	Phenomena related to earthquakes
Seismic Electric Signal	Electric phenomenon associated with an earthquake

Selenate	A chemical substance containing an ion with selenium and four oxygen atoms, valence two minus, $[\text{SeO}_4]^{2-}$, as a major constituent
Selenide	A chemical substance containing selenium, oxidation state two minus, Se^{2-} , as a major constituent
Selenite	A chemical substance containing an ion with selenium and three oxygen atoms, valence two minus, $[\text{SeO}_3]^{2-}$, as a major constituent
Self Potential	An electric potential in a porous medium or rock, caused by the motion of an ion-rich fluid, and by the inductive electrostatic charging of the material through which the flow occurs
Semiconductor	A material which conducts electricity when a certain voltage threshold has been reached, called the band gap
Serpentinite	A rock with serpentine minerals as the major constituent
Serpentinization	A metamorphic process wherein minerals in mafic and ultramafic rock are altered to serpentine minerals via low-temperature metamorphic processes involving water
Sferic	Radio-frequency atmospheric signal
Shale	A fine grained sedimentary rock with clay-sized ($< 1/256$ mm) constituent grains predominantly
Shear	Extension or slip along a plane by a force that is directed parallel to the plane, or at an acute angle
Shear Zone	A region of high tectonic stress where earthquakes occur
Shonkinite	An alkaline intrusive igneous rock similar to syenite, but with feldspathoids as major constituents
Siemens	A unit of electrical conductance, equivalent to Ω^{-1}
Sierra Cup	A cup made from metal with a thin metal handle that cools quickly enough for use while heating
Silicate	A mineral that contains the silicon tetrahedron, (O_2SiO_2) , as a primary constituent of the crystal lattice, or a rock composed of a high percentage of silicate minerals
Silicide	A chemical substance with silicon as the more electronegative constituent
Silicification	A geologic process whereby organic material in a substance is replaced with silica
Sill	A horizontal or nearly horizontal igneous sheet intrusion
Siltstone	A sedimentary rock with constituent grains of silt size ($1/16$ to $1/256$ mm) as major constituents

Six-Fold Symmetry	The quality that allows a shape to be rotated equally six times in 360°, whose form with each rotation is the same as the original form
Skarn	A rock containing calc-silicates, typically formed by the intrusion of granitic material into calcium-bearing or calcium-carbonate-rich rock
Skeletal Inclusion	An inclusion in a mineral that contains only the original edges of the including material
Slag	A partly glassy waste material from an industrial process, containing metal and silica
Slip Band	A crystal lattice region with a high concentration of dislocations
Slip System	A combination of slip plane and slip direction giving a unique orientation to deformation in a crystal
Slope	The difference in altitude divided by the difference in extent, also known as “rise over run”
Slurry	A fluid that contains solids
Solfataric	A material derived from sulfate-rich fumarole processes
Solid Solution	A crystal that can incorporate more than one type of atom into a lattice site
Solidus	The temperature boundary below which a material is completely solid, the values of which are dependent on pressure and chemistry
Sorosilicate	A silicate mineral whose framework is composed of pairs of silicate tetrahedra
Space Group	An organization of space based upon symmetry operations
Spodumene	A mineral of the pyroxene group containing lithium and aluminum
Spontaneous Polarization	The appearance of electric charge due to changes in temperature while other parameters are held constant
Sprue	A channel used during casting to allow molten material to enter the mold and to allow gases to escape
Stacking Fault	Misfitted edges in a crystal lattice caused by a combination of line or point defects
Stalactite	A dripstone hanging down from the roof of a cave
Stiffness	(1) The capacity of an elastic material to resist deformation; (2) the elastic modulus that one may use to convert strain data into stress data
Stoichiometry	A measure of the relative amounts of constituent elements or ions in chemical reactions
Strain	A normalized measure of length displacement caused by stress

Stratiform	A general term for a layered deposit
Stratosphere	The part of the Earth's atmosphere just above the troposphere, reaching from about 10 to 15 km to 50 km above the surface of the Earth for midlatitude regions, and that is stratified with the hotter layers at the higher positions
Streaming Potential	Electric potential caused by the electrokinetic effect
Stress	The average force per unit area that some particle of a body exerts on an adjacent particle across an imaginary internal surface
Stress Corrosion Cracking	Microfracture growth caused by a chemical reaction
Subcritical Microcrack Growth	A slow process of microfracture growth based on stress, temperature and the surrounding chemical environment
Subduction	A process in plate tectonics in which (generally oceanic) lithospheric plates descend into the mantle
Subgrain	A region in a crystal with a slightly different lattice orientation
Subgrain Rotation	A dynamic recrystallization process in which new grains are formed from subgrains in a crystal
Sublattice	A portion of a crystal lattice
Sublimate	A condensate; this usage is restricted to geology as, generally, sublimate means the reverse of condensate
Sulfantimonite	A chemical substance with three elements: a metal, antimony, and sulfur, as major constituents
Sulfarsenite	A chemical substance with three elements: a metal, arsenic, and sulfur, as major constituents
Sulfate	A chemical substance containing an ion with sulfur and four oxygen atoms, valence two minus, $[\text{SO}_4]^{2-}$, as a major constituent
Sulfbismuthite	A chemical substance with three elements: a metal, bismuth, and sulfur, as major constituents
Sulfide	A chemical substance containing sulfur, oxidation state two minus, S^{2-} , as a major constituent
Sulfite	A chemical substance containing an ion with sulfur and three oxygen atoms, valence two minus, $[\text{SO}_3]^{2-}$, as a major constituent
Sulfosalt	A chemical substance containing the negative ion of sulfur and two other elements, typically a metal and a semi-metal
Supergroup	A category in mineral taxonomy above mineral group
Superplasticity	A deformation mechanism in a fine-grained aggregate wherein the grains slide past one another to accommodate strain without any lattice-preferred orientation

Syenite	An alkaline felsic intrusive igneous rock, lacking quartz
Symmetry	Repetition of forms
Tactite	A synonym for skarn, typically formed by the intrusion of granitic material into calcium-bearing or calcium-carbonate-rich rock
Tecto-	A crystal lattice in a framework structure composed of the form that follows this prefix
Tectosilicate	A silicate mineral whose framework is composed of silicate tetrahedra connected to each other directly in an extensive structure
Tellurate	A chemical substance containing an ion with tellurium and four oxygen atoms, valence two minus, $[\text{TeO}_4]^{2-}$, or with tellurium and six oxygen atoms, valence six minus, $[\text{TeO}_6]^{6-}$, as a major constituent
Telluric	Phenomena of or relating to the Earth
Telluric Current	A natural electric current in the Earth or in a body of water, or in another planet or in a body of liquid other than water (as with lakes of methane on Titan), or an electric current in the Earth of unknown origin
Telluride	A chemical substance containing tellurium, oxidative state two minus, Te^{2-} , as a major constituent
Tellurite	A chemical substance containing an ion with tellurium and three oxygen atoms, valence two minus, $[\text{TeO}_3]^{2-}$, as a major constituent
Temperature	A measure of the ability to transmit heat for a material or system
Temperature Gradient	The rate of change in temperature when one measures temperature along a physical path
Temperature Slope	A measure of the rate of change in some parameter across a range of temperatures
Temperature Stiffness Slope	A measure of the change in elastic moduli across a range of temperatures
Tension	Elastic or permanent deformation in a material while being pulled apart
Tensor	A set of numbers in several dimensions; a vector, for example is a tensor in two dimensions, direction and magnitude, generally
Tensile Strength	The ability of a material to withstand being pulled apart
Tephrite	An extrusive igneous rock with abundant feldspathoid minerals and lacking quartz
Tesla	A unit of magnetic-field strength, defined as the strength of a magnetic field that allows a particle carrying a charge of one coulomb at a speed of one meter per second perpendicular to the field to experience one newton of force

Tetraborate	A chemical substance containing an ion with four boron atoms as a major constituent
Tetragonal	A form exhibiting four-fold symmetry
Tetragonal Crystal System	A category of crystals in which the unit cell displays four-fold symmetry and is prismatic along the <i>c</i> axis
Tetrahedron	A pyramid with a triangular base, so named because it has four corners
Thermocouple	A device made from two dissimilar metals to measure temperature, with an electric signal caused by the Seebeck effect
Thermodynamic Equilibrium	A state of balance for a system with no net flows of energy, matter, driving forces, or changes of phase
Thermodynamics	The study of how systems change over time, based on parameters that influence the energy inside a system
Thermoelectric Effect	Electric current caused by a temperature gradient within a conductor, as ions or other charge carriers are mobilized by the heat
Thermoplastic	A material that becomes soft on heating and can flow plastically
Thickness Compressional Coupling Factor	A value taken from a thin disk cut normal to a symmetry axis or parallel to a symmetry plane, so that the compressional component is not coupled to the shear component
Thio-	A substance containing sulfur, such as thiocyanate, $[\text{SCN}]^-$
Third Order Term	In crystallographic notation, a variable or constant with three indices
Thomson Effect	The generation of heat in an electrified conductor caused by a gradient in the Seebeck coefficient of that material
Three-Fold Symmetry	The quality that allows a shape to be rotated equally three times in 360° , whose form with each rotation is the same as the original form
Tiling	The study of how shapes cover space
Topology	The study of mathematics describing the classification of surfaces
<i>T-P-X</i> Model	A phase diagram or set of phase diagrams based on the temperature (<i>T</i>), pressure (<i>P</i>) and chemistry (<i>X</i>) of rock conditions
Trachyte	An extrusive igneous rock chemically equivalent to syenite, commonly with feldspathoids and lacking quartz
Transgranular Fracture	A discontinuity (plus some dilation) across grains
Translation	A symmetry operation of moving every point the same distance in the same direction
Tremolite	A metamorphic mineral of the amphibole group

Triboluminescence	A phenomenon in which light is generated via fracture, scratching, crushing or various other mechanical processes that break chemical bonds
Triborate	A chemical substance containing an ion with three boron atoms as a major constituent
Triclinic Crystal System	A category of crystals in which none of the walls of the unit cell are parallel
Trigonal	A form exhibiting three-fold symmetry
Trigonal Crystal System	A category of crystals in which the unit cell displays three-fold symmetry and is prismatic along the c axis
Trimer	A structure formed of three chemical units
Troposphere	The 7 to 20 km thick part of the Earth's atmosphere closest to its surface
Tuff	A rock consisting of consolidated volcanic ash
Tuffaceous	A rock consisting of greater than 50% tuff, but with other constituents
Turbidity Current	A density-driven subaqueous flow of water plus material in suspension, akin to a debris flow
Two-Fold Symmetry	The quality that allows a shape to be rotated equally two times in 360°, whose form with each rotation is the same as the original form
Ultramafic	A rock containing more than 90% mafic minerals and very low silica content
Undulose Extinction	A process of alignment between polarized light traveling through a crystal and the optic axes of the crystal in which the darkness (from the alignment) is not regionally uniform
Unit Cell	The basic repeating pattern for the arrangement of atoms in a crystal
Upset Forge Magnet	A magnet in which the magnetism is created via deformation or recrystallization of the crystal lattice of the material
Uranyl	A polyatomic ion with uranium and two oxygen atoms, valence two plus, $[\text{UO}_2]^{2+}$
Vacancy	An unfilled site within a crystal lattice
Vadose Zone	The part of an aquifer that is mostly unsaturated, lying between the surface of the Earth and the water table
Vanadate	A chemical substance containing an ion with vanadium and oxygen atoms as a major constituent
Variable	A mathematical expression that can represent different values depending on what information is given

Vector	A mathematical quantity characterized by both magnitude and direction
Vein	A rock structure containing a mass of minerals enclosed in a fissure, distinct from the minerals of the surrounding rock
Veinlet	A small vein
Very Low Frequency Radio Signal	A radio signal with a frequency from three thousand hertz to thirty thousand hertz (3 kHz to 30 kHz)
Vesicle	A small cavity in volcanic rock formed around a gas bubble
Voigt Notation	A crystallographic notation that uses the indices 1 through 6 to specify directions, with 1, 2, and 3 indicating the x , y , and z axes, and 4, 5, and 6 indicating planes perpendicular to the x , y , and z axes
Volatile	A material with a relatively low boiling point
Vug	A small or medium-sized cavity in rock, lined partially with crystals, or a void
Whistler	A change to the local magnetic field accompanying lightning discharge, including the induced electric currents associated with that change, and named for the signal interference caused by induction in telephone lines
Wolframate	A chemical substance containing an ion with tungsten and four oxygen atoms, valence two minus, $[\text{WO}_4]^{2-}$, as a major constituent
x Axis	One of the orthogonal axes in a Cartesian coordinate system, oriented horizontally by convention
X-Ray Diffraction	A technique for determining the arrangement of atoms in crystalline materials, by shining X-rays through them onto a film
Xenolith	A rock fragment encased within a larger (igneous) rock
xy Plane	The flat surface made by the intersection of the x and y axes in a Cartesian coordinate system
xz Plane	The flat surface made by the intersection of the x and z axes in a Cartesian coordinate system
y Axis	One of the orthogonal axes in a Cartesian coordinate system, oriented vertically by convention if the system is two-dimensional, or horizontally by convention if the system is three-dimensional
yz Plane	The flat surface made by the intersection of the y and z axes in a Cartesian coordinate system
z Axis	The axis that corresponds to the long axis of a hexagonal, tetragonal or trigonal crystal, and one of the orthogonal axes in a Cartesian coordinate system, oriented vertically by convention if the system is three-dimensional
Zeolite	A group of aluminosilicate minerals with a microporous form

CHAPTER 1

INTRODUCTION

Metamorphism is a chemical transformation of earth materials while in a solid state. One product of chemical reactions is the transfer of electrons or ions. Pressure, temperature, time and chemical composition drive metamorphic reactions, and electrical phenomena are associated with metamorphism based upon these parameters. The study of electricity and metamorphism is, however, in its infancy. Information is spread across several subdisciplines of geology, materials science, physics, and chemistry, and data are often not usable for the problems to which they might be applied, because the data are unknown to the person asking the question.

As an example, earthquakes are sometimes associated with electric discharges, traveling visibly in the air as lightning, or through the Earth (Freund 2011; Varotsos et al., 1998; Johnston, 1997), or as electromagnetic radiation that disturbs radio or television transmission (Matsumoto et al., 1998). Prediction of earthquakes based on these signals would be useful. One of the difficulties for this kind of prediction is the absence of generally-accepted, credible mechanisms to generate seismic electrical phenomena. The signals which travel through the ground are called seismic electric signals (SES). Their existence is well-documented, but a predictive model is not. A usable hypothesis for how earthquake rupture occurs is necessary, as well as a hypothesis on the mechanism for generating presumed SES that matches natural processes.

Shear zones, where earthquakes occur, are the site of metamorphic reactions. Metamorphism is thus associated with electricity. A study of the electrical phenomena related to metamorphism should provide a foundation for a practical, predictive model to match observed and purported seismic electric signals, and would also be useful in planetary science.

The study of metamorphism was transformed with George Barrow's observations of the distribution of minerals (e.g., Barrow, 1893) in the 19th and early 20th century. His observations led to the metamorphic facies concept, and are consistent with plate tectonic theory. Barrow's metamorphic zones, in which different minerals were cataloged, have been used to develop the concept of the geothermometer, minerals or structures that can be used to reconstruct the temperature at which a rock was formed, or at which deformation occurred. Likewise, microtectonics uses microscopy to examine deformation mechanisms and construct the past conditions of pressure and stress in shear zones and in metamorphic rock.

Electrical phenomena at the grain-size scale influence the kinetics of metamorphic reactions. Along with chemistry, temperature and pressure, they serve as one of the reservoirs of energy for thermodynamics, interacting with bond energy in a physical medium. Bond energy also influences mineral form, symmetry, and lattice defects, which are flaws in the arrangement of the atoms that constitute a crystal. Variations in the chemical composition of materials are created when the energy of an open system changes. Several processes occur whereby earth materials influence, and are influenced by electrical phenomena. Describing all of the relevant small-scale and large-scale electrical phenomena is one goal of this thesis. Several experimental options, and their strengths and weaknesses, will be presented.

As described earlier, large-scale electrical phenomena associated with metamorphism may be useful for modeling ideal seismic electric signals. Earthquake prediction through analyses of purported SES now has had some success. A positive correlation between presumed SES and earthquakes has been found in Greece, for earthquakes of $M_L \geq 5.0$ (Dologlou, 1993a; Shnirman et al., 1993), where M_L is the local earthquake magnitude on the Richter scale. Purported seismic electric signals are on the order of 1 to 10 mV (Thanassoulas and Tselentis, 1993). The timing between presumed SES and a seismic event can vary by days, tens of days, or more, though a new methodology may help to narrow the prediction window to a few days (Uyeda and Kamogawa, 2008). The location of the predicted event can vary by about 100 kilometers (km), but with selective sensitivity, so complete coverage can be problematic (Varotsos et al., 1993a). Selective sensitivity is a term to describe how purported SES may not travel uniformly. Monitoring stations may only be sensitive to SES from a restricted area or areas, and these may not be contiguous. The predictions can be well-constrained in magnitude, with uncertainty (ΔM_L) equal to about 0.7 (Hamada, 1993). Distinguishing man-made from natural signals has proven somewhat challenging (Pham et al., 1998). The predictive success rate, at 50%, has been only moderate (Hamada, 1993), but in

2001 a time series analysis method was developed that produces a higher (nearly 90%) success rate (Varotsos et al., 2011). The method is well-enough developed that other scientists ought to try and replicate the results. Also, a definitive mechanism for generating presumed SES ought to be developed.

Purported seismic electric signals are sometimes detectable more than 100 km from an earthquake epicenter. An appropriate mechanism is needed to account for the size of this electric circuit. These signals may be generated by changes in the capillarity of groundwater due to pore pressure variations prior to an earthquake. Moving ground water, for example, can generate an electric potential in rock, called a self potential (Jardani et al., 2008; Jardani et al., 2006; Revil et al., 2003; Birch, 1998; Aubert and Atangana, 1996). In association with pressure variation, charge dislocations caused by lattice defects, rather than self potential, may create an electric circuit with the surface (Freund, 2011). Alternately, temperature variations prior to an earthquake may be responsible for presumed SES, acting on magnetite via a thermoelectric effect (Junfeng Shen et al., 2010). Magnetite is common enough in a wide range of rocks for this possibility to be considered. Thermoelectricity is created in a conductor or semi-conductor when there is a temperature gradient, allowing the most mobile charge carrier to move and create a circuit (Shankland, 1975). Whatever their cause, purported seismic electric signals can occur early enough (a few days prior to a seismic event) to encourage further research, since that is the minimum time needed for evacuation if prediction is possible. Time series analysis of the signals over a longer period of time looks feasible (Uyeda and Kamogawa, 2008).

This thesis was written to promote further study in Earth electricity, not just related to SES, but in other applications as well. Topics range from small- to large-scale phenomena. Each section includes references to the current scientific literature and is meant to be as comprehensive as possible in presenting descriptions of phenomena and data. Short tables appear within the chapters, while tables longer than two or three pages have been placed in the Appendices, as have most tables containing numerical data or lists of references.

CHAPTER 2

TELLURIC CURRENTS

Introduction

The word “telluric” is from the Latin *tellus*, meaning Earth. Telluric currents were originally defined as natural electric currents passing through the Earth’s soil or rock layers or bodies of water, as opposed to its atmosphere. The term has been generalized to include electric currents in any planet, or in any body of liquid on the surface of a planet. For the Earth, any electric current in the soil, rock, or water of natural or unknown origin is classed as a telluric current. This usage is slightly different from that of exploration geophysicists, where most natural currents are called telluric, to distinguish them from self potential that may be present at ore bodies, and artificial current, used for study. Now, magnetotelluric surveys create artificial electric and magnetic fields to explore subsurface features and characterize rock, and many natural phenomena are considered noise in the survey signals. Sometimes the natural currents themselves are used to study subsurface characteristics (Gasperikova and Morrison, 2001). For the purposes of this thesis, any electric current in the Earth or on it may be classed as a telluric current.

Self Potential and GIC, Two Common Causes of Earth Electricity

The most common large electric potentials measurable at the Earth's surface are self potential, caused as groundwater streams through ore bodies, and geomagnetically-induced currents (GIC). (For more information, see subsections Groundwater Phenomena, p. 10, and Geomagnetically-induced currents, GIC, p. 4.) Self potential is caused by the transfer of ions in groundwater, and by rock-charging from the motion of these ions. It is not necessarily a nuisance during electrical surveys and can be used to examine the subsurface (Suski et al., 2006). For other electrical survey techniques, data must have any self potential signal calculated and subtracted out to be useful, called self potential buck-out (Sumner, 1976).

The ionosphere is composed of charged particles and located 85 to 600 km above the Earth’s surface. Electrical phenomena are caused as the solar wind or space weather impact the ionosphere. The solar wind and space weather create ionospheric electromagnetic phenomena in the radio spectrum, and these disrupt communication.

Eddies in the ionosphere also occur, and these create local electric current, from the motion of ions. This electric current affects the geomagnetic field, and the resulting geomagnetic anomalies induce telluric currents in the ground (Boteler et al., 1998). This is GIC. Geomagnetically-induced currents cause corrosion in pipes and pipelines, and are a problem at high latitudes, where the Earth’s magnetic flux lines point towards (or away from) the surface of the Earth.

Producing Electricity

Several models depict electricity-generation processes. Four of these are useful in conjunction with the study of telluric currents. These are listed in Table 1, with a brief explanation for each.

Charged particles, if they change location, transfer charge. Charged particles, such as electrons or ions, are termed charge carriers. The motions of ions or electrons are examples of the direct transfer of electric charge.

A deeper treatment of the ideas in the following description may be found in Jonassen (2002). Electrostatic induction is a special case of charged particle transfer. An external charge elicits an electrical response from a second material containing mobile charge carriers. The charge carriers move to neutralize the applied field. If the external charge is positive, for example, then negative charge carriers will migrate within the second material to the site of the external charge. This model is termed electrostatic induction because the charge transfer is induced within one of the materials, but no charge is transferred between them.

A more thorough treatment of the ideas in the following description may be found in Schieber (1986). Electromagnetic induction occurs in any electrical conductor where a change in a magnetic field occurs, so that the magnetic flux lines pass through the conductor. The combination of mobile charge carriers and magnetic flux creates an electromotive force. This is the principle behind electric power generation, for

TABLE 1. Electricity-Generation Models

Model	Explanation
Direct Transfer of Charge	Charge carriers such as ions or electrons change location, and their motion transfers electric charge
Electrostatic Induction	External electric charge creates an electromotive force within a material as particles move to neutralize the external charge
Electromagnetic Induction	Relative motion of a magnetic field creates an electromotive force on electric charge carriers within it
Rearrangement of Electrical Domains	Deformation creates electricity as it changes the position of immobile charge carriers in a material

example. A coil of wire moves through a magnetic field, and the motion creates electric current in the wire. Electricity is generated.

If the charge carriers in a material are not mobile, electricity can be generated by deformation of the material, or some other process that changes the configuration of the domains carrying electric charge. The rearrangement of electrical domains can generate electricity.

Causes: Telluric Currents

Several phenomena that can generate telluric currents have been described in scientific specializations whose members may not communicate with each other regularly. Along with artificial signals, these Earth electrical phenomena are summarized in Table 2, and Table 3 lists telluric currents by frequency, magnitude and signal duration. Thirty-two causes of Earth electricity within the above four models are described in the text that follows.

Space Phenomena

Cosmic-particle flux. Direct bombardment by high-energy charged particles and radiation coming from solar, stellar, and cosmic sources, acts generally to form GIC. For example, a gamma-ray flare from a neutron star 23,000 light years away was reported in 1999 as causing VLF amplitude changes of more than 20 decibels from interaction with the ionosphere. The Lyrid, delta-Aquarid and Perseid meteor showers have caused phase variations in a 16 kHz signal due to GIC (Barr et al., 2000).

For planetary bodies with no atmosphere, this flux of cosmic particles creates telluric currents directly (Madey et al., 2002). Cosmic ray ions have an energy flux of about $6 \times 10^9 \text{ eV cm}^{-2} \text{ s}^{-1}$ for bodies in the Solar System. For Mars, protons and neutrons strike the surface with energy fluxes of around 6000 and 1400 MeV cm^{-2} , respectively (Molina-Cuberos, et al., 2001). This process is not occurring on the Earth's surface at present; the atmosphere intervenes.

Geomagnetically-induced currents, GIC. Ore, or other rock bodies, or human-made structures, such as pipes and cables, respond to electrical changes in the ionosphere. The geomagnetic field interacts with these changes, so that a telluric current is induced in the ground. Pulkkinen et al. (2007), Constable and Constable (2004), Everett and Martinec (2003), Osella et al. (1998), and others have studied this phenomenon. Cycles are related to space weather, and are dominated by the influence of the Sun's eleven-year sunspot cycle, whose period predicts emissions of gas from the solar surface. Diurnal variations within this larger cycle have been recorded (Diodati et al., 2001). The ongoing diurnal currents are responsible for the corrosion of pipelines and cables in some locations, especially at high latitudes, and have been studied extensively in Scandinavia (Viljanen et al., 2006).

TABLE 2. Causes and Periods of Earth Electricity

Name	Cause	Cycle	Mechanism
<u>Space Phenomena</u>			
Cosmic Particle Flux (Cosmic Particle Flux: on bodies with little or no atmosphere)	Cosmic Events	Not Known	Charge Transmission
GIC Induction	Solar	11yr 24hr	Electromagnetic Induction
Planetary Magnetic Field Plasma (Earth to Moon)	Cosmic Magnetotail	Not Known 28d	Charge Transmission
<u>Atmospheric Phenomena</u>			
TID	Atmospheric Disturbance	Not Known	Electromagnetic Induction
Lightning Strikes	Lightning	Seasonal	Charge Transmission
Lightning-Strike Induction	Lightning	Seasonal	Electromagnetic Induction
Whistler Induction	Lightning	Seasonal	Electromagnetic Induction
Whistler Plasma	Lightning	Seasonal	Charge Transmission
Volcanic Lightning Strikes	Volcanic Lightning	Not Known	Charge Transmission
Storm Charging	Weather	Seasonal	Electrostatic Induction
<u>Oceanic Phenomena</u>			
Electrochemical Effect	Ocean Currents	Seasonal	Charge Transmission
Ocean Transport Induction	Ocean Currents	Seasonal	Electromagnetic Induction
Oceanic Charging	Ocean Electric Currents	Seasonal	Electrostatic Induction
Metabolic Electrochemistry	Microbes and Algae	Not Known	Charge Transmission
<u>Surface Phenomena</u>			
Artificial Signals	Industry	Various	Electromagnetic Induction
Metabolic Electrochemistry	Microbes and Plants	24hr	Charge Transmission
Exo-Electron Emission	Primed Material	Not Known	Charge Transmission
<u>Groundwater Phenomena</u>			
Electrochemical Effect	Fluid Flow	Seasonal	Charge Transmission
Electrokinetic Effect	Fluid Flow in Porous Media	Various	Electrostatic Induction
Seismic Dynamo Induction	Seismic Waves	Not Known	Electromagnetic Induction
Radioactive Ionization	Radioactive Decay	Not Known	Charge Transmission
<u>Other Terrestrial Phenomena</u>			
Volcanic EM Signals	Volcanism	Not Known	Not Known
Seismic EM Signals	Earthquakes	Not Known	Not Known
Seismic electric signals	Earthquakes	Not Known	Not Known
Fractoemission	Fracture	Not Known	Charge Transmission
Defect Charging	Material Defects	Not Known	Charge Transmission
Piezoelectric Effect	Crystal Lattice Geometry	Not Known	Domain Rearrangement
Thermoelectric Effect	Temperature Gradient	Not Known	Charge Transmission
Pyroelectric Effect	Temperature Gradient	Not Known	Domain Rearrangement
Magma Electrochemistry	Magma Processes	Not Known	Charge Transmission
Radioactive Emission	Radioactive Decay	Not Known	Charge Transmission
<u>Deep Terrestrial Phenomena</u>			
Geomagnetic Jerk	Geodynamo	Not Known	Electromagnetic Induction

Notes: GIC are geomagnetically induced currents, TID are traveling ionospheric disturbances, and EM stands for "electromagnetic."

TABLE 3. Magnitude, Duration and Transmission Frequency of Earth Electricity, Arranged by Magnitude

Name	Magnitude	Duration	Frequency
Lightning Strikes	10^5 A (peak)	1 ms	10^{-3} to 10^3 MHz
Lightning-Strike Induction	10^5 A (peak)	1 ms	10^{-3} to 10^3 MHz
Volcanic Lightning Strikes	10^4 A		
Artificial Signals	> 3 kA (peak)	Not Reported	Not Reported
GIC (Space Weather)	Various	Various	Various
	200 A (in metal)	≈ 10 s	10^{-3} to 10^{-2} Hz
	$50 \mu\text{V m}^{-1}$ (polar chorus)	Various	300 Hz to 2 kHz
	Not Reported (γ -ray flares)	Various	VLF
	Not Reported (meteor shower)	Various	16 kHz
Planetary Magnetic Field Plasma	5000 V (Lunar surface)	≈ 1 week	Not Reported
Storm Charging	10^{-2} A m^{-2}	hrs to days	Not Reported
Electrochemical Effect	5 V	Various	< 300 kHz (ocean)
Electrokinetic Effect	100 mV km^{-1}	Ongoing	0.1 to 0.5 Hz
Ocean Transport Induction	25 mV km^{-1} (in metal)	Ongoing	Some from $10^{-7.0}$ to $10^{-3.8}$ Hz
GIC (Diurnal)	1 mV km^{-1} (ionospheric)	≈ 1 d	0.4 Hz
Cosmic Particle Flux	6000 MeV cm^{-2} (proton-Mars)	Various	Not Reported
(On Bodies with Little or No Atmosphere)			
Whistler Plasma	$10^4 \text{ e}^- \text{ cm}^{-3}$ (striking land)	Not Reported	Not Reported
Seismic EM Signals	≈ 20 to 50 mV m^{-1}	$\approx 1 \mu\text{s}$	217 MHz
Fractoemission	10^{-5} C kg^{-1} (volcanic ash)	Various	10^3 to 10^5 Hz (ice)
Seismic Electric Signals	1 to 10 mV	Various	≤ 1 Hz
Seismic Dynamo Induction	μV to mV	Various	10 to 50 Hz
Thermoelectric Effect	10^{-5} V K^{-1}	Ongoing	Not Reported
Pyroelectric Effect	10^{-6} C m^{-2} K^{-1} (single crystal)	Ongoing	Not Reported
Piezoelectric Effect	10^{-12} C N^{-1} (single crystal)	Various	Not Reported
Defect Charging	10^{-9} A	Various	10^2 to 10^6 Hz
Exo-Electron Emission	$\leq 10^8 \text{ e}^- \text{ cm}^{-2}$	Various	Not Reported
Volcanic EM Signals	1 to 5 pT	Various	Radio frequencies
TID (Schumann Resonances)	1.0 pT	Ongoing	10.6, 18.4, 26.0, 33.5 and 41.1 Hz
Geomagnetic Jerk	Not Reported	Ongoing	Not Reported
Magma Electrochemistry	Not Reported	Ongoing	Not Reported
Radioactive Emission	Not Reported	Not Reported	Not Reported
Radioactive Ionization	Not Reported	Not Reported	Not Reported
Oceanic Charging	Not Reported	Ongoing	Not Reported
TID (Compressive Event)	Not Reported	Various	Not Reported
TID (Gravity Wave)	Not Reported	Ongoing	10^{-7} to 10^{-6} Hz
Whistler Induction	Not Reported	≈ 30 s	10 Hz to 30 kHz
Metabolic Electrochemistry (Hypothetical)	Not Reported	Not Reported	Not Reported

Notes: GIC are geomagnetically induced currents, TID are traveling ionospheric disturbances, EM stands for "electromagnetic" and e^- is electrons.

GIC typically are on the order of 200 amperes (A) in man-made conductors, with durations of approximately 10 seconds (Pulkkinen et al., 2008; Viljanen et al., 1999; Kappenman et al., 1981). The oscillating frequency is typically 0.01 to 0.001 Hz (Price, 2002). Peak current can be on the order of 2000 A, and these occur about 10 to 100 times in 100 years (Pulkkinen et al., 2008).

Diurnal flux rates at the sub-auroral latitudes are on the order of a few millivolts per kilometer (mV km^{-1}) (Mather et al., 1964). The strongest oscillation frequency of these diurnal signals is 0.4 Hz, and is

widespread at different latitudes (Mather et al., 1964). At high latitudes, the motion of charged particles also creates a distinct radio signal, termed the polar chorus, with a characteristic frequency of 300 Hz to 2 kHz (Barr et al., 2000). Polar chorus is associated with the solar wind, and the peak intensity is around $50 \mu\text{V m}^{-1}$ as recorded from stations on the ground in Antarctica. It typically exhibits a diurnal variation (Salvati et al., 2000).

Telluric currents (and specifically GIC) were first documented in the 1840s with the invention of the telegraph. Buried telegraph lines are electrical conductors, and susceptible to electrical induction. Geomagnetically-induced currents caused interference during telegraph transmission, so that the telegraph needles hung frozen by the signals of the GIC. At first this phenomenon was attributed to weather causes, but it was soon recognized that the hung needles coincided with the occurrence of aurora borealis and magnetic storms (Walker, 1861).

Planetary magnetic-field plasma. If ultraviolet and X-Ray emissions from a star encounter a magnetic field, the interactions will create a plasma of energetic electrons. Such a plasma is created in the Earth's magnetosphere from solar radiation, and strikes the moon's surface as it passes through the Earth's magnetotail, as described in Stubbs et al. (2007). The magnitude of the charging can be several thousand volts (Halekas and Fox, 2012). A magnetotail is the distal part of an oblong magnetic field, caused in this case by the solar wind.

Atmospheric Phenomena

Traveling ionospheric disturbances, TID. Atmospheric compression (i.e. acoustic waves) from a sudden event, such as an earthquake, tsunami, volcanic eruption, severe weather or a rocket launch can create traveling ionospheric disturbances (TID) (Afraimovich et al., 2001; Johnston, 1997; Georges, 1968), and these TID can induce telluric currents in the ground via the geomagnetic field. TID are themselves a category of GIC.

The ionosphere also has resonant electrical phenomena, called Schumann resonances, at a fundamental frequency of 10.6 Hz, with overtones at 18.4, 26.0, 33.5 and 41.1 Hz (Barr et al., 2000). The background amplitude of measured Schumann resonances is about 1.0 picoteslas (Schlegel and Füllekrug, 1999).

In addition to the above examples, TID can form as the result of gravity waves at the troposphere-ionosphere interface (Georges, 1968). A gravity wave is one where buoyancy or gravity (or both) act to oppose the displacement. A common example of a gravity wave is the wind-generated wave form one sees at the ocean with the ocean-air interface. Some TID are akin to these, occurring at the troposphere-ionosphere interface. No quantitative reports of the magnitudes of telluric currents resulting from TID are extant, to the best of the author's knowledge, though qualitative magnitudes are known. Space weather events are the strongest TID, and then, in descending order, daytime signals, atmospheric compression events, and gravity waves (Georges, 1968).

The effect of TID within the ionosphere is for the disturbance to develop a potential on the order of 1 millivolt per meter (Shiokawa et al., 2003). Frequency for the ionospheric dynamo region is modeled to be on the order of 10^{-6} to 10^{-7} Hz (Kaladze et al., 2003). Higher frequencies are also present (Munro, 1958). Short-term changes (on the order of hours) to the Earth's magnetic field may be caused by ionospheric activity. Kaladze et al. (2003) have modeled ionospheric activity that matches the magnitude and timing of ground observations of changes to the geomagnetic field.

The ionosphere is studied with dedicated ground-based facilities, such as the High Frequency Active Auroral Research Program (HAARP) and with satellites. A network of satellites measuring ionospheric disturbances are in place. A 1996 space experiment with a nearly 2 km long conducting line gathered electrical data in the ionosphere, and then compared these with satellite data. The accuracy of modeled ionospheric activity between satellites is low. Modeled electrical data are off by as much 140% (Szuszczewicz et al., 1998).

On the ground, HAARP has been in operation in Alaska since 1993 (Bailey and Worthington, 1997). That facility is designed to transmit radio-frequency electromagnetic radiation into the ionosphere for communication with submarines, with the electrolytes in the ocean acting as an antenna. HAARP is also suited for ionospheric studies.

HAARP experiments are designed to study the structure of the ionosphere, and to determine practical applications of wave propagation, such as radio signaling. Results have included techniques to produce very low frequency and extremely low frequency (VLF/ELF – 30 Hz to 30 kHz) radio waves (Cohen et al., 2008). Lightning channels broadcast electromagnetic radiation in the VLF range, and HAARP can duplicate this VLF. HAARP has also been used for magnetotelluric surveying.

In a magnetotelluric survey, both electric and magnetic fields are used for remote sensing, to determine the electrical resistivity of an area, and variations within it, according to an empirical equation

$$\rho = 1/5 f [\mathbf{E}/\mathbf{B}]^2, \quad (1)$$

where ρ is the resistivity in ohm meters (Ω m), f is frequency in Hertz (Hz), $\mathbf{E}$ is the electric field tensor in volts per meter (V m^{-1}), and $\mathbf{B}$ is the magnetic field tensor in nanoteslas (nT) (Wescott and Sentman, 2002). HAARP can generate magnetotelluric signals, and was used as the transmitter for a proof-of-concept controlled-source audio-magnetotelluric survey (CSAMT) in Alaska in 1999 and 2000, prospecting for petroleum (Wescott and Sentman, 2002). This is a new trend. Most magnetotelluric surveys have historically used natural fields (Simpson and Bahr, 2005). Simultaneous measurements of the geomagnetic field and of telluric currents are used to calculate a value for the electrical impedance at depth, to explore subsurface features.

Lightning strikes. Electric charge is transferred between the ground and the atmosphere during lightning strikes, and the tops of stormclouds close an electrical circuit with the ionosphere. Lightning discharge is energetic and creates plasma that we see. The first pulse of lightning occurs as charges within the cloud consolidate to form a strike leader, and plasma from the ground rises up to meet the leader in that cloud. The next pulse comes from the cloud to the ground. The process repeats, with alternating pulse initiations between ground and cloud. A lightning strike is a combination of about 30 nanosecond pulse events, and its overall duration is on the order of milliseconds (Uman, 1994). The bulk result is a negative charge given to the ground. Peak electric current is 99 ± 7 kA, measured by quantifying remanent magnetization of the ground and calculating the peak magnetic field (Verrier and Rochette, 2002). Oscillation signal frequencies are on the order of 10^{-3} MHz to 10^3 MHz, or higher (Uman and Krider, 1982). The previous data have been normalized to a 10 km distance, and higher frequency signals are known to attenuate. With some dry lightning and strikes which ignite fires, a positive charge is given from the cloud to the ground. The magnitude of charge carried by positive cloud to ground strikes is increased by the presence of aerosols and smoke (Nichitiu et al., 2009).

Lightning-strike induction. Lightning strikes can also cause transient changes to the geomagnetic field (Verrier and Rochette, 2002). Lightning can occur in various weather conditions, including thunderstorms, dust storms and tornadoes (Barr et al., 2000). Telluric currents arising from these phenomena ought to have frequencies of 10^{-3} MHz to 10^3 MHz, based on the ns to ms variations recorded in lightning itself. These are the same frequencies that a direct flash of lightning will display. Induction is localized, and portions of large buildings and towers are frequently subject to induction when they are struck. Hussein et al. (2003) compare data from several structures, and the average magnitudes are between 7 and 12 kA, with peak magnitudes from 20 to 100 kA.

Whistler induction. Lightning discharge heats the air and creates plasma. The entire lightning channel radiates electromagnetic energy. If in the radio frequency, it is called a radio atmospheric signal, or sferic. If the plasma from lightning discharge travels along geomagnetic lines, the resulting radio-frequency disturbances are termed “whistlers” and are named for the sound which this interference makes in telephone lines, as first described in 1919 (Schlatter, 2008). The sound was attributed to lightning phenomena in 1953. Whistlers typically occur in the ELF/VLF range of 3 Hz to 30 kHz (Barr et al., 2000). For example, observations made from Antarctica at 22.3 kHz show common changes in amplitude of 3 decibels to an artificially transmitted signal, with duration of around 30 seconds. These changes were associated with whistler activity (Helliwell et al., 1973). The propagation of whistlers along geomagnetic flux lines can induce changes to local magnetic fields, and these can cause induction of human-made conductors and ore bodies.

Whistler plasma. Whistlers are caused when plasma from lightning travels along the geomagnetic flux lines. The magnitude of the electron density striking the Earth is on the order of 10^4 electrons per cm^3 during whistler events at the equator. Poleward densities should be higher, as the flux lines there are more inclined to the Earth’s surface (Schlatter, 2008).

Volcanic lightning strikes. An electrical response in the ground as lightning strikes during volcanic eruptions has been described in Aizawa et al. (2010). They present magnetotelluric data from Sakurajima volcano in Kyushu, Japan, from May 2008 to July 2009. Magnetotelluric pulses were recorded coincident with several strikes.

Generally, volcanic plume heights where volcanic lightning has been observed are distributed bimodally: plume heights 1 to 4 km, and plume heights 7 to 12 km. In the former, volcanic lightning is

due to vent processes, and in the latter volcanic lightning is due to stratospheric processes (McNutt and Williams, 2010). The occurrence of volcanic lightning increases with height in the stratospheric plumes, and peak currents greater than three thousand amperes have been observed (Bennett et al., 2010). Ash erupted from a volcano is electrically charged. Whether a circuit is made between charged ash and the ionosphere has not yet been reported. Low frequency (30 kHz to 300 kHz) sferics are reported, as with meteorological lightning events, but the emission spectra of the flash itself has not been. Likewise, the author has not found reports of the magnitude of electric discharge during volcanic lightning.

James et al. (2000) have described a mechanism for ash charging. In a series of experiments, ash-sized particles were ground from several crustal rock samples in a non-conducting sample holder. The materials developed charges of both polarities, generally based on the chemical composition of the particles, with a net charge of $\approx 10^{-5}$ to 10^{-6} coulombs per kilogram ($C\ kg^{-1}$). Their data are consistent with measurements taken previously within ash fall plumes (James et al., 2000). They attribute the charge in the ash to fracture-charging, also called fractoemission, where electric charge is caused in a fracture as electrons are distributed unevenly during fracture processes.

Lightning in volcanic plumes is controlled by topography and wind direction, with negative strikes (negative charge carried to the ground) and positive strikes (positive charge carried to the ground) evolving over the course of an eruption (Hoblitt, 1994) or occurring simultaneously. The role of water in the magma and its influence in volcanic lightning is still an open question, though the occurrence of volcanic lightning is not related to latitude, and, hence, is likely not related to the ability of the air to hold water (McNutt and Williams, 2010).

Storm charging. Terrestrial electric fields occur during storm activity. Typically, a vertical field on the order of $100\ V\ m^{-1}$ and a current density at the surface of roughly $2 \times 10^{-2}\ A\ m^{-2}$ exist, with water droplet interactions in clouds serving as the source of the initial (negative) charge buildup. These induce a positive charge in the ground.

In thunderstorm clouds, the negative charge at the bottom of the cloud is offset by a positive charge in the top portion, that together form a conductive circuit flowing upward through the stratosphere, also called a thundercloud cell. In reality, negative charge is flowing downward. The current has been experimentally determined to be around 0.7 A per thundercloud cell (Troshichev et al., 2004).

Current flow in a thundercloud cell accounts for about 96% of the electrical activity of a storm, while lightning discharges account for a minority ($\approx 4\%$). Electric charging of storm clouds is offset by charging of the ocean surface, where daily electrical ocean surface variations are consistent with the daily change of the total area occupied by thunderstorms (Troshichev et al., 2004). Electrical frequency spectra in the ground from electrostatic storm charging are not reported, to the author's knowledge.

Oceanic Phenomena

Electrochemical effects in the ocean. In the oceans, different layers of water will be stratified by temperature and salinity, and each influences density. Both of these gradients influence electrical conductivity, and create variations in electric currents in the oceans (Chave and Luther, 1990). The signals are low-frequency (30 kHz to 300 kHz) or lower, typically. Voltages from temperature and salinity variations in the ocean are less than a few mV (silver/silver-chloride electrodes were used) and the differences in salinity and temperature were less than a few parts per thousand and a few degrees Celsius, respectively, between electrodes (Larsen, 1992). The electrode material affects the observed voltage. Internal waves (within the stratified ocean) are measurable electrically in their vertical component as gradients are crossed (Chave, 1984).

Ocean transport induction. Electrical induction in the oceans occurs by three processes: transport of seawater across the geomagnetic field (treated in this subsection); the influence of GIC on saltwater, a conductor (treated above); and variations in sea water due to variations in salinity and temperature (treated in the subsection above entitled Electrochemical effects in the ocean.) Bulk water transport was first measured electrically by Faraday in 1832, at the Waterloo Bridge with electrodes placed in the Thames River, but sunspot activity (unfortunately) masked the periodic influence of the Gulf Stream (Larsen, 1992). Induced voltage due to transport of saline water has been observed successfully, with a magnitude on the order of 25 mV per kilometer, measured on a cable fitted with electrodes in the Straits of Florida (Larsen, 1992). The GIC (with peaks up to about $50\ mV\ km^{-1}$ but with typical values of 10 to $20\ mV\ km^{-1}$) had been subtracted out of the data by hand. The voltages occur at frequencies from $10^{-3.8}$ to $10^{-7.0}$ Hz and are incomplete, and tidal variation and other outliers create peaks at around 10^{-5} Hz.

Oceanic charging. Two sources of electric currents in the ocean already described in this text are: storm clouds charging the ocean surface (above); and processes to charge water strata in the ocean itself. Electricity from both of these may be transmitted to the rock with which it is in contact via electrostatic induction (Cox, 1981). The oceanic lithosphere receives a quasi-static charge from the ocean. Due to the high metal content of the rock, both electrostatic and electromagnetic induction will occur if major changes to electric current in the oceans or to the geomagnetic field also occur.

Metabolic electrochemistry in the ocean. The metabolic action of micro- and macrobiota in the oceans may contribute to an electrical signal that is measurable. Bohlin et al. (1989) describes how fish are attracted to electric signals; this phenomenon might be related either to physiology or to food sensing. Brahic (2010) describes how an extensive network of microbial electric currents may exist in oceanic mud. Atekwana and Slater (2009) introduce the study of microbial geophysical signatures in a comprehensive manner; biogeophysics is an emerging field, and more research is warranted.

Surface Phenomena

Artificial signals. Earth electric currents may come from the transmission of electricity or electromagnetic radiation emanating from human-made sources (Pham et al., 1998; Keller, 1968) and also from on-ground activity, such as from electric trains. Telluric currents may come from electric fields set up intentionally as, for example, from a direct-current (DC) electric field designed to remove contaminants from soils (Probst and Hicks, 1993). Electromediation can be accomplished with a field strength of about 150 V m^{-1} . A complexing agent is added to the groundwater, and contaminants are attracted to wells for removal (Wong et al., 1997).

The magnitude of artificial telluric currents depends directly upon the generation process. Extremely low frequency radio waves are generated by heating the ionosphere, and are used by the US military to communicate with submarines, for example. Nuclear explosions above ground also create ionospheric VLF radiation, with frequencies of 10 kHz to 15 kHz (Barr et al., 2000).

Metabolic electrochemistry in soil. The daily action of plants, fungi, bacteria, lichen or algae that inhabit soil and rock fissures may produce electrical signals from electrochemical processes related to metabolism. Some evidence exists that soil microbes respond to changes in the geomagnetic field (Jie Li et al., 2009), though the converse has not been shown. Abdel Aal et al. (2010) report that the imaginary component of measured conductivity in sand is increased linearly as *Pseudomonas aeruginosa* are introduced to the grains. The imaginary component of conductivity is a measure of its dissipation, part of the field equations that model oscillating or alternating current. Abdel Aal et al. (2010) used low frequency (0.1 to 1000 Hz) signals for their study. No change to the real component of the conductivity was observed.

Regarding plants: despite the existence of diurnal electrical variations measured in sapwood (Gilbert et al., 2006), and in leaves and leaf stems (Gil et al., 2008), and also despite the invention of functional electrical circuitry powered by plants and trees (Yamaguchi and Hashimoto, 2012; Himes et al., 2010), no diurnal soil-root signal from plants has been detected (Love et al., 2008). A new sensor for these signals has recently been developed (Gurovich, 2009), but no evidence of diurnal signals has been published yet.

Exo-electron emission. The process of stress relaxation may release electrons after an initial priming, as can the addition of heat or photons to a previously stressed sample (Oster et al., 1999). These and related processes are termed exo-electron emission if the energy of the electrons is low (less than or equal to one electron volt), to distinguish them from high-energy electron emission phenomena, such as fractoemission. Exo-electron emission functions by means of traps and defects and requires a solid-gas or solid-vacuum interface for its action: it acts at a surface. Exo-electron emission may occur in the vadose zone or on the surface of the crust (Freund, 2011; Oster et al., 1999). Exo-electron flux is observed as less than or equal to 10^8 electrons (e^-) per square centimeter (Oster et al., 1999).

Groundwater Phenomena

Electrochemical effects in groundwater. As ionically-charged fluids travel in porous rock, an electric current is created by the motion of the suspended ions (Corwin and Hoover, 1979). This is the principle behind household chemical batteries, and is common in nature. The electrochemical effect found in ore bodies, for example, is akin to commercial electrochemical batteries in magnitude (a few volts) (Lile, 1996). While the chemistry of the fluid determines the voltage, the signal frequencies are controlled by the motion.

The electrokinetic effect. Just as the motion of ionically-charged fluids in porous rock creates an electrochemical current, so too the interaction of the charged fluid with the bounding rock creates a complementary charging in the rock itself. At the fluid-rock interface, a single layer of adsorbed ions attracts a second layer of the opposite sign, and these are sufficient to create an electric potential over a distance. This so-called streaming potential, caused by an electrokinetic effect, involves electrostatic induction by moving ions. Self potential is a combination of streaming potential (based on the electrokinetic effect) and of the diffusion of the ions themselves.

Typically, self potential is present in groundwater flows (Jardani et al., 2008; Jardani et al., 2006; Revil et al., 2003; Birch, 1998; Aubert and Atangana, 1996), and can be found in many geologic settings, such as sulphide ore bodies (Lile, 1996) and other mineral deposits, including graphitic deposits (Stoll et al., 1995), and at volcanoes, where the phenomenon is due to hydrothermal activity, changes in groundwater flow, and magma displacement (Zlotnicki and Nishida, 2003). In hydrothermal settings, streaming potential from electrokinetic effects is much stronger than associated thermoelectric effects (Corwin and Hoover, 1979). A streaming potential of up to 30 mV can be generated from a groundwater change of 50 cm, if the fluid resistivity is $10^2 \Omega \text{ m}$ and the rock permeability is 10^{-12} m^2 (Jouniaux and Pozzi, 1995). Streaming potential variations occur, with pulses in amplitude of 15 to 40 mV, and a frequency of 0.1 to 0.5 Hz (Jouniaux and Pozzi, 1997).

Seismic-dynamo induction. Rock is displaced as seismic waves pass through. Groundwater in the pore space is displaced as well, as are ions in the groundwater. The motion of ions relative to the geomagnetic field creates circularly or elliptically polarized electric fields, with opposite orientations for positive and negative ions. This effect was reported in 2009, and was observed both for artificial seismic waves from blasting and for natural seismic waves (Honkura et al., 2009). The magnitude of the seismic-dynamo effect is on the order of μV to mV, and frequency depends upon the ions in the groundwater, with observed values between approximately 10 and 50 Hz.

Cyclotron frequency is the name given for charged particles moving in circular motion perpendicular to a magnetic field. Each charged particle has a cyclotron frequency based on its charge, mass and velocity relative to the magnetic field. The observed seismic-dynamo effect reported in Honkura et al. (2009) shows electric frequencies that may be interpreted as resonances of the cyclotron frequency of particles and the geomagnetic field, with bicarbonate, chloride, sodium and calcium taken as constituents. These vary in abundance by location, and account for differences of orientation in the observed electric fields.

Radioactive ionization. Radionuclides release energy as they decay, and that energy can ionize surrounding material. Radon gas is one example. The most common isotope of radon (^{222}Ra) has a half-life of 3.8 days (Jordan et al., 2011). Several thousand scientific publications have described the presence of radon as co-seismic with major events. Radon at the Earth's surface ionizes particles in the air, and the motion of these ions creates atmospheric electrical phenomena linking the surface to the ionosphere (Pulinets, 2007). Co-seismic ionospheric anomalies might be attributed to the action of ions created as radon is released. Studies of radon occurrence as an earthquake precursor often look for radon concentrations in groundwater (Jordan et al., 2011). It is plausible to assume that radon ionizes other atoms in groundwater, and that the motion of these ions can create an electric signal. Other radionuclides could do the same.

Other Terrestrial Phenomena

Volcanic electromagnetic signals. Hata et al. (2001) report detection of consistent electromagnetic signals during the Izu-Miyake volcanic eruption of 2000 in Japan. The signals preceded the eruption by a week, and are associated with changes to the surface of the Earth from magma dike growth. The exact mechanism of the signal generation is unknown. The observational apparatus was set to detect extremely low frequency radio waves (between 10 Hz and 300 Hz). Below 10 Hz, ionospheric and other geomagnetic signals predominate, and above 300 Hz, lightning noise predominates. The full spectrum of the occurring radiation is not known.

Seismic electromagnetic signals. Matsumoto et al. (1998) report television signal interference associated with the 1995 Kobe earthquake in Japan. The electromagnetic radiation preceded the earthquake by 6.5 hours, and was characterized as having a magnitude of a few tens of mV m^{-1} , a frequency in the 217 MHz range with micro second duration. Other reports of electromagnetic phenomena during earthquakes are common, typically involving ionospheric disturbances (Zolotov et al., 2012; Heki, 2011; Perrone et al., 2010; Pulinets, 2007; Singh and Singh, 2007; Popov et al., 2004; Pulinets and Boyarchuk, 2004; Davies and Baker, 1965).

Seismic electric signals. Three types of signals have been reported from a network of monitoring stations in Greece (Varotsos et al., 1993a). First, a gradual variation in the electric field of the Earth (GVEF) has been recorded, on the order of weeks or more before an earthquake, and with voltage an order of magnitude higher than other purported precursory SES. These occur rarely. Second, presumed seismic electric signals, on the order of hours to 11 days before an earthquake, with an order of magnitude in the millivolt range, occur commonly. Third, a short duration pulse, 1 to 4 minutes precedent to seismic waves, with an order of magnitude in the volt range, occur rarely (Ralshovsky and Komarov, 1993; Varotsos et al., 1993a). All three are low-frequency signals, less than or equal to 1 Hz (Varotsos et al., 2011). Similar seismic signal data have been reported in Japan using the same method (Uyeda et al., 2009).

Fractoemission. Fractoemission, in which electrons escape from a freshly cleaved surface, has been described in James et al. (2000). Their observations show electric charging of about 10^{-5} coulombs per kilogram for volcanic ash. Fracture experiments have recorded up to 10 parts per million (ppm) ozone production from the crushing of typical terrestrial crustal rock, with the ozone being generated by electricity from physical charge separation during fracture (Baragiola et al., 2011). The energy of the emitted electrons can be very high, up to tens of thousands of electron volts (keV) or higher. The electrons are produced as the surface attains and maintains a charge, often pulling electrons from deep inside, termed the Malter effect (Oster et al., 1999). Electromagnetic emission resulting from a single crack in ice under various stress regimes has a frequency of 10^3 to 10^5 Hz, with a change in potential of about 2 mV (Shibkov et al., 2005).

Defect charging. Pressure can cause defects in materials. Defects can both liberate charge carriers, such as ions or electrons, and create charge acceptors, such as holes or lattice vacancies. Pressure changes can also result in the reorientation and charging of lattice defects, called defect charging. These processes have characteristic electromagnetic emissions, with frequencies in the range 10^2 to 10^6 Hz for crystals with predominantly ionic bonds (Shibkov et al., 2005).

Defect charging has been studied as a candidate for the cause of electric signals associated with earthquake phenomena (Freund, 2011; Varotsos et al., 1998). Takeuchi and Nagao (2013) demonstrate an electromotive force of 80 mV in gabbro with 50 MPa of load. Freund (2011) proposes that peroxy defects present in silicate rocks, where the tetrahedral silicate bonds are $O_3Si - OO - SiO_3$ instead of $O_3Si - O - SiO_3$, can be a source of mobile charge carriers. Peroxy bonds commonly break under pressure. The new structure can accept an electron from a neighboring silica-oxygen tetrahedron. That transfer, in turn, creates a positive hole in the electron donor. Positive holes can also interact with negative ions liberated from the lattice by changes in pressure, e.g. from seismic waves. This condition may form paths for electric current to flow.

Such defect phenomena are fundamental to how semiconducting materials work, and are probably widespread in nature. General terms for the process described above are "charge-vacancy coupling" or "defect and charge transport" (Raymond and Smyth, 1996). Peroxy bonds exist in silicate rocks in enough numbers to create measurable electricity. The process of charge-vacancy coupling is nontrivial in all rocks, given the right conditions. Typical electric currents from defect charging in rock are on the order of 1 nanoampere at 20 megapascals of pressure (Freund, 2011).

The piezoelectric effect. The piezoelectric effect (electric field or charge caused by applied pressure) has been modeled as a crystal lattice effect, as deformation from stress or strain displaces the positions of shared electrical bonds (Mason, 1950; Cady, 1946). This is the mechanism first described by Voigt (1910) (Katzir, 2006). Stress is an internal pressure of particles acting on each other, caused by external load. Strain is a change to the shape of a material, caused by stress. Piezoelectricity is based on the symmetry of a crystal.

A more in-depth treatment of the ideas in the following paragraph can be found in Sands (1994). Crystals can have three types of symmetry. If the coordinates of a crystal lattice are hypothetically reflected through a point, a new inverse lattice with new inverse coordinates is created. If the inverse lattice is identical to the original crystal lattice, the crystal is centrosymmetric. If the inverse lattice is not identical to the original crystal lattice, but the inverse lattice can be rotated to match the original lattice, then the crystal is non-centrosymmetric. If the inverse lattice is not identical to the original crystal lattice, and the inverse lattice cannot be rotated to match the original lattice, then the crystal is chiral, also called enantiomorphic. The terms "chiral" and "enantiomorphic" are synonyms and refer to handedness. These crystals occur in both left-handed and right-handed forms.

For a more in depth treatment of the following descriptions of piezoelectricity, see Cady (1946). A centrosymmetric crystal lattice ought not allow for any electric charge to build up under pressure. Every

bond displaced will be countered by another bond whose displacement can cancel the charge of the first. However, some minerals with centrosymmetric crystal lattices, such as zeolites and topaz, express electricity under stress and strain. No explanation has yet been proposed for this anomaly.

Many chiral and non-centrosymmetric minerals display the piezoelectric effect. The most well-known is quartz, and the most intuitive application at one time was in record needles or microphones, to change variations in pressure into an electrical signal. The electric signals in these devices are very small, on the order of 10^{-12} coulombs per newton (C N^{-1}) for a single crystal. Piezoelectric data for minerals are presented in Chapter 5.

The thermoelectric effect. A homogeneous conductor expresses a voltage when there is a temperature gradient, with electrons (the more negative) at the cold end. This is called the Seebeck effect (or the thermoelectric effect), and is directly observable as electric current when two dissimilar conductors are connected to each other under a thermal gradient (Goupil et al., 2011). Thermocouples are based on this effect. For more information on the following discussion, see von Baeckmann et al. (1997). Corrosion of bridges and other metal structures where dissimilar metals are found is caused by this phenomenon. In the crustal materials of the Earth, the thermoelectric effect is important in ore bodies, and in regions with high heat flux. The magnitude is on the order of 10^{-5} volts per degree Kelvin. (See Chapter 5, Mineral Data, p. 49.)

Geologic case studies are abundant. Shankland (1975) describes measurements of thermoelectricity from rock samples in a laboratory setting. Leinov et al. (2010) describe thermoelectric effects in brine-saturated sandstone *in situ*. The thermoelectric effect from ore minerals, for example from pyrite during computer-aided resistivity surveying for gold (called pyrite-thermoelectric surveying), has also been described (Zhang Yun-qiang et al., 2010; Cao Ye et al., 2008), as has thermoelectricity from magnetite grains in the Earth's crust, and especially in the middle-lower crust (Junfeng Shen et al., 2010). This widespread effect is similar to defect charging (described in the Defect Charging subsection above, p. 12) in that both processes mobilize charge carriers and holes (acceptors), the one with a temperature gradient, the other with pressure.

Note that both the temperature effect listed in this section and the pyroelectric effect, listed below, have sometimes been lumped together as the thermoelectric effect. They have been described as such by Corwin and Hoover (1979), who treat temperature effects as unwanted signal noise in self potential surveying. They are unwanted if one is looking for electrical indications of water flow (from the motion of ion-rich water, and from the electrokinetic effect) for geothermal use.

The pyroelectric effect. Water is a polar molecule. Any material whose structure has an axis with dissimilar ends, and whose ends are of uneven electric charge, is a polar material. The dissimilar ends are called a permanent electric dipole. In polar minerals, electric charges located at the ends of the permanent electric dipole are rapidly neutralized by the environment under normal conditions. During heating or cooling, however, the charges do not have time to dissipate, and are detectable. This phenomenon is called pyroelectricity, or the pyroelectric effect (Bhalla et al., 1993). It is sensitive to both the change in temperature and the rate of change in temperature of a polar material. Tourmalines are common minerals that exhibit this effect (Hawkins et al., 1995). Typical magnitudes are on the order of 10^{-6} coulombs per square meter per Kelvin for single crystal samples.

Magma electrochemistry. The motion of magma during volcanic processes and also of volatiles related to volcanism can hypothetically create an electric signal. Volatiles can in some instances ionize surrounding materials, and magma itself can be rich with ions. No study of these natural electrical phenomena is found in the literature, to the author's knowledge. Toramaru and Yamauchi (2012), in trying to create an analog to layered dikes and sills, used an externally applied electric field to create cyclically-layered structure in an artificial material, PbI_2 .

Radioactive emission. Electric current can hypothetically be caused directly by the motion of charged particles released by the breakdown of radionuclides. For example, α -particle emission is a steady source of charged particles, and therefore creates an electric signal. Significant radioactive decay has been reported in natural fission reactors as having occurred in the past (Stille et al., 2003; Jensen and Ewing, 2001; Gauthier-Lafaye, 1997). Electrical observations of this phenomenon are not in the published literature, to the author's knowledge.

Deep Terrestrial Phenomena

Geomagnetic jerk. Short-term changes to the second derivative of the geomagnetic field are termed geomagnetic jerks, and arise from electrical signals traveling through the mantle during deep (core) events

(Nagao et al., 2003). The transmission of electricity from the upper mantle to the lower crust is likely, but has not been observed. Separate geomagnetic jerks of limited extent have been modeled as having been caused by single events originating in and traveling through Earth's core, as described in Chulliat et al. (2009). The physical models suggest that quantifying mantle conductivity is still a work in progress (Malin and Hodder, 1982).

The electrical conductivity of the deep mantle is two orders of magnitude higher than that of the shallow mantle, with a transition depth of 670 km. Another region of higher conductivity transition occurs at 2700 km, the D'' layer, so named as part of Keith Bullen's Earth taxonomy from the 1940s (Duffy, 2008; Ohta et al., 2008; Constable and Constable, 2004; Chao, 2000). The increased conductivity has been modeled using a combination of proton conduction if hydrogen is present, and polaron conduction, which is electron hole hopping between Fe^{2+} and Fe^{3+} ions in minerals that contain iron (Yoshino, 2010). Both of these are semiconductor phenomena. A wet mantle is not generally required to fit the observations (Yoshino et al., 2008). The increase at the D'' layer is also related to the transition from perovskite, an orthorhombic mineral, to post-perovskite, a sheet mineral, that occurs at this depth (Duffy, 2008).

Bulk rock responses to local changes in the geomagnetic field caused by changes in the Earth's core ought to affect ore bodies or other rock with high conductivity. No articles are apparently available that report long-term telluric currents caused by fluctuations in the geomagnetic field originating in the Earth's core.

Monitoring Telluric Currents

Thirty-two distinct causes of telluric currents have been listed above. Mechanisms that occur with regular cycles include: artificial signals, eleven-year GIC, diurnal GIC, and seasonal phenomena in the atmosphere (such as storm charging and lightning strikes), in the oceans (such as ocean transport induction) and in groundwater (such as the electrochemical effect). Lightning phenomena, GIC, TID and the thermoelectric effect are the mechanisms that have been of the greatest interest to society, since these can disrupt communications or destroy structures and equipment.

The geomagnetic field is currently monitored by an extensive network of government-run observatories and includes a near-real-time international data repository (Intermagnet, 2012; Kerridge, 2001). The same is not the case for Earth's telluric phenomena, but some national institutions and systems are in place and usually produce freely-available data. China, Russia, South Africa, Japan, Greece, the United States and Canada, for example, all have networks of magnetotelluric stations to monitor seismic events as they sometimes correlate with electrical and magnetic signals. References or websites exist for China (Xuhui Shen et al., 2011), Russia (ISTP SB RAS, 2012), South Africa (Facebook, 2012; Fourie, 2011), Japan (Geospatial Information Authority of Japan, 2010; Uyeshima et al., 2001; Kawase et al., 1993), Greece (Varotsos et al., 1993a), and the U.S. and Canada (Incorporated Research Institutions for Seismology, 2012; Zhdanov et al., 2011). No global correlation network of electric signal data exists in real time, though the MTNet, maintained by a working group of the International Association of Geomagnetism and Aeronomy will likely assume this role (MTNET, 2012). This association houses research results and data, acts as an international forum, and hosts workshops and conferences.

Magnetotelluric stations generally consist of portable magnetic and telluric sensors, and are used for economic geological exploration. Their application is widespread. A global, permanent network of dedicated electrical-measurement stations would be a complement, as would enough data on how Earth electric currents are formed and transmitted to construct a mathematical model to correlate magnetic and electrical phenomena.

CHAPTER 3

CRYSTALLOGRAPHY OVERVIEW

Definition of a Crystal

Among the various definitions of a crystal, the following from Dyson (2009, p. 214) is mathematically astute: “a [crystal] is a distribution of discrete point masses whose Fourier transform is a distribution of discrete point frequencies” in reciprocal space. Fourier transforms perform this: they take coordinates and create a new space out of them, where periodic patterns are easily recognized. The new space is called a reciprocal space.

The arrangement of atoms in a crystal lattice is periodic. Their positions relative to the other atoms are specified, and the entire arrangement, called a unit cell, repeats itself, forming the crystal. The positions of atoms and the geometry of the unit cell are observable in X-ray diffraction patterns (XRD), made by shining X-rays through a crystal and exposing a film. X-ray diffraction is, for example, how Franklin, Watson and Crick were able to determine the double-helical structure of deoxyribonucleic acid crystals (DNA). Franklin made the films; Watson and Crick utilized them (Watson et al., 2012). A large percentage of crystallographers are currently engaged in biomedical pursuits; the arrangement of atoms within molecules may indicate properties suited (or unsuitable) to medical applications.

Dyson’s definition of a crystal, above, is generalizable to two-dimensional cases, such as tiling problems. For example: what regular tile shapes can cover a floor without leaving gaps or overlapping, in a periodic pattern? For another example: what regular tile shapes can cover a floor without leaving gaps or overlapping, in a non-periodic pattern? These latter are called Penrose tiles, and periodicity can sometimes be found in looking at the non-periodic tiling from a higher dimension, as a projection (Senechal, 1995).

Dyson’s definition of a crystal is generalizable to one-dimensional cases, such as the distribution of prime numbers among the natural numbers (Dyson, 2009). It is also generalizable to high-dimensional theoretical cases. Mathematics allows for this view. The more mundane is here: in three dimensions, atoms are connected in a crystal lattice, influencing the shape and parting of the material.

By definition, all minerals are crystalline. In a crystal, atoms are connected by chemical bonds that repeat periodically. Patterns in these bonds influence the various forms of energy available to a system. A pyroelectric mineral, for example, will translate some heat energy into electricity, as shown by the line connecting “Temperature” and “Field” in the Heckmann diagram in Figure 1. A Heckmann diagram is a schematic representation of the coupling between mechanical energy and other physical effects (Ballato, 1995; Heckmann, 1925).

Minerals in a real setting serve as home to ions and elements, and these may be liberated or sequestered, depending on thermodynamic conditions. This is an activation-moderated process. Minerals host defects of form, vacancies, interstitials, lattice displacements and dislocations, including the newly discovered pleat dislocation (Irvine et al., 2010), and these hold energy. Mineral defects can serve as holes to carry electric charge, such as is of utmost importance to materials science and computing. Also, minerals, being regular forms, are subject to resonant phenomena that may be important on various scales, from small to large (e.g., thin-film applications, radio oscillators, laser-beam generation, strain-hardening in metal fabrication, etc.)

Crystal Systems

For a more in-depth discussion of the following description, see Sands (1994). Minerals exist in different phases depending on external perturbations or the parameters of the system where they grow, such as temperature, pressure, or the abundance or mobility of various atoms and ions. Available energy can dictate the structure of the lattice, and the transitions between forms of different symmetries indicate different amounts of internal energy. Ideally, crystals are limited to forms that can fill the space continuously, without leaving gaps or overlapping. Periodic repetitions about an axis, so that six equal rotations return the unit cell to its original location, for example, constitutes a type of rotational symmetry.

FIGURE 1. Heckmann diagram showing couplings among mechanical, electrical and thermal effects. Drawing © 1995 IEEE, from Figure 1 of Ballato, A., 1995, Piezoelectricity: Old effect, new thrusts: IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, v. 42, p. 916–926. Reproduced with permission.

Six-fold rotational symmetry defines the hexagonal crystal system. If the unit cell is built upon a triangle instead of a hexagon, the crystal is part of the trigonal crystal system. These two crystal systems have a rotational axis, labeled the *c* axis. Growth along the *c* axis forms a hexagonal or trigonal cylinder. In mineralogy, such cylinders are called prisms. If the prism has square sides instead, the crystal is tetragonal.

If the unit cell is not prismatic, but the sides of the cell are perpendicular to each other, then the crystal is either cubic (equal side lengths), or orthorhombic (unequal side lengths). If the sides of the unit cell are not perpendicular to each other, but one set of sides is parallel, then the crystal is monoclinic. If none of the sides of the unit cell are parallel, the crystal is triclinic. The seven crystal systems are: hexagonal, trigonal, tetragonal, cubic, orthorhombic, monoclinic, and triclinic. With three axes from which to work (in three-dimensional space), and also the possibilities of extra symmetries, such as mirrored forms, these seven crystal systems make up 32 crystal classes.

Symmetry is an ordinal concept. Some symmetries are higher than others. A crystal with a six-fold rotational axis (angles are 60° , which is $360^\circ/6$) has higher symmetry than one with a two-fold axis (angles

are 180°, which is 360°/2). Likewise, a crystal with three two-fold rotational axes has higher symmetry than a crystal with only two two-fold axes. The complexity is an indicator of internal energy (Slater, 1972).

Thermodynamics

For a deeper treatment of the following description, see Goodisman (1987). The thermodynamic relations of internal energy that determine transformations in rocks and minerals may be modeled using the equation for internal energy of a system:

$$U = TS - PV + \mathbf{pE} - \mathbf{MB} + \sum \mu_X N_X, \quad (2)$$

where U is the internal energy of the system, T is the temperature, S is the entropy, P is the pressure, V is the volume, $\mathbf{p}$ is the electric polarization tensor, $\mathbf{E}$ is the electric field tensor, $\mathbf{M}$ is the magnetization tensor, $\mathbf{B}$ is the magnetic field tensor, μ_X is the chemical potential of each phase present, and N_X is the number of constituent particles of each phase, with $\sum$ taking the mathematical meaning summation for the various values of the product μ_X times N_X where a unique X corresponds to each phase present. For each pair of terms on the right side of Equation 2, the first term is intensive, and the second term extensive. Intensive parameters depend upon the amount of material in a system. Extensive parameters do not.

Manning and Pichavant (1983), writing of thermodynamic properties, report that the presence of boron and fluorine greatly reduce the solidus temperature in wet granitic melts. This would imply the formation of tourmaline and topaz, materials in which fluorine and boron can be sequestered, respectively, from the melt. (See Table 4 in Appendix A, p. 148, for a description of the minerals tourmaline and topaz.) Using their data, 15% boron oxide (B_2O_3) in a powdered sample (called a charge) of Qz-Ab-Or lowers the solidus temperature at 10^8 pascals (Pa) (1 kbar) from 715° Celsius (C) to less than 600°C. The solidus is the temperature (and/or pressure) below which a material is completely solid, and the mineral-name abbreviations are Qz as quartz, Ab as the plagioclase feldspar albite, and Or as orthoclase feldspar. In short, adding 15% boron oxide to the charge lowers the solidus temperature by 16% at the cited pressure. Likewise, adding 4% fluorine to a separate Qz-Ab-Or charge lowers the solidus temperature by 23%.

In the first case of adding boron oxide, tourmaline may take up 16% of the internal energy of the system, if the other parameters are constant. In the second case of adding fluorine, topaz may take up 23% of the internal energy of the system, if the other parameters are constant. Manning and Pichavant (1983) do not report any electrical or magnetic data in their study.

Phase Transitions

For a more thorough treatment of the following description, see Snider (1986). Physical parameters within a thermodynamic system may depend on each other. For example, in an ideal gas,

$$PV = n_m RT, \quad (3)$$

where P is the pressure, V is the volume, n_m is the number of moles of the gas, R is the ideal gas constant (the product of the Boltzmann constant and Avogadro's number) and T is the temperature. (An ideal gas is one where the physical interactions of the gas molecules are perfectly elastic; they behave as point masses.)

The difference between the number of variables and the number of controlling conditions on those variables is the degrees of freedom of a system, and these can be used in descriptions of the history of a system or in materials fabrication:

$$N_f = n_v - n_c, \quad (4)$$

where N_f is the number of degrees of freedom, n_v is the number of variables, and n_c is the number of controlling conditions. The term n_v includes both dependent and independent variables; the addition of a dependent variable to the system is accompanied by its controlling condition, so N_f stays the same.

In a thermodynamic system, materials with different chemical compositions or physical states are called phases. Liquid water and water vapor are two separate phases in this conception. The number of phases coexisting at thermodynamic equilibrium within a simple substance is described by Gibbs' phase rule:

$$\Phi = N_v + 2, \quad (5)$$

where Φ is the number of phases in equilibrium and N_v is the number of independent variables (Gibbs, 1878). Never has this been seen to be violated, but it is not clear why this arises if from anything other than the definitions of the system at equilibrium. Matsunaga and Tamaki (2008), for example, define a quasi-liquid state, composed of two phases (solid and liquid) taken as a single phase in the pre-melting regions of ionic crystals. Their system is not at equilibrium, but their definition is an attempt to bridge the gap. Their quasi-liquid will occur if the phase transition is continuous, with both phases coexisting during the transition (a first order transition) but not if it is discontinuous (a second order transition).

Man (1986) presents a topological treatment of Gibbs' phase rule, arguing mathematically that if the topological surface mapped from this rule is slightly perturbed, there should be a nonempty set of spaces in which the phase rule is violated. This is true for any mathematical rule or use of language.

Using Mathematics to Describe Crystal Properties

Voigt notation is used for describing crystal phenomena (Bass, 1995). Here is an extended example to illustrate the notation: imagine a directed pressure acting on a crystal. The crystal might transmit the directed pressure in a few different ways. Stress (internal) and, perhaps, strain (external deformation) will occur, and some of the energy from these may now be available for other processes such as piezoelectric generation. The original directed pressure provides this energy to the crystal lattice. The orientation influences the outcome.

There are two types of stress and strain: compression (being pressed together); and tension (being pulled apart). In Voigt notation, these two are described differently. For compression, with an x , y , and z axis (in the Cartesian basis, in three dimension), the indices 1, 2, and 3 are used. Compressional stress and strain along the x axis are described with the index 1, for example. Likewise, index 2 denotes (compressional) stress or strain directed along the y axis; the stress or strain squarely strike a crystal face if that face lies normal to the y axis. The same follows for 3, the z axis, and crystal faces perpendicular to the z axis.

Tension is annotated differently. Tensional stress and strain are described as a shear. Two opposing forces (causing the shear) are laterally separated. In Voigt notation, the indices 4, 5, and 6 denote shear planes. Number 4 stress and strain indicate shear along the plane made by the y and z axes (called the yz plane). Number 5 stress and strain indicate shear along the xz plane. Number 6 stress and strain indicate shear along the xy plane. The indices 4, 5, and 6 denote effects perpendicular to the x , y , and z axes, respectively. By using both sets of indices one can annotate both compression (1, 2, and 3) and tension (4, 5, and 6) to get an accurate description of forces and other coefficients acting on or through a crystal in three dimensions. In practice, crystals are cut into thin plates perpendicular to the x , y , and z axes, and the properties of these plates are reported, with their Voigt indices. Cut samples are called plates or crystal plates.

Elastic Moduli

Compliance (s) is the ability to turn stress into strain. Stiffness (c) is the ability to receive mechanical energy as stress and resist deformation. Together, the compliance and stiffness coefficients are termed the elastic moduli of a material. Equations for elastic moduli were developed conceptually from Hooke's law, which states that the deformation in a spring is proportional to the load on it (Bentahar, 2000). The equation

$$\sigma(i) = c(ij) \eta(j) \quad (6)$$

relates stress to strain, where $\sigma(i)$ is stress in the i direction (whether 1, 2, 3, 4, 5, or 6, in Voigt notation) $\eta(j)$ is strain in the j direction (whether 1, 2, 3, 4, 5, or 6), and $c(ij)$ is the stiffness coefficient. Every and McCurdy (1992) offer a more thorough treatment of this and the following description. The coefficient $c(ij)$ describes stress (σ) in the i direction and strain (η) in the j direction. The coefficient $c(14)$ signifies the stiffness for stress (σ) along the x axis, and strain (η) along the yz plane. Values can be negative. As a

mnemonic, the sigma (σ) has an “s” sound, just like the last letters in “stress.” The eta (η) looks like an “n,” just like the last letter in “strain.”

Likewise,

$$\eta(i) = s(ij) \sigma(j) \quad (7)$$

relates strain to stress, where $s(ij)$ is the compliance coefficient, and the other symbols are as above. Note that the coefficient $s(14)$ signifies the compliance for strain (η) along the x axis, and stress (σ) along the yz plane.

The elastic moduli described above have two indices, one for stress and one for strain. These moduli are denoted second-order because they have two indices. Elastic moduli may also be measured for one stress and two strain directions (denoted third-order, with three indices) or higher. For both stiffnesses and compliances in moduli higher than second-order, the first subscript denotes the direction of stress, and all of the following subscripts denote strain directions, so $c(615)$, for example, denotes shear stress along the xy plane (perpendicular to the z axis), normal strain on the x plane, and shear strain along the xz plane (perpendicular to the y axis). If values are available for the two strains (1 and 5) and for the stiffness $c(615)$, then the shear stress along the xy plane (6) can be calculated. The two strain values and the stiffness coefficient are multiplied.

Voigt Notation for Other Crystal Coefficients

Other crystallographic terms use Voigt notation, and Nye (1957) offers a broad introduction. For example, relative dielectric strength (the ability to store electric charge) is written as $K(i)$ with the index taking a value of 1, 2, or 3. Likewise, $d(ij)$ denotes a piezoelectric strain rate, with the location of the electricity shown by the first subscript, and strain by the second. It is called the piezoelectric strain coefficient and signifies change in strain per change in electric field. The four piezoelectric coefficients are $d(ij)$, $e(ij)$, $g(ij)$, and $h(ij)$. The piezoelectric stress coefficient is $e(ij)$ and signifies the same as $d(ij)$, except that stress is denoted instead of strain. The other two coefficients, $g(ij)$, and $h(ij)$, are analogous to $d(ij)$ and $e(ij)$, but denote electric polarization instead of electric field. Strain versus electric field is the easiest to measure, and, in practice, $d(ij)$ is the most widely reported. Piezoelectricity is also generalizable to a single coefficient, the electromechanical coupling factor, $k(ij)$. In every instance, whether $d(ij)$, $e(ij)$, $g(ij)$, $h(ij)$, or $k(ij)$, the first index indicates the location of the electricity.

Piezoelectric phenomena occur in various crystals, and a number of specialized cuts can be made to examine electrical properties. A quartz plate with an AT orientation, for example, is cut in a plane that contains the x axis and is inclined $35^\circ 15'$ from the z axis, and is used for quartz resonators (Reed et al., 1990). A Z-cut plate, likewise, is cut perpendicular to the z axis, which corresponds to the c axis of the crystal. An X cut is similar, but perpendicular to the x axis.

The crystallographic axes a , b , and c correspond to the x , y and z axes if the crystal form is orthogonal. If not, the c axis takes precedence as the z axis, and the rest of the Cartesian coordinate system is matched up according to the symmetry. If possible, an a axis of the crystal will be set to correspond with the x axis, as is the case with quartz, for example, in which one of three a axes are set to x ; the y is set orthogonal to x .

Measurements of other phenomena generally make use of Voigt notation. Those besides stress, strain, dielectricity, and piezoelectricity are discussed in the section Electric and Magnetic Properties, p. 20. Terms in the following section make use of Voigt notation.

Crystal Properties Across a Range of Temperatures and Pressures

The following descriptions are from Every and McCurdy (1992). Measurements across several temperatures and pressures are termed temperature slopes and pressure slopes, respectively, if the functions are linear. For stiffness coefficients of the elastic moduli, these are defined as

$$Tc(ij) = \partial (\ln c(ij)) / \partial T, \quad (8)$$

where $Tc(ij)$ is the temperature stiffness slope, $c(ij)$ is the elastic stiffness, T is the temperature, $\ln$ signifies the natural log, and ∂ signifies the partial derivative. The natural log is used in Equation 8 to compare

numbers of different magnitudes more easily. The partial derivatives are used in the same way that rise over run is used in generating the slope of any line. This equation is empirical (rather than theoretical); the natural log is used to make looking at a wide spread of values manageable.

Likewise, the equation

$$Pc(ij) = \partial (\ln c(ij)) / \partial P, \quad (9)$$

where $Pc(ij)$ is the pressure stiffness slope, P is the pressure, and the other terms are as above, gives a value for the change in stiffness with a change in pressure. Where the entropy or temperature are constant, the pressure stiffness slopes are

$$Pc^S(ij) = \partial (\ln c^S(ij)) / \partial P, \quad (10) \quad \text{and}$$

$$Pc^T(ij) = \partial (\ln c^T(ij)) / \partial P, \quad (11)$$

where $Pc^S(ij)$ is the adiabatic pressure stiffness slope, $c^S(ij)$ is the adiabatic stiffness coefficient, $Pc^T(ij)$ is the isothermal pressure stiffness slope, $c^T(ij)$ is the isothermal stiffness coefficient, and the other terms are as above. The adjective "adiabatic" signifies constant entropy; the adjective "isothermal" signifies constant temperature.

Where the relations are not linear as the slope of the natural log, polynomial terms are used, defined as

$$Tc^{(n)}(ij) = [1 / (n! c_0(ij))] [\partial^n c(ij) / \partial T^n], \quad (12)$$

where $Tc^{(n)}(ij)$ is the polynomial temperature stiffness factor, $c_0(ij)$ is a stiffness value (from observation), n is the degree of the derivative, $!$ signifies factorial, and the other terms are as above (Every and McCurdy, 1992). All the terms on the right side of Equation 12 constitute the coefficients of a MacLaurin series, which takes differentiable functions and breaks them into distinct parts for each dimension of analysis, with differentiation about the origin. The values of $Tc^{(1)}$, $Tc^{(2)}$, $Tc^{(3)}$, and so on, are added together to give a result. Higher values of n give a more precise result. Like the equations above, Equation 12 is built upon the concept of rise over run, which, in this case, is change in the stiffness coefficient over change in temperature.

Various properties of crystals are measured across a range of temperatures and pressures, and the equations for them take a similar form to the equations discussed here. Note that the compliance coefficient s can be substituted for c into any of these equations, though they might still be termed "stiffness" slopes in the literature rather than compliance slopes. Generating empirical temperature and pressure equations requires more data than are often gathered. While graphs of temperature and pressure variation data are not uncommonly found, equations themselves are somewhat uncommon for minerals and other earth materials to date.

Electric and Magnetic Properties

This section lists twenty-four mineral properties that produce electric and magnetic phenomena or are related to them. Further information can be found in Sidebottom (2012) and Hoddeson et al. (1992).

Conductivity and Dielectricity

The inverse of resistance is called conductance and is measured in Ω^{-1} (called siemens, S, in *le système international d'unités* (SI) notation). Conductors generally have conductance values of 10^5 to 10^8 S, semiconductors of 10^{-7} to 10^5 S, and insulators of less than 10^{-7} S (Guéguen and Palciauskas, 1994). The range in conductance is about 32 orders of magnitude, from 10^{12} to 10^{-20} S. The charge carriers in conductors (metals) and semiconductors are electrons. The difference lies in the amount of energy it takes to mobilize the charge carrier, with semiconductors requiring energy to overcome the band gap. At extremely low temperatures, metals are optimized for conduction, while semiconductors behave nearly as insulators at extremely low temperatures, because the required activation energy is not present. Insulators are similar to semi-conductors in that there is an activation energy required for the flow of electric charge, but the charge carriers are ions rather than electrons (Parkhomenko, 1967).

Resistance in a material increases as more material is added. A standard measure for electric current flow is resistivity, measured in $\Omega \text{ m}$ typically; this measure does not change with the size of the material. Resistivity can be measured by applying current to a material of known cross-section, and dividing by the length. Geophysical techniques exist for measuring resistivity in the ground (Loke and Barker, 2006). Conductivity is the inverse of resistivity and is typically measured in S m^{-1} .

A material which impedes the flow of electric current by storing some of the energy is characterized as being dielectric. Dielectric materials store charge, and this is termed capacitance. For materials subjected to alternating electric current, dielectric loss (as heat) is a measure of capacitance (Parkhomenko, 1967).

Piezoelectricity, Piezomagnetism and Their Converse Effects

Some minerals translate seismic energy into electrical signals, termed piezoelectricity. The converse effect is also observed. In the converse piezoelectric effect, an electric field (or polarization) will produce stress and strain (Cady, 1946). Both the piezoelectric effect and the converse piezoelectric effect have magnetic analogs. The piezomagnetic effect is the production of magnetization or a magnetic field caused by stress or strain. Under the converse piezomagnetic effect, a mineral exposed to a magnetic field will deform. All four effects are limited to materials whose lattices are asymmetrical, to allow for a net result caused by deformation.

Electrostriction and Magnetostriction

For a more extensive treatment of the following, see Blinc (2011). All non-conducting materials will constrict under an applied electric field, as the opposite charges on separated material faces attract; this phenomenon is called electrostriction. Ferromagnetic minerals will change shape as they magnetize; this is called magnetostriction.

Pyroelectricity, the Seebeck Effect and Thermoelectricity

A mineral that is by nature polar (e.g. water ice) ought to have a spontaneous electric charge on its c axis, but this charge commonly dissipates to the environment, and is not observed. A change in temperature will produce a new charge build-up, and this is termed pyroelectricity. Two types exist, namely, primary pyroelectricity, which arises from the contribution of polarity within the lattice, as described above, and secondary pyroelectricity, which is caused by the piezoelectric effect as the lattice expands or contracts while heated or cooled. Pyroelectricity is measured as

$$p = \Delta p / \Delta T, \quad (13)$$

where p is the pyroelectric coefficient, p is the electric polarization in C m^{-2} , T is the temperature in Kelvin or Celsius, and Δ signifies change (Bhalla et al., 1993). From Equation 13, the product of the pyroelectric coefficient and the change in temperature will give the change in polarization.

The Seebeck effect is seen at the junction of two dissimilar conductors subjected to a temperature gradient, and produces electric current (Gould et al., 2008). More information related to the following description can be found in Goldsmid (2009). Thermoelectricity is a general term for the liberation of charge carriers in a material with heating, and includes both the Peltier effect and the Thomson effect. While the Seebeck effect describes how a temperature gradient within a material mobilizes charge carriers, the Peltier effect describes heating at the junction of two dissimilar conductors, that opposes the electricity generation; the Thomson effect is a generalization of the Peltier effect to a single material wherein the Seebeck effect varies with temperature, acting as if extra junctions exist. These three are thermoelectric effects.

Ferroelectricity, Antiferroelectricity and Paraelectricity

A more in-depth treatment of the ideas contained in the following three paragraphs can be found in Blinc (2011). Some materials may exhibit piezoelectricity. If the effect is reversible (so that the sign of the polarization can be switched by applying a larger electric field of opposite sign), then the material is termed ferroelectric. The name “ferroelectric” is akin to “ferromagnetic,” not for its reference to iron, but in signifying reversibility. Some magnets (ferromagnets) can have their magnetic polarity switched by the application of an external magnetic field. The analogous is true in ferroelectrics.

The ferroelectric effect is due to the presence of two competing sublattice orientations in the crystal. A sublattice is a part of the crystal lattice, which, when taken separately, may have a different symmetry from

the overall lattice. The applied field allows the sublattices to reorient, favoring one of these two. Ice is a common ferroelectric mineral (Cubioti and Geracitano, 1967). The competing crystal sublattices are responsible for ice being lighter than water and for other anomalies. A ferroelectric crystal need not have an asymmetrical unit cell to express piezoelectricity; the sublattices provide the asymmetry.

Antiferroelectricity and paraelectricity are also caused by sublattice competition. If the two competing crystal orientations are at right angles to each other, then the material is called antiferroelectric, and generally polarizes more strongly in one direction than the other. If an external electric field polarizes a mineral, but is unable to switch its polarity, and interacts with the mineral in such a way that the applied field then causes extra polarization (an increase that is more than linear), the material is termed paraelectric.

In general, “linear” refers to functions whose graph is a line. If x is proportional to y , then

$$y = \underline{m}x + b, \quad (14)$$

where x and y are variables, $\underline{m}$ is the slope of the line ($\Delta y / \Delta x$), and b is the value of y when x is zero. In a non-linear increase, $\underline{m}$ is an increasing or decreasing function, rather than a single value.

Ferromagnetism, Ferrimagnetism, Paramagnetism and Diamagnetism

A thorough treatment of magnetism in materials can be found in Morrish (1965). One type of magnetism is ferromagnetism; the polarity in ferromagnetism is based on a previous exposure to a magnetic field, but some minerals exhibit spontaneous magnetization whose orientation is set without a previous exposure. Ferromagnetism is also called remanent magnetization. A second type of magnetism is ferrimagnetism; ferrimagnetism is based on internal domain and lattice structure. It is not switchable. Both ferromagnetism and ferrimagnetism are considered permanent magnetizations, in contrast to the next type, which is an induced magnetization.

This third type of magnetism is paramagnetism; if a material cannot be magnetized, but can interact with an externally applied magnetic field, and makes an addition to the field that is non-linear (and, specifically, greater than linear), the material is called paramagnetic. Paramagnetism is the analog of paraelectricity. A fourth type of magnetism is diamagnetism; if a material can interact with an externally applied magnetic field to make it weaker, that material is termed diamagnetic.

The Piezooptic, Rotooptic, Electrooptic and Magneto optic Effects; Electrogyration and Magnetogyration

For a more thorough treatment of the following subsection, see Nelson (1996). In transparent minerals, photons, whether of visible light or infrared, are transmitted in their original orientation. In refractive minerals, the frequency of the transmitted photon is changed. In birefringent minerals, the frequency of the transmitted photon is changed, dependent on its orientation within the crystal as it is being transmitted. Birefringent minerals have two axes for refraction.

Some minerals translate seismic energy into a change in the frequency of a photon being transmitted. This is called the piezooptic effect. Some minerals translate seismic energy into a change in the direction of a photon being transmitted. This is called the rotooptic effect.

Some photons are affected by the presence of an external electric or magnetic field, and the energy results in a change in frequency for the transmitted photons. These phenomena are called the electrooptic effect and magneto optic effect, respectively. If an applied electric field rotates a transmitted photon, the rotation is called electrogyration. The analogous effect under a magnetic field is termed magnetogyration. Gyration rotates the photons themselves, while a rotooptic effect changes the crystal lattice, rotating the transmission medium.

These four “optic” and two “gyration” effects act upon photons. A distinction is made among these effects, which are called high-frequency electromagnetic effects, and the effects (such as piezoelectricity) described in the other subsections above. The latter are called low-frequency electromagnetic effects. High-frequency electromagnetic effects act upon electromagnetic radiation (photons). Low-frequency effects act via electric or magnetic fields.

Computer Modeling

The previous sections of this chapter have briefly examined mineral systems, thermodynamics, crystal notation, and crystal properties. For earth materials, the present notation system, and ones like it, though cumbersome, lend themselves easily to computer-based modeling. Kuo-An Wu et al. (2010), Elder and

Grant (2004) and Long-Qing Chen (2002) use phase field models (PFM) to explore stress and strain. A phase field model is a mathematical system that describes boundary interfaces with partial differential equations. Software packages using PFM are MICRESS (Microstructure Evolution Simulation Software) (MICRESS, 2013) and MMSP (Mesoscale Microstructure Simulation Project) (MMSP, 2013). Wang and Khachaturyan (1997) describe a different field model based on stochastics. Likewise, Elmer, Code Aster and pdnMesh are free open-source finite element software modeling programs found on the OpenScience Project website, and are also potentially useful (OpenScience, 2012). Computers are necessary because of the size of the calculations needed to present the data cogently.

CHAPTER 4

EXPERIMENTAL METHODS

Many techniques for gathering mineralogical and petrologic data are easy to perform, and most are accessible, for example, in a university material characterization laboratory (as a guest user) if specialized equipment is needed. This section provides an overview of methods for gathering material data relevant to Earth electricity. It is organized as sample identification, sample preparation, pressure and temperature techniques, elastic data, electrical data, magnetic data and simulating metamorphic reactions. Specific equipment details, such as model numbers and brand names, as well as the names of retail outlets where supplies may be purchased are listed in Tables 5 and 6 in Appendix F, p. 220 and 221.

Sample Preparation

Making Aligned Cuts

For phenomena based on the symmetry of a crystal, it is often necessary to cut plates from the crystal that are oriented with respect to the crystal lattice, and are much thinner than their extent. Crystal plates can be used to measure the piezoelectric effect of pressure along the crystallographic *c* axis, for example, to see how much electricity is expressed along that axis. If strain measurements are to be taken, the piezoelectric coefficient would be termed *d* (33), and a *Z* plate should be cut from the crystal. (See Chapter 3, Voigt Notation for Other Crystal Coefficients, p. 19.)

With a track mount, X-ray diffraction can be used to calculate the arrangement of the atoms of a crystal, and then (with an alignment microscope) align the material to a preferred orientation. The same orientation is maintained so that a slow-speed cut off saw will then cut one or several layers from the material, as desired. If money is an object, and no laboratory is nearby that allows guest users can be found, the following strategy designed by the author works for a more approximate procedure. A sample box may be made from 6.35 mm (1/4") thick melamine-coated board, available in the U.S. at hardware stores. The sides and bottom may be glued together with a hot glue gun; a top is not needed. An angle gauge should be used to ensure that the sides of the box are orthogonal. (See Figure 2.) The digital angle gauge in the figure displays a readout to 0.1° and is accurate to better than 0.5°.

The sample may be oriented in the sample box with water-based clay. (See Figure 3.) Once the sample is oriented as desired, a heat gun may be used to melt wax that will then be poured into the box. (See Figure 4.) The wax in Figure 4 is sold for making sprues in metal art casting, and can be purchased cheaply at an art store. The heat gun is rated at 1500 watts. The box is torn apart, and the resulting sample, encased in wax, is ready for cutting. (See Figure 5.) A pine board may be glued onto the wax-plus-sample with cyanoacrylate to make the cutting safer for holding by hand while cutting, and more stable, if using a jig or other holder. Practice samples were cut with a 1.5 horsepower wet table saw fitted with a thin-kerf 0.635 mm thick (0.025") diamond blade. Kerf is the term used in construction and industry to signify saw-blade thickness. As a cheaper alternative to expensive commercial diamond saw blades, a home-made brass (or other soft metal, such as copper) blade without teeth can be cut from a metal sheet with a hole cutter or metal scribe, and then used in a dry saw with a slurry of glycerine and abrasive. The glycerine adheres to the saw blade, and holds the abrasive in place. (See Figures 6 and 7.) The teeth in Figure 6 were cut with a metal file after the image in Figure 7 was taken. The saw in Figure 7 operates up to 7800 rotations per minute (RPM). The motor is not power-rated in the documentation, but it is underpowered for this type of work, and not recommended. No usable sample cuts were made. A typical dry saw for cutting crystals is higher powered but slower speed, to prevent a sample from cracking during the cut. The glycerine used was a food-grade vegetable glycerine, and the added abrasive was 50.0 micron silicon carbide powder.

Sample Lapping

The next stage in sample preparation is lapping to make the thickness of the cut sample uniform; the etymology is obscure (OED Online, 2013), but the term may have the same root as the word for what dogs

FIGURE 2. Sample box with digital angle gauge. The box is unfinished. Author image.

do with water, or from the Latin *lapis* meaning stone. Lapping can be done by hand using a glycerin slurry (as described in the section above) and a steel plate, such as the one shown in Figure 8. Lapping is done by placing the slurry on the steel plate, placing the crystal plate on top of the slurry, and then placing the fingers on the crystal and moving the crystal vigorously. The thickness of the crystal plate is measured with calipers. Tourmaline samples were lapped to less than 0.1 mm uniform thickness with this technique. Two calipers were used for measurements, and these have stated accuracies of 0.1 mm and 0.0254 mm (0.001").

Many material science perapartion labs will include a mechanical lapper, which is a motor-driven rotating disk housed in a stand that accommodates water. An abrasive pad fits on the lapper's disk, and a jig made from a hard metal holds the sample. Typically, samples are held in the jig with a synthetic wax, or thermoplastic. The target thickness can be specified by moving the sample holder within the jig up or down relative to the jig's base. The jig is placed on the pad on the wheel, and the lapper is turned on. Rubber bumpers keep the jig in place, generally rotating either clockwise or counterclockwise, or a combination of the two. The lapper's wheel used should also be able to rotate in either direction, so that the jig may rotate in the same direction or the opposite from the wheel, according to the user's preference.

Sample Polishing

As with lapping, crystal plates may be polished by hand, with successively finer grits in the slurry. Final polishing is accomplished with a buffing cloth and a colloidal suspension. Typically, colloidal silica and then colloidal diamond are used. Tourmaline samples were polished by hand with good results, excluding the colloidal diamond step. Abrasives used in the glycerine slurry were 50.0 micron (240 grit) silicon carbide powder, 600 grit silicon carbide powder, 1200 grit silicon carbide powder, and 0.5 micron precision alumina powder. Polishing with colloidal silica was accomplished with Colloidal Silica Type SBT.

FIGURE 3. Sample box with oriented sample. The sample is a commercial granite scrap. Author image.

Colloidal diamond polishing of tourmaline samples was accomplished as a guest at the University of California Irvine's Calit2 (LEXI) laboratory, equipped with a lapper. Rayon polishing cloths and 3 micron diamond suspension were used for polishing, with 0.05 micron alumina suspension used for final polishing. Diamond polishing was attempted at both 10 minutes per sample side and 5 minutes per sample side, before 7 minutes per side was chosen, which produced results as satisfactory as polishing for 10 minutes per sample side. Colloidal alumina was used at 2 minutes per sample side. Polishing cloths were changed between samples, and between abrasives. The heat from the thermoplastic fractured some of the samples as they were being affixed to the jig. Subsequently, carbon tape was used instead, with good results.

Confirming Alignment

Currently, the practice for examining a crystal lattice (and confirming its orientation) is X-ray diffraction. For a standard treatment of this technique, see Stout and Jensen (1989). Alternately, a scanning electron microscope (SEM) fitted with electron backscatter diffraction (EBSD) may be used, and results are faster than with XRD. Figure 9 shows a tourmaline crystal plate cut perpendicular to the *c* crystallographic axis viewed in an SEM fitted with EBSD. The sample was identified as manganoan elbaite via the HKL Channel 5 Flamenco acquisition system and a standard inorganic crystal structure Kikuchi line database (Oxford Instruments, 2013). Kikuchi lines are detectable bands of electrons caused during electron microscopy by diffractions of the crystal lattice (von Heimendahl et al., 1964). The forms can be generated by computer simulation if the lattice arrangement of atoms is known. The orientation of the elbaite is given as 109.1, 6.2, 44 (Euler angles) with a mean angular deviation (MAD) equal to 0.990°, as seen in the detail box titled "Solution" in the figure. Euler angles are a system of representing a form in three-dimensional Euclidean space based on three rotations. MAD numbers are calculated by comparing the observed Kikuchi lines with ones generated from a database of unit cells. MAD numbers less than 1 are preferred with EBSD. Practice data were gathered at UC Irvine during February and March, 2012.

FIGURE 4. Sample ready to be encased in wax. Bottom left: sample ready to be encased in wax. Top left: sprue wax in a Sierra cup, ready for melting. Top right: heat gun. Author image.

The technique described above produced results easily, with the drawback that SEM and EBSD use requires sputtering a thin layer (≈ 10 nm) of a conductive material onto the surface of the sample. The author used iridium, which allowed excess electrons from the electron beam of the microscope to disperse, as is necessary for imaging.

Determining Error

For linear properties of a crystal, the following formula, adapted from Hawkins et al. (1995), may be used to determine the error due to misorientation of a cut plate:

$$(m_t - m_o) / m_t = 1 - \cos \theta, \quad (15)$$

where m_t is the true magnitude, m_o is the observed magnitude, and θ is the angular difference between the true orientation and the actual orientation. $\cos \theta$ will be one if θ is zero. This relationship is shown graphically in Figure 10.

Sample Identification

Rao (2011) discusses the identification of minerals in hand sample. For more accuracy, the chemical composition of minerals can be identified in the laboratory: an SEM fitted with energy dispersive X-ray

FIGURE 5. Cut sample. Author image.

spectroscopy (EDS) can perform this function, if the sample is prepared as above. Goldstein et al. (2003) contains a relevant summary.

Phase transitions are evident in electrical and magnetic data. Capacitance (Gonzalo, 2006) and magnetic susceptibility (Fisher and Franz, 1995) can reach extreme values during transitions, and have been widely used to determine these, and pyroelectricity (Fisher and Franz, 1995). Other phenomena may also be used.

Rocks are identified according to their constituent minerals, based on the International Union of Geological Sciences (IUGS) nomenclature guides. Bulk samples of rock may also be chemically analyzed, and an article by Jeffrey and Hutchison (1981) contains a standard description. If present, an orientation of the minerals within rock samples lends a structural anisotropy to the rock. Anisotropy is a general term meaning that some property is not uniformly distributed or transmitted. Amadei (1983) discusses mechanical anisotropy in rocks.

Temperature and Pressure Techniques

Metamorphism in the Earth's crust occurs at temperatures from about 200°C to about 900°C, and at pressures from near-atmospheric to about 6 gigapascals (GPa) (Chopin, 2003). These correspond to depths well in excess of 100 km. The range is large due to variations, such as the presence of water in subduction zones, for example, and other subsurface features (Kearey et al., 2009).

Some of these conditions can be simulated with commonly available laboratory equipment. Temperatures up to 260°C (500°F) (at which polytetrafluoroethylene (Teflon®), a popular electrical insulator, starts to degrade) and 430°C (800°F) were easily attained with a heat gun heating an unsealed home-made sample holder. (See Figures 11 and 12.) The sample holder was made from 25 mm (1") household copper pipe and copper plate (wall thickness is 1 mm) bought at a hardware store, and cut with a

FIGURE 6. Home-made mini saw blade from brass. Author image.

punch and die. The bottom was oversized and wedged in place with a punch; the top is loose. The hole is for a thermocouple lead, and measurements were taken with an Omega K-Type thermocouple (chromel (90% nickel / 10% chromium) attached to alumel (95% nickel / 2% manganese / 2% aluminum / 1% silicon)) connected to a laptop using an Omega UTC-USB Universal Thermocouple Connector. Data logging and visualization were done with Omega software TRH Central, Version 1.02.10.907.

For directed (not hydrostatic/uniform) pressure, sample holders were made modified from the design by Morgan et al. (1984). (See Figures 13 and 14., p. 36 and 37) The plungers in Figure 14 were cut from copper lightning rod material, and the springs were hand wound from copper wire. The polytetrafluoroethylene was carved and sanded down by hand.

As a modification to the design by Morgan et al. (1984), the plungers can be fitted with holders, and masses of known weight can be added to these holders, thereby providing applied pressure. For shear stress, the polytetrafluoroethylene attached to the plunger and the base can be fitted with a slot in each, and torque may be applied to the sample by twisting the plunger. For a standard treatment of high temperature and pressure techniques, see Ulmer (1971).

Elastic Data

For a theoretical treatment of stress, strain and plasticity in earth materials, see Hai-Sui Yu (2006). For details of measuring stress and strain coefficients of materials, refer to the thorough overview by Suryanarayana (2011).

FIGURE 7. Home-made brass saw blade with slurry. The blade at the bottom right of the image is a commercial blade for cutting wood. Author image.

Electric and Magnetic Data

A comparison of some electrode materials applied to crystals can be found in Glass (1969). He reports that fired gold provides an electrical signal of the greatest magnitude, then evaporated gold or aluminum, next fired platinum, and, finally: air-dried silver paste is the least sensitive of the electrode materials. Care should be taken in choosing a wire to connect with this material. If it is of a dissimilar metal, then a separate experiment should be run to quantify the thermoelectric effect that is produced here.

Several books and articles summarize methods for collecting ferroelectric, pyroelectric and piezoelectric data (Kang Min Ok et al., 2006; Bhalla et al., 1993; Ikeda, 1990; Lines and Glass, 1977). An innovative technique involves using XRD to determine piezoelectric coefficients (Yu et al., 2007; Annaka, 1977). Gathering electrical resistance, resistivity and capacitance data is discussed in Mason and Jaffe (1954), in Parkhomenko (1967) and in Bartnikas (1987). Pearce et al. (2006) present methods of measuring electric and magnetic properties of minerals. Laboratory requirements for determining magnetic data from different materials are described in Yimei Zhu (2005).

Simulating Metamorphic Reactions

It should be possible to simulate metamorphic reactions. An experimental setup for inducing a metamorphic reaction could include a pressure chamber containing a fluid with a composition of interest inside (such as excess silica or iron suspended in water). The experiment is run with the sample at an appropriate temperature and pressure. Such an experiment might be conducted at low pressures initially (300 kPa (3 bar; 43.5 psi)) and briefly (2 weeks), to test for the sensitivity of the reaction. Samples would

FIGURE 8. Steel plate for lapping and polishing by hand. Author image.

have their chemical compositions examined, and electrical and magnetic properties tested before and after the pressure-chamber process. The data might be used to construct or refine pressure-temperature-chemical composition (T - P - X) diagrams. This would add to the literature on metamorphism, and could provide data that would allow the inclusion of electric and magnetic values into metamorphic reaction modeling. Baxter (2003) provides a summary of laboratory simulations of metamorphic reactions, along with natural constraints.

FIGURE 9. Crystal lattice orientation with EBSD. The sample is a manganous elbaite from the Pala mine in San Diego, California. The large image is the SEM view of the crystal surface. The three smaller windows are “Live EBSD,” “Band Detection” and “Solution” going counter-clockwise from the bottom left, respectively. The hexagon on the left is a computer generated image of the oriented crystal form. The acquisition software is Flamenco from Oxford Instruments, for use with EBSD. Author image.

FIGURE 10. Geometric (vector) relationship between the true and observed magnitudes in a misoriented crystal plate. Drawing adapted from Hawkins, K.D., MacKinnon, I.D.R., and Schneeberger, H. (1995), Influence of chemistry on the pyroelectric effect in tourmaline: *American Mineralogist*, v. 80, p. 492. Reproduced with permission.

FIGURE 11. Copper sample holder for heating at ambient pressure. The hole in the cover is there to allow a thermocouple to pass inside. Author image.

FIGURE 12. Sample heating with a heat gun. The curve for heating to 800°F is similar to this. Author image.

FIGURE 13. Sample holder for electrical measurements under applied pressure. The idea of adding weight or torque to the plunger is new. Reprinted with permission from Morgan, S.H., Silberman, E., and Springer, J.M., American Journal of Physics, Vol. 52, Page 543, (1984). Copyright 1984, American Association of Physics Teachers. The drawing is taken from Figure 2 in that article.

FIGURE 14. Plungers for sample holders of various sizes. Author image.

CHAPTER 5

FERROELECTRIC, PYROELECTRIC, PIEZOELECTRIC, AND SELECTED THERMOELECTRIC, DIELECTRIC AND MAGNETIC DATA FROM THE SCIENTIFIC LITERATURE

Introduction

The literature sources of electrical and magnetic data for minerals are of two kinds: current and historic. Current sources available online include the Mineralogical Society of America's Handbook of Mineralogy (Anthony et al., 2012), which maintains a list of piezoelectric and pyroelectric minerals (Shannon, 2011) with sixty-nine minerals given. None have measured electric constants included. Also, the websites mindat.org (Ralph and Chau, 2012) and webmineral.com (Barthelmy, 2012) are used: they are both incorporated into the International Mineralogical Association (IMA) Database of Mineral Properties on the RRUFF Project website, a comprehensive repository of Raman spectroscopy data to be used in planetary remote sensing (RRUFF Project, 2013; Downs, 2006). RRUFF is a proper name (for a cat), not an abbreviation.

Another current source is the Landolt-Börnstein Database, which was recently renamed SpringerMaterials (Springer, 2012), and many of the data in the tables in this chapter were taken from this resource. The Landolt-Börnstein Database (LBD) currently lists hundreds of thousands of substances and their properties (Madelung and Poerschke, 2008; Poerschke, 2002), though the data listed for minerals are sparse: 100 minerals for elastic moduli, and 33 for other electrical properties appear in the volume on piezoelectricity (Nelson, 1993). The coverage is expanded if a search is made by chemical formula rather than by mineral name. For magnetic data for minerals, LBD is voluminous, and includes data for silicates and many other rock-forming minerals.

Historic sources for electrical properties in minerals include a comprehensive paper on piezoelectricity in minerals from Bell Laboratories (Bond, 1943), showing the results of 830 mineral tests, with 17 displaying strong piezoelectric properties; and also classic sources such as Nye (1957), Mason (1950), Cady (1946), and papers that reference these. Many of the piezoelectric minerals listed in these sources are unquantified, or are only partially quantified, with data often lying outside the temperature and pressure ranges that are of interest to geologists. In contrast, Parkhomenko (1971; 1967) and Parkhomenko and Bondarenko (1972) are classic texts that deal with rocks and minerals in geologic settings.

Lists of Minerals

Table 4 lists descriptions of minerals for reference, and is located in Appendix A, p. 90. It includes chemical formulas, crystal symmetry classes, a black-and-white drawing of each symmetry class, the Nickel-Strunz mineral classifications, and a brief description of the geologic settings for each mineral. Some phase transition temperatures are given, as well. Nickel-Strunz is one of several classification systems for minerals, and is used commonly. Also included in Table 4 is an entry describing whether each mineral is ferroelectric, pyroelectric, or piezoelectric; selected thermoelectric, dielectric, electrical conduction and magnetic properties are included where available. Table 4 lists 44 minerals that exhibit ferroelectricity, antiferroelectricity or paraelectricity, 175 that exhibit pyroelectricity, and 217 that exhibit piezoelectricity. All ferroelectric, antiferroelectric, or paraelectric minerals exhibit pyroelectricity and piezoelectricity, and all pyroelectric minerals are piezoelectric. Table 7 lists 44 ferroelectric minerals, Table 8 lists 131 pyroelectric (but not ferroelectric) minerals and Table 9 lists 42 piezoelectric (but not ferro- or pyroelectric) minerals. A key to the crystal symmetry notation is given in Table 10. Table 11 in Appendix G, p. 224 lists references for the crystal structure data in Table 4, the list of minerals.

A group of minerals is a set whose members have the same crystal lattice arrangements, but with different atoms occupying some of the lattice sites. If the mineral group is very large, it will be turned into

TABLE 7. Ferroelectric, Antiferroelectric and Paraelectric Minerals

Altaite	Demicheleite-Cl	<u>Nitratine</u>
Alum-Na	<u>Demicheleite-I</u>	Oxycalciopyrochlore
<u>Archerite</u>	<u>Diomignite</u>	Oxyplumbopyrochlore
<u>Barioperovskite</u>	Ericaite	Perovskite
<u>Biphosphammite</u>	<u>Gwihabaite</u>	<u>Proustite</u>
Bismuthinite	<u>Heftetjernite</u>	<u>Pyrargyrite</u>
<u>Boracite</u>	Hydroxycalcioroméite	<u>Pyrolusite</u>
Cassiterite	(Ferroan Variety)	<u>Russellite</u>
Cervantite	<u>Ice</u>	Schultenite
Chalcocite	Koechlinite	<u>Sillénite</u>
Chalcostibite	Lakargiite	Srebrodolskite
<u>Chambersite</u>	<u>Lueshite</u>	<u>Stibiotantalite</u>
<u>Changbaiite</u>	<u>Macedonite</u>	Stibnite
Clinocervantite	Mariinskite	<u>Tausonite</u>
<u>Demicheleite-Br</u>	<u>Niter</u>	<u>Wakefieldite-Nd</u>

Notes: Underlined minerals have data associated with them. References are listed in Table 15 in Appendix G, p. 226.

a group of groups, called a supergroup, by members of the International Mineralogical Association. The IMA is also responsible for approving the names of minerals. Tables 12, 13 and 14 in Appendix C, p. 176 through 186, relist the minerals in Tables 7, 8 and 9 by group, and show the other minerals in each group. Where mineral group taxonomy was equivocal, a frequently updated academic mineralogy resource was taken as definitive (Witzke, 2012). Thomasite is placed in the zeolite group, as per Yaping Li et al. (2000), though this may not reflect its IMA status. Bold typeface in Tables 12, 13 and 14 signifies that the mineral has been listed in a reference as having the electrical property in question. Tables 15, 16 and 17 in Appendix G, p. 226 through 228, list these references. The headings of the 10th edition of the Nickel-Strunz classifications of the IMA approved minerals are listed in Table 18 in Appendix C, p. 187 through 210, and the classification numbers are underlined for ferroelectric, pyroelectric and piezoelectric minerals, and also for the selected thermoelectric minerals included in this thesis. Table 18 also lists these minerals, the first class in bold, and the second in italic typeface. The 10th edition is the latest version of the Nickel-Strunz classification (Ralph and Chau, 2012). Finally, note that the long list of minerals in Table 4 includes 14 minerals exhibiting strong thermoelectricity, 46 minerals whose magnetic properties are given, and six extra, with dielectric properties.

Centrosymmetric Minerals Exhibiting Symmetry-Based Electricity

Ferroelectric, antiferroelectric, paraelectric, pyroelectric and piezoelectric minerals all may exhibit electrical phenomena based upon the symmetrical orientation of their crystal lattices. Table 19 in Appendix D, p. 212, lists these symmetry-based electrical minerals by crystal system, crystal class, and symmetry. Excerpted from these in Table 20, p. 43, are minerals that are centrosymmetric. In a crystal with a centrosymmetric lattice, any displacement will be met with a complementary (orthogonal) displacement, and the electric charges should cancel out. In contrast, ferroelectric (or antiferroelectric, or paraelectric) minerals exhibit electrical phenomena based on the orientation of an asymmetrical sublattice. The sublattice bonds may allow for an expression of electricity, even though the general lattice unit cell is symmetric (Blinic, 2011). The minerals that are not ferroelectric, antiferroelectric or paraelectric have been underlined in Table 20. For these minerals that are centrosymmetric and exhibit symmetry-based electrical phenomena (but are not ferroelectric, antiferroelectric or paraelectric) a reference has been provided below to confirm the structure, and to provide a possible explanation for further ordering, which in general reduces the symmetry of the mineral. The author believes that the reduction in symmetry allows for the electrical phenomena. The minerals are arranged alphabetically.

TABLE 8. Pyroelectric Minerals

Afwillite	Dravite	Larsenite	Quenselite
Alunite	Dyscrasite	Liebigite	Röntgenite-Ce
Amesite	Elbaite	Marialite	Sarcosite
Ammoniojarosite	Elpidite	Meionite	<u>Schorl</u>
Ardealite	Enargite	Melanovanadite	Scolecite
Argentojarosite	Eosphorite	Meliphanite	Searlesite
Arsenogoyazite	Epistilbite	Mesolite	Seligmannite
Artinite	Epistolite	Millerite	Shortite
Batisite	Feruvite	Minyulite	Sinoite
Benstonite	Finnemanite	Moissanite	Spangolite
Berthierine	Flagstaffite	Mordenite	<u>Stephanite</u>
Bertrandite	Fluor-dravite	Murmanite	Stibiocolumbite
Beryl	Fluor-liddicoatite	Muthmannite	Struvite
<u>Bournonite</u>	Fluor-schorl	Nacrite	Suolunite
Breithauptite	Foitite	Natroalunite	Swedenborgite
<u>Bromellite</u>	<u>Fresnoite</u>	Natrojarosite	Syngenite
Brucite	Georgbarsanovite	Natrolite	Thaumasite
Brushite	Goyazite	<u>Nepheline</u>	Thomsonite-Ca
Buergerite	<u>Greenockite</u>	Neptunite	Tilasite
Bultfonteinitite	Halloysite-7Å	Nickeline	<u>Tourmaline</u>
Burbankite	Halloysite-10Å	Nolanite	Tyrolite
<u>Cadmoselite</u>	Halotrichite	Olenite	Uranophane
Caledonite	Harmotome	Oxy-schorl	Ussingite
<u>Cancrinite</u>	Hartite	Parkerite	Uvite
Childrenite	Hemimorphite	Pharmacolite	Vermiculite
Chromium-dravite	Heulandite-Ca	Pickeringite	Weloganite
Clinohedrite	Hilgardite	Pinnoite	Whitlockite
Colemanite	Hydrocalumite	Pirssonite	Wulfenite
Coquimbite	Innelite	Plumbojarosite	<u>Wurtzite</u>
Crandallite	Iodargyrite	Povondraite	Yugawaralite
Creedite	Jarosite	Prehnite	Zinkenite
Cronstedtite	Junitoite	Pyrochroite	
Dawsonite	Kaliborite	Pyromorphite	
Diaboleite	Krennerite	Pyrrhotite	

Notes: Though a mineral supergroup (and not a mineral), tourmaline is also listed above. Underlined minerals have data associated with them. References are given in Table 16 in Appendix G, p. 227.

Aminoffite

Aminoffite's chemical formula and crystal structure have been recently refined (Huminicki and Hawthorne, 2002a), and the authors of that study note that Pb, Mn and As are commonly incorporated into the ideal formula of Aminoffite. Piezoelectric phenomena are perhaps related to ordering in the placement of these ions.

Analcime, Gismondine-Ca, Gmelinite-Na, Thomsonite-Ca and Thornasite

The five minerals described in this subsection are zeolites. Zeolite minerals often exist in several forms, and multiple crystal class (and symmetry) references have been listed for these minerals in Table 15, p. 226. The zeolite group's symmetries can be found in Armbruster and Gunter (2001). Ordering of ions within the structure is commonplace, and may explain the observed electric phenomena. For evidence that thornasite exhibits a microporous lattice, and should be included in the zeolite group, see Yaping Li et al. (2000).

TABLE 9. Piezoelectric Minerals

Aminoffite	Gismondine-Ca	Nitrobarite	<u>Sphalerite</u>
<u>Analcime</u>	Gmelinite-Na	Olsacherite	<u>Stilleite</u>
Bastnäsrite-Ce	<u>Goslarite</u>	<u>Paratellurite</u>	<u>Tellurium</u>
Bavenite	Gugiaite	Pharmacosiderite	Thornasite
<u>Berlinite</u>	Helvine	<u>Quartz</u>	Tiemannite
<u>Cinnabar</u>	Jeremejevite	<u>Retgersite</u>	Topaz
Diopside	<u>Langbeinite</u>	Rhodizite	Tugtupite
Edingtonite	Leucophanite	Roquesite	<u>Zincite</u>
<u>Epsomite</u>	Londonite	<u>Sal Ammoniac</u>	Zunyite
<u>Eulytine</u>	Mimetite	<u>Selenium</u>	
Gallite	<u>Morenosite</u>	<u>Sodalite</u>	

Notes: Underlined minerals have data associated with them. References are listed in Table 17 in Appendix G, p. 228.

TABLE 10. Crystal Symmetry Notation Key

Symbol	Meaning	Rotational Symmetry
1	One-fold rotational symmetry axis	360° (trivial)
2	Two-fold rotational symmetry axis	180°
3	Three-fold rotational symmetry axis	120°
4	Four-fold rotational symmetry axis	90°
6	Six-fold rotational symmetry axis	60°
<i>m</i>	Mirror plane	
/	Rotational axis (numerator) $\perp$ to mirror plane (denominator), e.g. 6/<i>m</i>	
—	Rotoinversion about an axis	

Notes: The symbol $\perp$ means perpendicular. The symbol for rotoinversion is typically a macron (bar over the number), but here it is written as an underline. Rotoinversion consists of a rotation about an axis and an inversion. Rotoinversion with a two-fold rotation (**2**) is written as ***m*** and is the most familiar: it is what mirrors do with light.

Arsenogoyazite

Frost et al. (2013a) report the results of Raman spectroscopy on the crandallite subgroup of alunite-group minerals, of which arsenogoyazite is a member. Raman spectroscopy is a non-invasive technique which uses lasers to obtain a unique emission spectrum for each material. They observed a signal band attributable to the interference of symmetric and antisymmetric vibrational stretching modes, supporting the assignment of a reduced symmetry for the crandallite minerals. Ordering of cations (in the strontium site) is likely.

Artinite

Frost et al. (2009), using Raman spectroscopy, report that the carbonate anions in artinite are disordered. They attribute this disorder to strong hydrogen bonding, and find evidence for this in their spectroscopic data.

TABLE 20. Centrosymmetric Minerals That Exhibit Symmetry-Based Electricity

Altaite	<u>Eosphorite</u>	<u>Nitrobarite</u>
Alum-Na	<u>Epistolite</u>	<u>Parkerite</u>
<u>Aminoffite</u>	<u>Finnemanite</u>	Perovskite
<u>Analcime</u>	<u>Gismondine-Ca</u>	<u>Pinnoite</u>
<u>Arsenogoyazite</u>	<u>Gmelinite-Na</u>	<u>Plumbojarosite</u>
<u>Artinite</u>	<u>Goyazite</u>	Proustite
<u>Bavenite</u>	Gwihabaite	<u>Pyrochroite</u>
<u>Benstonite</u>	<u>Harmotome</u>	Pyrolusite
<u>Beryl</u>	Heftetjernite	<u>Pyromorphite</u>
Bismuthinite	<u>Heulandite-Ca</u>	<u>Quenselite</u>
<u>Breithauptite</u>	Hydroxycalcioroméite	<u>Sal Ammoniac</u>
<u>Brucite</u>	Ice	<u>Sarcolite</u>
<u>Bultfonteinite</u>	<u>Innelite</u>	<u>Seligmannite</u>
Cassiterite	<u>Jeremejevite</u>	Srebrodolskite
Cervantite	<u>Kaliborite</u>	Stibnite
Chalcocite	Lakargiite	<u>Syngenite</u>
Chalcostibite	Lueshite	Tausonite
Clinocervantite	<u>Marialite</u>	<u>Thaumasite</u>
<u>Coquimbite</u>	Mariinskite	<u>Thomsonite-Ca</u>
<u>Crandallite</u>	<u>Meionite</u>	<u>Thornasite</u>
<u>Creedite</u>	<u>Melanovanadite</u>	<u>Topaz</u>
<u>Dawsonite</u>	<u>Mimetite</u>	<u>Tyrolite</u>
Demicheleite-Br	<u>Murmanite</u>	<u>Ussingite</u>
Demicheleite-Cl	<u>Muthmannite</u>	<u>Vermiculite</u>
Demicheleite-I	<u>Nickeline</u>	Wakefieldite-Nd
<u>Diopase</u>	Niter	<u>Wulfenite</u>
<u>Elpidite</u>	Nitratine	

Notes: Ferroelectric, antiferroelectric or paraelectric materials may be centrosymmetric if they have a sublattice that shows some asymmetry. Underlined minerals are not ferroelectric, antiferroelectric or paraelectric. References are listed in Table 11 in Appendix G, p. 224.

Bavenite

Piezoelectric phenomena are perhaps related to ordering in the placement of cations. This is speculation based on the presence of cations in the chemical formula. Bavenite's crystal structure and chemical formula have been recently refined (Lussier and Hawthorne, 2011), with assignment to the space group **Cmcm**. This is equivalent to orthorhombic crystal class **mmm**. Space groups are organized according to the configuration of the space rather than points; crystallographic space groups are one of several space groups found in the mathematical literature.

Benstonite

Scheetz and White (1977) report ordering in the cations calcium and barium in benstonite, thereby reducing the symmetry of the mineral.

Beryl

Tančić et al. (2010) discuss the structure of beryl, whose lattice sites accommodate various impurities, including cations and water. Ordering in cations is present and is responsible for lowered symmetry in beryl. Orientation in the hydrogen and oxygen atoms (in constituent water) also contributes to lower symmetry (Libowitzky and Beran, 2006).

Breithauptite

No explanation for lowered symmetry was found in the literature, but Hewitt (1948) reports that the antimony site in breithauptite is shared with arsenic, forming a solid solution with nickeline. Ordering of impurities within this site may explain a lowered symmetry.

Brucite

The observed pyro- and piezoelectric effects are possibly attributed to short range bonds that hold together the negatively-charged hydroxyl anions in a layered structure. Hydroxyl is composed of hydrogen and oxygen, $[\text{OH}]^-$. See Peterson et al. (1979) for more information on the layer structure of brucite.

Bultfonteinite

McIver (1963) reports that the structures of bultfonteinite and afwillite are similar, while Malik and Jeffery (1976) report a reassignment of afwillite to the polar monoclinic (*m*) crystal class. Bultfonteinite's structure has not been reevaluated, and may also belong to this polar class.

Coquimbite

Majzlan et al. (2010) report that H_2O (hydrogen) in coquimbite occupies two different lattice sites, and these form a cyclohexane-like structure, having a vacancy in the middle. Cyclohexane is a saturated hydrocarbon with a six-carbon ring. Clockwise and anticlockwise symmetries are possible, thereby reducing the symmetry of coquimbite. The observed electrical phenomena are attributable to this asymmetry.

Crandallite

Goreaud and Raveau (1980) report that isochemical intergrowths are likely in alunite and crandallite, due to similar structures being easily interchangeable (i.e. those of crandallite, alunite and pyrochlore). In addition, Frost et al. (2013a) suggest that reduced symmetry observed in crandallite minerals is due to the ordering of impurities in the strontium lattice site. Finally, Breitingner et al. (2006) demonstrate with Raman spectroscopy that the sites occupied by $[\text{PO}_4]^{3-}$ and $[\text{HPO}_4]^{2-}$ are randomly distributed, and disturb the translational and site symmetries of crandallite.

Creedite

Frost et al. (2013b) report that the symmetry of the sulfate ion in creedite is reduced by coordination with the water molecules attached to Al^{3+} in the crystal lattice.

Dawsonite

Frost and Bouzaid (2007) report on the Raman spectroscopy of dawsonite and attribute a lowered symmetry to it. This reduction in symmetry is due to ordering in carbonate and hydroxide ions in Dawsonite's crystal structure.

Diopase

For more information on the crystal structure of the cyclosilicate diopase, and of the Jahn-Teller effect producing lattice distortion, see Belokoneva et al. (2002). That effect is essentially caused by a natural degenerate configuration of electrons in the ground state, causing the lattice to distort itself, to achieve a lower, non-degenerate state. In a molecule, electron degeneracy consists of two or more electron bonds with identical energies. The presence of the lattice distortion due to this effect is a possible cause of the observed piezoelectricity in diopase.

Elpidite

Zubkova et al. (2011) report that water in the elpidite lattice is ordered, with at least three different molecular arrangements, and that natural elpidite contains excess water not in the stoichiometric formula: 3.28 moles H_2O instead of three, with the excess easily driven off by a flow of argon gas. Elpidite, like the zeolite minerals, is an example of a microporous crystalline material, and this type of material is often used in industry to exchange ions. The impurities (K, Nb, Hf, and Al) reported by Zubkova et al. (2011) are insignificant in quantity compared to the regular lattice components, and ordering of water or excess water seem the likely explanations for the observed pyro- and piezoelectricity.

Eosphorite

Hoyos et al. (1993) report that manganese and iron ions, which share a lattice-site in eosphorite, cause lattice deformation. Pyro- and piezoelectricity may be caused by this deformation, or by impurities, notably Cr^{3+} , as was detected during a photoluminescence experiment.

Epistolite

Sokolova and Hawthorne (2004) in their refinement of the crystal structure of epistolite report on earlier work by Karup-Møller (1986) that describes an unidentified submicroscopic phase commonly forming intergrowths in epistolite. There are subsidiary cation sites within epistolite that are occupied about 10% of the time, ascribed to this unidentified phase. Pyro- and piezoelectricity in epistolite may be related to these intergrowths.

Finnemanite

Bahfenne and Frost (2010) report that the various $[\text{AsO}_3]^{3-}$ units in finnemanite are not equivalent in the crystal lattice, as implied by the Raman spectroscopic data. Reduced symmetry and electrical phenomena in finnemanite can be attributed to the ordering of this ion.

Goyazite

Breitinger et al. (2006) report that the $[\text{HPO}_4]^{2-}$ ions in goyazite are essentially randomly distributed with the $[\text{PO}_4]^{3-}$ ions. Their distribution perturbs the translational and site symmetries in the crystal lattice.

Harmotome

Armbruster and Gunter (2001) report that H_2O in the harmotome crystal lattice is ordered, with only one in the four of these that coordinate with the barium ion being fixed with hydrogen bonding. Pyro- and piezoelectricity may be attributable to this ordering, or to ordering of vacancies in the Ca/Na lattice site.

Heulandite-Ca

Armbruster and Gunter (2001) summarize reports of lower symmetry in heulandites, and conclude that ordering in Si and Al within the lattice framework may be responsible. Further, Ruiz-Salvador et al. (2000) provide details for how slight changes in the Si:Al ratio produce different occupation rates of Al in the framework lattice, which, in turn, affects where the Ca^{2+} cation will reside, causing some displacement. Pyro- and piezoelectricity (plus lowered symmetry) are likely due to this displacement.

Innelite

For more information on the crystal structure of innelite, see Sokolova et al. (2011), where the intergrowth of the two coextant forms (triclinic **1** and monoclinic **2/m**) is described. The electrical bonding associated with this intergrowth may explain the observed pyro- and piezoelectric effects.

Jeremejevite

According to Rodellas et al. (1983), the best method for assigning jeremejevite to the centrosymmetric **6/m** structure was to model an absence of $[\text{OH}]^-$ groups, and assume fluorine $[\text{F}]^-$ occupancy of their sites. The presence of $[\text{F}]^-$ and $[\text{OH}]^-$ (whether ordered, or not) in jeremejevite reduces the symmetry of the mineral, and is a possible explanation for the observed piezoelectricity.

Kaliborite

Burns and Hawthorne (1994) report that kaliborite polymerizes chains of three $\text{B}(\text{O},\text{OH})_4$ tetrahedra and three $\text{B}(\text{O},\text{OH})_3$ triangles (what they call the fundamental building blocks) along the **b** axis. These chains along the **b** axis may be responsible for the observed pyro- and piezoelectricity.

Marialite

Sokolova et al. (1996) report that water molecules reside in the lattice of marialite in a preferred orientation. This orientation may be responsible for the observed pyro- and piezoelectricity.

Meionite

Sherriff et al. (2000) distinguish two framework-lattice sites which may contain Si and Al in meionite. They report that Si and Al atoms occupy these sites in different ratios (1:3 and 5:3, respectively). This preference is a possible explanation to account for observed pyro- and piezoelectricity in meionite.

Melanovanadite

Konnert and Evans (1987) describe the structure of melanovanadite, and divide it into vanadate layers and an interlayer structure composed of ordered $[\text{Na}]^+$ and $[\text{Ca}]^{2+}$ ions, as well as H_2O . Schindler et al. (2000) echo this result. The layered structure of melanovanadite may account for the observed pyro- and piezoelectricity.

Mimetite

Piezoelectricity in mimetite is potentially attributable to ordering of the lead ions with minor impurities (see Pyromorphite, below), or perhaps due to the proximity of the transition temperature for monoclinic (*m*, polar) and hexagonal (*6/m*, centrosymmetric) polytypic forms in mimetite. A preliminary treatment can be found in Yongshan Dai et al. (1991).

Murmanite

Cámara et al. (2008) report that the murmanite lattice consists of titanium silicate blocks stacked in the *c* direction. This anisotropy may be sufficient to allow for the observed pyro- and piezoelectricity.

Muthmannite

Bindi and Cipriani (2004) report that the structure of muthmannite consists of Te layers alternating with gold and silver cations. The layers are aligned parallel to $[100]$. This anisotropy is consistent with pyro- and piezoelectricity.

Nickeline

Gritsenko and Spiridonov (2005) report that nickeline from several sites contains 20% or more antimony. As with breithauptite, ordering of the arsenic and antimony may create a lowered symmetry and account for the observed pyro- and piezoelectricity.

Nitrobarite

Nowotny and Heger (1983) report that, previously, nitrobarite had been placed in chiral cubic class **23** by Birnstock (1967) according to very weak reflectors violating centrosymmetric cubic *m3* symmetry during a neutron diffraction study, and though Nowotny and Heger dismissed that assignation on the basis of the decent fit of an *m3* assignment and a lack of observed “piezoelectric, linear electrooptic and nonlinear optic effects or optical activity,” it seems possible that nitrobarite has been misassigned to centrosymmetric cubic class *m3*. The IMA Handbook of Mineralogy (Shannon, 2011) lists nitrobarite as piezoelectric. A new refinement of the structure of nitrobarite could provide some insight.

Parkerite

Although the unit cell of parkerite is centrosymmetric, Baranov et al. (2001) show that parkerite exhibits a superstructure of layers perpendicular to the *c* axis, and that empty channels of around 4Å length parallel to plane $[110]$ are present. These observations are possible explanations for the observed pyro- and piezoelectricity in parkerite.

Pinnoite

Heller (1970) reports that pinnoite's structure is built with islands of $[\text{B}_2\text{O}(\text{OH})_6]^{2-}$ ions, though the $[\text{BO}_2]_n^{n-}$ ion in general can form chains. Lower symmetry and piezoelectricity are possibly due to either the interactions of the H_2O molecule in the crystal lattice, or to polymerization of the diborate ion. The structure refinement of pinnoite has not been updated since the work of Krogh-Moe (1967).

Plumbojarosite

Szymanski (1985) describes the structure of plumbojarosite as composed of tilted layers of $\text{Fe}(\text{OH})_4\text{O}_2$ octahedra combined with sulfate tetrahedra and alkali co-ordinated icosahedra. Lead in the lattice only partially occupies its lattice sites, and alternates along the *c* axis. This results in a preferred orientation for

the layers, as a superstructure. The layering and lead-ion ordering are a plausible explanation for the observed electrical phenomena.

Pyrochroite

Like brucite, pyrochroite is composed of structural layers held together with hydrogen bonds (Parise et al., 1998). Compressibility along the **c** axis is twice as easy as along the **a** axis below 6 GPa, as is the case with brucite. The reason for the change at 6 GPa is not known. The hydrogen bonds and layered structure are consistent with the observed pyro- and piezoelectricity in pyrochroite.

Pyromorphite

For a treatment of the structure of pyromorphite, and a description of ordering in the lead cation and minor cation impurities, refer to Hashimoto and Matsumoto (1998). Pyro- and piezoelectricity may be due to this ordering, or to the proximity of the transition temperature for monoclinic (**m**, polar) and hexagonal (**6/m**, centrosymmetric) polytypic forms in chlorapatites such as pyromorphite.

Quenselite

Rouse (1971) describes the structure of quenselite as a brucite-type layered lattice, with manganese-oxide layers and lead-hydroxide layers alternating, and this view is represented in Manceau et al. (2002). Hydrogen bonds hold the structure together, and the observed electrical phenomena may be related to these hydrogen bonds.

Sal Ammoniac

Gilberg (1981) describes anomalous frequencies in the electronic spectroscopy of sal ammoniac as attributable to the Jahn-Teller effect, which causes a structure to distort if the electron orbitals will be stabilized by that distortion. The Jahn-Teller effect, and its associated distortion of the lattice of sal ammoniac are consistent with the observed electrical phenomena.

Sarcolite

Maras and Paris (1987) summarize the work on the structure of sarcolite, and refine the structure and chemistry. Fluorine can substitute for $[\text{OH}]^-$, and the $[\text{F}]^-$, $[\text{OH}]^-$ and H_2O are in a relationship with the site of $[\text{CO}_3]^{2-}$ or $[\text{SO}_4]^{2-}$ occupancy, such that a sulfate ion causes a double vacancy of $[\text{F}]^-$, $[\text{OH}]^-$, or H_2O and a carbonate ion causes a single vacancy there. Absent carbonate or sulfate, two units of $[\text{F}]^-$, $[\text{OH}]^-$, or H_2O will be present. Pyro- and piezoelectricity may be due to ordering in these, or in other constituents that are typically present in sarcolite, namely (Ca, Na), (Na, K, Sr, Ti, Mn), (Al, Fe, Mg) and (Si, P).

Seligmannite

Takeuchi and Haga (1969) report on the crystal structure of seligmannite as being formed by sheets of Cu-S_4 tetrahedra, connected by Pb and As, stacked along the **c** direction. The larger layered structure may account for the observed pyro- and piezoelectricity.

Syngenite

Kloprogge et al. (2002) report that the Ca-O polyhedra in syngenite form a zigzag chain along the **c** direction, and also that distinct overtones and other modes in the Raman spectra of $[\text{OH}]^-$ in syngenite indicate a complexity in its hydrogen bonding. Both of these are fruitful preliminary explanations for the observed electrical phenomena in syngenite.

Thaumasite

Barnett et al. (2000) describe the structure of thaumasite as consisting of columnar $\text{Ca}_3[\text{Si}(\text{OH})_6 \cdot 12\text{H}_2\text{O}]^{3+}$ units oriented parallel to the **c** axis, with sulfate and carbonate ions in the channels alongside. This orientation may explain the observed electrical phenomena, as may complexities in the hydrogen bonding.

Topaz

Piezoelectricity in topaz is perhaps due to ordering of the fluorine and hydroxide, with ordering described in Akizuki et al. (1979). The $[\text{F}]^-$, $[\text{OH}]^-$ lattice ordering reduces its symmetry, and likely allows for the anomalous optical and electrical properties.

Tyrolite

Krivovichev et al. (2006) detail the structure of two polytypes of tyrolite, which consist of different sequences of stacking nanolayers held together with hydrogen bonds. Electrical phenomena in tyrolite are consistent with these structural observations.

Ussingite

Johnson and Rossman (2004) report that two of the nine oxygen atoms in ussingite are involved in strong hydrogen bonding, while the others are bridging oxygens, linking Al and Si tetrahedra. They call this an "interrupted" aluminosilicate framework structure. Hydrogen bonding in ussingite may account for the observed electrical phenomena.

Vermiculite

Badreddine et al. (2002) report on the structure of vermiculites. Electrical phenomena may be due to layer stacking, or to ordering in the Fe^{2+} and Fe^{3+} cations, which each contribute to the electric gradient.

Wulfenite

For more information on the structure of wulfenite and ordering of the molybdenum ions, see Hibbs et al. (2000).

Explanations for the Apparent Violations of Piezoelectric Theory

In the minerals above, the exceptions fall into ten categories. These are:

1. The mineral has been assigned to the wrong point group. This is possible for bultfonteinite and nitrobarite, and should be investigated further.
2. Intergrowths of two chemically-equivalent phases may occur commonly in the mineral, and the observed effect may be caused by the phase whose symmetry allows for pyro- or piezoelectricity, or the phenomenon may be related to the structure of their contact. Evidence exists that innelite belongs to this class. Crandallite may, as well.
3. Intergrowths of a submicroscopic phase occur in the mineral, and pyro- or piezoelectricity may be caused by the contact between the host and intergrowth phase, or by the intergrowth phase itself. This explanation is consistent with what is known of epistolite.
4. The mineral undergoes a lattice transition to a crystal class that does exhibit pyro- or piezoelectricity near the temperature where the electricity is observed, and the phenomenon is attributable to that other phase. Evidence exists for this in mimetite and pyromorphite.
5. Multi-atomic constituents (such as $[\text{OH}]$, H_2O or carbonate) are present in the lattice structure, and the disorder or preferred orientation of these larger groups reduces the symmetry of the crystal as they interact with the other lattice constituents. Evidence exists for this in artinite, beryl, brucite, coquimbite, crandallite, creedite, dawsonite, elpidite, finnemanite, goyazite, harmotome and marialite, and this is a potential explanation for electrical phenomena in pinnoite, sarcolite, syngenite, thaumasite and ussingite, as well.
6. Equivalent lattice sites are shared by more than one type of atom, ion, or group from the chemical formula of the mineral, and the ordering of these components may reduce the symmetry of the lattice to allow for pyro- or piezoelectricity. Evidence of this exists for marialite, meionite, topaz, vermiculite, wulfenite, and the minerals of the zeolite group. It is also a plausible explanation for the electric phenomena in bavenite, jeremejevite, eosphorite and sarcolite.
7. Impurities not in the officially recognized chemical formula of the mineral share some of the lattice sites with the mineral, and the ordering of these components likewise reduces the symmetry of the lattice to allow for pyro- or piezoelectricity. Evidence exists for this in aminoffite and pyromorphite, and, by extension, in mimetite, which belongs to the same mineral subgroup as pyromorphite and shares some properties with it. This explanation is consistent with what is known of arsenogoyazite, breithauptite, crandallite, eosphorite, nickeline and sarcolite, as well, but further study is needed.
8. A pattern or order in the distribution of vacancies in specific lattice site in the mineral may be present. This ordering may reduce the symmetry of the crystal, and account for observed pyro- or piezoelectricity. This mechanism has been suggested for the pyro- and piezoelectric effects in harmotome. See Chapter 6, p. 68 for more information related to lattice vacancies.

9. The mineral has a larger structure (e.g. layering) or polymerization which is not centrosymmetric. This is the case for kaliborite, parkerite and vermiculite, and possibly for brucite, melanovanadite, murmanite, muthmannite, pinnoite, plumbojarosite, pyrochroite, quenselite, seligmannite, syngenite, thaumasite and tyrolite. If the mineral has a layered structure, the short-range bonds holding the layers together may be the source of the observed electric effects.

10. The Jahn-Teller effect, where a ground-state configuration of the electrons is degenerate, and the energy relations favor a distorted lattice to resolve the electron state, can be responsible for a lowering of symmetry in the crystal, and allow for piezoelectricity. Evidence suggests that diopside and sal ammoniac belong to this class.

The above findings are summarized in Table 21. They are consistent with Voigt's (1910) original explanation of piezoelectricity as a crystal-lattice based phenomenon. The effect is a feature of intact lattices, and of the geometry of the electron bonds that comprise the crystal. It is thus a function of both chemistry and symmetry, as well as of the crystalline environment, under an influence of intergrowths, impurities and transition temperatures and pressures.

TABLE 21. Explanations for Pyro- and Piezoelectricity in Centrosymmetric Minerals

Category	Explanation	Brief Explanation
1	Wrong Point Group	Trivial
2	Intergrowths of Chemically-Equivalent Phases	Intergrowths
3	Intergrowths of Submicroscopic Phases	Intergrowths
4	Lattice Transition Creates Electricity	Lattice Transition
5	Large Ions Distort the Lattice	Lattice Organization
6	Ordering of Atoms, Ions or Groups	Lattice Organization
7	Ordering of Impurities	Lattice Organization
8	Ordering of Vacancies	Lattice Organization
9	Large-Scale Structure	Lattice Organization
10	Jahn-Teller Effect	Electron Bonding

Mineral Data

Mineral data are listed in Appendix B, and are organized according to physical phenomena:

1. Ferroelectricity, pyroelectricity and thermoelectricity data are presented. (See Tables 22 through 26 in Appendix B, p. 156 through 159.) These relate closely to temperature as the proximal cause of the electric charge, current, voltage or field. The references for the data are listed separately. (Data references: see Tables 27, 28 and 29 in Appendix G, p. 228 and 229.)

2. Piezoelectricity data are provided. (See Tables 30 through 36, p. 160 through 166.) These relate closely to pressure and physical displacement. (Data references: see Table 37 in Appendix G, p. 229.)

3. Capacitance data are presented. (See Tables 38 and 39, p. 167 and 171.) Capacitance, measured as dielectric coefficients, relates to the electrical environment near minerals. (Data references: see Table 40 in Appendix G, p. 230.)

4. Magnetic data are provided. These relate to the magnetic environment near minerals. (See Tables 41 through 44, p. 172 through 174.)

A description of some credible features in the data follows. The paper on tourmalines by Hawkins et al. (1995) reports that the strength of pyroelectricity in tourmalines is inversely related (linearly) to the abundance of the Fe^{2+} ion in the Y site of the lattice. Their equations are listed in the pyroelectricity data (Table 25, p. 158) under the Tourmaline entry. The chemical formula for tourmaline is $\text{X}(\text{Y})_3\text{Z}_6(\text{BO}_3)_3\text{Si}_6\text{O}_{18}(\text{V})_3\text{W}$. The letters V, W, X, Y and Z signify lattice sites where a variety of atoms may be present. The greater the iron in the Y site, the less the pyroelectric effect. Schorl, for example, with its high Fe^{2+} content, has a much smaller pyroelectric coefficient than other tourmalines.

For minerals in Tables 30 through 36, p. 160 through 166, piezoelectric coefficients are given showing the effects of stress and/or strain. None of these indicates what happens when stress and strain are so great or long-acting that they lead to pressure dissolution or to fracture. Further study is indicated.

Additional minerals have not yet been tested. As an aside: icosahedrite ($\text{Al}_{63}\text{Cu}_{24}\text{Fe}_{13}$), the only naturally occurring quasicrystal, identified recently in Russia, was tested for physical and chemical properties, as well as for its lattice parameters (Bindi et al., 2011). A quasicrystal shows a regular tiling pattern when the atoms are arranged within a higher-dimensional framework, but not when the lattice is constructed in three dimensions. Icosahedrite was not tested for electrical or magnetic effects, though other man-made quasicrystals have been, and are known to be piezoelectric. Wang and Pan (2008) give a summary of the work through 2008 for devising appropriate tensor notation for the coefficients, and for the various symmetries explored so far; research is ongoing. Chengzheng Hu et al. (1997) describe icosahedral quasicrystals specifically, and demonstrate non-negative piezoelectric coefficients. It is likely that icosahedrite is piezoelectric.

Electric and Magnetic Mineral Data in Metamorphic Settings

Table 45 in Appendix E, p. 216, arranges the minerals from the prior tables by petrologic localization, e.g. mafic igneous intrusions, granitic pegmatites, and similar. This classification is based on descriptions of mineral occurrence in the Mineralogical Society of America's Handbook of Mineralogy (Anthony et al., 2012). Figures 15 through 25 on the next six pages take each metamorphic setting and graphically display the associated data.

Electric and magnetic values vary according to the diameters of the circles, according to the equations in Table 46, p. 56. Where there were no thermoelectric data, pyroelectric or ferroelectric data were used instead. Where several kinds of piezoelectric data were known, only one was used (d , which treats strain and charge density). In a few cases where d was unknown, another coefficient was used (e , which treats stress and charge density). Data were excluded if the temperatures were not likely in a metamorphic or metasomatic setting; that is, data taken below the freezing point of water were excluded. Metasomatic settings are included. Metasomatism is a solid-state chemical transformation similar to metamorphism, but it occurs at near-surface temperatures and pressures, and often involves fluids.

Bulk Rock Electric Phenomena

For materials that are semiconductors, the band gap is a minimum voltage that must be present to allow for an outer valence electron to act as a charge carrier. If a voltage equal to the band gap is available, the electron will conduct. This is relevant for the transmission of electricity, to create a natural circuit.

Minerals in aggregate form are termed rocks, and these are mostly semiconductors, with the notable exception of ore bodies, which are conductors. Conductivity ranges from about 10^{-14} to 10^2 S m^{-1} for minerals, and minerals typically have three values, varying by the crystallographic axes (Parkhomenko, 1967).

For rocks, electrical conductivity varies according to the rock type. For non-weathered rocks, conductivity in sulfides ranges from about 10 to 10^3 S m^{-1} , while igneous and metamorphic non-weathered rocks generally have conductivities in the range of 10^{-5} to 10^{-3} S m^{-1} , though values can be as low as $10^{-14} \text{ S m}^{-1}$. Weathered rocks generally have conductivities in the range 10^{-4} to 10^{-1} S m^{-1} . Water has values from around 10^{-2} to 1 S m^{-1} , and brine is higher, nearly up to 10 S m^{-1} (Guéguen and Palciauskas, 1994). Notably, water content greatly influences rock conductivity values.

Capacitance is the ability to store charge, and is synonymous with the dielectric strength of materials. Capacitance occurs by the rearrangement of electric dipoles: from elementary particles with a combined net electric dipole moment of zero (i.e. in a neutral material); or from polar molecules whose net electric dipole moment is constant (i.e. in a polar material) (Parkhomenko, 1967). Polarization itself may be caused by one of four mechanisms (Guéguen and Palciauskas, 1994):

1. Electronic polarization is caused by the slight displacement of electrons.
2. Ionic polarization is caused by the slight displacement of atoms or ions.
3. Electric dipole polarization is caused by coherent orientations of polar molecules.
4. Space-charge polarization is caused by migration of charged particles through a substance.

Metamorphic Ore Minerals, plus Hydrothermal	Heat Electricity	Pressure Electricity	Capacitance	Magnetism	Heat Electricity	Pressure Electricity	Capacitance	Magnetism
Altaite								
Argentojarosite					•			•
Arsenogoyazite					•			
Bastnäsite-Ce						•		
Bismuthinite								•
Bournonite		•	•					•
Breithauptite				•				
Carrollite	•			•		•	•	
Chalcocite								
Chalcostibite								•
Cinnabar		•	•		•	•	•	
Clinohedrite						•	•	
Coulsonite	•							•
Cronstedtite								•
Cuprokalinitite	•							
Cuprospinel	•		•		•	•		
Dyscrasite								
Enargite								•
Epistilbite						•	•	
Eskolaite				•				
Eulytine		•	•			•	•	
Ferberite				•				
Finnemanite								
Franklinite								
Gallite								
Harmotome								
Hauerite				•				
Hematite				•				
Hydroxycalcioroméite								
Ilmenite								
Indite	•					•		
Jacobsite	•							
Kalinitite	•							
Kamiokite				•				
Karelianite								
Krennerite								
Krut'aitite				•				
Linnaeite	•							
Löllingite				•				
Maghemite								
Magnesiocoulsonite	•							
Magnetite	•							
Morenosite						•		
Nickeline								•
Nisbite								•
Nolanite								
Paratellurite						•	•	
Parkerite								
Penroseite								•
Proustite	•	•	•			•	•	
Pyrargyrite						•	•	
Pyrite								•
Pyrite (Bravoite)								•
Pyrochroite								
Pyrolusite	•	•						
Pyrophanite								
Pyrrhotite								•
Quartz		•	•			•	•	
Quenselite								
Retgersite		•	•					
Roquesite								
Selenium		•						
Siderite								
Siegenite	•							
Sphalerite		•	•			•	•	
Stephanite		•	•					
Stibnite							•	
Stilleite		•	•					
Tellurium						•		
Thaumasite								
Tiemannite								
Tilasite								
Trevorite	•						•	
Uraninite								
Wakefieldite-Nd	•						•	
Wurtzite	•	•	•			•	•	
Zincite						•	•	
Zinkenite								

FIGURE 15. Electricity and magnetism in metamorphic and hydrothermal ore minerals. A blank field indicates no data. All data are at or near (ambient) room temperature except for that of minerals shown in Table 47, p. 57.

Secondary Ore Minerals	Magnetism			
	Capacitance			
	Pressure Electricity			
	Heat Electricity			
Argentojarosite				
Arsenogoyazite				
Caledonite				
Cervantite		Large		
Chalcocite				
Clinocervantite		Large		
Coquimbite				
Cuprospinel	.	.		
Diaboleite				
Diopase				
Dyscrasite		.		
Goslarite	.	.	.	
Greenockite	.	.	.	
Halotrichite				
Hematite				●
Hemimorphite				
Hydroxycalcioroméite				
Indite	.			
Iodargyrite				
Jacobsite	.			
Jarosite				
Junitoite				
Koechlinite		●		
Larsenite				
Liebigite				
Linnaeite	.			
Melanovanadite				
Millerite				
Mimetite				

	Magnetism			
	Capacitance			
	Pressure Electricity			
	Heat Electricity			
Morenosite	.			
Muthmannite				
Natrojarosite				
Nolanite				
Olsacherite				
Parkerite				
Pharmacolite				
Pharmacosiderite				
Pickeringite				
Plumbojarosite				
Pyrargyrite	●	.		
Pyrochroite				
Pyrolusite	.	●		
Pyromorphite				
Quenselite				
Retgersite	.	.		
Russellite	.	Large		
Schultenite		.		
Selenium	.			
Sillénite	.	.		
Spangolite				
Tellurium	●			
Tyrolite				
Uranophane				
Vaesite				
Wulfenite				
Wüstite				
Zincite	.	.		

FIGURE 16. Electricity and magnetism in secondary ore minerals. A blank field indicates no data. All data are at or near (ambient) room temperature except for that of minerals shown in Table 47, p. 57.

FIGURE 17. Electricity and magnetism in primary minerals from metamorphism of mafic rock. A blank field indicates no data. All data are at or near (ambient) room temperature.

FIGURE 18. Electricity and magnetism in secondary minerals from metamorphism of mafic rock. A blank field indicates no data. All data are at or near (ambient) room temperature.

FIGURE 19. Electricity and magnetism in primary minerals from high-grade metamorphism of silica-rich rock. A blank field indicates no data. All data are at or near (ambient) room temperature except for that of minerals shown in Table 47, p. 57.

FIGURE 20. Electricity and magnetism in minerals from contact or low-grade metamorphism of silica-rich rock. A blank field indicates no data. All data are at or near (ambient) room temperature.

Secondary Minerals: Metamorphism of Si-Rich Rock	Magnetism				Magnetism			
	Capacitance				Capacitance			
	Pressure Electricity				Pressure Electricity			
	Heat Electricity				Heat Electricity			
Alunite					Pickeringite			
Changbaiite					Prehnite			
Halloysite-7Å					Quartz	.	.	
Halloysite-10Å					Vermiculite			
Jarosite					Zunyite			
Natrojarosite								

FIGURE 21. Electricity and magnetism in secondary minerals from metamorphism of silica-rich rock. A blank field indicates no data. All data are at or near (ambient) room temperature.

Minerals from Metamorphism of Alkalic (Si-Poor) Rock	Magnetism				Magnetism			
	Capacitance				Capacitance			
	Pressure Electricity				Pressure Electricity			
	Heat Electricity				Heat Electricity			
Coulsonite	.				Natrolite		.	
Gugiaite					Nepheline		.	
Lueshite	.		Large		Pyrite			.
Magnetite	.				Thomsonite-Ca			

FIGURE 22. Electricity and magnetism in secondary minerals from metamorphism of alkalic, silica-poor rock. A blank field indicates no data. All data are at or near (ambient) room temperature except for that of minerals shown in Table 47, p. 57.

Minerals from Regional Metamorphism of Carbonate Rock	Magnetism				Magnetism			
	Capacitance				Capacitance			
	Pressure Electricity				Pressure Electricity			
	Heat Electricity				Heat Electricity			
Breithauptite				.	Löllingite		.	.
Brucite					Magnesioferrite		.	
Dravite			.		Marialite			
Franklinite	.	.			Meionite			
Kalininite	.				Rutile		●	

FIGURE 23. Electricity and magnetism in minerals from regional metamorphism of carbonate-rich rock. A blank field indicates no data. All data are at or near (ambient) room temperature except for that of minerals shown in Table 47, p. 57.

FIGURE 24. Electricity and magnetism in skarn minerals and minerals from contact metamorphism of carbonate-rich rock. A blank field indicates no data. All data are at or near (ambient) room temperature except for that of minerals shown in Table 47, p. 57.

FIGURE 25. Electricity and magnetism in metasomatic minerals. A blank field indicates no data. All data are at or near (ambient) room temperature.

TABLE 46. Constructing the Circles in Figures 15 through 25, Pages 51 through 56

Data Category	Circle Diameter = Data x Factor
Heat Electricity	0.0001
Pressure Electricity	0.001
Capacitance	0.001
Magnetism	0.001

Notes: All data units are as given in Table 22, p. 156, Table 25, p. 158, Table 26, p. 159, Table 30, p. 160, Table 31, p. 163, Table 38, p. 167 and Table 41, p. 172, except for the magnetic data, which have been normalized to 10^{-5} . Circle diameters are in inches. The circles for löllingite and nisbite in Figures 15 and 23, p. 51 and 55, represent diamagnetism rather than paramagnetism.

TABLE 47. Mineral Data Measurement Temperatures in Figures 15 through 25, Pages 51 through 56

Mineral	Data	Temperature: °C
Cervantite	All	565
Clinocervantite	All	565
Lueshite	Capacitance	350
Magnesioferrite	Magnetism	425
Magnetite	All	1000
Russellite	Capacitance	920
Spinel	All	500
Srebrodolskite	All	450

The amount of time it takes to store or release electric charge depends on the mechanism involved, whether electronic, ionic, electric dipole or space-charge. These are also affected by the frequency of an incident electric signal. Capacitance in space-charging (and in the other mechanisms) is reduced when the signal frequency is high (Parkhomenko, 1967). Space-charging is the most sensitive to frequency, electronic charging is the least and the other mechanisms having intermediate sensitivities according to the order listed on p. 50.

For dielectric materials where polarization is due entirely to electronic charging, the dielectric permittivity is approximately equal to the square of the index of refraction for the material (Parkhomenko, 1967). Photons, as gauge bosons for the electromagnetic force, are fundamentally connected to electrons, so it makes sense that the state of electrons in a material would affect both the transmission of light through that material and the transmission of electric charge. Thus, dielectric values may sometimes be approximated with refraction data, and one may imagine the indicatrix for the dielectric constant of biaxial and uniaxial crystals as being similar to the indicatrix for the refractive index of those crystals (Parkhomenko, 1967). More optically refractive minerals have higher capacitance, provided that the dielectricity is caused by the electron configuration.

For ionic materials, dielectric permittivity varies inversely with the hardness of crystals: salts and other softer crystals have a higher capacitance. Ionic materials have lower capacitance than electronic materials. The minerals with the highest capacitance are oxides and sulfides, generally (Parkhomenko, 1967). Dielectric permittivity may also increase with the coordination number of metal ions present in the crystal lattice (Parkhomenko, 1967).

The dielectric permittivity of minerals varies over about two orders of magnitude, from about three (for several minerals) to 173 (for rutile) (Parkhomenko, 1967). This is the relative dielectric permittivity, which refers to the ability of a substance to store electrical energy from an externally applied electric field. Permittivity values for rocks range from three to about 20 (Parkhomenko, 1967). The dielectric permittivity for carbonate is about 1.5 times that for quartz, and carbonate-bearing rock will have higher capacitance than silicate rock, with an important caveat: the presence of mafic (and ultramafic) minerals, such as olivine and pyroxene, can increase the capacitance of any rock considerably, e.g. an increase in the dielectric coefficient from five to 15 (Parkhomenko, 1967). Likewise, the presence of carbon (in coals, for example) increases the capacitance of rock.

Water

Water can have electrical conductivity values of 10 orders of magnitude larger than those of rock. For rock bodies near the surface of the Earth, water content is the prime consideration in determining the transmission of electricity, or the storage of electric charge.

The effective electrical conductivity of saturated rock is calculated from the electrical conductivity of water, divided by the formation factor for the rock, which depends on the pore structure of the rock and also on the electrical conductivity ratio of the dry rock versus water (Guéguen and Palciauskas, 1994).

Electrical conductivity can be used as a proxy for strength in rock. The more electrically conductive rock has a higher water content, and, hence, is weaker (Parkhomenko, 1967). Note that oil, natural gas, and air have much lower electrical conductivities than water, and can also lower rock strength. The fraction of these or other volatiles in the pore space of rock will complicate the rock-strength calculations (Guéguen

and Palciauskas, 1994). Volatiles are substances with low boiling points compared with other materials, and tend to vaporize under ambient or moderate geologic temperatures. Further, the presence of a clay coating along mineral grains will increase the residence time of solute ions there because of the charge of the clay, and this will necessitate adding another term to the calculations (Guéguen and Palciauskas, 1994). The interaction of rock and water is complex.

Regarding capacitance: the dielectric coefficient of water is 81, and for saline water, the value is even higher. There is some anomalous behavior reported of very high values (10^3 to 10^5) for the dielectric permittivity of sedimentary rock with 10 to 12% water if the signal frequency is below 10 kHz (Parkhomenko, 1967). The capacitance is not as high with higher signal frequencies. The sensitivity to frequency implies that this anomaly may be related to a space-charge mechanism (from the migration of charged particles) or to an electric dipole mechanism (from the orientation of polar molecules) but further study is needed. There is no difference in low- and high- frequency capacitance if the rock is dry (Parkhomenko, 1967).

Piezoelectric Effect in Rock

Electric circuits in rock are typically made by either the electrokinetic effect, based on the transfer of water and electrolyte, or through an activation potential, a solid-state effect wherein lattice holes are the positive charge carriers. Of relatively minor significance is the piezoelectric effect from individual piezoelectric minerals in crustal rocks. Most minerals are not strongly piezo-, pyro- nor ferroelectric.

Furthermore, for rocks containing quartz, which is strongly piezoelectric, the bulk effect is often much less (e.g. by three orders of magnitude) than the effect of the individual grains (Sasaoka et al., 1998; Tuck et al., 1977). Even for quartz-rich rocks that show a crystallographic (oriented) fabric, it is exceptional for a rock to show a true piezoelectric effect due to fabric; most of the electrical effects have a non-polar statistical distribution (Bishop, 1981). The same is true for tourmaline-rich rocks (Baird and Kennan, 1985).

Moreover, piezoelectricity is observed in rocks that contain no piezoelectric minerals, such as limestones (Frid et al., 2009) and marble (Kuksenko and Makhmudov, 2004). Some other mechanism must be at work. Teisseyre et al. (2001) provide an introductory treatment of piezoelectric effects in rocks with no piezoelectric components (e.g. limestone, tuff), and conclude that there are at least two (one slow, one fast) mechanisms acting on these materials. They do not identify what these two mechanisms are.

Temperature and Pressure Effects

Rocks have electrical conductivities that may vary markedly with temperature and pressure. For metamorphism, a few considerations are notable.

High temperatures lower capacitance generally. With increased temperature, thermal agitation will displace particles, and the polarizability (and capacitance) of the material will decrease. Further, if the source of capacitance is electron or hole conductivity, higher temperature will allow for more mobility of the charge carrier or hole, and act to reduce the effective capacitance (Parkhomenko, 1967).

On the other hand, conductivity increases with temperature. Both impurities and lattice atoms will have greater mobility, and different charge carriers (requiring higher activation energies) may become mobile at higher temperatures (Parkhomenko, 1967). An increase in temperature from 25 to 400°C can increase the conductivity of dry rock by several orders of magnitude (Parkhomenko, 1967). This change corresponds to a depth of about 10 or 12 km.

With increased pressure, the dielectric permittivity of rock may increase or decrease (Parkhomenko, 1967). Increased pressure may close pore spaces, and increase density, and this will allow for increased capacitance, if the cause is electronic (and not ionic) charging (Parkhomenko, 1967). Increased pressure may also create lattice defects in the material, and that will serve to increase capacitance. (See Chapter 6, p. 68).

Dielectric anisotropies in mylonites have been modeled by Muto and Nagahama (2004) with an equation to relate strain to anisotropic dielectric behavior. These anisotropies are observed in shear zones. A similar treatment has also been done for the upper mantle (Shaocheng Ji et al., 1996), where olivine is thought to control the electrical conductivity. Both microanisotropy and macroanisotropy are involved. The mechanisms whereby pressure influences capacitance in rock is done on a case-by-case basis.

Electrical conductivity in rocks generally increases with depth (Parkhomenko, 1967). Some rock types, e.g. pyroxenite, serpentinized dunite and augite porphyry, reach a maximum value of conductivity at some pressure, and then the value begins to decrease (Parkhomenko, 1967). This variance may be caused

by changes in the type of deformation mechanism active in the constituent minerals in the rock. (See Chapter 6).

Here are two cases: the breaking of peroxy bonds, which are a common defect in silicates, allows oxygen to accept electrons from nearby atoms, creating positive-charge holes. Peroxy is a theoretically-consistent pathway for describing an increase in conductivity with pressure (Takeuchi et al., 2011). On the other hand, if fluid is providing the electrical conductivity, then deformation will increase the length of the fluid path. A longer fluid path will reduce conductivity (Büttner, 2005).

An increase in pressure from ambient to 4×10^9 pascals can increase the conductivity of dry rock by about 70% (Parkhomenko, 1967). This change corresponds to a depth of about 150 km.

Bulk Rock Magnetic Phenomena

Most minerals have low magnetic susceptibilities (lower than 10^{-4}), and they will not induce a noticeable magnetic anomaly (Guéguen and Palciauskas, 1994). Typical values for rock vary by type. The magnetic susceptibility of sedimentary rock is generally less than 10^{-4} , for granites and gneisses it is 10^{-4} to 10^{-3} , and for intrusive mafic rocks it is often greater than 10^{-3} (Guéguen and Palciauskas, 1994). Iron-rich minerals contribute much to the magnetic susceptibility of rock.

Magnetic susceptibility varies inversely with temperature. Thermal agitation tends to disorder the magnetic domains of crystals (Guéguen and Palciauskas, 1994). The effect of pressure on the magnetic domains is not simple, and will be addressed in Chapter 6.

CHAPTER 6

ELECTRICITY AND MAGNETISM WITHIN METAMORPHIC REACTIONS AND DEFORMATION MECHANISMS

Chemical Reactions in Metamorphism

Metamorphism is a solid-state (as opposed to liquid or gas) change in chemical composition or form, related to temperature and pressure. Three parameters define metamorphic conditions: temperature (T), pressure (P) and chemistry (X). T - P - X models are a reference for defining geologic conditions to construct the natural history of deformation and rock formation over time (Spear, 1995). Metamorphism may or may not be accompanied by deformation. Metamorphism is distinguished from metasomatism, which is also a solid-state change, and consists of a fluid-based transfer of mass (Harlov and Austrheim, 2012). For sedimentary rock, metasomatism takes place at or near the temperature of the original rock formation. Metamorphic temperatures are higher, and include all the transformations until melting (whether from temperature or pressure) is complete.

Fluid phases may be present in metamorphism, and aqueous solutions often contain CO_2 , and peripherally CH_4 , N_2 , F and B. Fluids can greatly reduce rock melting temperatures and pressures. Models for diffusion range over varying time scales and are often most focused on determining when a reaction has stopped (closure) and on dating (Hudgins et al., 2011; Gardés and Montel, 2009). Below are three examples of metamorphic reactions, from Miyashiro (1994), out of hundreds known. For fine-grained clastic sedimentary rock, also called pelitic rock, with increasing temperature,

For pelitic rocks containing dolomite, with increasing temperature,

Computational resources for thermodynamic properties associated with these types of reactions are available. SUPCRT92 includes data for minerals from 1 to 5000 bar and 0 to 1000°C (Johnson et al., 1992) and has been updated in SUPCRT96. Other currently available software seems to be focused on aqueous (hydrologic) geochemistry, e.g. Geochemist's Workbench (Aqueous Solutions, 2013), EQ3/6 (Wolery et al., 1990). These are models to develop P - T - X relations.

Chemical changes are rearrangements to the bonds between atoms and ions, and new bonds and compounds are created during the process. Though none of the computational packages described above include electricity or magnetism, electric fields do promote (or retard) chemical reactions. For example, electric or magnetic fields can influence the diffusion of ions in mineral systems (Frantz and Popp, 1979), and introduce new lattice orientations (Rüssel, 1997; Keding and Rüssel, 1996).

In the field of chemistry generally, changes in chemical reactions with the application of electricity have been described involving ions (Agladze and De Kepper, 1992), the growth of carbon filaments and the decomposition of organic compounds (Calderón-Moreno et al., 2006; Pol et al., 2006), and the crystallization of amorphous silicon (Kim, 2002). Applied magnetic fields also affect chemical reaction rates (Hyun-Sik Seo et al., 2008; Fejfar et al., 2005). A summary of the examples above, quantifying how electric or magnetic fields can affect chemical reaction rates, is given in Table 48.

In a geologic setting, electric or magnetic fields ought to speed the timing of certain chemical reactions, and metamorphic reactions specifically. An initial diffusion of material may be promoted by an electric or magnetic field, and the resulting new mineral growth may conform with the field. Electricity and magnetism affect both the kinetics and geometry of chemical reactions.

TABLE 48. Electric and Magnetic Influences on Chemical Reactions

Parameters	Effect
50 mA DC current	Initiates crystallization in Ba ₂ TiSi ₂ O ₈ -SiO ₂ glass at 1300°C
36 mA DC current	Increases wave propagation rate in HBrO ₂ gel reaction by 400%
1.5 to 5 A DC current	Alters shape of carbon precipitate (filament) from mesitylene gas
1.5 to 5 A AC current	Alters shape of carbon precipitate (zig-zag) from mesitylene gas
360 V cm ⁻¹ electric field	Lowers annealing temperature of amorphous silicon to 380°C
0.4 T magnetic field	Initiates crystallization in amorphous silicon thin film at 100°C
0.05 T magnetic field	Initiates crystallization in amorphous silicon thin film at 430°C

Deformation Mechanisms

Temperature and pressure influence the form of minerals, and mineral grains are subject to distinct deformation mechanisms that depend on these parameters. If strain rates outstep recovery rates, as occurs in fault zones, mylonites and other fault-related metamorphic rocks will be formed. Passchier and Trouw (2005) list several categories of deformation mechanisms working on a grain-sized scale. These deformations are summarized here, in order of increasing pressure and temperature. The lowest temperature and pressure mechanism (brittle fracturing) is listed first. The text that follows, from Brittle Fracturing through Granular Flow, is based on Passchier and Trouw (2005).

Brittle Fracturing

Brittle fracturing includes intergranular fractures (between grains), transgranular fractures (across grains), impingement microcracks (at grain contacts), subcritical microcrack growth (a slow process depending on stress and temperature), and stress corrosion cracking (due to chemical reactions).

Dissolution-Precipitation

The primary mechanism of dissolution-precipitation, another class of deformation mechanism, is pressure solution, occurring at grain boundaries. If there is solution transfer, the resulting precipitation may be described as an incongruent pressure solution.

Crystal Plastic Deformation

Crystal plastic deformation is intracrystalline and occurs through the movement of lattice defects. These are point defects (vacancies, interstitial atoms) and line defects (edge dislocations, screw dislocations, and pleat dislocations). Edge dislocations are formed at the edge of an extra lattice plane, whose growth disrupts a crystal lattice. Screw dislocations form as a twist about an axis made to accommodate three-dimensional lattice defects. Pleat dislocations are a distinct combination of screw and edge dislocation that look like a pleat. Line defects in combination can form a circle or loop (dislocation loop), or misfitted crystal lattice edges (stacking faults). Ductile deformation is accomplished by the movement of dislocations and vacancies.

Deformation by dislocation alone is called dislocation glide, and a crystal changes shape as the dislocations migrate within the crystal lattice. The conditions necessary for dislocation glide are unique for each mineral. Moreover, dislocation glide may occur under different conditions for each crystallographic axis, and are named according to the crystal geometry. Basal dislocation glide on the **c** plane in the **a** direction is written as (c)<a> glide. This combination of slip plane and slip direction is known as a slip system.

Dislocation glide depends strongly on temperature. For example, quartz at low grade conditions (300 to 400°C) exhibits (c)<a> glide. The temperature for other slip systems in quartz are higher.

Vacancies in a lattice can move during crystal plastic deformation, and allow a glide plane or other defect to migrate to a different position while maintaining its original orientation in the crystal. This migration is called dislocation climb. Dislocation climb can allow a glide plane to climb over a site blocked by an interstitial, for example. If glide and climb dislocations are active, the deformation is termed dislocation creep.

These processes tend to create a similar alignments in an aggregate of like crystals as deformation occurs, termed lattice-preferred orientation. This lattice-preferred orientation is quantifiable with a scanning electron microscope (if it is equipped with electron backscatter diffraction equipment). The SEM builds a map of the alignment of the crystal grains. That alignment is determined by the active slip system.

Twinning and Kinking

Twinning and kinking can occur from deviatoric stress. Deformation twinning generally follows crystallographic axes and is often concentrated at high strain sites; kinking does not. Such twinned (or kinked) regions are often microscopic. They may be visible only as constituents within grains in thin section.

Recovery

Deformation mechanisms that lower the internal stress of a crystal are called recovery mechanisms. These include the formation of deformation bands and subgrains. As lattice dislocations migrate and collect in one place, they form dislocation bands. If these are dense enough with dislocations, subgrains will form and the deformation band will become a boundary between subgrains. Each subgrain has a slightly different lattice orientation, and this can be observed as undulose extinction under cross-polarized light (as the polarized light aligns with the optic axis of the crystal) in thin section. Annealing includes both recovery and recrystallization, discussed below.

Dynamic Recrystallization

Like recovery, dynamic recrystallization acts to reduce the dislocation density in an aggregate of crystals. It may alter the size, shape or orientation of crystal grains or grain boundaries to produce an environment in which crystal lattices have fewer (or minimal) defects. Dynamic recrystallization mechanisms include bulging recrystallization (BLG), subgrain rotation (SGR) and grain boundary migration (GBM). Bulging recrystallization occurs when small appendages bulge from one grain into an adjacent grain, capturing material. Subgrain rotation completes the creation of new grains from subgrains. Grain boundary migration gives a “jigsaw puzzle” aspect to an aggregate of crystals. These three listed above are in order of increasing temperature of formation. If all else is equal, BLG occurs at lower temperatures than SGR, and SGR occurs at lower temperatures than GBM.

Diffusion Creep

Diffusion creep can be thought of as the random movement of vacancies in the solid state. There are two types: Coble creep refers to vacancy migration along grain boundaries, and Nabarro-Herring creep signifies vacancy migration throughout the crystal lattice. Diffusion creep occurs at high temperatures, close to the melting temperature of the constituent minerals.

Granular Flow

Granular flow denotes crystals sliding past one another in a fine-grained aggregate. Superplasticity refers to the same process, but without the development of any lattice-preferred orientation. Granular flow is the most intensive strain mechanism of the eight mechanisms listed.

Electric and Magnetic Phenomena Associated with Deformation Mechanisms

A selection of articles relating to all of these mechanisms is presented below. The articles describe electric and magnetic phenomena associated with each deformation mechanism. Observed phenomena are summarized in Table 49, and Table 50 lists relevant data from the articles.

Electric and Magnetic Phenomena with Brittle Fracture Mechanisms

Electric. Makarets et al. (2002) show that fracturing of piezoelectric minerals in rocks causes transient magnetization due to the moving crack, and that this causes electromagnetic emission. The frequency of the electromagnetic emission is in the kHz range, and the radiation energy is proportional to the energy that causes the crack. Takeuchi and Nagahama (2002) summarize research showing that fracturing and frictional sliding in quartz and granite under dry conditions generates fractoluminescence, charged particle emission, and electromagnetic radiation. Surface charge density is approximately 10^{-4} to 10^{-2} C m⁻². Baragiola et al. (2011), James et al. (2000) and Oster et al. (1999) describe fractoemission of electric

TABLE 49. Deformation Mechanisms and Associated Electric and Magnetic Phenomena Summarized

Mechanism	Summary
Brittle Fracture	Brittle fracture can cause electrical and electromagnetic emission and fractoluminescence. Magnetic fields weaken materials and promote fracture.
Dissolution-Precipitation	The presence of electrolyte-bearing fluids can promote pressure solution. Mineral precipitation is responsible both for the conductivity anisotropy in the upper mantle shear zone and for magnetic fabrics in some slate, migmatites and granites.
Crystal Plastic Deformation	Dislocations allow for greater charge transfer and conductivity, while high-current discharge can create dislocations in metals. Crystal plastic deformation alters the orientations of magnetic domains and is used to create permanent magnets. It is responsible for similar changes in minerals. It is the cause of magnetic fabrics in some migmatites and other rock.
Pressure Twinning and Kinking	Twinning is responsible for some piezoelectric fabric in rock. Kinking is controlled by the energy to turn bonding into anti-bonding electrons. Pressure twinning can create magnetic anisotropy in materials with ferromagnetic dopants.
Recovery / Annealing Mechanisms	An applied direct electric current can increase the rate of recovery processes at the expense of grain growth rate. The presence of subgrains decreases magnetic susceptibility in ferromagnetic materials.
Dynamic Recrystallization	An applied electric field can increase the rate of dynamic recrystallization in metals, but direct current will decrease the occurrence of grain boundary migration in the direction of the applied current. Grain boundary migration decreases electrical conductivity. An applied magnetic field makes fine-scale grain boundary structure more uniform. Dynamic recrystallization can be used to create permanent magnets in metals.
Diffusion Creep	Vacancies increase both electrical conductivity and magnetic susceptibility.
Granular Flow	An applied electric field promotes superplasticity. If lattice-preferred orientation is destroyed (as with superplastic deformation), other earlier anisotropies will be destroyed as well. The process whereby grains slide past each other in granular flow can create magnetic fabrics.

Notes: Pressure solution–precipitation, crystal plastic deformation, and granular flow have each been singled out as the major cause of magnetic fabrics in different rocks by different authors. References for the summaries in this table are given in the text on p. 63 through 68.

TABLE 50. Data on Deformation Mechanisms and Associated Electric and Magnetic Phenomena

Mechanism	Data	Phenomenon
Brittle Fracture		
Electric Emission	10^{-6} to 10^{-5} C kg ⁻¹ 10^{-4} to 10^{-2} C m ⁻² > 30 kV cm ⁻¹	Electric charge (volcanic ash) Surface charge density (granite) Electric field (crustal rock)
Electromagnetic Emission	kHz range 10^3 to 10^5 Hz Radiation energy $\propto$ applied force	Frequency (mineral 32 class) Frequency (ice)
Weakness Caused by Magnetism	> 25%	Loss of tensile strength (nickel)
Dissolution-Precipitation		
Dissolution Rate	45 pm hr ⁻¹ 0.1 nm hr ⁻¹	<u>Fused silica</u> , 10^{-12} to 10^{-10} A <u>Silica glass-gold</u> , 500 mV
Precipitation Rate	1 to 4 nm min ⁻¹ (start) 0.01 nm min ⁻¹	<u>Quartz-mica</u> , 50 to 150 mV <u>Quartz-mica</u> , 50 to 150 mV
Crystal Plastic Deformation		
Edge Dislocations	3×10^{-12} C m ⁻²	Charge density (rock, estimate)
Electrically-Induced Plasticity	4×10^4 A cm ⁻² 1×10^5 A cm ⁻²	Current density (aluminum wire) Current density (copper wire)
Magnetic Anisotropy	1.3 (max / min)	Susceptibility (magnetite)
Pressure Twinning and Kinking		
Twinning	≤ 0.7 mV	Electric field (quartz vein)
Recovery Mechanisms		
Recovery	10^5 A cm ⁻²	DC enhances annealing (Cu)
Dynamic Recrystallization		
Recrystallization	+10 to 30% 1.2 MA m ⁻¹	Zone width (Fe-Al-Ni-Co alloy, 6 kV) Magnetic field enhances growth (Ni)
Grain Boundary Migration	+400%	Resistivity increase (halite, fluid path)
Upset Forging	9.55×10^2 A m ⁻¹ 1.05 T	H (Pr-Fe-B-Cu alloy) B (Pr-Fe-B-Cu alloy)
Diffusion Creep		
Vacancies and Proton Mobility	8×10^{-5} S m ⁻¹ 3×10^{-4} S m ⁻¹	Strained conductivity (talc-rich rock) Strained conductivity (serpentine)
Granular Flow		
Superplasticity	10^5	Strain rate increase (metal, 10^6 A cm ⁻²)

Notes: Underlining above indicates the material dissolving for "Dissolution Rate" and the material precipitating for "Precipitation Rate." References for the summaries in this table are given in the text on p. 63 through 68.

charge. Baragiola et al. (2011) describe ozone formation from the electric energy emitted at the fracture, and demonstrate that the electric field must be greater than the electricity needed to chemically decompose air (30 kV cm^{-1}). James et al. (2000) describe fracture charging of volcanic rock to simulate ash formation, with electric charge approximately equal to 10^{-6} to $10^{-5} \text{ C kg}^{-1}$. For ice, electromagnetic emission resulting from a single crack under various stress regimes has a frequency of 10^3 to 10^5 Hz (Shibkov et al., 2005).

Magnetic. Jagasivamani (1987) shows how previous reports of magnetic field emission during fracture of ferromagnetic materials are flawed, the result of mistakes in the experimental set up. Li Xiangde (1997) shows decreasing strength in diamond with an applied magnetic field. Tian et al. (2009) describe a decrease in tensile strength (by at least 25%) in nickel with an applied magnetic field.

Electric and Magnetic Phenomena with Dissolution-Precipitation Mechanisms

Electric. Shaocheng Ji et al. (1996) describe how electrical anisotropy and seismic anisotropy are oblique to each other in an upper mantle shear zone, with the magnetotelluric component following the foliation, and the seismic component following the shear plane, which coincides with slip in the **a** direction in olivine. According to the articles below (in the Magnetic part of this subsection, and then in the Crystal Plastic Deformation subsection), these results are due to solution-precipitation and crystal plastic deformation, respectively. If dynamic recrystallization is active, the crystallographic data are reset, and the strain markers give only a minimum strain value of the last event.

Greene et al. (2009) describe increased rates of pressure solution at mica-quartz contacts due to the addition of aqueous electrolyte solutions plus acid. The electrostatic potential resulting from the contact (or proximity) of the plates (at pH 3) is 50 to 150 mV. The precipitation rate onto the quartz plate is initially 1 to 4 nm min^{-1} , and then (after several hours) settles into a stable rate of 0.01 nm min^{-1} . Andersen et al. (2011) describe such solutions, driven by a pressure differential (and a streaming potential), as dissolving fused silica. The dissolution rate is approximately 45 pm hr^{-1} under a streaming current (from fluid flow) of about 10^{-12} to 10^{-10} amperes. The pressure differential is about 8 MPa to set up the streaming potential, and pH values are 5.6 and 9.2 for various experimental trials. Kristiansen et al. (2012) describe the role of surface potential in pressure solution. Silica glass (in contact with a gold electrode) is dissolved at a rate of approximately 0.1 nm hr^{-1} in an electrolyte solution and acid (pH 3) under a few atmospheres of pressure. The difference in potential between the silica glass and the gold electrode is about 500 mV. The gold must carry the more negative sign for the dissolution rate to be this high. Laubach et al. (2010) review the literature on low-temperature diagenesis.

Magnetic. Borradaile et al. (1988) describe pressure solution and precipitation of magnetite in a slate, as an explanation of the observed magnetic fabric, while Borradaile and Tarling (1981) describe the influence of pressure solution (forming stylolites) and grain boundary sliding on magnetic fabrics, and suggest that the process initiates a tectonic magnetic fabric within cleavage surfaces.

Kratinová et al. (2007) report a magnetic fabric in successively-emplaced granite sheets, with some migmatites (and granites) showing quartz ribbons alternating with regions of biotite flakes, the result of strong recrystallization processes. Most of the field from the magnetic fabric is attributable to the paramagnetic silicate (e.g. biotite) phases.

Electric and Magnetic Phenomena with Crystal Plastic Deformation Mechanisms

Electric. Dubovitskaia et al. (1980) describe electric discharge in a molybdenum single crystal as generating dislocations and dislocation pile-ups. Slifkin (1993) posits that charged dislocations in rock may be responsible for seismic electric signals, and describes the thermodynamics involved. Excess charge density in rock due to edge dislocations in the constituent minerals are estimated at $3 \times 10^{-12} \text{ C m}^{-2}$. This estimate is based on dislocation density and a dislocation charge model of $3 \times 10^{-11} \text{ C m}^{-1}$ for the crystal surface, with a potential of a few tenths of a volt on the surface relative to the interior (as measured for edge defects in alkali and silver halides, and then generalized) and a lattice spacing of about $5 \text{ \AA}$ for the constituent minerals. Shibkov et al. (2006) and Shibkov et al. (2009) discuss electromagnetic emission signals from single-crystal and polycrystalline ice undergoing plastic deformation and fracture, and describe how lattice dislocations allow for charge transfer. Shibkov et al. (2005) provides an atlas of waveforms correlated with electromagnetic emission caused by various processes (e.g. the generation of a slip band) in ice. A list of previous work on the subject of electromagnetic emission in relaxation processes (deformation and fracture) in crystals is also given in Shibkov et al. (2005).

Savenko and Shchukin (2006) describe the role of dislocations in creating electromechanical effects in halite. Eremenko et al. (2007) describe electrically-active layers formed by dislocation glide in silicon, and

Eremenko et al. (2009) describe further the increased conduction in silicon subjected to crystal plastic deformation. Crystal plastic deformation creates a very dense system of extended (electrically active) defects trailing from the dislocations that comprise the slide, climb and glide of the crystal plastic deformation. Conrad (2000) reports plastic deformation initiated in aluminum wire under an applied electric current density of $4 \times 10^4 \text{ A cm}^{-2}$ and in copper wire under an applied electric current density of $1 \times 10^5 \text{ A cm}^{-2}$.

Magnetic. Borradaile (1988) observed that the alignment of magnetic domains change rapidly with advancing strain, especially as minerals undergo crystal plastic deformation. This affects their magnetic susceptibility. Shang-Shiang Hsu and Tein-Tai Chang (1995), in their work characterizing nuclear pressure vessels with magnetic methods, summarize research that shows how the stability of pinning walls for magnetic domains in ferromagnetic materials is correlated inversely with the flow of dislocations in such materials.

Grünberger (2001) reports on deformation-induced RE-TM-B (rare earth - transition metal - boron) permanent magnets, invoking crystal plastic deformation in the *c* direction (perpendicular to the growth direction for these crystals) as one method of producing anisotropy. Several papers in the materials science literature relate to the subject of upset forge magnet fabrication. Upset forge fabrication includes any forge process that compresses the length of the material and increases the cross-sectional area (Dadras and Thomas, 1983).

Ferré et al. (2003) and Ferré et al. (2004) describe the development of magnetic fabrics in migmatites. Titanomagnetite (ferrimagnetic) and biotite (paramagnetic) change their magnetic orientations while undergoing crystal plastic deformation under deviatoric stresses and magnetic fields. The earlier work describes anisotropy in magnetite grains as being about 1.3 (the ratio of maximum to minimum magnetic susceptibility) (Ferré et al., 2003). For one migmatite studied, the magnetic anisotropy in the melanosome occurred via crystal plastic deformation, while in the leucosome, it occurred via this and granular flow (Ferré et al., 2004). The melanosome and leucosome are regions in rock in which dark- and light-colored minerals predominate, respectively. The terms are used to describe rocks where minerals are segregated.

Electric and Magnetic Phenomena with Pressure Twinning and Kinking Mechanisms

Electric. Essen (1935) describes what is now known to be Dauphiné twinning in quartz. These are twins rotated by 60° about the *c* axis, such that mechanical pressure along the *a* axis produces electrical signals from each twin that either interfere or cancel each other. Dauphiné twins in quartz, also called electrical twins, are optically indistinguishable.

Nikitin and Ivankina (1995) describe a mechanism whereby polycrystal aggregate (vein) β -quartz that formed at high temperature may undergo deformation and acquire a lattice-preferred orientation, as is commonly observed. The quartz may then be brought to a cooler setting, where it makes a transformation to α -quartz. The resulting grains undergo twinning. If the twinning follows a combined twin law with twinning on both $[0001]$ and $[11\bar{2}0]$, then the twinned grains will share their polarity, and the rock will become piezoelectrically active. The Dauphiné twin law refers to twins along the plane $[0001]$ and this contains the *c* axis. The Brazil twin law refers to twins along the plane $[11\bar{2}0]$. Neither of these twins alone will create a piezoelectrically active structure under isotropic pressures. If there is some non-hydrostatic, directed stress, the growth of one crystal will be favored over the other under either twin law. The resulting distributions of twinned quartz will be unequal in mass, and result in piezoelectricity. In their sample of vein quartz, the measured electric field values are up to 0.7 mV and vary according to the orientation of the pressure with respect to the lattice-preferred orientation (Nikitin and Ivankina, 1995).

Bertagnolli et al. (1981) produced stress-induced twins in X-cut quartz plates when stress was applied non-uniformly. X-cut crystal plates are named for the *x* axis and are perpendicular to one of the *a* axes of the crystal. Arlt (1990) describes the relationship between twin-wall energy and grain size in ferroelectric and ferroelastic ceramics, and shows that a minimum grain size exists for each mineral system, below which twinning won't further minimize the local energy. Gilman (2008) describes kinking in covalent crystals as requiring the excitation of bonding electrons into anti-bonding states, as measured by the band-gap density. For a kink to move, it must shear covalent bonds, and does so via this excitation.

Magnetic. Evans (2006) reports on the anisotropy of magnetic susceptibility in a ferroan calcite cement related to twinning deformation.

Electric and Magnetic Phenomena with Recovery Mechanisms

Electric. Conrad et al. (1988) report that pulses of DC current (10^5 A cm^{-2} for short durations) enhanced the rate of recovery and recrystallization, but retarded the rate of grain growth in 99.9% copper wires.

Magnetic. Bose (1986) attributes a decrease in magnetic induction in ferromagnetic materials during strain to subgrain formation and changes in dislocation density.

Electric and Magnetic Phenomena with Dynamic Recrystallization Mechanisms

Electric. Fu et al. (2003) describe how an applied electric field (6 kV) can accelerate the nucleation of dynamic recrystallization grains in a metal weld under pressure, resulting in a wider area of recrystallization (10 to 30%) and a more equant aspect ratio for the new grains. Kemmochi and Hiramoto (1975) demonstrate that an applied DC current ($6 \times 10^3 \text{ A cm}^{-2}$) reduces grain boundary migration in the current direction in aluminum and enhances grain boundary migration in the direction perpendicular to the current direction. This result is consistent with data cited in Bose (1986). The process of grain boundaries being influenced by an applied electric field is called electromigration.

Watanabe and Peach (2002) describe increased resistivity (+400%) with deformation in halite. Wet samples deformed via dynamic recrystallization (grain boundary migration) exhibited more resistivity than dry samples, which showed no recrystallization structures. The experiments were undertaken at 125°C and 50 MPa. This type of increase in resistivity is likely caused by deformation and the consequent lengthening of the fluid paths (Watanabe, 2010).

Magnetic. Harada et al. (2003) report that an applied magnetic field (1.2 MA m^{-1}) can affect the grain boundary microstructure in nanocrystalline nickel, making it more homogenous and increasing the rate of grain growth during annealing. The standard deviation in the grain sizes decreased by about 10% in experiments with an applied magnetic field as compared to those without an applied field. Watanabe et al. (2006) follow up on this with a summary of magnetic field applications for grain boundary engineering in metals.

Kwon et al. (1992) report that dynamic recrystallization is responsible for alignment of the magnetic field in upset forge cast ingots for permanent Pr-Fe-B-Cu magnets. The measured strengths were $H \approx 9.55 \times 10^2 \text{ A m}^{-1}$ and $B \approx 1.05 \text{ T}$.

Electric and Magnetic Phenomena with Diffusion Creep Mechanisms

Electric. Conrad (2000) reports that a current density of $2.5 \times 10^3 \text{ A cm}^{-2}$ increases the rate of creep in V_3Si . Xinzhuang Guo et al. (2011) cite hydrogen mobility and vacancies in talc- and serpentine-rich rocks as the mode for creating electrical conductivity in the mantle lithosphere, with experimental results taken at 3 GPa. The conductivities due to hydrogen and vacancy mobility for talc-rich rock and serpentinite were $8 \times 10^{-5} \text{ S m}^{-1}$ and $3 \times 10^{-4} \text{ S m}^{-1}$, respectively, parallel to lineation. Xiaozhi Yang (2012) describes enhanced electrical conductivity of hydrated olivine, clinopyroxene, and hydrated plagioclase under conditions of 10 kbar at 200°C to 800°C as being caused by point defects. The hydrated plagioclase exhibits a large electrical anisotropy, but the other two minerals do not. The anisotropy (ratio of the maximum to the minimum conductivity) ranges from 3 to 8 for the strained plagioclase.

Magnetic. Osorio-Guillén et al. (2007) tackle the problem of ferromagnetic behavior in oxides (such as CaO and HfO_2) that lack unpaired electrons in the d-orbital, and show that vacancies, while they can create a magnetic moment, are insufficient to produce the observed bulk magnetic moment, which they attribute to nonstoichiometric factors. These are overgrowths and grain boundaries that lead to a net violation of the stoichiometry. Antiferromagnetic coupling of nearby vacancies precludes them from being the sole source of ferromagnetism.

Electric and Magnetic Phenomena with Granular Flow Mechanisms

Electric. Conrad (2000) details how applied electric fields influence plastic deformation in metals and oxides. The results showing that a decrease in flow stress during superplasticity (making deformation easier), cavitation and grain growth are all positively correlated with applied electric fields. Cavitation is the formation and subsequent collapse of voids. At current densities of 10^6 A cm^{-2} , strain rates in metals abruptly increased by five orders of magnitude.

Magnetic. Egydio-Silva et al. (2005) use granulites exhibiting magnetic anisotropies to orient models of deformation regimes for their sample regions. Both ferromagnetic oxides (e.g. titanohematite), sulphides (e.g. pyrrhotite) and paramagnetic components (e.g. ferromagnesian silicates) are discussed.

CHAPTER 7

SEISMIC ELECTRIC SIGNAL (SES) RESEARCH

Introduction

Geophysical research in the 1960s and 1970s had a significant focus on the coupling between earthquake and electrical phenomena, especially in work from the United States, Soviet Union, China and Japan. Significantly, observational evidence shows that compression is associated with a marked decrease in rock resistivity, oriented parallel to the compressive force (Dmowska, 1977). Similar work is ongoing; a study in Greece shows the superposition of twenty-four-hour wavelet variations in signals preceding and following an earthquake (Thanassoulas and Tselentis, 1993). See Figure 26. It is not suggested in their study, but such superposition of twenty-four-hour wavelets may be the result of decreased rock resistivity during the seismic event, combined with the typical telluric variation caused by solar flux.

FIGURE 26. Record of electric field variations before and after the magnitude 4.8 earthquake of February 9, 1982 in the North Aegean. The onset of the twenty-four-hour field variations are indicated with an arrow captioned "START." SP refers to self potential. Filtering was accomplished via a moving average. The image is adapted from Figure 2 in Thanassoulas, C., and Tselentis, G., 1993, Periodic variations in the Earth's electric field as earthquake precursors: Results from recent experiments in Greece: *Tectonophysics*, v. 224, p. 103–111. Reproduced with permission.

Varotsos-Alexopoulos-Nomikos (VAN) Method

In 1981, a network of eighteen electrical stations was set up in Greece, and then connected by telephony in 1983, for earthquake prediction (Varotsos et al., 1993a), with mixed results. The typical VAN method (named for the three co-authors, Varotsos, Alexopoulos and Nomikos) includes choosing a site, laying down sets of short-separation (50 to 400 m apart) and long-separation (2 to 20 km apart) electrodes in north-south and east-west orientations, along with magnetometers to measure the concurrent changes in

the magnetic field (Varotsos et al., 1993a). The multiple electrodes are important in distinguishing noise, and the longer electrodes can demonstrate whether changes in voltage increase with the length of the area measured. These length data, combined with polarity data of the pulses, can distinguish local from regional events.

Finding a location that is relatively insensitive to magnetotelluric variation is important, since variations in the geomagnetic field can introduce electric field variations that are unrelated to seismic activity (Varotsos et al., 2011). As a first filter for the electric data, the magnetotelluric data are examined and electric field variations are calculated based on changes to the geomagnetic field. These calculated regional electric field variations are subtracted from the electric field measurements, yielding a baseline from which to look for seismic electric signals (Arvidsson and Kulhánek, 1993; Hadjioannou et al., 1993).

A time lag between the electric and magnetic signals is sometimes measured at the magnetometers. If there is some difference in the rate of transmission of magnetic and electric fields in the rock, then the time lag can perhaps be used to discriminate against local electrical noise for the following reason: it may indicate that the signal has traveled some distance. For some monitoring stations in Greece, comparison with the seismic record indicates that a 1 second time lag is caused by approximately 100 km of travel (Varotsos et al., 2011).

An early procedure is calibrating the measuring station. A station's electric data are checked against seismic data, to see whether seismic events are correlated with anomalies recorded in the electric data, and from which region. This procedure is used to build the selectivity map of the station. The selectivity map should show the area where seismic signals produce electrical phenomena detectable at a station if the correlations are taken as valid.

In Greece, major ophiolite suture zones divide the occurrence and character of purported seismic electric phenomena (Papanikolaou, 1993). See Figure 27. Electric transmission through crystalline rock is affected by chemistry and form, with mafic rock being more suitable than felsic, and dikes being much better locations for stations than sills. Because of selectivity, a station may be sensitive to seismic activity at a distance (150 to 200 km), but not to local activity.

The station is then used to gather predictive data. The location of a signal is deduced from the variance between north-south and east-west trending electrode pairs, correlated with previous seismic detection history. Magnitude is calculated according to the following equation:

$$\log (\Delta V / L) \approx (0.34 \text{ to } 0.37) M_L + b, \quad (19)$$

where ΔV is the change in electric potential in millivolts, L is the length of the electrode spacing in meters, M_L is the local magnitude and b is empirical and based on previous data, with values different for NS or EW electrodes, but the slope (0.34 to 0.37) is the same for both (Varotsos et al., 1993a). No vertical (z) component of the electric field was recorded in the above studies, nor have correlations been made to rule out atmospheric and weather influences on the fields. Other sources of electrical phenomena, such as man-made interference (e.g. heavy use of electrical lines for a planned construction project), or local electrochemical alterations (e.g. corrosion of the electrodes) are tracked manually. Several sites in the French Alps have been set up following this method, with some preliminary selectivity completed (Maron et al. 1993), as has a set of stations in Japan, where telephone cables were used for the electrodes (Kawase et al., 1993). Both show correlative results between seismic activity and electric phenomena.

Criticism of the VAN Method

Critical work in 1993 (Tectonophysics, Volume 224) and 1996 (Lighthill, 1996) highlights seven features of this VAN method:

1. There is no one-to-one correlation between signals recorded and earthquakes, and perhaps 50% of the larger events are missed (Hamada, 1993).
2. The temporal correlation of the signals is of two types: a single signal for a single event, and multiple signals for a period of seismic activity. The second of these yields no definite timing for the prediction (Varotsos et al., 1993a).
3. The transmission of purported seismic electric signals is selective, and a station may only receive seismic signals for a specific region, perhaps not strictly related to distance. The selectivity bias needs to be calibrated with other stations in the network and is subject to human error (Varotsos et al., 1993a).
4. Inaccuracy of location, based on selectivity, highlights the unknown origin of supposed SES (Dologlou, 1993a).

FIGURE 27. Selectivities of three SES stations, Greece. Areas covered by Ioannina (IOA), Assiros (ASS) and Keratea (KER) are shown by textures 1, 2 and 3, respectively; events for each are shown by symbols 5, 6 and 7, respectively. Stations are at symbol 4. Ophiolite zones separate IOA and ASS; and KER is sited on a granitic dike. Reproduced with permission from Papanikolaou, D., 1993, The effect of geological anisotropies on the detectability of seismic electric signals: *Tectonophysics*, v. 224, p. 181–187.

5. Confusion exists between man-made and so called seismic signals (Pham et al., 1998).
6. Building the selectivity map of a station is prone to a lack of falsifiability, in a region where earthquakes are common enough that correlation is a given (Kagan, 1997).
7. Some problems of scientific rigor have been noted, especially regarding conflicts in choosing whose calculated earthquake seismic data to use for correlations (Drakopoulos et al., 1993; Varotsos et al., 1993b).

These difficulties are significant. Note that there is a difference of opinion between Uyeda (1996) and Hamada (1993), on the one hand, and Kagan (1997) and Wyss (1996) on the other, relating to statistical significance, in the main because correlations are only very strong with $M_L \geq 5.0$ (or perhaps 5.5) earthquakes, whose occurrence is infrequent enough that the data population is too small for statistical analysis. For example, eight $M_L \geq 5.5$ earthquakes occurred in Greece from January 1, 1984 through September 10, 1995, and the VAN network forecast six of these (Uyeda, 1996). All of the above are less damaging than the blow to public opinion that false alarms issued by the VAN team have generated. More than anything else, these have created ill will. In short, using presumed SES to predict earthquakes did not have unqualified success.

Time Series Analysis of Presumed SES

In 2001 Varotsos et al. (2001) published work with SES using a novel time series analysis, and this new method is summarized in Varotsos et al. (2011). For testing the coherence of the electric signal data, Varotsos et al. use a detrended fluctuation analysis (DFA) (Bashan et al., 2008), breaking the data into time-segments which can be graphed separately with polynomial modeling functions of various orders, generally one (linear), two (quadratic) and three (cubic). A measure of the variation in the data (as expressed by the square root of the sum of the squares of the lengths of data where there are no polynomial trends) is then taken as a power law of the time-segment size chosen:

$$\text{Var}(s) \approx s^a, \quad (20)$$

where s is the time-segment size, $\text{Var}(s)$ is the variation in the data described above, and a is an indicator variable. If $a \approx 0.5$ then the signal is incoherent and there is no pattern on a range of scales. If $a < 0.5$ then the data are anticorrelated, with scaling indicating some change in the trend according to scale. If $a > 0.5$ then trends in the data are correlated across a range of scales, and therefore coherent. (Varotsos et al., 2011).

For SES, DFA leads to $a \approx 1$ for four orders of magnitude in s . For variations in the magnetic field (spikes of alternating sign) which accompany major earthquakes (moment magnitude approximately equal to 6.5 or greater), $a \approx 0.5$ for $s < 12$ seconds (indicating white noise), and $a \approx 0.89$ for $s > 12$ seconds (indicating a coherent trend) (Varotsos et al., 2011). White noise is ubiquitous in natural signals, due to the nature of how random distributions occur (Ming Li and Lim, 2006).

For looking at the signals themselves, Varotsos et al. introduce two quantities, χ_i and Q_i :

$$\chi_i = i/n, \quad (21)$$

where χ_i is the natural time coefficient, i is an integer based on the order of events (i.e., the i -th event), and n is the total number of events. Q_i is the quantity of energy (electric, seismic or other) released by the process being studied. The product $\chi_i Q_i$ assigns more weight to the most recent and the largest energy events.

A related quantity, p_i , is the fractional quantity of energy, defined by

$$p_i = Q_i/Q_{\text{tot}}, \quad (22)$$

where p_i is the fractional quantity of energy of the i -th event, Q_i is the energy released by the i -th event, and Q_{tot} is the total energy released during the period of study. This mathematical framework is called natural time analysis by Varotsos et al. (2011).

The normalized power spectrum of a set of events in natural time is given by

$$I(\nu) = \left(\sum p_i e^{i\nu(i/n)} \right)^2, \quad (23)$$

where $\Pi(v)$ is the power spectrum, $\sum$ signifies summation, for $i = 1$ to n , p_i is the fractional quantity of energy for the i -th event, e is the euler number, $2.71828...$, i is the square root of negative one, v is an angle in radians times 2π and is present to model sinusoidal variation, i is the event index, and n is the number of events. The quantity v is plotted versus $\Pi(v)$ to get an indication of signal variation (Varotsos et al., 2011). Sinusoidal variation is an explicit assumption of this formula.

One variance term used for critical discrimination in natural time is given by

$$\kappa_1 = [\sum p_i (i/n)^2] - [\sum (i/n) p_i]^2, \quad (24)$$

where κ_1 is the variance in natural time, $\sum$ signifies summation, for $i = 1$ to n , p_i is the fractional quantity of energy for the i -th event, i is the event index, and n is the number of events. This variance puts extra weight on p_i .

For a uniform distribution of data, with χ_i and p_i each taking values between 0 and 1, $\kappa_1 \approx 0.0833...$ or $1/12$. Empirically, with SES data, if $\kappa_1 \approx 0.070$ or less the SES are valid and indicate an impending seismic event (Varotsos et al., 2011). SES datasets with values of κ_1 between 0.070 and 0.083 can be considered noise. Typically, a time period of at least three weeks passes between the detection of true SES in a region and the occurrence of the largest associated seismic event (Varotsos et al., 2011).

Another variance term for exploring criticality in natural time is given by

$$S_n = [\sum [(i/n) \ln (i/n) p_i]] - [[\sum (i/n) p_i] \ln [\sum (i/n) p_i]], \quad (25)$$

where S_n is the entropy in natural time analysis, $\sum$ signifies summation, for $i = 1$ to n , i is the event index, n is the number of events, $\ln$ signifies the natural log function, and p_i is the fractional quantity of energy for the i -th event. This variance also puts extra weight on the energy term, p_i . The term S_n , entropy in natural time, is based on numerical signal data and does not indicate a thermodynamic relation. It is related to the field of information entropy (Shannon, 1948).

For a uniform distribution of data, with χ_i and p_i each taking values between 0 and 1, $S_n \approx 0.0966$. Empirically, with SES data, if S_n values (and reversed-order S_n values) are markedly lower than this, the SES are valid and indicate an impending seismic event (Varotsos et al., 2011).

A third variance term in natural time analysis is calculated by reversing the order of the energy data, and subtracting the value of this new inverted S_n from the original S_n . This is the time-reversal entropy in natural time analysis, ΔS_n . This variance is most sensitive to the ordering of the signal data.

For all these terms in natural time, Q_i can be any energy term, and need not be the magnitude of electric signals. For example, the moment magnitude of seismic events may be substituted for Q_i , and the evolution of seismic data may be analyzed in natural time. The value of $\kappa_1 \approx 0.066$ indicates that the time series may have reached a critical state, and a large seismic event might be imminent in the region being studied: the results outperform chance, but not by very much.

The current protocol for earthquake prediction is as follows. SES are analyzed for $\kappa_1 \approx 0.070$, indicating criticality. Once a critical state is found, the region for the impending seismic activity is calculated based on the geometry of the SES occurrences. The differences between the long and short electrodes of NS and EW orientation are plotted using the sensitivity map for the detection station, which was previously made from correlations between electric signals and seismic signals in the public record, and an estimate of the critical area is made. The predictive magnitude is estimated with Equation 19. Then the SES are set aside. The next focus is to use natural time analysis on the seismic (not electric) signals occurring in the critical region.

The procedure is as follows. The order index i is set to zero, and a new time series is constructed as new seismic data are recorded. The difference is noted between $\Pi(v)$ of this seismic data and

$$\Pi(v)_{\text{ideal}} \approx 1 - 0.070v^2, \quad (26)$$

where $\Pi(v)_{\text{ideal}}$ is an ideal power spectrum, v is an angle in radians times 2π . Values of v for $\Pi(v)_{\text{ideal}}$ are restricted to between 0 and 0.5. If $\Pi(v)$ approaches $\Pi(v)_{\text{ideal}}$ from below for the seismic data, or if $\kappa_1 \approx 0.070$ for the seismic data, then the critical state is indicated, and a major earthquake is imminent, generally occurring within a few days. The location and magnitude of the impending earthquake are taken from the SES data analysis, described above.

For increased accuracy, an updated method (Varotsos et al., 2011), which splits all the seismic data into overlapping regions (like a giant Venn diagram of rectangles, where each region includes at least two seismic epicenters), indicates an impending critical seismic state when the distributions of κ_1 values for the regions that include the last seismic event have a maximum at 0.070.

The above methods and parameters described are based on empirical attempts to optimize the data, and have been successful in predicting all but three of the 28 major earthquakes from N36 to N41 latitude and E19 to E27 longitude between 2001 and 2010 (Varotsos et al., 2011). SES were also recorded for two of the three missed events, but data analyses were insufficient. New predictions are uploaded to arXiv, a pre-print archive of scientific papers hosted by Cornell University. These predictions can be searched for with the following terms: seismic, prediction, Greece.

If there is severe data corruption in the SES detection protocol, as happens, for example, in regions with electric trains causing ground electrification during a period of time, (e.g. running from 06:00 to 22:00) the corrupted data are discarded. The remaining data are then used for SES analysis. Even with partial data, this protocol has been successful in predicting earthquakes, notably the Izu Island regional earthquake swarm in Japan in 2000 (Varotsos et al., 2011; Uyeda et al., 2009).

Mechanisms Causing SES

The presence of co-seismic electric signals during some earthquake events is well-established (Matsumoto et al., 1998). There is no unequivocal evidence that pre-seismic electric signals are SES. The Gutenberg-Richter law predicts the frequency of occurrence of earthquakes based on their magnitude, with an exponential relationship,

$$\log_{10} n = k_1 - (k_2 m_t), \quad (27)$$

where n is the number of events with magnitude less than or equal to m_t , k_1 and k_2 are constants, and m_t is the true magnitude of an earthquake event. This law holds true down to small magnitude earthquakes. All SES might be co-seismic. Alternately, all electric signals preceding major earthquakes may be related to some other phenomena. The following text makes the conjecture that some electric signals preceding major earthquakes are SES.

The primary mechanism for generating presumed seismic electric activity, if one takes into account the selectivity of various stations and the time lag between electric and magnetic signals, might be distinguished from among four proposed categories, which are given below (Gershenzon et al. 1993; Gershenzon and Gokhberg 1993; Varotsos et al. 1993a). These four categories are: solid state and pressure, solid state and temperature, groundwater, and ore bodies.

Solid state and pressure. Electrical signals might be formed from changes in the effective stress acting on the rock, and the signals might travel to the observation sites. There are four mechanisms within this category.

1. The charge-vacancy hypothesis proposes that strain liberates crystal lattice vacancies to carry electric charge.
2. The displacement hypothesis proposes that ions carrying charge are displaced by strain and this is the major source of electric current.
3. The piezoelectric hypothesis proposes that the signal is generated from the pressure acting on crystal lattices and symmetry is the major consideration.
4. The piezomagnetic hypothesis proposes that a magnetic field, which induces the electric signal, is generated from the pressure acting on crystal lattices.

Solid state and temperature. The thermoelectric hypothesis proposes that changes in temperature act to generate charge-carrying holes in the rock material, and also to liberate other charge carriers. These are responsible for the observed electric signals.

Groundwater. There are three mechanisms in which groundwater might generate SES.

1. The location of fluids, notably groundwater, will be affected by changes in pore pressure with changes to both position and saturation. These changes can generate electric signals. This is the streaming-potential hypothesis.
2. Rock strain might release radon gas, and this can ionize surrounding material to form ions (Jordan et al., 2011). This is the radon-decay hypothesis.
3. Ground motion is introduced by the passage of seismic waves. This motion displaces water in the pore space of rock. The water contains ions, and the relation of the motion of the ions to the geomagnetic

field creates electric fields. These are circularly polarized, depending on the charge of the ion. This is the seismic-dynamo hypothesis (Honkura et al., 2009).

Ore bodies. Crystals in bodies might be displaced during strain, and create an electrical signal by induction with the Earth's magnetic field. This is the induction hypothesis.

Data Relating to the Mechanisms of SES Generation

The charge-vacancy hypothesis has some literature support in the following:

1. Takeuchi and Nagahama (2002) show that the magnitude of surface charge density from fracture or frictional slip in quartz or granite under dry conditions is consistent with the data for hole- and electron-trapping centers in semiconductors.

2. Chapter 6 in this thesis lists several deformation mechanisms which can produce charge-carrying vacancies in crystal lattices or allow for their migration.

The thermoelectric hypothesis has some literature support in the following:

1. Enomoto et al. (1993) confirm that thermally-stimulated exo-electron emission in granites occurs at temperatures ranging from 300 to 400°C.

2. Dologlou (1993b) shows that thermally-stimulated electric currents in rocks follow the Arrhenius equation, that is, the currents are a function of e to the power of the ratio of the energy divided by a function of the temperature.

The streaming-potential hypothesis has some literature support in the following:

1. Lazarus (1993) describes the hypothesis that a pressure-induced transition from hydrous to anhydrous mineralogy may result in the liberation of water contemporaneous with earthquake phenomena.

2. Hautot and Tarits (1998) measured electric potential variations on a ridge separating two lakes in the French Alps, and these lakes underwent water-level variations of several tens of meters on a yearly cycle, enough to induce stress variations and fluid percolation. Electric-potential variations were linearly related to water-level variations, with an expression of 2 mV per meter of water level change.

3. Hunt et al. (2007) show that electric conductivity and electrokinetic current in a porous water-saturated medium are proportional to the square of the difference between the porosity of the medium and the porosity required for percolation, and also to the square of the difference between the moisture content of the medium and the moisture content required for percolation. Hence, an increase in porosity or moisture content can markedly increase both electrical conductivity and electrokinetic current.

4. Jouniaux and Pozzi (1997) demonstrate that observed 0.1 Hz and 0.5 Hz co-seismic electric signals may be attributed to generation by streaming potentials, based on laboratory experiments on saturated sediments.

The seismic-dynamo hypothesis has strong support in the following:

1. Honkura et al. (2009) report observations of the seismic dynamo effect in both artificial and natural seismic events.

The streaming-potential hypothesis, often referred to as the electrokinetic hypothesis, was historically favored, along with a mechanism for earthquake formation, the dilatancy-diffusion model (DD), in the 1970s and 1980s, although DD has since fallen out of favor. It describes earthquake nucleation as a process of strain cracking (dilation), and then fluid motion (diffusion) into the new pore space. The dilatancy-diffusion model does perhaps account for some results, for example, increased radon gas emission (Dutta et al., 2012) and an increase in seismic wave velocity immediately prior to rock failure. It also accounts for the positive correlation between variance in high frequency seismic noise and diurnal ground temperature, as described in Gordeev et al. (1992), since surface heating causes diurnal fluctuations in groundwater pressure.

Some problems exist with DD, notably (Bakhmutov and Groza, 2008), that strain cracks are on the order of microns, and are perhaps too small for water to penetrate; that the variation of underground fluid levels (10 to 15 cm) is too large to be caused by the deformation alone (typically $\eta = 10^{-6}$); and that no mechanism has been found to describe the return of the groundwater to pre-dilatancy levels. The Lazarus (1993) hypothesis, that hydrous to anhydrous transitions in minerals may make up these discrepancies, has not been investigated.

Transmission of SES

The solid-state hypotheses and the seismic-dynamo hypothesis make use of groundwater running through faults to account for the electric signals travelling to observation sites. Faults have high measured conductivities (Wannamaker et al., 2004), as much as 100 to 1000 times that of surrounding rock (Varotsos

et al., 2011). Further, the termination of a conductive path (such as a fault) will result in an increase in the electric field near the termination (Varotsos et al., 2011).

Proponents of the ore body hypothesis could also make use of the the increased conductivity in faults to account for the transmission of the signal, but there is an additional consideration: the possibility that ore bodies are not present at some sites where SES are produced.

Mechanisms Acting in Concert

There are also some reports of several mechanisms acting in concert. Yoshida et al. (1998) demonstrate that a water-saturated sandstone will accept extra water immediately before rupture (i.e. 9 seconds prior in their experiment) and, based on the magnitudes, timing and polarity of the voltage signals, that both piezoelectric and electrokinetic effects are present in the observed electric potential changes.

It is reasonable to assume that several effects come into play with presumed seismic electric signals. Rock resistivity is reduced by strain. Groundwater and other fluids or volatiles are liberated prior to some earthquakes. Deformation mechanisms do create charge-vacancies, and liberate ions. Seismicity is characterized by numerous small and very small seismic events in a region, and the seismic-dynamo effect is driven thereby. Heat flow may be increased during earthquakes (Jordan et al., 2011), and heat does generate charge carriers in rock. Piezoelectric effects may be large enough to detect in some rocks.

For SES that occur long before an earthquake, the combination of fluids, deformation, heat and rock chemistry act in concert. Electricity, from whatever source, weakens rock. Also, artificial electric signals can regulate seismic dynamics (Chelidze and Matcharashvili, 2003).

Short-Duration SES during an Earthquake

During rupture, fractoemission can produce the triboluminescence and radio signals characteristic of short-duration SES that occur near the time of the earthquake (Chapter 2, Seismic electric signals, p. 12). Further, a mechanism similar to short-duration SES may cause earthquake lightning, which, like storm-caused lightning, can be associated with radio emissions. Localized fracture can generate the charge.

Other Ongoing Research

Current research in electric prediction of earthquakes is ongoing in China, with a satellite launch planned for 2014 to determine whether observed ionospheric phenomena already known to precede earthquakes by a few hours to days are in fact caused by electric phenomena on the ground (Xuhui Shen et al., 2011). Chinese scientists favor a thermoelectric (charge-vacancy) mechanism for SES generation, with magnetite-temperature interactions as the proposed source (Xuhui Shen et al., 2011; Junfeng Shen et al., 2010). For both the charge-vacancy and groundwater mechanisms, lattice and phase transitions in minerals play an essential role.

CHAPTER 8

DISCUSSION AND SUGGESTIONS FOR FURTHER WORK

Introduction

The text of this chapter addresses four areas: earthquake prediction, planetary science research, energy dependence and global warming, and science education. A summary at the end includes important results. Chapter references are given in parentheses.

Earthquake Prediction

Earthquake prediction is a pressing need. The VAN method of earthquake prediction has had preliminary success, predicting 25 out of 28 major earthquakes within N36 and N41 latitude and E19 to E27 longitude between 2001 and 2010 (Chapter 7, Time Series Analysis of Presumed SES, p. 72). That is an 89% success rate. The margin of error in location and earthquake magnitude are, respectively, 100 km and 0.7, while the lead time is a few days (Chapter 1, p. 1). These values fall within public safety requirements.

These results should be tested by other researchers. The VAN method ought to be attempted in several regions, to see whether the results are reproducible. The equipment needed, such as electrodes, magnetic field sensors, data loggers, computers and cable networking, do not seem prohibitive in economic or technical terms, nor does access to relevant seismic data once the SES indicate criticality in a region. Seismic data are available in real time online from several sources, including the U.S. Geological Survey (USGS Earthquake Hazards Program, 2013), the European-Mediterranean Seismological Center (European-Mediterranean Seismological Center, 2013), the National Research Institute for Earth Science and Disaster Prevention in Japan (NIED, 2013), and the Incorporated Research Institutions for Seismology (IRIS, 2013). IRIS links to several other sites for seismic data (IRIS, 2010).

A major consideration for the set up of SES monitoring stations involves correlating observations of SES with seismic data, to build a selectivity map of the area of study. There are some pitfalls with building a selectivity map. First, SES are well-correlated with seismic events when they are the type that coincide with the event, such as the signals associated with the 1995 Kobe earthquake in Japan (Chapter 7, Short-Duration SES during an Earthquake, p. 76). Telluric currents in an area are not necessarily correlated with contemporaneous seismic activity. Distinguishing the causes of telluric currents from the thirty two mechanisms listed in Chapter 2 seems very important. Except for the short-duration SES that occur during an earthquake, SES might be spurious, caused by other phenomena. Although the empirical result of the predictions seems promising, the sample size is small. Other areas might have geological constraints that would diminish the success rate.

Verification of supposed SES in a region, to build the selectivity map, seems like a difficult step. The proof currently resides only in the results. Therefore, it may be useful to have a better electrical conductivity map of the Earth. A conductivity map could help to assess the validity of the selectivity map.

Selectivity Mapping for SES and Testing the Groundwater Hypotheses for SES

Rock conductivity is fundamental to understanding seismic electric signal propagation. Parkhomenko's works are classic (e.g., Parkhomenko and Bondarenko, 1972), but more research ought to be done to determine the conductivity of crustal rock. Likewise, the conductivity values for water and brine are as many as ten orders of magnitude higher than for crustal rock, and this highlights the role of groundwater in conductivity (Chapter 5, Bulk Rock Electrical Phenomena, p. 50). Since conductivity is to a large degree a function of water content, a comprehensive system of groundwater data ought to be organized, and hosted online. This is a current area of work, and the U.S. Geological Survey (ACWI, 2013) and the United Nations Educational, Scientific and Cultural Organization (IGRAC, 2013) have preliminary websites.

If the streaming-potential hypothesis, the radon-decay hypothesis or the seismic-dynamo hypothesis for SES generation are of interest, then studies may be undertaken to determine the electrical signals from

various fluids and volatiles traveling in different types of rock (Chapter 7, Mechanisms Causing SES, p. 74 and 75 and Transmission of SES, p. 75 and 76.) Experimental data comparing the electrical response of different fluids and volatiles traveling through rock could be compared with on site monitoring of groundwater and volatiles. Similarly, radon is currently studied as a tracer for modeling the flows of air masses, to record data relevant to pollution, weather and climate (Zahorowski et al., 2004). Ground-based radon collection stations exist but their numbers ought to be increased; this will help to clarify the relationship between radon and earthquakes.

If conductivity data are insufficiently correlated with the selectivity maps that are to be generated for new SES monitoring stations, then a more rigorous study of electric signal generation based on broader parameters is indicated. These include an examination of the minerals within the rock, of the chemical reactions occurring, and of the deformation mechanisms active within the rock in the region at depth. This is a major undertaking. Some of the experimental methods the author has outlined in Chapter 4 may be useful (Chapter 4, Making Aligned Cuts, p. 25, Sample Polishing, p. 26, Confirming Alignment, p. 27, Temperature and Pressure Techniques, p. 29 and Simulating Metamorphic Reactions, p. 31). An online repository for relevant information ought to be established.

Geomagnetic and Telluric Data

A network of satellites measuring ionospheric disturbances is already in place, but the accuracy of modeled ionospheric activity between satellites is low. The launch in 2014 of a satellite for ionospheric monitoring by the Chinese space agency may inspire more satellite launches to allow for increased measurements (Chapter 7, Other Ongoing Research, p. 76).

Access to ionospheric data may help to distinguish potential seismic electric signals. Other than seismic dynamo induction, any number of the thirty-one remaining mechanisms that cause telluric currents may be mistaken for SES or may interfere with SES (Chapter 2: Telluric Currents). The data from a network of satellites measuring the ionosphere plus a careful examination of other causes for Earth electricity might be used in conjunction with a map of conductivity in the Earth to help identify and pinpoint SES and thereby provide a theoretical basis to the VAN group's natural time analysis.

Earthquake Prevention

It is not known to what extent artificial electric fields could enhance the monitoring of SES. Edward (Todd) Tyler, a colleague at the Department of Geological Sciences, California State University, Long Beach, suggests that an artificial electric field at a site might allow for a stable baseline and enhance signal analysis. More study is needed.

It is possible that artificial electric or magnetic fields might trigger earthquakes. Earthquakes can already be triggered by the injection of fluid into wells at high pressure (Raleigh et al., 1976). The legal difficulties with triggering earthquakes are likely to be complex. For this reason, to the best of the author's knowledge, prophylactic triggering of earthquakes has not been carried out. Likewise, a study involving SES and artificial electric fields ought to be sited far from human habitation, industry or other source of risk.

If artificial electric or magnetic fields are effective triggers for earthquakes, and if the timing of the seismic events after the application of the field is well-constrained, then earthquakes could be manageable. Regions of a fault might be induced to rupture under controlled conditions in the same way that forest fires are managed with controlled burns to limit long-term fuel supply. Inhabited regions might be triggered after planned evacuations. The potential for legal liability due to property damage from this course of action is tremendous, and forecasting seismic events seems to be a more realistic goal.

Electricity and Magnetism as Hypothetical Causes for Seismic Events

No mechanism to explain earthquake rupture currently has widespread acceptance by the scientific community. Earthquakes are caused by directed stresses that overcome rock strength. The proximal trigger that allows a seismic event to happen today, for example, and not next week, is not well understood. The dilatancy diffusion model has been rejected by some researchers typically for three reasons. First, dilation from microcracking is not large enough to allow for the diffusion of groundwater to match the observed changes in groundwater height. Second, no mechanism is accepted to account for the return of groundwater heights to pre-earthquake levels after a seismic event has occurred. Third, no mechanism is accepted to account for why groundwater changes do not always occur with an associated earthquake (Chapter 7, Data Relating to the Mechanisms of SES Generation, p. 75).

Earthquakes might be triggered in nature by electricity or magnetism, and SES imply this. It is also known both that magnetic fields can weaken earth materials (Chapter 6, Electric and Magnetic Phenomena with Brittle Fracture Mechanisms: Magnetic, p. 66), and that applied electric fields have some effect on seismic events (Chapter 7, Mechanisms Acting in Concert, p. 76). That earthquakes may be triggered naturally by electricity or magnetism is a testable hypothesis. The mechanical process of applying electric or magnetic fields is straightforward. If the results of laboratory testing of rock are conclusive, and a threshold of electric or magnetic field is found to trigger seismic rupture in rock under directed stress, then two further considerations are worth examining. First, can the required field strength be generated in rock from natural processes? Second, is there evidence that this field strength is being attained in nature, and by what means? To answer these questions it may be necessary to determine the various net electrical effects of the deformation mechanisms described in Chapter 6 (Deformation Mechanisms, p. 62), of the temperature changes associated with fault zones (Chapter 7, Data Relating to the Mechanisms of SES Generation, p. 75), and to have more data relating to the magnitudes of the electrochemical potentials of the chemical reactions that occur during metamorphism (Chapter 6, Chemical Reactions in Metamorphism, p. 61).

Mineral Lattices or Fluid Path Tortuosity as Hypothetical Causes of Groundwater Fluctuations Associated with Earthquakes

Hydrous to anhydrous transitions in minerals might account for some of the observed fluctuations in groundwater levels around the time of earthquake events (Chapter 7, Data Relating to the Mechanisms of SES Generation, p. 75). Further study is needed to determine whether minerals can reincorporate enough volatiles into crystal lattice sites once pressures and stresses are reduced after seismicity to match the range of observed drops in groundwater levels. If so, crystal lattice dynamism is a strong candidate to account for the observed fluctuations in groundwater levels associated with earthquakes.

On the other hand, the tortuosity of the pore space in rock may be the more important influence on groundwater fluctuation relative to earthquake phenomena. Rock deformation from strain might create short paths for fluid flow. These short paths should allow for more rapid fluid flow. Faster fluid flow might account for the observed rise in groundwater levels. What happens to sequester groundwater after an earthquake is unknown. The seismic waves might increase the pore-space volume and close some of the short fluid paths described above.

Changes to the volatile content of mineral lattices or to the fluid path length and volume in rock might either or both be responsible for groundwater fluctuations proximal to earthquake events. Differences in rock composition would then account for regional differences in the presence of volatiles contemporaneous with earthquake activity. Laboratory study is needed to determine the volatile-crystal-lattice dynamics for a wide range of minerals. Additionally, further laboratory study is needed to determine the evolution of pore space geometries and volume in rock under seismic conditions.

Electricity, Magnetism and Volatiles as Hypothetical Causes for Seismic Events

For earthquakes, a mechanism involving electricity, magnetism and chemistry might be responsible for criticality. A simplified overview may be thought of as follows. Directed pressure creates deformation, and the deformation generates electric charge. The electric charge may provide some energy to minerals systems, to liberate water, radon and other volatiles from minerals within a source rock. The presence of these volatiles generates more electric charge via a groundwater effect. The resulting magnetic field weakens the rock making it more susceptible to deformation. The additional volatiles and fluid in the rock pore space also weaken the rock. The rock again deforms and generates electric charge, and again creates the conditions favorable for the liberation of water and other volatiles. The process repeats itself until the rock strength is overcome and an earthquake occurs.

Testing this feedback hypothesis may require a more intimate knowledge of the process whereby volatiles are liberated from minerals. For example, a significant number of centrosymmetric minerals that exhibit piezoelectricity do so because of the locations of volatiles such as CO₂ or H₂O in their crystal lattices (Chapter 5, Centrosymmetric Minerals Exhibiting Symmetry-Based Electricity, p. 40). Whether applied electricity or magnetism can influence crystal lattices to release volatiles from minerals, and whether this release can weaken rock sufficiently to support an electrical-magnetic-volatile trigger hypothesis are open questions. These depend on a body of data that has not yet been gathered. If the release of water before an earthquake is caused by changes to the geometry of rock pore space, then the influence of electricity on the tortuosity of fluid paths ought to be determined, as well.

Here is a related case. Volcanic criticality is based on the liberation of volatiles. The release of gases from a magma is due to decreased hydrostatic pressure as the magma ascends. Their release both lowers the tensile strength of the magma and provides sites for the further exsolution of gases. When there are enough sites, the rate of volatile exsolution increases exponentially. The exponential release of volatiles causes the force of the volcanic eruption.

While it is volatiles that cause volcanic criticality, it might be a combination of electricity, magnetism and volatiles that causes earthquake criticality. If this is the case, then the analytical techniques described by Varotsos et al. (2011), which allow one to distinguish predictable SES data, may be valid because the SES are, in fact, the trigger to seismic rupture. A Heckmann diagram would be useful for this type of modeling (Chapter 3, Definition of a Crystal, p. 15). The time delay between regional SES and large seismic events might hypothetically be attributed to the interplay of electricity, magnetism and volatiles in rock weakening.

Planetary Science Research

This section examines various features relevant to planetary science. These include details of the dielectric strengths of minerals and the influence of frequency in an applied electric field; mantle anisotropy and the possibility of using mineral data to constrain the composition of the mantle; the possibility that electric and magnetic data will make thermodynamic models of metamorphic reactions more accurate; a hypothesis that the ability to transmit infrared photons in earth materials is related to the conditions of their formation; the importance of creating an online, collaborative model of the Earth's electric field; some possibilities for magnetotellurics as they relate to Solar dynamics; and the application of rock electrification to astrobiology. A brief treatment of each of these follows.

Dielectric Strengths of Minerals

Relative dielectric strength data are given in Table 38, p. 167, where changes to the dielectric properties of minerals with temperature and pressure are available. Dielectric strength is a measure of a material to store electric charge, and the increase in lattice defects in crystals increases dielectric strength. The dielectric behavior of crystals during changes in pressure and temperature is complicated by differences in strain regime: some deformation mechanisms serve to increase lattice defects, while others lower the internal energy of a crystal by reducing the number of defects (Chapter 6, Deformation Mechanisms, p. 62).

Phase transitions are described by a physical quantity that diverges at transition with a certain power of the parameter called the critical exponent, as with

$$\mathbf{E} \propto T^D, \quad (28)$$

where $\mathbf{E}$ is the electric field tensor, T is temperature, D is the critical exponent, and $\propto$ signifies “is proportional to.” In this case, $\mathbf{E}$ is the physical quantity, T is the parameter, and D determines when criticality is reached. Equation 27 is a power law, and is determined empirically (Newman, 2005). One looks for changes to the values of the physical quantity, such as peak values. Several peak values are evident in Table 38 and these data were originally gathered to constrain phase transitions.

In contrast, the general trend of the dielectric behavior of earth materials with variations in temperature and pressure is not well-constrained in this set of data. With quartz, for example, temperature zones exist within which the correlation is negative, i.e. relative dielectric strength decreases as temperature increases. Within other temperature zones in quartz, and also in most minerals in Table 38 (p. 167 through 170) in which data exist across a range of temperatures, variation is positively correlated with relative dielectric strength for the minerals given. The hotter it is, the stronger the dielectric property.

The sample size is small, and the trend might be attributed to natural variations in sample material and experimental variations. In addition, the dielectric strength of minerals might be closely related to changes in water content with heating. The question remains open.

Here is a further consideration. Dielectric values show some variation with changes to the frequency of the applied electric field. Lower dielectric strength with higher frequency electric fields are evident in Table 38 in the entries for greenockite, lecontite, sphalerite, stibnite and wurtzite, with the entries for berlinite and quartz being equivocal. This is an open question.

Mantle Anisotropy

The Earth's upper mantle is known to be both seismically and electrically anisotropic (Wolfe and Silver, 1998; Backus, 1965). It reflects and transmits seismic and electric waves preferentially, according to their orientation. This effect is notable under most continental cratons at a depth range of 250–400 km, comprising the Benioff-Gutenberg low velocity zone (Yuancheng Gung et al., 2003; Fouch et al., 2000), named for seismic velocity anomalies. The observed anisotropies might help determine mantle composition if a more thorough knowledge of mineral elastic and electrical properties were available. Models of the Earth's mantle could be constructed for a range of mineral compositions, to see which are consistent with both types of anisotropy data.

Metamorphic Models

Deformation mechanisms create changes in rock conductivity and dielectric strength, and can generate energy. It makes sense to see whether the energy terms are large enough to have an influence on chemical reaction rates. The inclusion of electricity and magnetism in thermodynamic models ought to match the observations of *P-T-X* diagrams.

In each of the eight deformation mechanisms described in Chapter 6, p. 62 through 68, the energy contributions of electric and magnetic fields have not been described systematically. The extant work is preliminary only. Further study would be useful for gaining a deeper understanding of how deformation occurs. For example, in grain boundary migration, individual minerals are likely influenced by the electrical or magnetic expressions of their nearest mineral neighbors while undergoing deformation. This influence may account for why one grain grows at another's expense when the grains themselves are nearly identical (Chapter 6, Dynamic Recrystallization, p. 63).

The contributions of electricity and magnetism in metamorphism are worthwhile in their own right, and ought to be pursued. Phase diagrams that take into account electric and magnetic fields are worth constructing. Quantitative data for minerals at a range of geologic temperatures and pressures are needed.

Heat Environment

Since heat drives plate tectonics, it is worthwhile to note which minerals are favored in metamorphic reactions, and whether these are refractory to heat, or if they transmit heat well. For crystals whose electron bonding is principally covalent, the dielectric coefficient is a function of the refractive index for visible light (Chapter 5, p. 57). Dielectric strength is a link between low frequency electrical phenomena, such as the voltage of an electric field, and high frequency electrical phenomena, such as electromagnetic transmission. A trend might exist relating the dielectric strength of minerals, the optic transmission of infrared photons, and *P-T-X* diagrams. This trend, if it exists, might suggest a framework for determining which chemical reactions are favored in the solid state. A framework like this would be useful in determining the mineral compositions of rock at high temperatures and pressures, where data are scarce.

Online Model of the Electric Fields of the Earth

It would be useful to set up an online institute and model the possible electrical states of the different regions of the Earth's crust, based on mechanisms of telluric current generation. Predictions of telluric currents could be compared to actual data. Models might reasonably be constructed with time-stepping, much as the weather is modeled, and would be more data intensive than the predictions for the weather. Applications to fluid flow, tectonics, earthquake prediction, volcanism, hydrology, solar weather, storm activity, planetary exploration, ocean salinity, man-made energy transmission, geothermal resources, mineral exploration, mineralogy and petrology might be generated.

The complexity of data required to model metamorphic reactions and deformation in a rock is high. Notwithstanding, it is reasonable to assume that a block of rock could undergo brief metamorphism in a laboratory setting, and many of the relevant parameters could be observed. An online framework would allow for collaboration.

Weather forecasting takes an immense amount of computer space. It is reasonable to assume that electrical modeling of the Earth's crust would take a similar amount of space. The benefit of modeling the weather is to prevent human tragedy and economic losses. The benefit of modeling the Earth's electrical phenomena is much broader, and includes such things as could take humanity to the edges of the solar system and beyond.

Generalization to Other Planets

The Earth-Moon system is connected via space weather with the Sun. The various electrical frequencies involved in GIC may be worth studying in conjunction with geomagnetic data, as is done by the Polar Geophysical Institute of the European Union (EURISGIC Project, 2013) to see whether patterns may be used to model space plasma (ECLAT Project, 2013). Also, since the magnetic field of the Sun encompasses the entire Solar System, magnetotelluric studies may provide more information about Solar processes.

Application to Astrobiology

Rock electricity is relevant to astrobiology and the origin of life. Organic molecules can be created from the application of electricity on a primordial Earth atmosphere (Miller and Urey, 1959). Research is ongoing (Green, 2009; Hill and Nuth, 2003), and more may be done to explore the thermodynamics of various reactions and the electrical contributions of minerals, deformation and metamorphism.

Energy Dependence and Climate Change

This thesis started as an exploration to see whether minerals might be useful in generating electricity, and whether that generation could be applied somehow to help prevent climate change. The initial idea was to take advantage of the diurnal freeze-thaw cycle of water in some locations. Water would freeze and generate pressure, which would then generate electricity if a piezoelectric material were present. Ice itself is paraelectric, so the setup might be even simpler than originally conceived.

The magnitudes of the electricity involved are tiny, but this does not preclude further study. It is hoped that the electrical data for minerals listed in Chapter 5 and in the tables and figures referenced therein will be useful in this regard or in a related project. For example, the strength of piezoelectricity in greenockite is influenced by the presence of photons. Further study is warranted.

Here is a second idea. Streaming potential is generated from the flow of fluid in rock due to differences in pressure. This phenomenon might be worth study for electricity generation. In short, the force of gravity from the orbit of the moon might create enough motion of an electrolyte-rich fluid in a porous medium to generate some usable electricity. As the "groundwater" level rises and falls with the tides, electric current is generated through the electrokinetic effect as well as from the motion of the ions themselves (Chapter 2, The electrokinetic effect, p. 11; Chapter 7, Mechanisms Causing SES: Groundwater: 3, p. 74). A series of electrically insulated and partially depressurized containers with porous media and electrolyte solutions might be fabricated to take advantage of the Moon's motion without any other energetic inputs needed.

Science Education

Studies of Earth electricity and of electrification of minerals are useful for promoting the outreach of science to children and adults. Complementing the intrinsic interest, the need for mineral data is great. For example, the observed piezoelectric phenomena in centrosymmetric minerals follow any of ten mechanisms (Chapter 5, Explanations for the Apparent Violations of Piezoelectric Theory, p. 48 and 49), and these exceptional materials open the possibility that there are many more minerals that may have interesting electrical properties, currently untested. Crowdsourcing the work is a reasonable plan, since there are more than 4,000 minerals now approved by the IMA. Classroom work might generate some of the data needed, as well. If there were an online repository of these data, some of the projects described in this chapter would benefit, e.g. a model of electric fields of the Earth would be more feasible.

Some of the experimental techniques outlined in Chapter 4 are relevant for classroom and laboratory activities, since they are simple and/or inexpensive. These might be useful: if an approximate orientations of samples is acceptable, then the techniques of using a wet tile saw and a wax box are worthwhile. Polishing samples by hand on a steel plate works well. Lapping by hand is not recommended. Machines can generate a more uniform thickness. Using a heat gun to heat samples is very simple. The sample holders after Morgan et al. (1984) remain untested for applying a directed load or torque, but they are straightforward to fabricate.

The following major groups of minerals are prominent and seismoelectrically active: alunite, apatite, beryl, cancrinite, epsomite, galena, ice, nepheline, prehnite, pyrochlore, quartz, rutile, serpentine, sodalite, sphalerite, topaz, tourmaline and zeolite (Appendix C, Tables 12, 13 and 14, p. 176 through 186).

Minerals of the spinel group, including magnetite, are thermoelectrically active. Minerals of the tourmaline supergroup are formed in igneous, metamorphic and metasomatic conditions, and might be used either to demonstrate how electrical data can be gathered, or to explore electrical changes during metasomatism or metamorphism.

Members of several of the above mineral groups can be collected without much difficulty from many locales. Other materials might be procured for free from museums, universities, or research institutes. Schools would have the opportunity to perform scientific observations where the outcome is not known. In short, gathering electrical and magnetic data for minerals is a real opportunity for science education.

Summary

In order to aid the reader, important results from this thesis are summarized in Table 51. The possibilities for earthquake prediction seem extremely useful. Likewise, the presence of electric and magnetic fields generated by deformation mechanisms ought to deepen peoples' understandings of metamorphism and of telluric currents, both for the Earth, and for other planets. Further, there are potential discoveries to be made in mineralogy and electricity. The study of electricity in earth materials and in the Earth's crust might be promoted, as well, for this inherent joy of discovery.

TABLE 51. Selected Results, Hypotheses and Recommendations for Further Study

Chapter	Result
2*	List of 32 mechanisms that generate telluric currents
2	<u>Further study:</u> A global, permanent network of electrical measurement stations might be established, to correlate and contrast geomagnetic data
3	List of 24 mineral properties that generate electricity or magnetism or are related to them
4	Carbon tape can be used instead of thermoplastic to affix a sample to the jig for lapping
4*	EBSD can give crystal orientation reliably, and is quicker than XRD
4	A heat gun can be used safely to heat samples to high temperature
4*	<u>Further study:</u> Sample holders modified from Morgan et al. (1984) should be tested for their use in generating the directed loads or torques needed to measure piezoelectric phenomena
5	List of 44 minerals exhibiting ferroelectricity, with data for 24
5	List of 131 other minerals exhibiting pyroelectricity, with data for 11
5	List of 42 other minerals exhibiting piezoelectricity, with data for 18
5*	List of 53 centrosymmetric minerals that exhibit pyro- or piezoelectricity despite having a center of symmetry
5*	List of 10 mechanisms to account for pyro- or piezoelectricity in minerals that have a center of symmetry
5	<u>Further study:</u> Elastic moduli, conductance, capacitance, magnetic susceptibility and symmetry-based electrical and magnetic data should be gathered for more minerals at a range of temperatures and pressures
5	<u>Further study:</u> More data should be gathered to explain why the dielectric strengths of some minerals and rocks are sensitive to frequency
5	<u>Further study:</u> Geomagnetic data from the ionosphere should be gathered via satellite
6*	Examples for how each of eight different deformation mechanisms either produce electricity or magnetism, or are influenced by electricity or magnetism
6*	<u>Further study:</u> Electricity and magnetism generated by different deformation mechanisms should be measured for different minerals under various conditions
7*	<u>Hypothesis:</u> Wavelets with a twenty-four-hour period in purported SES are due to greater rock conductivity from increased strain, and the diurnal signal itself is due to solar radiation
7	<u>Hypothesis:</u> Groundwater fluctuations and the release of other volatiles at about the time of major seismic activity are caused by hydrous-anhydrous transitions in minerals
7*	<u>Hypothesis:</u> SES are caused by the release of radon gas into groundwater, and the subsequent ionization and motion of material
7	<u>Further study:</u> The seismic-dynamo effect and correlations with SES should be verified by other researchers
7	<u>Further study:</u> The VAN method of earthquake prediction should be verified by other researchers and at other locations
8	<u>Further study:</u> More electrical conductivity values of crustal rock should be measured, with data available online
8	<u>Further study:</u> More groundwater levels should be measured, with data available online
8*	<u>Hypothesis:</u> An applied electric field enhances presumed SES data collection
8*	<u>Hypothesis:</u> An applied magnetic field enhances presumed SES data collection
8*	<u>Further study:</u> Magnitudes of electric signals generated from various ions and volatiles in various rock types should be measured
8	<u>Further study:</u> The number of ground-based radon monitoring stations should be increased
8	<u>Hypothesis:</u> Electric and/or magnetic phenomena are the trigger mechanisms for earthquakes
8	<u>Hypothesis:</u> The controlled triggering of earthquakes can be used to manage earthquake damage as controlled burns manage wildfires, but only if the legal problems can be resolved
8*	<u>Hypothesis:</u> Electricity, magnetism and volatile liberation form a trigger mechanism for earthquakes
8*	<u>Hypothesis:</u> The time lag of several weeks to several months between purported SES and major seismic events are due to the time it takes for volatiles to be released from the rock and the interaction of electricity, magnetism and volatiles

TABLE 51. Continued

Chapter	Result
8	<u>Hypothesis</u> : Groundwater fluctuations and the release of other volatiles at about the time of major seismic activity are caused by changes to the geometry of the fluid paths in rock
8*	<u>Hypothesis</u> : The formation of highly refractive minerals is favored in regions where heat flow is high
8	<u>Further study</u> : An online model of the Earth's electric field should be constructed
8	<u>Further study</u> : The Earth's intrinsic magnetic field and solar activity should be compared to look for long term patterns
8	<u>Further study</u> : The amount of electrical energy potentially generated by rock should be compared with the energy needed for generating organic molecules
8	<u>Further study</u> : Electrical properties of minerals should be studied to see whether any alternative energy projects are implied
8*	<u>Further study</u> : A test apparatus should be built to see whether paraelectricity in ice could be used to generate significant electricity from diurnal freeze-thaw cycles
8*	<u>Further study</u> : A test apparatus should be built with suspended ions in porous media, to see whether the electrokinetic effect, electrochemistry, the geomagnetic field and the moon's gravity can be used to generate significant electricity

Notes: Entries with an asterisk are original to this thesis, to the best of the author's knowledge.

APPENDICES

APPENDIX A

LIST OF MINERALS EXHIBITING SYMMETRY-BASED ELECTRICAL
PROPERTIES, PLUS SOME MINERALS WITH THERMOELECTRIC OR
MAGNETIC PROPERTIES

TABLE 4. List of Minerals Exhibiting Symmetry-Based Electrical Properties, plus Some Minerals with Thermoelectric or Magnetic Properties

AFWILLITE

m Monoclinic

Polar

Nickel-Strunz: 9.AG.75 - SILICATES (Germanates) - Nesosilicates with additional anions, cations in greater than [6] coordination.

- **Pyroelectric, Piezoelectric** -

From contact metamorphism of limestones.

ALTAITE

Galena Group

m3m Cubic

Centrosymmetric

Nickel-Strunz: 2.CD.10 - SULFIDES and SULFOSALTS (sulfides, selenides, tellurides; arsenides, antimonides, bismuthides; sulfarsenites, sulfantimonites, and sulfbismuthites) - Metal Sulfides, [Metal:Sulfur = 1:1] with Sn, Pb and Hg.

- **Ferroelectric, Pyroelectric, Piezoelectric** -

Typically found in hydrothermal vein Au-Te-bearing deposits.

ALUM-NA

Alum Group

m3 Cubic

Centrosymmetric

Nickel-Strunz: 7.CC.20 - SULFATES (selenates, tellurates, chromates, molybdates, wolframates) - Sulfates (and selenates) without additional anions, with H₂O, with medium-sized and large cations.

- **Ferroelectric, Pyroelectric, Piezoelectric** -

From the combustion of coal, or as a precipitate near coal.

ALUNITE

Alunite Supergroup: Alunite Subgroup

3m Trigonal

Polar

Nickel-Strunz: 7.BC.10 - SULFATES (selenates, tellurates, chromates, molybdates, wolframates) - Sulfates (and selenates) with additional anions, without H₂O, with medium-sized and large cations.

- **Pyroelectric, Piezoelectric** -

From the action of sulfate and sulfuric acid on aluminous rocks at moderate temperatures, commonly accompanied by kaolinitization and silicification.

AMESITE

Serpentine Group

1 Triclinic

Chiral

Polar

Nickel-Strunz: 9.ED.15 - SILICATES (Germanates) - Phyllosilicates with kaolinite layers composed of tetrahedral and octahedral nets.

- **Pyroelectric, Piezoelectric** -

From low-grade metamorphism of aluminum- and magnesium-rich source rock.

TABLE 4. Continued

AMINOFFITE **4/m** Tetragonal

Centrosymmetric

Nickel-Strunz: 9.BH.05 - SILICATES (Germanates) - Sorosilicates with Si_3O_{10} , Si_4O_{11} and similar anions, with cations in tetrahedral [4] and greater coordination.

- Piezoelectric -

Found in cavities in massive magnetite; in fluorite veins at the contact between marbles and hornblende granites; and in fluorite veins in dikes.

AMMONIOJAROSITE

Alunite Supergroup: Jarosite Subgroup

3m Trigonal

Polar

Nickel-Strunz: 7.BC.10 - SULFATES (selenates, tellurates, chromates, molybdates, wolframates) - Sulfates (and selenates) with additional anions, without H_2O , with medium-sized and large cations.

- Pyroelectric, Piezoelectric -

Formed in shales containing both lignite and pyrite.

ANALCIME

Zeolite Group

3 Trigonal

Centrosymmetric

Note that several forms of *ANALCIME* coexist at standard temperature and pressure: Cubic (**m3m** Centrosymmetric), Tetragonal (**4/mmm** Centrosymmetric), Orthorhombic (**mmm** Centrosymmetric), as well as Trigonal (shown here). The trigonal form is likely the most stable. At 12 kbar of pressure and ambient temperature, *ANALCIME* undergoes a phase transition to a Triclinic form.

Nickel-Strunz: 9.GB.05 - SILICATES (Germanates) - Tectosilicates with zeolitic H_2O , zeolite family - Chains of singly connected four-membered rings.

- Piezoelectric -

In the groundmass or vesicles of silica-poor intermediate and mafic igneous rocks. In lake beds, altered from pyroclastics or clays, or as a primary precipitate; authigenic in sandstones and siltstones.

ARCHERITE

Biphosphammite Group

2 or **2/m** Monoclinic

Polar and Chiral, or Centrosymmetric

(Not Known)

42m Tetragonal

Non-centrosymmetric

Transition Temperature: 450 K

Transition Temperature: 123 K

mm2 Orthorhombic

Polar

Below 123 K *ARCHERITE* undergoes a phase transition to a ferroelectric form.

Nickel-Strunz: 8.AD.15 - PHOSPHATES, ARSENATES, VANADATES - Phosphates, without additional anions, without H_2O , with only large cations.

- Paraelectric, Pyroelectric, Piezoelectric -

A component of stalactites and crusts on the walls of caves containing bat guano deposits.

TABLE 4. Continued

ARDEALITE *m* Monoclinic

Polar

Nickel-Strunz: 8.CJ.50 - PHOSPHATES, ARSENATES, VANADATES - Phosphates without additional anions, with H₂O, with only large cations.

- **Pyroelectric, Piezoelectric** -

From the breakdown of bat guano in calcitic caves.

ARGENTOJAROSITE

Alunite Supergroup: Jarosite Subgroup

3m Trigonal

Polar

Nickel-Strunz: 7.BC.10 - SULFATES (selenates, tellurates, chromates, molybdates and wolframates) - Sulfates (and selenates) with additional anions, without H₂O, with medium-sized and large cations.

- **Pyroelectric, Piezoelectric** -

A secondary mineral in oxidized deposits with both silver and sulfide.

ARSENOGOYAZITE

Alunite Supergroup: Crandallite Subgroup

3m Trigonal

Centrosymmetric

Nickel-Strunz: 8.BL.10 - PHOSPHATES, ARSENATES, VANADATES - Phosphates, with additional anions, without H₂O, with medium-sized and large cations, [OH : XO₄ = 3 : 1].

- **Pyroelectric, Piezoelectric** -

Found as a secondary mineral in polymetallic hydrothermal barite-fluorite deposits.

ARTINITE

Artinite Group

2/m Monoclinic

Centrosymmetric

Nickel-Strunz: 5.DA.10 - CARBONATES (NITRATES) - Carbonates with additional anions, with H₂O, with medium-sized cations.

- **Pyroelectric, Piezoelectric** -

A low-temperature alteration product found as veinlets or crusts in serpentinized ultramafic rocks.

TABLE 4. Continued

BARIOPEROVSKITE
Perovskite Group
6/mmm Hexagonal
Centrosymmetric

BaTiO₃

Transition Temperature: 1733 K

m3m Cubic
Centrosymmetric

Transition Temperature: 396 K

4mm Tetragonal
Polar

Transition Temperature: 278 K

mm2 Orthorhombic
Polar

Transition Temperature: 183 K

3m Trigonal
Polar

Above 396 K **BARIOPEROVSKITE** undergoes a phase transition to paraelectric forms. **BARIOPEROVSKITE** is an electrical semiconductor.

Nickel-Strunz: 4.CC.30 - OXIDES (Hydroxides, V[5,6] vanadates, arsenites, antimonites, bismuthites, sulfites, selenites, tellurites, iodates) - [Metal : Oxygen = 2 : 3 and 3 : 5] with large and medium-sized cations.

- **Ferroelectric, Pyroelectric, Piezoelectric** -

Found in benitoite as micro- to submicroscopic inclusions.

BASTNÄSITE-CE

(Ce,La)(CO₃)F

Bastnäsite Group

6m2 Hexagonal
Non-centrosymmetric

Nickel-Strunz: 5.BD.20a - CARBONATES (NITRATES) - Carbonates with additional anions, without H₂O, with rare earth elements.

- **Piezoelectric** -

The most abundant rare-earth-bearing mineral, typically hydrothermal, although primary igneous occurrences are known. In granite and alkali syenites and pegmatites; in carbonatites; in contact-metamorphic deposits; rarely as a detrital mineral in placers.

BATISITE

BaNa₂Ti₂(Si₄O₁₂)O₂

Batisite Group

(mm2) Orthorhombic
Polar

Symmetry group **mm2** is an estimate.

Nickel-Strunz: 9.DH.20 - SILICATES (Germanates) - Inosilicates with four-periodic single chains, Si₄O₁₂.

- **Pyroelectric, Piezoelectric** -

In pegmatites in dunites.

TABLE 4. Continued

BAVENITE

Bavenite – Bohseite Series

mmm Orthorhombic

Centrosymmetric

Nickel-Strunz: 9.DF.25 - SILICATES (Germanates) - Inosilicates with two-periodic multiple chains.

- Piezoelectric -

As druses in cavities in granite and associated pegmatites, formed by alteration of beryl and other beryllium-bearing minerals. Also in hydrothermal veins and skarns.

BENSTONITE **3** Trigonal

Centrosymmetric

Nickel-Strunz: 5.AB.55 - CARBONATES (NITRATES) - Carbonates without additional anions, without H_2O - Alkali-earth (and other metal²⁺) carbonates.**- Pyroelectric, Piezoelectric -**

Found in barite and as veins in carbonatite deposits.

BERLINITE

Berlinite Group

622 Hexagonal

Chiral

32 Trigonal

Chiral

Transition Temperature: 857 K

Nickel-Strunz: 8.AA.05 - PHOSPHATES, ARSENATES, VANADATES - Phosphates, without additional anions, without H_2O , with small cations (some also with larger ones).**- Piezoelectric -**

High-temperature hydrothermal or metasomatic processes.

BERTHIERINE

Serpentine Group

m Monoclinic

Polar

Nickel-Strunz: 9.ED.15 - SILICATES (Germanates) - Phyllosilicates with kaolinite layers composed of tetrahedral and octahedral nets.

- Pyroelectric, Piezoelectric -

Found in unmetamorphosed marine sediments and in tropical (lateritic) and polar soils.

BERTRANDITE **mm2** Orthorhombic

Polar

Nickel-Strunz: 9.BD.05 - SILICATES (Germanates) - Sorosilicates - Si_2O_7 groups, with additional anions, with cations in tetrahedral [4] and greater coordination.**- Pyroelectric, Piezoelectric -**

In fissures in granites, pegmatites and in miarolitic cavities; commonly an alteration product of beryl, more rarely as a primary mineral.

TABLE 4. Continued

<p>BERYL Beryl Group 6/mmm Hexagonal Centrosymmetric Nickel-Strunz: 9.CJ.05 - SILICATES (Germanates) - Cyclosilicates - $[\text{Si}_6\text{O}_{18}]_{12}$ six-membered single rings, without insular complex anions. - Pyroelectric, Piezoelectric - Found in granites, granite pegmatites, nepheline syenites, rhyolite vugs, mafic metamorphic rocks, and in low- to high-temperature hydrothermal veins.</p>	<p>$\text{Be}_3\text{Al}_2(\text{Si}_6\text{O}_{18})$</p>
<p>BIPHOSPHAMMITE Biphosphammite Group 42m Tetragonal Non-centrosymmetric 222 Orthorhombic Chiral Below 148 K <i>BIPHOSPHAMMITE</i> undergoes a phase transition to an antiferroelectric form. Nickel-Strunz: 8.AD.15 - PHOSPHATES, ARSENATES, VANADATES - Phosphates, without additional anions, without H_2O, with only large cations. - Paraelectric, Pyroelectric, Piezoelectric - An alteration product of phosphammite in guano, or a reaction product of bat guano with urea.</p>	<p>$\text{NH}_4(\text{H}_2\text{PO}_4)$</p> <p>Melting Temperature: 463 K</p> <p>Transition Temperature: 148 K</p>
<p>BISMUTHINITE Stibnite Group (Not Known) mmm Orthorhombic Centrosymmetric Nickel-Strunz: 2.DB.05 - SULFIDES and SULFOSALTS (sulfides, selenides, tellurides; arsenides, antimonides, bismuthides; sulfarsenites, sulfantimonites, and sulfbismuthites) - Metal Sulfides, [Metal : Sulfur = 2 : 3]. - Ferroelectric, Pyroelectric, Piezoelectric - Typically found in low- to high-temperature hydrothermal vein deposits, as well as in some tourmaline-bearing copper deposits in granite, and in some gold veins formed at high temperatures, and also in recent volcanic exhalation deposits.</p>	<p>Bi_2S_3</p> <p>(Not Known)</p> <p>Transition Temperature: 290 to 330 K</p>
<p>BORACITE Boracite Group 43m Cubic Non-centrosymmetric mm2 Orthorhombic Polar Above 538 K <i>BORACITE</i> undergoes a phase transition to a paraelectric form. Nickel-Strunz: 6.GA.05 - BORATES - Heptaborates and other megaborates - Tecto-heptaborates. - Ferroelectric, Pyroelectric, Piezoelectric - Found in bedded sedimentary salt and potash deposits of marine and salt spring evaporite origin, with boron probably derived from nearby volcanic activity.</p>	<p>$\text{Mg}_3\text{B}_7\text{O}_{13}\text{Cl}$</p> <p>Transition Temperature: 538 K</p>

TABLE 4. Continued

BOURNONITE

Bournonite Group

***mm*2** Orthorhombic

Polar

Nickel-Strunz: 2.GA.50 - SULFIDES and SULFOSALTS (sulfides, selenides, tellurides; arsenides, antimonides, bismuthides; sulfarsenites, sulfantimonites, and sulfbismuthites) - Sulfarsenites, sulfantimonites, sulfbismuthites - Neso-sulfarsenites, without additional sulfur.

- **Pyroelectric, Piezoelectric** -

In hydrothermal veins subjected to moderate temperatures.

BREITHAUPHITE

Nickeline Group

6/mmm Hexagonal

Centrosymmetric

BREITHAUPHITE is paramagnetic and is a metallic electrical conductor.

Nickel-Strunz: 2.CC.05 - SULFIDES and SULFOSALTS (sulfides, selenides, tellurides; arsenides, antimonides, bismuthides; sulfarsenites, sulfantimonites, and sulfbismuthites) - Metal Sulfides, [Metal : Sulfur = 1 : 1] with Ni, Fe, Co and platinum group elements.

- **Pyroelectric, Piezoelectric** -

Associated with Co–Ni–Ag ores in hydrothermal calcite veins.

BROMELLITE

Zincite Group

6mm Hexagonal

Polar

Nickel-Strunz: 4.AB.20 - OXIDES (Hydroxides, V[5,6] vanadates, arsenites, antimonites, bismuthites, sulfites, selenites, tellurites and iodates) - [Metal : Oxygen = 1 : 1, and up to 1 : 1.25] with small to medium-sized cations only.

- **Pyroelectric, Piezoelectric** -

Found in hydrothermal calcite veins in hematite skarn and skarnized limestones; in vugs in natrolite, hydrothermally altered from nepheline, and in syenite pegmatite.

BRUCITE

Brucite Group

3m Trigonal

Centrosymmetric

Nickel-Strunz: 4.FE.05 - OXIDES (Hydroxides, V[5,6] vanadates, arsenites, antimonites, bismuthites, sulfites, selenites, tellurites and iodates) - Hydroxides (without vanadium or uranium) - Hydroxides with OH, without H₂O, with sheets of edge-sharing octahedra.

- **Pyroelectric, Piezoelectric** -

From alteration of periclase in marble; also a low-temperature hydrothermal vein mineral in metamorphic limestones and chlorite schists; and formed during serpentinization of dunites.

TABLE 4. Continued

BRUSHITE *m* Monoclinic

Polar

Nickel-Strunz: 8.CJ.50 - PHOSPHATES, ARSENATES, VANADATES - Phosphates without additional anions, with H_2O , with only large cations.

- Pyroelectric, Piezoelectric -

Formed at low pH by reaction of phosphate-rich solutions with calcite and clay; a cave mineral, in guano deposits and in phosphorites.

BUERGERITE

Tourmaline Supergroup: Alkali Group

3m Trigonal

Polar

Nickel-Strunz: 9.CK.05 - SILICATES (Germanates) - Cyclosilicates - $[\text{Si}_6\text{O}_{18}]_{12}$ six-membered single rings, with insular complex anions.

- Pyroelectric, Piezoelectric -

Pneumatolytic origin in cavities in rhyolite.

BULTFONTEINITE *1* Triclinic

Centrosymmetric

Nickel-Strunz: 9.AG.80 - SILICATES (Germanates) - Nesosilicates with additional anions, with cations in greater than [6] coordination.

- Pyroelectric, Piezoelectric -

Found in the contact zones of thermally-metamorphosed limestone, and in kimberlite dikes.

BURBANKITE *6mm* Hexagonal

Polar

Nickel-Strunz: 5.AC.30 - CARBONATES (NITRATES) - Carbonates without additional anions, without H_2O - Alkali and alkali-earth carbonates.

- Pyroelectric, Piezoelectric -

Accessory mineral in carbonatites and intrusive syenite gabbros.

CADMOINDITE

Linnaeite Group: Thiospinel Group

m3m Cubic

Centrosymmetric

Nickel-Strunz: 2.DA.05 - SULFIDES and SULFOSALTS (sulfides, selenides, tellurides; arsenides, antimonides, bismuthides; sulfarsenites, sulfantimonites, and sulfbismuthites) - Metal Sulfides, [Metal : Sulfur = 3 : 4].

- Thermoelectric -

Found close to the vents of some high-temperature fumaroles.

TABLE 4. Continued

CADMOSELITE

CdSe

Wurtzite Group

6mm Hexagonal

Polar

Nickel-Strunz: 2.CB.45 - SULFIDES and SULFOSALTS (sulfides, selenides, tellurides; arsenides, antimonides, bismuthides; sulfarsenites, sulfantimonites, and sulfbismuthites) - Metal Sulfides, [Metal : Sulfur = 1 : 1] with Zn, Fe, Cu, and Ag.

- Pyroelectric, Piezoelectric -

Found in sedimentary rocks, in alkaline, reducing environments.

CALEDONITE $\text{Pb}_5\text{Cu}_2(\text{SO}_4)_3(\text{CO}_3)(\text{OH})_6$ **mm2** Orthorhombic

Polar

Nickel-Strunz: 7.BC.50 - SULFATES (selenates, tellurates, chromates, molybdates and wolframates) - Sulfates (and selenates) with additional anions, without H_2O , with medium-sized and large cations.

- Pyroelectric, Piezoelectric -

Secondary mineral in the oxidized zones of copper-lead deposits.

CANCRINITE $\text{Na}_x\text{Ca}_y(\text{AlSiO}_4)_6(\text{CO}_3) \cdot n\text{H}_2\text{O}$

Cancrinite Group

6 Hexagonal

Polar and Chiral

Nickel-Strunz: 9.FB.05 - SILICATES (Germanates) - Tectosilicates without zeolitic H_2O - Tectosilicates with additional anion.

- Pyroelectric, Piezoelectric -

A primary mineral in some alkalic igneous rocks, including pegmatites in nepheline syenites; also as an alteration product of nepheline.

CARROLLITE $\text{Cu}(\text{Co,Ni})_2\text{S}_4$

Linnaeite Group: Thiospinel Group

m3m Cubic

Centrosymmetric

CARROLLITE is paramagnetic and is a metallic electrical conductor.

Nickel-Strunz: 2.DA.05 - SULFIDES and SULFOSALTS (sulfides, selenides, tellurides; arsenides, antimonides, bismuthides; sulfarsenites, sulfantimonites, and sulfbismuthites) - Metal Sulfides, [Metal : Sulfur = 3 : 4].

- Thermoelectric -

From hydrothermal vein deposits.

TABLE 4. Continued

<p>CASSITERITE Rutile Group 4/mmm Tetragonal Centrosymmetric Nickel-Strunz: 4.DB.05 - OXIDES (Hydroxides, V[5,6] vanadates, arsenites, antimonites, bismuthites, sulfites, selenites, tellurites, iodates) - [Metal : Oxygen = 1 : 2] with medium-sized cations, with chains of edge-sharing octahedra. - Ferroelectric, Pyroelectric, Piezoelectric - Found in medium- to high-temperature hydrothermal veins and greisen, in granites, granite pegmatites, rhyolites, and rarely in contact metamorphic deposits.</p>	<p>SnO₂</p>
<p>CERVANTITE Cervantite Group mm2 Orthorhombic Polar</p> <hr/> <p>mmm Orthorhombic Centrosymmetric Below 838 K <i>CERVANTITE</i> undergoes a phase transition to <i>CLINOCERVANTITE</i>, a ferroelectric form. Nickel-Strunz: 4.DE.30 - OXIDES (Hydroxides, V[5,6] vanadates, arsenites, antimonites, bismuthites, sulfites, selenites, tellurites and iodates) - [Metal : Oxygen = 1 : 2] with medium-sized cations, with various polyhedra. - Paraelectric, Pyroelectric, Piezoelectric - A secondary mineral formed from the oxidation of stibnite.</p>	<p>Sb₂O₄</p> <p>Transition Temperature: 838 K</p>
<p>CHALCOCITE Chalcocite-Digenite Group 6/mmm Hexagonal Centrosymmetric</p> <hr/> <p>2/m Monoclinic Centrosymmetric Nickel-Strunz: 2.BA.05 - SULFIDES and SULFOSALTS (sulfides, selenides, tellurides; arsenides, antimonides, bismuthides; sulfarsenites, sulfantimonites and sulfbismuthites) - Metal Sulfides, [Metal : Sulfur > 1 : 1 (mainly 2 : 1)] with Cu, Ag and Au. - Ferroelectric, Pyroelectric, Piezoelectric - Found in or below the zone of oxidation in hydrothermal veins and in large low-grade porphyry copper ore bodies, and an uncommon primary hydrothermal mineral.</p>	<p>Cu₂S</p> <p>Transition Temperature: 377 K</p>
<p>CHALCOSTIBITE Chalcostibite Group (Not Known)</p> <hr/> <p>mmm Orthorhombic Centrosymmetric Nickel-Strunz: 2.HA.05 - SULFIDES and SULFOSALTS (sulfides, selenides, tellurides; arsenides, antimonides, bismuthides; sulfarsenites, sulfantimonites and sulfbismuthites) - Sulfosalts of SnS structure, with Cu, Ag and Fe (without Pb). - Ferroelectric, Pyroelectric, Piezoelectric - Found with other sulfides in hydrothermal veins.</p>	<p>CuSbS₂</p> <p>Transition Temperature: 366 K</p>	<p>(Not Known)</p>

TABLE 4. Continued

CHAMBERSITE

Boracite Group

Cubic

Transition Temperature: 680 K

(Not Known)

 $mm2$ Orthorhombic

Polar

Above 680 K *CHAMBERSITE* undergoes a phase transition to a paraelectric form.

Nickel-Strunz: 6.GA.05 - BORATES - Heptaborates and other megaborates - Tecto-heptaborates.

- Ferroelectric, Pyroelectric, Piezoelectric -

Found in the brine residues of extraction wells in salt domes.

CHANGBAIITE

Melting Temperature: 1626 K

 $4/mmm$ Tetragonal

Centrosymmetric

Transition Temperature: 833 K

 $mm2$ Orthorhombic

Polar

Above 833 K *CHANGBAIITE* undergoes a phase transition to a paraelectric form.Nickel-Strunz: 4.DF.10 - OXIDES (Hydroxides, V[5,6] vanadates, arsenites, antimonites, bismuthites, sulfites, selenites, tellurites and iodates) - [Metal : Oxygen = 1 : 2] with large ($\pm$ medium-sized) cations, with dimers and trimers of edge-sharing octahedra.**- Ferroelectric, Pyroelectric, Piezoelectric -**

Found in kaolinite-filled veins and cavities in some potassic granites.

CHILDRENITE

Childrenite—Eosphorite Series

 $mm2$ Orthorhombic

Polar

Nickel-Strunz: 8.DD.20 - PHOSPHATES, ARSENATES, VANADATES - Phosphates, with additional anions, with H_2O , with only medium-sized cations, $[\text{OH} : \text{XO}_4 = 2 : 1]$.**- Pyroelectric, Piezoelectric -**

A low-temperature alteration product of phosphate minerals, and also found in some granite pegmatites.

CHROMIUM-DRAVITE

Tourmaline Supergroup: Alkali Group

 $3m$ Trigonal

Polar

Nickel-Strunz: 9.CK.05 - SILICATES (Germanates) - Cyclosilicates - $[\text{Si}_6\text{O}_{18}]_{12}$ six-membered single rings, with insular complex anions.**- Pyroelectric, Piezoelectric -**

Found in metasomatic micaceous clay-carbonate rocks.

TABLE 4. Continued

CINNABAR Hexagonal	HgS	(Not Known)
43m Cubic Non-centrosymmetric	Transition Temperature: ≈ 800 K
32 Trigonal Chiral	Transition Temperature: ≈ 600 K
<p>Note that the low temperature phase is <i>CINNABAR</i>, the middle temperature, <i>METACINNABAR</i>, and the high temperature phase, <i>HYPERCINNABAR</i>. Electrical data in this paper refer to <i>CINNABAR</i> only.</p> <p>Nickel-Strunz: 2.CD.15a - SULFIDES and SULFOSALTS (sulfides, selenides, tellurides; arsenides, antimonides, bismuthides; sulfarsenites, sulfantimonites, sulfbismuthites and similar) - Metal Sulfides, [Metal : Sulfur = 1 : 1] with Sn, Pb and Hg.</p> <p>- Piezoelectric -</p> <p>Formed from low-temperature hydrothermal solutions in veins, and in sedimentary, igneous, and metamorphic host rocks.</p>		
CLINOCERVANTITE Cervantite Group mm2 Orthorhombic Polar	Sb_2O_4
mmm Orthorhombic Centrosymmetric	Transition Temperature: 838 K
<p>Above 838 K <i>CLINOCERVANTITE</i> undergoes a phase transition to <i>CERVANTITE</i>, a paraelectric form.</p> <p>Nickel-Strunz: 4.DE.30 - OXIDES (Hydroxides, V[5,6] vanadates, arsenites, antimonites, bismuthites, sulfites, selenites, tellurites, iodates) - [Metal : Oxygen = 1 : 2] with medium-sized cations, with various polyhedra.</p> <p>- Ferroelectric, Pyroelectric, Piezoelectric -</p> <p>Found in small cavities associated with some antimony-iron-lead ore bodies.</p>		
CLINOFERROSILITE Pyroxene Group: Clinopyroxene Subgroup 2/m Monoclinic Centrosymmetric	$FeSiO_3$
mmm Orthorhombic Centrosymmetric	Transition Temperature: (Not Known)
(Not Known)	Transition Temperature: 43 K	(Not Known)
<p><i>CLINOFERROSILITE</i> is paramagnetic. The lower temperature phase, above 43 K, is <i>FERROSILITE</i>.</p> <p>Nickel-Strunz: 9.DA.10 - SILICATES (Germanates) - Inosilicates with two-periodic single chains, Si_2O_6 - Pyroxene family.</p> <p>Found as acicular crystals in cavities in some obsidian.</p>		

TABLE 4. Continued

CLINOHEDRITE *m* Monoclinic

Polar

Nickel-Strunz: 9.AE.30 - SILICATES (Germanates) - Nesosilicates with additional anions (oxygen, OH, fluorine and H₂O), with cations in tetrahedral [4] coordination.

- **Pyroelectric, Piezoelectric** -

Found in metamorphic zinc ore.

COLEMANITE *2/m* Monoclinic

Centrosymmetric

Transition Temperature: 266 K

2 Monoclinic

Polar and Chiral

Note that *COLEMANITE* is the higher temperature phase.

Nickel-Strunz: 6.CB.10 - BORATES - Triborates - Ino-triborates.

- **Pyroelectric, Piezoelectric** -

A common constituent in borate deposits formed in arid alkaline lacustrine environments, deficient in sodium and carbonate.

COQUIMBITE

Coquimbite Group

3m Trigonal

Centrosymmetric

Nickel-Strunz: 7.CB.55 - SULFATES (selenates, tellurates, chromates, molybdates and wolframates) -

Sulfates (and selenates) without additional anions, with H₂O, with only medium-sized cations.

- **Pyroelectric, Piezoelectric** -

Found as a secondary mineral in weathering iron-sulfide deposits in arid regions, and in fumaroles.

COULSONITE

Spinel Group

m3m Cubic

Centrosymmetric

Nickel-Strunz: 4.BB.05 - OXIDES (Hydroxides, V[5,6] vanadates, arsenites, antimonites, bismuthites, sulfites, selenites, tellurites and iodates) - [Metal : Oxygen = 3 : 4] with only medium-sized cations.

- **Thermoelectric** -

Found in veinlets of magnetite, with silicate minerals, cutting metamorphosed andesites, or exsolved from magnetite in mantle xenoliths in basalt.

CRANDALLITE

Alunite Supergroup: Crandallite Subgroup

3m Trigonal

Centrosymmetric

Nickel-Strunz: 8.BL.10 - PHOSPHATES, ARSENATES, VANADATES - Phosphates, with additional anions, without H₂O, with medium-sized and large cations, [OH : XO₄ = 3 : 1].

- **Pyroelectric, Piezoelectric** -

Found in phosphate-rich rocks, including aluminous sedimentary rock, carbonatites, and phosphatic nodules, as well as some granite pegmatites and amphibolite-grade metaquartzites, plus as an authigenic mineral in anoxic marine sediments or depleted tropical clays.

TABLE 4. Continued

<p>CREEDITE $2/m$ Monoclinic Centrosymmetric Nickel-Strunz: 3.CG.15 - HALIDES - Complex halides - Aluminofluorides with CO_3, SO_4 and PO_4. - Pyroelectric, Piezoelectric - Found in fluorite-rich hydrothermal deposits.</p>	<p>$\text{Ca}_3\text{SO}_4\text{Al}_2\text{F}_8(\text{OH})_2 \cdot 2\text{H}_2\text{O}$</p>
<p>CRONSTEDTITE Serpentine Group $3m$ Trigonal Polar Nickel-Strunz: 9.ED.15 - SILICATES (Germanates) - Phyllosilicates with kaolinite layers composed of tetrahedral and octahedral nets. - Pyroelectric, Piezoelectric - A low-temperature hydrothermal product in ore veins</p>	<p>$\text{Fe}_2^{2+}\text{Fe}^{3+}[(\text{SiFe}^{3+})_2\text{O}_5](\text{OH})_4$</p>
<p>CUPROKALININITE Linnaeite Group: Thiospinel Group (Not Known) <hr/> $m\bar{3}m$ Cubic Centrosymmetric CUPROKALININITE is ferromagnetic and is a metallic electrical conductor. Nickel-Strunz: 2.DA.05 - SULFIDES and SULFOSALTS (sulfides, selenides, tellurides; arsenides, antimonides, bismuthides; sulfarsenites, sulfantimonites and sulfbismuthites) - Metal Sulfides, [Metal : Sulfur = 3 : 4]. - Thermoelectric - Found in metamorphic rock with Cr-V-bearing quartz diopside.</p>	<p>CuCr_2S_4 Transition Temperature: 398 K</p>	<p>(Not Known) (Not Known)</p>
<p>CUPRORHODSITE Linnaeite Group: Thiospinel Group $m\bar{3}m$ Cubic Centrosymmetric <hr/> (Not Known) CUPRORHODSITE is paramagnetic and is a metallic electrical conductor. Nickel-Strunz: 2.DA.05 - SULFIDES and SULFOSALTS (sulfides, selenides, tellurides; arsenides, antimonides, bismuthides; sulfarsenites, sulfantimonites and sulfbismuthites) - Metal Sulfides, [Metal : Sulfur = 3 : 4]. - Thermoelectric - Found as alluvial placer deposits derived from dunite massifs.</p>	<p>$(\text{Cu,Fe})\text{Rh}_2\text{S}_4$ Transition Temperature: 25 K</p>	(Not Known)

TABLE 4. Continued

CUPROSPINEL Spinel Group (Not Known)	CuFe_2O_4 Transition Temperature: 747 K	(Not Known)
$m\bar{3}m$ Cubic Centrosymmetric Nickel-Strunz: 4.BB.05 - OXIDES (Hydroxides, V[5,6] vanadates, arsenites, antimonites, bismuthites, sulfites, selenites, tellurites and iodates) - [Metal : Oxygen = 3 : 4] with only medium-sized cations. - Thermoelectric - In highly oxidized material in some ore.		
DAUBRÉELITE Linnaeite Group: Thiospinel Group $m\bar{3}m$ Cubic Centrosymmetric (Not Known)	FeCr_2S_4 Transition Temperature: 171 K	(Not Known)
DAUBRÉELITE is paramagnetic. Below 171 K DAUBRÉELITE undergoes a phase transition to a ferrimagnetic form. DAUBRÉELITE is an electrical semiconductor. Nickel-Strunz: 2.DA.05 - SULFIDES and SULFOSALTS (sulfides, selenides, tellurides; arsenides, antimonides, bismuthides; sulfarsenites, sulfantimonites and sulfbismuthites) - Metal Sulfides, [Metal : Sulfur = 3 : 4]. - Thermoelectric - Found in small amounts in many meteorites.		
DAWSONITE mmm Orthorhombic Centrosymmetric Nickel-Strunz: 5.BB.10 - CARBONATES (NITRATES) - Carbonates with additional anions, without H_2O , with alkalis. - Pyroelectric, Piezoelectric - Found as hydrothermal minerals associated with nepheline syenites, and in alkaline shales and coal-bearing rocks.	$\text{NaAlCO}_3(\text{OH})_2$
DEMICHELEITE-BR Demicheleite Group mmm Orthorhombic Centrosymmetric (Not Known)	BiSBr Transition Temperature: 103 K	(Not Known)
Below 103 K DEMICHELEITE-BR undergoes a phase transition to a ferroelectric form. DEMICHELEITE-BR is diamagnetic. Nickel-Strunz: 2.FC.25 - SULFIDES and SULFOSALTS (sulfides, selenides, tellurides; arsenides, antimonides, bismuthides; sulfarsenites, sulfantimonites and sulfbismuthites) - Sulfides of arsenic, alkalis; sulfides with halide, oxide, hydroxide and H_2O , with Cl, Br and I (halide-sulfides). - Paraelectric, Pyroelectric, Piezoelectric - An alteration product of fumarolic pyroclastic breccia.		

TABLE 4. Continued

DEMICHELEITE-CL

BiSCl

Demicheleite Group

mmm Orthorhombic

Centrosymmetric

DEMICHELEITE-CL is diamagnetic.

Nickel-Strunz: 2.FC.25 - SULFIDES and SULFOSALTS (sulfides, selenides, tellurides; arsenides, antimonides, bismuthides; sulfarsenites, sulfantimonites and sulfbismuthites) - Sulfides of arsenic, alkalies; sulfides with halide, oxide, hydroxide and H₂O, with Cl, Br and I (halide-sulfides).

- Paraelectric, Pyroelectric, Piezoelectric -

An alteration product of fumarolic pyroclastic breccia.

DEMICHELEITE-I

BiSI

Demicheleite Group

mmm Orthorhombic

Centrosymmetric

Transition Temperature: 113 K

(Not Known)

(Not Known)

Below 113 K *DEMICHELEITE-I* undergoes a phase transition to a ferroelectric form. *DEMICHELEITE-I* is diamagnetic.

Nickel-Strunz: 2.FC.25 - SULFIDES and SULFOSALTS (sulfides, selenides, tellurides; arsenides, antimonides, bismuthides; sulfarsenites, sulfantimonites and sulfbismuthites) - Sulfides of arsenic, alkalies; sulfides with halide, oxide, hydroxide and H₂O, with Cl, Br and I (halide-sulfides).

- Paraelectric, Pyroelectric, Piezoelectric -

An alteration product of fumarolic pyroclastic breccia.

DIABOLEITEPb₂CuCl₂(OH)₄**4mm** Tetragonal

Polar

Nickel-Strunz: 3.DB.05 - HALIDES - Oxyhalides, hydroxyhalides and related double halides, with Pb and Cu.

- Pyroelectric, Piezoelectric -

Found in oxidized manganese ores and as a secondary mineral in highly-oxidized Pb-Cu ores, as well as in slag exposed to seawater.

DIOMIGNITELi₂B₄O₇**4mm** Tetragonal

Polar

DIOMIGNITE melts at 1190 K at ambient pressure.

Nickel-Strunz: 6.DD.05 - BORATES - Tetraborates - Tecto-tetraborates.

- Ferroelectric, Pyroelectric, Piezoelectric -

Found in some granite pegmatites; within fluid inclusions in spodumene.

DIOPTASECuSiO₃ • H₂O**3** Trigonal

Centrosymmetric

Nickel-Strunz: 9.CJ.30 - SILICATES (Germanates) - Cyclosilicates - [Si₆O₁₈]₁₂ six-membered single rings, without insular complex anions.

- Piezoelectric -

In the oxidized zone of some copper deposits.

TABLE 4. Continued

DRAVITE

Tourmaline Supergroup: Alkali Group

3m Trigonal

Polar

Nickel-Strunz: 9.CK.05 - SILICATES (Germanates) - Cyclosilicates - $[\text{Si}_6\text{O}_{18}]_{12}$ six-membered single rings, with insular complex anions.

- Pyroelectric, Piezoelectric -

Found in metamorphosed limestones or mafic igneous rocks with metasomatically introduced boron; rarely in pegmatites; as authigenic overgrowths in sedimentary rocks.

DYSCRASITE **mm2** Orthorhombic

Polar

Nickel-Strunz: 2.AA.35 - SULFIDES and SULFOSALTS (sulfides, selenides, tellurides; arsenides, antimonides, bismuthides; sulfarsenites, sulfantimonites and sulfbismuthites) - Alloys - Alloys of metalloids with Cu, Ag and Au.

- Pyroelectric, Piezoelectric -

Found as both a primary and secondary mineral in hydrothermal veins with other silver minerals.

EDINGTONITE

Zeolite Group

222 Orthorhombic

Chiral

Some authors have also listed *EDINGTONITE* as Tetragonal (**42m**, Non-centrosymmetric), and the two forms coexist, along with triclinic zones. Ordering of the (Si, Al) atoms generally reduces the orthorhombic symmetry to tetragonal.

Nickel-Strunz: 9.GA.15 - SILICATES (Germanates) - Tectosilicates with zeolitic H_2O , zeolite family - Zeolites with X_5O_{10} units, the fibrous zeolites.

- Piezoelectric -

Found in cavities in mafic igneous rocks and nepheline syenites; in carbonatites; and in hydrothermal veins.

ELBAITE

Tourmaline Supergroup: Alkali Group

3m Trigonal

Polar

Nickel-Strunz: 9.CK.05 - SILICATES (Germanates) - Cyclosilicates - $[\text{Si}_6\text{O}_{18}]_{12}$ six-membered single rings, with insular complex anions.

- Pyroelectric, Piezoelectric -

Found in granites, granite pegmatites, and some metamorphic rocks; and in high-temperature hydrothermal veins.

ELPIDITE **mmm** Orthorhombic

Centrosymmetric

Nickel-Strunz: 9.DG.65 - SILICATES (Germanates) - Inosilicates with three-periodic single and multiple chains.

- Pyroelectric, Piezoelectric -

Found in albitized nepheline syenites and other alkalic rocks, as well as in granites rich in aegirine.

TABLE 4. Continued

ENARGITE

Enargite Group

mm2 Orthorhombic

Polar

Nickel-Strunz: 2.KA.05 - SULFIDES and SULFOSALTS (sulfides, selenides, tellurides; arsenides, antimonides, bismuthides; sulfarsenites, sulfantimonites and sulfbismuthites) - Sulfarsenates with (As, Sb)S₄ tetrahedra.

- Pyroelectric, Piezoelectric -

Found in medium-temperature hydrothermal vein deposits, and as a late-stage mineral in low-temperature deposits.

EOSPHORITE

Childrenite—Eosphorite Series

mmm Orthorhombic

Centrosymmetric

Nickel-Strunz: 8.DD.20 - PHOSPHATES, ARSENATES, VANADATES - Phosphates, with additional anions, with H₂O, with only medium-sized cations, [OH : XO₄ = 2 : 1].

- Pyroelectric, Piezoelectric -

Found as a secondary mineral in phosphate-rich granite pegmatites.

EPISTILBITE

Zeolite Group

2 Monoclinic

Polar and Chiral

EPISTILBITE has also been analyzed as Triclinic (**1**, Polar and Chiral). Both forms are seen as equally stable under current knowledge, and both exist at standard temperatures and pressures.

Nickel-Strunz: 9.GD.45 - SILICATES (Germanates) - Tectosilicates with zeolitic H₂O, zeolite family - Chains of six-membered rings, the tabular zeolites.

- Pyroelectric, Piezoelectric -

Found in cavities in basalts and gneisses.

EPISTOLITE

Murmanite Group

1 Triclinic

Centrosymmetric

Nickel-Strunz: 9.BE.30 - SILICATES (Germanates) - Sorosilicates - Si₂O₇ groups, with additional anions; cations in octahedral [6] and greater coordination.

- Pyroelectric, Piezoelectric -

Found in alkalic pegmatites, albitites, sodalite xenoliths, and hydrothermal veins.

TABLE 4. Continued

EPSOMITE

Epsomite Group

222 Orthorhombic

Chiral

Nickel-Strunz: 7.CB.40 - SULFATES (selenates, tellurates, chromates, molybdates and wolframates) - Sulfates (and selenates) without additional anions, with H_2O , with only medium-sized cations.

- Piezoelectric -

Found as efflorescences on the walls of mines, caves, and outcrops of sulfide-bearing magnesian rocks; a product of evaporation at mineral springs and saline lakes; a hydration product of kieserite and langbeinite; and rarely as a fumarolic sublimate.

ERICAITE

Boracite Group

43m Cubic

Non-centrosymmetric

mm2 Orthorhombic

Polar

Monoclinic

3m Trigonal

Polar

(Not Known)

Transition Temperature: 610 K

Transition Temperature: 543 K

Transition Temperature: 523 K

Transition Temperature: 11.5 K

(Not Known)

(Not Known)

Above 523 K *ERICAITE* undergoes a phase transition to a paraelectric form. *ERICAITE* is paramagnetic.

Below 11.5 K *ERICAITE* undergoes a phase transition to an antiferromagnetic form.

Nickel-Strunz: 6.GA.05 - BORATES - Heptaborates and other megaborates - Tecto-heptaborates.

- Ferroelectric, Pyroelectric, Piezoelectric -

An uncommon constituent of marine evaporite deposits.

ESKOLAITE

Hematite Group

3m Trigonal

Centrosymmetric

(Not Known)

Transition Temperature: 307 K

(Not Known)

ESKOLAITE is paramagnetic. Below 307 K *ESKOLAITE* undergoes a phase transition to an antiferromagnetic form. This transition temperature varies with pressure as 1.50 K / kbar.

Nickel-Strunz: 4.CB.05 - OXIDES (Hydroxides, V[5,6] vanadates, arsenites, antimonites, bismuthites, sulfites, selenites, tellurites and iodates) - [Metal : Oxygen = 2 : 3 and 3 : 5] with medium-sized cations.

Found in chromium-rich tremolite skarns, metaquartzites, and chlorite veins; on greywacke pebbles in some glacial boulder clay deposit; and as a very rare component in chondritic meteorites.

TABLE 4. Continued

EULYTINE **43m** Cubic

Non-centrosymmetric

Nickel-Strunz: 9.AD.40 - SILICATES (Germanates) - Nesosilicates without additional anions, with cations in [6] and/or greater coordination.

- Piezoelectric -

Found in bismuth-rich hydrothermal veins.

FAYALITE

Olivine Group

mmm Orthorhombic

Centrosymmetric

Transition Temperature: 66 K

(Not Known)

(Not Known)

FAYALITE is paramagnetic. Below 66 K *FAYALITE* undergoes a phase transition to an antiferromagnetic form.

Nickel-Strunz: 9.AC.05 - SILICATES (Germanates) - Nesosilicates without additional anions, with cations in octahedral [6] coordination.

Found in ultramafic volcanic and plutonic rocks, less commonly in felsic plutonic rocks; rarely in granite pegmatite; in cavities in obsidian; in metamorphosed iron-rich sediments; and in impure carbonate rocks.

FERBERITE

Wolframite Group

2/m Monoclinic

Centrosymmetric

Below 66 K *FERBERITE* undergoes a phase transition. *FERBERITE* is paramagnetic.

Nickel-Strunz: 4.DB.30 - OXIDES (Hydroxides, V[5,6] vanadates, arsenites, antimonites, bismuthites, sulfites, selenites, tellurites and iodates - [Metal : Oxygen = 1 : 2] with medium-sized cations; chains of edge-sharing octahedra.

Found in high-temperature hydrothermal veins, greisen, and granitic pegmatites.

FERUVITE

Tourmaline Supergroup: Calcic Group

3m Trigonal

Polar

Nickel-Strunz: 9.CK.05 - SILICATES (Germanates) - Cyclosilicates - $[\text{Si}_6\text{O}_{18}]_{12}$ six-membered single rings, with insular complex anions.

- Pyroelectric, Piezoelectric -

Formed by hydrothermal replacement of silicates in pegmatitic rock

FINNEMANITE **6/mmm** Hexagonal

Centrosymmetric

Nickel-Strunz: 4.JB.45 - OXIDES (Hydroxides, V[5,6] vanadates, arsenites, antimonites, bismuthites, sulfites, selenites, tellurites and iodates) - Arsenites, antimonites, bismuthites, with additional anions, without H_2O .

- Pyroelectric, Piezoelectric -

Found in contact with hematite in metamorphosed Fe-Mn ore.

TABLE 4. Continued

FLAGSTAFFITE **mm2** Orthorhombic

Polar

Nickel-Strunz: 10.CA.10 - ORGANIC COMPOUNDS - Miscellaneous Organic Minerals.

- Pyroelectric, Piezoelectric -

Lining cracks in decomposing buried pine logs.

FLUOR-DRAVITE

Tourmaline Supergroup: Alkali Group

3m Trigonal

Polar

Nickel-Strunz: 9.CK.05 - SILICATES (Germanates) - Cyclosilicates - $[Si_6O_{18}]_{12}$ six-membered single rings, with insular complex anions.**- Pyroelectric, Piezoelectric -**

Found at or near the boundary of granitic pegmatite and surrounding country rock.

FLUOR-LIDDICOATITE

Tourmaline Supergroup: Calcic Group

3m Trigonal

Polar

Nickel-Strunz: 9.CK.05 - SILICATES (Germanates) - Cyclosilicates - $[Si_6O_{18}]_{12}$ six-membered single rings, with insular complex anions.**- Pyroelectric, Piezoelectric -**

Detrital in soil, from pegmatites. (Nearly all liddicoatite is now classed as fluor-liddicoatite.)

FLUOR-SCHORL

Tourmaline Supergroup: Alkali Group

3m Trigonal

Polar

Nickel-Strunz: 9.CK.05 - SILICATES (Germanates) - Cyclosilicates - $[Si_6O_{18}]_{12}$ six-membered single rings, with insular complex anions.**- Pyroelectric, Piezoelectric -**

In granites and granite pegmatites, high-temperature hydrothermal veins, and some metamorphic rocks; also detrital.

FOITITE

Tourmaline Supergroup: X-Vacant Group

3m Trigonal

Polar

Nickel-Strunz: 9.CK.05 - SILICATES (Germanates) - Cyclosilicates - $[Si_6O_{18}]_{12}$ six-membered single rings, with insular complex anions.**- Pyroelectric, Piezoelectric -**

Found in granite pegmatites.

TABLE 4. Continued

<p>FRANKLINITE Spinel Group: Fe-Series <i>m3m</i> Cubic Centrosymmetric</p>	<p>ZnFe_2O_4</p> <p>Transition Temperature: 15 K</p>	(Not Known)
<p>(Not Known)</p> <p><i>FRANKLINITE</i> is paramagnetic.</p> <p>Nickel-Strunz: 4.BB.05 - OXIDES (Hydroxides, V[5,6] vanadates, arsenites, antimonites, bismuthites, sulfites, selenites, tellurites and iodates) - [Metal : Oxygen = 3 : 4] with only medium-sized cations.</p> <p>Found in beds and veins formed by high-temperature metamorphism of Fe, Zn, Mn-rich marine carbonate sediments, and also as a minor mineral in some manganese and iron deposits.</p>		
<p>FRESNOITE <i>4mm</i> Tetragonal Polar</p>	<p>$\text{Ba}_2\text{Ti}(\text{Si}_2\text{O}_7)_2\text{O}$</p>	(Not Known)
<p>Nickel-Strunz: 9.BE.15 - SILICATES (Germanates) - Sorosilicates - Si_2O_7 groups, with additional anions, with cations in octahedral [6] and greater coordination.</p>		
<p>- Pyroelectric, Piezoelectric -</p> <p>Disseminated in gneissic metamorphic rocks composed mainly of sanbornite and quartz.</p>		
<p>GALLITE Chalcopyrite Group <i>42m</i> Tetragonal Non-centrosymmetric</p>	<p>CuGaS_2</p>	(Not Known)
<p>Nickel-Strunz: 2.CB.10a - SULFIDES and SULFOSALTS (sulfides, selenides, tellurides; arsenides, antimonides, bismuthides; sulfarsenites, sulfantimonites and sulfbismuthites) - Metal Sulfides, [Metal : Sulfur = 1 : 1] with Zn, Fe, Cu and Ag.</p>		
<p>- Piezoelectric -</p> <p>Found in base-metal vein deposits with relatively high gallium content.</p>		
<p>GEORGBARSANOVITE Eudialyte Group <i>3m</i> Trigonal Polar</p>	<p>$\text{Na}_{12}(\text{Mn}, \text{Sr}, \text{REE})_3\text{Ca}_6\text{Fe}_3^{2+}\text{Zr}_3\text{NbSi}_{25}\text{O}_{76}\text{Cl}_2 \cdot \text{H}_2\text{O}$</p>	(Not Known)
<p>Nickel-Strunz: 9.CO.10 - SILICATES (Germanates) - Cyclosilicates - $[\text{Si}_9\text{O}_{27}]_{18}$ nine-membered rings.</p>		
<p>- Pyroelectric, Piezoelectric -</p> <p>Found in some nepheline pegmatites.</p>		
<p>GISMONDINE-CA Zeolite Group <i>2/m</i> Monoclinic Centrosymmetric</p>	<p>$\text{CaAl}_2\text{Si}_2\text{O}_8 \cdot 4\text{H}_2\text{O}$</p>	(Not Known)
<p>Nickel-Strunz: 9.GC.05 - SILICATES (Germanates) - Tectosilicates with zeolitic H_2O, zeolite family - Chains of doubly-connected four-membered rings.</p>		
<p>- Piezoelectric -</p> <p>Found in cavities in nepheline and olivine basalt and leucite tephrite.</p>		

TABLE 4. Continued

GMELINITE-NA

Zeolite Group

6/mmm Hexagonal

Centrosymmetric

Nickel-Strunz: 9.GD.05 - SILICATES (Germanates) - Tectosilicates with zeolitic H_2O , zeolite family - Chains of six-membered rings, the tabular zeolites.

- Piezoelectric -

Formed from sodium-rich fluids, in basalts and related igneous rocks, also pegmatites.

GOSLARITE

Epsomite Group

222 Orthorhombic

Chiral

Nickel-Strunz: 7.CB.40 - SULFATES (selenates, tellurates, chromates, molybdates and wolframates) - Sulfates (and selenates) without additional anions, with H_2O , with only medium-sized cations.

- Piezoelectric -

A secondary mineral in oxidized portions of zinc-sulfide deposits, particularly as coatings on walls of mine passages.

GOYAZITE

Alunite Supergroup: Crandallite Subgroup

3m Trigonal

Centrosymmetric

Nickel-Strunz: 8.BL.10 - PHOSPHATES, ARSENATES, VANADATES - Phosphates, with additional anions, without H_2O , with medium-sized and large cations, $[\text{OH} : \text{XO}_4 = 3 : 1]$.

- Pyroelectric, Piezoelectric -

Found in granite pegmatites, as an alteration product in hydrothermal or tuffaceous claystones, in carbonatites, and as a detrital mineral.

GREENOCKITE

Wurtzite Group

6mm Hexagonal

Polar

Nickel-Strunz: 2.CB.45 - SULFIDES and SULFOSALTS (sulfides, selenides, tellurides; arsenides, antimonides, bismuthides; sulfarsenites, sulfantimonites and sulfbismuthites) - Metal Sulfides, $[\text{Metal} : \text{Sulfur} = 1 : 1]$ with Zn, Fe, Cu and Ag.

- Pyroelectric, Piezoelectric -

Found as earthy coatings, especially on sphalerite; also rarely as crystals in cavities in mafic igneous rocks; and in high-temperature hydrothermal vein deposits.

GUGIAITE

Melilite Group

42m Tetragonal

Non-centrosymmetric

Nickel-Strunz: 9.BB.10 - SILICATES (Germanates) - Sorosilicates - Si_2O_7 groups, without non-tetrahedral anions, with cations in tetrahedral [4] and greater coordination.

- Piezoelectric -

Found in cavities in skarns and melanite adjacent to alkalic syenite.

TABLE 4. Continued

GWIHABAITE *mmm* Orthorhombic

Centrosymmetric

Nickel-Strunz: 5.NA.15 - CARBONATES (NITRATES) - NITRATES - Without OH or H₂O.**- Ferroelectric, Pyroelectric, Piezoelectric -**

Formed by bacterial action on bat guano in caves, and found as crusts or efflorescences.

HALLOYSITE-7Å

Serpentine Group

m Monoclinic

Polar

Nickel-Strunz: 9.ED.10 - SILICATES (Germanates) - Phyllosilicates with kaolinite layers composed of tetrahedral and octahedral nets.

- Pyroelectric, Piezoelectric -

Formed by hydrothermal alteration or surface weathering of aluminosilicate minerals, plus dehydration at 110°C (of Halloysite-10Å).

HALLOYSITE-10Å

Serpentine Group

m Monoclinic

Polar

Nickel-Strunz: 9.ED.10 - SILICATES (Germanates) - Phyllosilicates with kaolinite layers composed of tetrahedral and octahedral nets.

- Pyroelectric, Piezoelectric -

Formed by hydrothermal alteration or surface weathering of aluminosilicate minerals.

HALOTRICHITE

Halotrichite Group

2 Monoclinic

Polar and Chiral

Nickel-Strunz: 7.CB.85 - SULFATES (selenates, tellurates, chromates, molybdates and wolframates) - Sulfates (and selenates) without additional anions, with H₂O, with only medium-sized cations.**- Pyroelectric, Piezoelectric -**

Found in arid climates as efflorescences in weathered sulfide deposits or pyrite-rich coal rocks, and as a precipitate around volcanic fumaroles and hot springs.

HARMOTOME

Zeolite Group

2/m Monoclinic

Centrosymmetric

Nickel-Strunz: 9.GC.10 - SILICATES (Germanates) - Tectosilicates with zeolitic H₂O, zeolite family - Chains of doubly-connected four-membered rings.**- Pyroelectric, Piezoelectric -**

Formed hydrothermally in cavities in basalts, phonolites and trachytes, as well as in gneisses and ore veins.

TABLE 4. Continued

HARTITE

1 Triclinic

Polar and Chiral

Nickel-Strunz: 10.BA.10 - ORGANIC COMPOUNDS - Hydrocarbons.

- Pyroelectric, Piezoelectric -

Formed by reprecipitation of lignite, often in coalified or silicified tree trunks and in lignite seams.

HAUERITE

Pyrite Group

 $\bar{m}3$ Cubic

Centrosymmetric

HAUERITE is paramagnetic and is an electrical semiconductor.

Nickel-Strunz: 2.EB.05a - SULFIDES and SULFOSALTS (sulfides, selenides, tellurides; arsenides, antimonides, bismuthides; sulfarsenites, sulfantimonites and sulfbismuthites) - Metal Sulfides, [Metal : Sulfur = 1 : 2] with Fe, Co, Ni and platinum group elements.

A low-temperature mineral commonly associated with solfataric waters, in clay deposits rich in sulfur, and from decomposed extrusive rocks.

HEFTETJERNITE

Wolframite Group

 $2/m$ Monoclinic

Centrosymmetric

Melting Temperature: 2613 K

 2 Monoclinic

Polar and Chiral

Transition Temperature: 280 K

Below 280 K *HEFTETJERNITE* undergoes a phase transition to a ferroelectric form.

Nickel-Strunz: 4.DB.30 - OXIDES (Hydroxides, V[5,6] vanadates, arsenites, antimonites, bismuthites, sulfites, selenites, tellurites and iodates) - [Metal : Oxygen = 1 : 2] with medium-sized cations; chains of edge-sharing octahedra.

- Paraelectric, Pyroelectric, Piezoelectric -

Found in some cleavelandite-amazonite pegmatites.

HELVINE

Helvine Group

 $\bar{4}3m$ Cubic

Non-centrosymmetric

Nickel-Strunz: 9.FB.10 - SILICATES (Germanates) - Tectosilicates without zeolitic H_2O - Tectosilicates with additional anions.**- Piezoelectric -**

Found in granites, granite pegmatites, gneisses, and contact zones and skarns.

TABLE 4. Continued

HEMATITE Hematite Group (Not Known)	Fe_2O_3	(Not Known)
$\underline{3m}$ Trigonal Centrosymmetric	Transition Temperature: 950 K
$\underline{3m}$ Trigonal Centrosymmetric	Transition Temperature: 263 K
<p><i>HEMATITE</i> is (incompletely) antiferromagnetic. Below 263 K <i>HEMATITE</i> undergoes a phase transition to a (complete) antiferromagnetic form. There are several forms of Fe_2O_3: <i>HEMATITE</i> is the $\alpha\text{-Fe}_2\text{O}_3$ form, while the $\gamma\text{-Fe}_2\text{O}_3$ form is <i>MAGHEMITE</i> (p. 124).</p> <p>Nickel-Strunz: 4.CB.05 - OXIDES (Hydroxides, V[5,6] vanadates, arsenites, antimonites, bismuthites, sulfites, selenites, tellurites and iodates) - [Metal : Oxygen = 2 : 3 and 3 : 5] with medium-sized cations. Found as an accessory mineral in felsic igneous rocks, a late-stage sublimate in volcanic rocks, and in high-temperature hydrothermal veins; and as a product of contact metamorphism and in metamorphosed banded iron formations; as well as a common cement in sedimentary rocks and a major constituent in oolitic iron formations; also, abundant on weathered iron-bearing minerals.</p>		
HEMIMORPHITE $mm2$ Orthorhombic Polar	$\text{Zn}_4\text{Si}_2\text{O}_7(\text{OH})_2 \cdot \text{H}_2\text{O}$
<p>Nickel-Strunz: 9.BD.10 - SILICATES (Germanates) - Sorosilicates - Si_2O_7 groups, with additional anions; cations in tetrahedral [4] and greater coordination.</p> <p>- Pyroelectric, Piezoelectric -</p> <p>A secondary mineral typically found in the oxidized zone of zinc-bearing mineral deposits.</p>		
HEULANDITE-CA Zeolite Group $2/m$ Monoclinic Centrosymmetric	$(\text{Ca,Na})_{2-3}\text{A}_{13}(\text{Al,Si})_2\text{Si}_{13}\text{O}_{36} \cdot 12\text{H}_2\text{O}$
<p>Nickel-Strunz: 9.GE.05 - SILICATES (Germanates) - Tectosilicates with zeolitic H_2O, zeolite family - Chains of $\text{X}_{10}\text{O}_{20}$ tetrahedra.</p> <p>- Pyroelectric, Piezoelectric -</p> <p>Found as a devitrification product in tuffs and volcanic glasses, as well as in cavities in basalts, and in weathered andesites and diabases.</p>		
HILGARDITE Hilgardite Group 1 Triclinic Polar and Chiral	$\text{Ca}_2\text{B}_5\text{O}_9\text{Cl} \cdot \text{H}_2\text{O}$
<p>Nickel-Strunz: 6.ED.05 - BORATES - Pentaborates - Tecto-pentaborates.</p> <p>- Pyroelectric, Piezoelectric -</p> <p>Found in marine evaporite deposits.</p>		

TABLE 4. Continued

HYDROCALUMITE

2 Monoclinic

Polar and Chiral

Nickel-Strunz: 4.FL.10 - OXIDES (Hydroxides, V[5,6] vanadates, arsenites, antimonites, bismuthites, sulfites, selenites, tellurites and iodates) - Hydroxides (without vanadium or uranium) - Hydroxides with $\text{H}_2\text{O} \pm (\text{OH})$, with sheets of edge-sharing octahedra.

- Pyroelectric, Piezoelectric -

A late-stage hydrothermal mineral in skarns formed from contact metamorphism of limestone or in xenoliths in lava.

HYDROXYCALCIOROMÉITE: FERROAN VARIETY

Pyrochlore Supergroup: Roméite Group

 $m\bar{3}m$ Cubic

Centrosymmetric

Nickel-Strunz: 4.DH.20 - OXIDES (Hydroxides, V[5,6] vanadates, arsenites, antimonites, bismuthites, sulfites, selenites, tellurites and iodates) - [Metal : Oxygen = 1 : 2] with large ($\pm$ medium-sized) cations, with sheets of edge-sharing octahedra.

- Ferroelectric, Pyroelectric, Piezoelectric -

A secondary mineral found in some hydrothermal deposits that commonly have undergone metamorphism.

ICE

Melting Temperature: 273 K

 $6/mmm$ Hexagonal
Centrosymmetric

Transition Temperature: 173 K

 $m\bar{3}m$ Cubic
Centrosymmetric

Transition Temperature: 72 K

 $mm2$ Orthorhombic
Polar

Below 72 K *ICE* undergoes a phase transition to a ferroelectric form.

Nickel-Strunz: 4.AA.05 - OXIDES (Hydroxides, V[5,6] vanadates, arsenites, antimonites, bismuthites, sulfites, selenites, tellurites and iodates) -

[Metal : Oxygen = 2 : 1 and 1.8 : 1].

- Paraelectric, Pyroelectric, Piezoelectric -

Found in glacial flows and thick masses of near-continental dimensions, and formed at low temperatures by sublimation in the atmosphere and in layers over open bodies of water.

ILMENITE

Ilmenite Group

 $\bar{3}$ Trigonal

Centrosymmetric

Below (55 to 70 K) *ILMENITE* undergoes a phase transition. *ILMENITE* is paramagnetic.

Nickel-Strunz: 4.CB.05 - OXIDES (Hydroxides, V[5,6] vanadates, arsenites, antimonites, bismuthites, sulfites, selenites, tellurites and iodates) - [Metal : Oxygen = 2 : 3 and 3 : 5] with medium-sized cations.

A common accessory mineral disseminated in igneous rocks, as granites, gabbros, and kimberlites, and in granite pegmatites, carbonatites, and high-grade metamorphic rocks.

TABLE 4. Continued

INDITE

Linnaeite Group: Thiospinel Group

 $m\bar{3}m$ Cubic

Centrosymmetric

Nickel-Strunz: 2.DA.05 - SULFIDES and SULFOSALTS (sulfides, selenides, tellurides; arsenides, antimonides, bismuthides; sulfarsenites, sulfantimonites and sulfbismuthites) - Metal Sulfides, [Metal : Sulfur = 3 : 4].

- Thermoelectric -

Generally of hydrothermal origin, replacing botryoidal cassiterite.

INNELITE **$\bar{1}$** Triclinic

Centrosymmetric

INNELITE is also listed as Monoclinic (**$2/m$** , Centrosymmetric), a similarly stable phase at standard temperature and pressure.

Nickel-Strunz: 9.BE.40 - SILICATES (Germanates) - Sorosilicates - Si_2O_7 groups, with additional anions; cations in octahedral [6] and greater coordination.

- Pyroelectric, Piezoelectric -

Found in miarolitic cavities of aegirine-eckermannite-microcline pegmatites in dunites; in pulaskite and shonkinite.

IODARGYRITE **$6mm$** Hexagonal

Polar

Nickel-Strunz: 3.AA.10 - HALIDES - Simple halides, without H_2O - [Metal : Halogen = 1 : 1, 2 : 3 and 3 : 5].

- Pyroelectric, Piezoelectric -

A secondary mineral in the oxidized portions of silver-bearing deposits.

JACOBSITE

Spinel Group

Jacobsite-Magnetite Series

 $m\bar{3}m$ Cubic

Centrosymmetric

Above 573 K *JACOBSITE* undergoes a phase transition. *JACOBSITE* is ferromagnetic.

Nickel-Strunz: 4.BB.05 - OXIDES (Hydroxides, V[5,6] vanadates, arsenites, antimonites, bismuthites, sulfites, selenites, tellurites and iodates) - [Metal : Oxygen = 3 : 4] with only medium-sized cations.

- Thermoelectric -

Found as a primary mineral or an alteration product of other manganese-bearing minerals in metamorphosed ore deposits.

TABLE 4. Continued

JAROSITE

Alunite Supergroup: Jarosite Subgroup

3 Trigonal

Polar and Chiral

Nickel-Strunz: 7.BC.10 - SULFATES (selenates, tellurates, chromates, molybdates and wolframates) - Sulfates (and selenates) with additional anions, without H₂O, with medium-sized and large cations.

- Pyroelectric, Piezoelectric -

A secondary mineral in oxidized portions of sulfide-bearing rocks, typically altering from pyrite; less common as a low-temperature, primary hydrothermal mineral, including as deposits around hot springs.

JEREMEJEVITE

6/m Hexagonal

Centrosymmetric

Nickel-Strunz: 6.AB.15 - BORATES - Monoborates - BO₃, with additional anions, with single triangles plus OH.

- Piezoelectric -

A late hydrothermal mineral formed in granitic pegmatites.

JUNITOITE

mm2 Orthorhombic

Polar

Nickel-Strunz: 9.BD.15 - SILICATES (Germanates) - Sorosilicates - Si₂O₇ groups, with additional anions, with cations in tetrahedral [4] and greater coordination.

- Pyroelectric, Piezoelectric -

In a retrogressively altered tactite zone, closely related to the breakdown of sphalerite.

KALIBORITE

2/m Monoclinic

Centrosymmetric

Nickel-Strunz: 6.FB.10 - BORATES - Ino-hexaborates.

- Pyroelectric, Piezoelectric -

Found in potassium-bearing marine salt deposits, and as efflorescences.

KALININITE

Linnaeite Group: Thiospinel Group

m3m Cubic

Centrosymmetric

Below 15.5 K *KALININITE* undergoes a phase transition. *KALININITE* is paramagnetic and is an electrical semiconductor.

Nickel-Strunz: 2.DA.05 - SULFIDES and SULFOSALTS (sulfides, selenides, tellurides; arsenides, antimonides, bismuthides; sulfarsenites, sulfantimonites and sulfbismuthites) - Metal Sulfides, [Metal : Sulfur = 3 : 4].

- Thermoelectric -

Found in metamorphic diopside-quartz-calcite rock, generally in garnet-pyroxene regions.

TABLE 4. Continued

KAMIOKITE Nolanite Group 6mm Hexagonal Polar	$\text{Fe}_2\text{Mo}_3\text{O}_8$ Transition Temperature: 59 K	(Not Known)
<p>(Not Known)</p> <p><i>KAMIOKITE</i> is paramagnetic.</p> <p>Nickel-Strunz: 4.CB.40 - OXIDES (Hydroxides, V[5,6] vanadates, arsenites, antimonites, bismuthites, sulfites, selenites, tellurites and iodates) - [Metal : Oxygen = 2 : 3 and 3 : 5] with medium-sized cations. Found in molybdenite-rich quartz veins associated with granite porphyry dikes, and also in fissure veins filled during low-grade regional metamorphism of basalt.</p>		
KARELIANITE Hematite Group 3m Trigonal Centrosymmetric	V_2O_3 Transition Temperature: (Not Known)	(Not Known)
Monoclinic	Transition Temperature: 160 K	
3 Trigonal Centrosymmetric	Transition Temperature: 10 K	(Not Known)
<p>(Not Known)</p> <p>The semiconducting phase of <i>KARELIANITE</i> above 160 K is 7 orders of magnitude more electrically resistant than the metallic conducting phase below that transition. <i>KARELIANITE</i> is paramagnetic.</p> <p>Nickel-Strunz: 4.CB.05 - OXIDES (Hydroxides, V[5,6] vanadates, arsenites, antimonites, bismuthites, sulfites, selenites, tellurites and iodates) - [Metal : Oxygen = 2 : 3 and 3 : 5] with medium-sized cations. Found in sulfide-rich, resistant portions of glacial boulders derived from high-grade metamorphic rocks, as schists and quartzites, as well as in primary unoxidized uranium-vanadium ores, and in vanadiferous bitumen.</p>		
KOECHLINITE Koechlinite Group	Bi_2MoO_6 Melting Temperature: 1201 K	
2/m Monoclinic Centrosymmetric	Transition Temperature: 843 K
mm2 Orthorhombic Polar		
<p>Above 843 K <i>KOECHLINITE</i> undergoes a phase transition to a paraelectric form.</p> <p>Nickel-Strunz: 4.DE.15 - OXIDES (Hydroxides, V[5,6] vanadates, arsenites, antimonites, bismuthites, sulfites, selenites, tellurites and iodates) - [Metal : Oxygen = 1 : 2] with medium-sized cations; with various polyhedra.</p> <p>- Ferroelectric, Pyroelectric, Piezoelectric -</p> <p>Found as an alteration product in the oxidation zone of Bi-Mo deposits.</p>		

TABLE 4. Continued

KRENNERITE **mm2** Orthorhombic

Polar

Nickel-Strunz: 2.EA.15 - SULFIDES and SULFOSALTS (sulfides, selenides, tellurides; arsenides, antimonides, bismuthides; sulfarsenites, sulfantimonites and sulfbismuthites) - Metal Sulfides, [Metal : Sulfur = 1 : 2] with Cu, Ag, Au.

- **Pyroelectric, Piezoelectric** -

Found in hydrothermal veins with other telluride minerals.

KRUT'AITE

Pyrite Group

m3 Cubic

Centrosymmetric

(Not Known)

Transition Temperature: 30 K

(Not Known)

(Not Known)

Transition Temperature: 2.40 K

(Not Known)

KRUT'AITE is paramagnetic. Below 30 K the mineral becomes (incompletely) antiferromagnetic and is a metallic electrical conductor. Below 2.40 K *KRUT'AITE* is an electrical superconductor.

Nickel-Strunz: 2.EB.05a - SULFIDES and SULFOSALTS (sulfides, selenides, tellurides; arsenides, antimonides, bismuthides; sulfarsenites, sulfantimonites and sulfbismuthites) - Metal Sulfides, [Metal : Sulfur = 1 : 2] with Fe, Co, Ni and platinum group elements.

A hydrothermal mineral.

LAKARGITE

Perovskite Group

mmm Orthorhombic

Centrosymmetric

Nickel-Strunz: 4.CC.30 - OXIDES (Hydroxides, V[5,6] vanadates, arsenites, antimonites, bismuthites, sulfites, selenites, tellurites and iodates) - [Metal : Oxygen = 2 : 3 and 3 : 5] with large and medium-sized cations.

- **Paraelectric, Pyroelectric, Piezoelectric** -

Found as xenoliths in ignimbrites from some high temperature calc-silicate skarns.

LANGBEINITE

Langbeinite Group

23 Cubic

Chiral

Nickel-Strunz: 7.AC.10 - SULFATES (selenates, tellurates, chromates, molybdates and wolframates) - Sulfates (and selenates) without additional anions, without H_2O , with medium-sized and large cations.

- **Piezoelectric** -

Found in marine salt deposits.

TABLE 4. Continued

LARSENITE <i>mm2</i> Orthorhombic Polar Nickel-Strunz: 9.AB.10 - SILICATES (Germanates) - Nesosilicates without additional anions, with cations in [4] and greater coordination. - Pyroelectric, Piezoelectric - A secondary mineral found in veins in metamorphosed zinc deposits.	PbZnSiO_4
LECONTITE 222 Orthorhombic Chiral (Not Known)	$(\text{NH}_4, \text{K})\text{NaSO}_4 \cdot 2\text{H}_2\text{O}$ Transition Temperature: 101 K	(Not Known)
LEUCOPHANITE 222 Orthorhombic Chiral Nickel-Strunz: 9.DH.05 - SILICATES (Germanates) - Inosilicates with four-periodic single chains, Si_4O_{12} . - Piezoelectric - Found in pegmatites in augite syenite; and in albitization zones in pegmatites at the contact of alkalic massifs intruding carbonaceous quartz-sericite schists.	$\text{NaCaBeSi}_2\text{O}_6\text{F}$
LIEBIGITE <i>mm2</i> Orthorhombic Polar Nickel-Strunz: 5.ED.20 - CARBONATES (NITRATES) - Uranyl Carbonates - $[\text{UO}_2 : \text{CO}_3 = 1 : 3]$. - Pyroelectric, Piezoelectric - Formed as a secondary mineral as an alteration product of uraninite through the action of an alkaline carbonate solution.	$\text{Ca}_2(\text{UO}_2)(\text{CO}_3)_3 \cdot 11\text{H}_2\text{O}$
LINNAEITE Linnaeite Group: Thiospinel Group <i>m3m</i> Cubic Centrosymmetric (Not Known)	$\text{Co}^{2+}\text{Co}_2^{3+}\text{S}_4$ Transition Temperature: 95 K	(Not Known)
LINNAEITE is paramagnetic and is a metallic electrical conductor. Nickel-Strunz: 2.DA.05 - SULFIDES and SULFOSALTS (sulfides, selenides, tellurides; arsenides, antimonides, bismuthides; sulfarsenites, sulfantimonites and sulfbismuthites) - Metal Sulfides, [Metal : Sulfur = 3 : 4]. - Thermoelectric - Found in hydrothermal veins with other cobalt and nickel sulfides.		

TABLE 4. Continued

LÖLLINGITE

Löllingite Group

Löllingite – Safflorite Series

mmm Orthorhombic

Centrosymmetric

LÖLLINGITE is diamagnetic and is an electrical semiconductor.

Nickel-Strunz: 2.EB.15a - SULFIDES and SULFOSALTS (sulfides, selenides, tellurides; arsenides, antimonides, bismuthides; sulfarsenites, sulfantimonites and sulfbismuthites) - Metal Sulfides, [Metal : Sulfur = 1 : 2] with Fe, Co, Ni and platinum group elements.

Found in mesothermal deposits associated with other sulfides and with calcite gangue, and also in pegmatites.

LONDONITE

Rhodizite Group

Londonite – Rhodizite Series

43m Cubic

Non-centrosymmetric

Nickel-Strunz: 6.GC.05 - BORATES - Heptaborates and other megaborates - Tecto-dodecaborates.

- Piezoelectric -

From the central zones of granite pegmatites; and in miarolitic cavities.

TABLE 4. Continued

LUESHITE Perovskite Group (<i>m3m</i>) Cubic Centrosymmetric	NaNbO ₃
4/mmm Tetragonal Centrosymmetric	Transition Temperature: 916 K	
mmm Orthorhombic Centrosymmetric	Transition Temperature: 845 K	
mmm Orthorhombic Centrosymmetric	Transition Temperature: 793 K	
mmm Orthorhombic Centrosymmetric	Transition Temperature: 753 K	
mmm Orthorhombic Centrosymmetric	Transition Temperature: 638 K	
3m Trigonal Polar	Transition Temperature: 73 K	

Above 916 K **LUESHITE** is paraelectric; below 73 K it is ferroelectric. Note that the various orthorhombic phases of **LUESHITE** have different atomic arrangements, with different space group notations: ***Pbma***, ***Pnmm***, ***Pnmm***, ***Ccmm***, from low temperature to high temperature, respectively.

Nickel-Strunz: 4.CC.30 - OXIDES (Hydroxides, V[5,6] vanadates, arsenites, antimonites, bismuthites, sulfites, selenites, tellurites and iodates) - [Metal : Oxygen = 2 : 3 and 3 : 5] with large and medium-sized cations.

- Antiferroelectric, Pyroelectric, Piezoelectric -

Found in veins cutting nepheline syenites, and in sodalite xenoliths in alkalic gabbro-syenites, as well as in contacts between syenite and carbonatite, and as a common accessory mineral in fenites formed from pyroxenite or gabbro.

MACEDONITE Perovskite Group (<i>m3m</i>) Cubic Centrosymmetric	PbTiO ₃
4mm Tetragonal Polar	Transition Temperature: 763 K	

Below 763 K **MACEDONITE** undergoes a phase transition to a ferroelectric form. Structural transitions at 298, 158 and 90 K are reported for **MACEDONITE**, all within the **4mm** Tetragonal system.

Nickel-Strunz: 4.CC.35 - OXIDES (Hydroxides, V[5,6] vanadates, arsenites, antimonites, bismuthites, sulfites, selenites, tellurites and iodates) - [Metal : Oxygen = 2 : 3 and 3 : 5] with large and medium-sized cations.

- Paraelectric, Pyroelectric, Piezoelectric -

A rare accessory mineral in syenite pegmatite veins cutting pyroxene amphibole schist, and as inclusions in hematite and magnetoplumbite in a metamorphosed Fe-Mn orebody.

TABLE 4. Continued

MAGHEMITE

Maghemite Group

Transition Temperature: 1020 K

23 Cubic

Chiral

MAGHEMITE is ferrimagnetic and is an electrical semiconductor.

Nickel-Strunz: 4.BB.15 - OXIDES (Hydroxides, V[5,6] vanadates, arsenites, antimonites, bismuthites, sulfites, selenites, tellurites and iodates) - [Metal : Oxygen = 3 : 4] with only medium-sized cations.

Formed by weathering or low-temperature oxidation of spinels containing ferrous iron, commonly magnetite or titanian magnetite.

MAGNESIOCOULSONITE

Spinel Group

m3m Cubic

Centrosymmetric

MAGNESIOCOULSONITE is paramagnetic.

Nickel-Strunz: 4.BB.05 - OXIDES (Hydroxides, V[5,6] vanadates, arsenites, antimonites, bismuthites, sulfites, selenites, tellurites and iodates) - [Metal : Oxygen = 3 : 4] with only medium-sized cations.

- Thermoelectric -

An accessory mineral in chromium-vanadium-bearing metamorphic rocks.

MAGNESIOFERRITE

Spinel Group

Magnesioferrite-Magnetite Series

Transition Temperature: 679 K

m3m Cubic

Centrosymmetric

MAGNESIOFERRITE is ferrimagnetic.

Nickel-Strunz: 4.BB.05 - OXIDES (Hydroxides, V[5,6] vanadates, arsenites, antimonites, bismuthites, sulfites, selenites, tellurites and iodates) - [Metal : Oxygen = 3 : 4] with only medium-sized cations.

Most commonly of fumarolic origin, also found in high-grade (sanidine facies) combustion-metamorphosed marls and burning coal heaps, in metamorphosed dolostones; as an accessory mineral in some kimberlites, carbonatites, and alkali gabbros, and as skeletal inclusions in glassy spherules in sediments attributed to bolide impact debris.

TABLE 4. Continued

MAGNETITE Spinel Group	$\text{Fe}^{2+}\text{Fe}^{3+}_2\text{O}_4$	
<i>m3m</i> Cubic Centrosymmetric	Transition Temperature: 850 K
(Not Known)	Transition Temperature: 119 K	
(Not Known)	Transition Temperature: 45 K	
<p>Electrical conduction in <i>MAGNETITE</i> operates via exchanges between the Fe^{2+} and Fe^{3+} centers. Below 119 K <i>MAGNETITE</i> is paraelectric; below 45 K it is ferroelectric. <i>MAGNETITE</i> is ferrimagnetic.</p> <p>Nickel-Strunz: 4.BB.05 - OXIDES (Hydroxides, V[5,6] vanadates, arsenites, antimonites, bismuthites, sulfites, selenites, tellurites and iodates) - [Metal : Oxygen = 3 : 4] with only medium-sized cations.</p> <p>A common accessory mineral in igneous and metamorphic rocks, in which magmatic segregation or contact metamorphism may produce economic deposits; in sedimentary banded iron formations; a biogenic product; and detrital.</p>		(Not Known)
MARIALITE Scapolite Group	$\text{Na}_4\text{Al}_3\text{Si}_9\text{O}_{24}\text{Cl}$	
<i>4/m</i> Tetragonal Centrosymmetric
Nickel-Strunz: 9.FB.15 - SILICATES (Germanates) - Tectosilicates without zeolitic H_2O - Tectosilicates with additional anions.		
<p>- Pyroelectric, Piezoelectric -</p> <p>Found in regionally metamorphosed calcareous rock, and in skarns as well as some mafic igneous rock, ejecta and pegmatites as an alteration product.</p>		
MARIINSKITE Chrysoberyl Group	BeCr_2O_4	
<i>mmm</i> Orthorhombic Centrosymmetric
Orthorhombic	Transition Temperature: 28 K	
<p><i>MARIINSKITE</i> is paramagnetic. Below 28 K <i>MARIINSKITE</i> undergoes a phase transition to a ferroelectric, antiferromagnetic form.</p> <p>Nickel-Strunz: 4.BA.05 - OXIDES (Hydroxides, V[5,6] vanadates, arsenites, antimonites, bismuthites, sulfites, selenites, tellurites and iodates) - [Metal : Oxygen = 3 : 4] with small and medium-sized cations.</p> <p>- Paraelectric, Pyroelectric, Piezoelectric -</p> <p>Associated with emerald deposits in pegmatite or hydrothermal-metamorphic complexes.</p>		(Not Known)
MATTAGAMITE Marcasite Group Frobergite-Mattagamite Series	CoTe_2	
<i>mmm</i> Orthorhombic Centrosymmetric
<i>MATTAGAMITE</i> is paramagnetic and is an electrical semiconductor.		
<p>Nickel-Strunz: 2.EB.10a - SULFIDES and SULFOSALTS (sulfides, selenides, tellurides; arsenides, antimonides, bismuthides; sulfarsenites, sulfantimonites and sulfbismuthites) - Metal Sulfides, [Metal : Sulfur = 1 : 2] with Fe, Co, Ni and platinum group elements.</p> <p>Found in telluride zones of some zinc-rich stratiform volcanic deposits.</p>		

TABLE 4. Continued

MEIONITE

Scapolite Group

4/m Tetragonal

Centrosymmetric

Nickel-Strunz: 9.FB.15 - SILICATES (Germanates) - Tectosilicates without zeolitic H_2O - Tectosilicates with additional anions.**- Pyroelectric, Piezoelectric -**

Found in regionally metamorphosed calcareous rock, and in skarns as well as some mafic igneous rock, ejecta and pegmatites as an alteration product.

MELANOVANADITE **1** Triclinic

Centrosymmetric

Nickel-Strunz: 4.HE.05 - OXIDES (Hydroxides, V[5,6] vanadates, arsenites, antimonites, bismuthites, sulfites, selenites, tellurites and iodates) - V[5,6] Vanadates - Phyllo-vanadates.

- Pyroelectric, Piezoelectric -

Found as an alteration product in vanadium-rich shale and in uranium-vanadium deposits.

MELIPHANITE **4** Tetragonal

Non-centrosymmetric

Nickel-Strunz: 9.DP.05 - SILICATES (Germanates) - Inosilicates - Transitional ino-phyllosilicate structures.

- Pyroelectric, Piezoelectric -

Found in augite syenite.

MESOLITE **mm2** Orthorhombic

Polar

Nickel-Strunz: 9.GA.05 - SILICATES (Germanates) - Tectosilicates with zeolitic H_2O , zeolite family - Zeolites with X_5O_{10} units, the fibrous zeolites.**- Pyroelectric, Piezoelectric -**

Found in cavities of volcanic rocks, typically basalt; also in andesites, porphyries, and hydrothermal veins.

MILLERITE

Millerite Group

3m Trigonal

Polar

Nickel-Strunz: 2.CC.20 - SULFIDES and SULFOSALTS (sulfides, selenides, tellurides; arsenides, antimonides, bismuthides; sulfarsenites, sulfantimonites and sulfbismuthites) - Metal Sulfides, [Metal : Sulfur = 1 : 1] with Ni, Fe, Co and platinum group elements.

- Pyroelectric, Piezoelectric -

Found in cavities in limestones, carbonate veins and barite as a low-temperature mineral, and as an alteration product of nickel minerals, as well as in association with coal, and uncommonly with serpentines.

TABLE 4. Continued

MIMETITE

Apatite Supergroup: Pyromorphite Subgroup

6/m Hexagonal

Centrosymmetric

An **m** Monoclinic polytype form originally called clinomimetite, now called mimetite-M, is also common.Nickel-Strunz: 8.BN.05 - PHOSPHATES, ARSENATES, VANADATES - Phosphates, with additional anions, without H₂O, with only large cations, [OH : XO₄ = 0.33 : 1].**- Piezoelectric -**

A secondary mineral found in the oxidized zone of arsenic-bearing lead deposits.

MINYULITE **mm2** Orthorhombic

Polar

Nickel-Strunz: 8.DH.05 - PHOSPHATES, ARSENATES, VANADATES - Phosphates, with additional anions, with H₂O, with large and medium-sized cations, [OH : XO₄ < 1 : 1].**- Pyroelectric, Piezoelectric -**

Found as a weathering product in phosphate-rich ironstones.

MOISSANITE

Moissanite Group

6mm Hexagonal

Polar

Nickel-Strunz: 1.DA. - ELEMENTS (Metals and intermetallic alloys; metalloids and nonmetals; carbides, silicides, nitrides and phosphides) - Nonmetallic carbides.

- Pyroelectric, Piezoelectric -

Found in iron meteorites, as inclusions in diamond, in kimberlites and eclogite, as well as in rhyolite, and in alluvium.

MORDENITE

Zeolite Group

mm2 Orthorhombic

Polar

Nickel-Strunz: 9.GD.35 - SILICATES (Germanates) - Tectosilicates with zeolitic H₂O, zeolite family - Chains of six-membered rings, the tabular zeolites.**- Pyroelectric, Piezoelectric -**

Formed as a secondary mineral in various igneous rocks, including volcanic glasses, and as an authigenic mineral in sediments.

MORENOSITE

Epsomite Group

222 Orthorhombic

Chiral

Nickel-Strunz: 7.CB.40 - SULFATES (selenates, tellurates, chromates, molybdates and wolframates) - Sulfates (and selenates) without additional anions, with H₂O, with only medium-sized cations.**- Piezoelectric -**

A low-temperature hydrothermal mineral found in nickel-bearing deposits.

TABLE 4. Continued

MURMANITE

Murmanite Group

1 Triclinic

Centrosymmetric

Nickel-Strunz: 9.BE.27 - SILICATES (Germanates) - Sorosilicates - Si_2O_7 groups, with additional anions, with cations in octahedral [6] and greater coordination.

- **Pyroelectric, Piezoelectric** -

Found in alkalic pegmatites and associated igneous rocks.

MUTHMANNITE 2/m Monoclinic

Centrosymmetric

Nickel-Strunz: 2.CB.85 - SULFIDES and SULFOSALTS (sulfides, selenides, tellurides; arsenides, antimonides, bismuthides; sulfarsenites, sulfantimonites and sulfbismuthites) - Metal Sulfides, [Metal : Sulfur = 1 : 1] with Zn, Fe, Cu and Ag.

- **Pyroelectric, Piezoelectric** -

A low-temperature hydrothermal mineral found in association with other tellurides.

NACRITE

Serpentine Group

m Monoclinic

Polar

Nickel-Strunz: 9.ED.05 - SILICATES (Germanates) - Phyllosilicates with kaolinite layers composed of tetrahedral and octahedral nets.

- **Pyroelectric, Piezoelectric** -

Formed by hydrothermal processes.

NATROALUNITE

Alunite Supergroup: Alunite Subgroup

3m Trigonal

Polar

Nickel-Strunz: 7.BC.10 - SULFATES (selenates, tellurates, chromates, molybdates and wolframates) - Sulfates (and selenates) with additional anions, without H_2O , with medium-sized and large cations.

- **Pyroelectric, Piezoelectric** -

Formed by solfataric or hydrothermal sulfate-bearing solutions reacting with clays, rarely with sillimanite; or as an authigenic sedimentary mineral.

NATROJAROSITE

Alunite Supergroup: Jarosite Subgroup

3m Trigonal

Polar

Nickel-Strunz: 7.BC.10 - SULFATES (selenates, tellurates, chromates, molybdates and wolframates) - Sulfates (and selenates) with additional anions, without H_2O , with medium-sized and large cations.

- **Pyroelectric, Piezoelectric** -

Formed by the alteration of pyrite in the presence of sodium, and rarely as a volcanic sublimate.

TABLE 4. Continued

NATROLITE

Zeolite Group

mm2 Orthorhombic

Polar

Nickel-Strunz: 9.GA.05 - SILICATES (Germanates) - Tectosilicates with zeolitic H_2O , zeolite family - Zeolites with X_5O_{10} units, the fibrous zeolites.

- Pyroelectric, Piezoelectric -

Found in cavities in amygdaloidal basalts and related igneous rocks, one of the last minerals to form; fills seams in granite, gneiss, and syenite.

NEPHELINE **6** Hexagonal

Polar and Chiral

Nickel-Strunz: 9.FA.05 - SILICATES (Germanates) - Tectosilicates without zeolitic H_2O - Tectosilicates without additional non-tetrahedral anions.

- Pyroelectric, Piezoelectric -

Found in alkalic rocks, including syenites, gabbros, tuffs, lavas, pegmatites and gneisses; and, as a product of sodium-rich metasomatism.

NEPTUNITE **m** Monoclinic

Polar

Nickel-Strunz: 9.EH.05 - SILICATES (Germanates) - Phyllosilicates - Transitional structures between phyllosilicate and other silicate units.

- Pyroelectric, Piezoelectric -

Found in serpentinite in natrolite veins cutting glaucophane schist.

NICKELINE

Nickeline Group

6/mmm Hexagonal

Centrosymmetric

NICKELINE is Pauli paramagnetic, with the (weak) paramagnetism arising from the spins of the valence electrons.

Nickel-Strunz: 2.CC.05 - SULFIDES and SULFOSALTS (sulfides, selenides, tellurides; arsenides, antimonides, bismuthides; sulfarsenites, sulfantimonites and sulfbismuthites) - Metal Sulfides, [Metal : Sulfur = 1 : 1] with Ni, Fe, Co and platinum group elements.

- Pyroelectric, Piezoelectric -

Found as a minor component of Ni-Cu ores in high-temperature hydrothermal veins, and in disseminations in peridotite and norite.

TABLE 4. Continued

NISBITE

Löllingite Group

mmm Orthorhombic

Centrosymmetric

NISBITE is diamagnetic and is a metallic electrical conductor.

Nickel-Strunz: 2.EB.15a - SULFIDES and SULFOSALTS (sulfides, selenides, tellurides; arsenides, antimonides, bismuthides; sulfarsenites, sulfantimonites and sulfbismuthites) - Metal Sulfides, [Metal : Sulfur = 1 : 2], with Fe, Co, Ni and platinum group elements.

Found very rarely in altered mafic rock, and in Pb–Zn–Cu–Ag ore deposits remobilized by hydrothermal solutions from younger granite emplacement.

NITER

Melting Temperature: 606 K

3m Trigonal

Centrosymmetric

Transition Temperature: 398 K

3m Trigonal

Polar

Transition Temperature: 388 K

mmm Orthorhombic

Centrosymmetric

Above 398 K *NITER* is paraelectric.

Nickel-Strunz: 5.NA.10 - CARBONATES (NITRATES) - NITRATES - Without OH or H₂O.

- **Ferroelectric, Pyroelectric, Piezoelectric** -

Found in some caves, typically formed by bacterial action on animal matter, such as bat guano, or from vegetable matter, such as humus, exposed to seeping groundwater, and an efflorescence on soils or cliff faces in arid regions.

NITRATINE

Melting Temperature: 581 K

3m Trigonal

Centrosymmetric

Transition Temperature: 547.4 K

3m Trigonal

Centrosymmetric

The phase transition at 547.7 K in *NITRATINE* is from space group **R3c** to **R3m** as the temperature rises. A ferroelectric high pressure **3m** Trigonal (polar) phase of *NITRATINE* exists for $P > 4.3$ GPa at ambient temperatures.

Nickel-Strunz: 5.NA.05 - CARBONATES (NITRATES) - NITRATES - Without OH or H₂O.

- **Paraelectric, Pyroelectric, Piezoelectric** -

Principally found in bedded deposits formed in playas, and in caves, deposited from seeping groundwater leaching nitrates from overlying rocks, especially in very dry and cold climates.

NITROBARITE **m3** Cubic

Centrosymmetric

Nickel-Strunz: 5.NA.05 - CARBONATES (NITRATES) - NITRATES - Without OH or H₂O.

- **Piezoelectric** -

Found in nitrate deposits.

TABLE 4. Continued

NOLANITE

Nolanite Group

6mm Hexagonal

Polar

Nickel-Strunz: 4.CB.40 - OXIDES (Hydroxides, V[5,6] vanadates, arsenites, antimonites, bismuthites, sulfites, selenites, tellurites and iodates) - [Metal : Oxygen = 2 : 3 and 3 : 5] with medium-sized cations.

- Pyroelectric, Piezoelectric -

Found as a hydrothermal mineral in uranium deposits, and in gold deposits in greenstone belts.

OLENITE

Tourmaline Supergroup: Alkali Group

3m Trigonal

Polar

Nickel-Strunz: 9.CK.05 - SILICATES (Germanates) - Cyclosilicates - $[\text{Si}_6\text{O}_{18}]_{12}$ six-membered single rings, with insular complex anions.

- Pyroelectric, Piezoelectric -

Found in pegmatitic veins crosscutting metasediments.

OLSACHERITE

Baryte Group

222 Orthorhombic

Chiral

Nickel-Strunz: 7.AD.35 - SULFATES (selenates, tellurates, chromates, molybdates and wolframates) - Sulfates (and selenates) without additional anions, without H_2O , with only large cations.

- Piezoelectric -

A secondary mineral found in the oxidized zone of selenium-bearing hydrothermal mineral deposits.

XYCALCIOPYROCHLORE

Pyrochlore Supergroup: Pyrochlore Group

Melting Temperature: 1853 K

2 Monoclinic

Polar and Chiral

Nickel-Strunz: 4.DH.15 - OXIDES (Hydroxides, V[5,6] vanadates, arsenites, antimonites, bismuthites, sulfites, selenites, tellurites and iodates) - [Metal : Oxygen = 1 : 2] with large ($\pm$ medium-sized) cations, with sheets of edge-sharing octahedra.

- Ferroelectric, Pyroelectric, Piezoelectric -

Found in pegmatites in nepheline syenites, in granitic pegmatites and greisen, and in carbonatites.

OXYPLUMBOPYROCHLORE

Pyrochlore Supergroup: Pyrochlore Group

(Not Known)

(Not Known)

Nickel-Strunz: 4.DH.15 - OXIDES (Hydroxides, V[5,6] vanadates, arsenites, antimonites, bismuthites, sulfites, selenites, tellurites and iodates) - [Metal : Oxygen = 1 : 2] with large ($\pm$ medium-sized) cations, with sheets of edge-sharing octahedra.

- Ferroelectric, Pyroelectric, Piezoelectric -

Found in pegmatites in nepheline syenites, in granitic pegmatites and greisen, and in carbonatites.

TABLE 4. Continued

OXY-SCHORL

Tourmaline Supergroup: Alkali Group

3m Trigonal

Polar

Nickel-Strunz: 9.CK.05 - SILICATES (Germanates) - Cyclosilicates - $[\text{Si}_6\text{O}_{18}]_{12}$ six-membered single rings, with insular complex anions.

- Pyroelectric, Piezoelectric -

Found in granitic pegmatites.

PARATELLURITE

Rutile Group

422 Tetragonal

Chiral

Nickel-Strunz: 4.DE.25 - OXIDES (Hydroxides, V[5,6] vanadates, arsenites, antimonites, bismuthites, sulfites, selenites, tellurites and iodates) - [Metal : Oxygen = 1 : 2] with medium-sized cations, with various polyhedra.

- Piezoelectric -

As thin seams in tellurium from hydrothermal Au–Te deposits.

PARKERITE **2/m** Orthorhombic

Centrosymmetric

Nickel-Strunz: 2.BE.20 - SULFIDES and SULFOSALTS (sulfides, selenides, tellurides; arsenides, antimonides, bismuthides; sulfarsenites, sulfantimonites and sulfbismuthites) - Metal Sulfides, [Metal : Sulfur > 1 : 1, mainly 2 : 1] with Pb and Bi.

- Pyroelectric, Piezoelectric -

Found as grains in hydrothermal sulfide and arsenide minerals.

PENROSEITE

Pyrite Group

m3 Cubic

Centrosymmetric

PENROSEITE is weakly paramagnetic, and is a metallic electrical conductor.

Nickel-Strunz: 2.EB.05a - SULFIDES and SULFOSALTS (sulfides, selenides, tellurides; arsenides, antimonides, bismuthides; sulfarsenites, sulfantimonites and sulfbismuthites) - Metal Sulfides, [Metal : Sulfur = 1 : 2] with Fe, Co, Ni and platinum group elements.

Found in hydrothermal veins.

TABLE 4. Continued

<p>PEROVSKITE Perovskite Group</p> <hr/> <p>($m\bar{3}m$) Cubic Centrosymmetric</p> <hr/> <p>mmm Orthorhombic Centrosymmetric</p>	<p>CaTiO₃</p> <p>Melting Temperature: 2233 K</p> <p>Transition Temperature: 1533 K</p>
<p>Nickel-Strunz: 4.CC.30 - OXIDES (Hydroxides, V[5,6] vanadates, arsenites, antimonites, bismuthites, sulfites, selenites, tellurites and iodates) - [Metal : Oxygen = 2 : 3 and 3 : 5] with large and medium-sized cations.</p> <p>- Paraelectric, Pyroelectric, Piezoelectric -</p> <p>An accessory mineral found in alkaline mafic rocks, such as nepheline syenites, kimberlites, carbonatites, commonly deuteric; also found in calcareous skarns, and as a common accessory in Ca–Al-rich inclusions in some carbonaceous chondrites.</p>		
<p>PHARMACOLITE m Monoclinic Polar</p>	<p>Ca(HAsO₄) • 2H₂O</p>
<p>Nickel-Strunz: 8.CJ.50 - PHOSPHATES, ARSENATES, VANADATES - Phosphates without additional anions, with H₂O, with only large cations.</p> <p>- Pyroelectric, Piezoelectric -</p> <p>Found as a secondary mineral in oxidized arsenic-rich rock.</p>		
<p>PHARMACOSIDERITE Pharmacosiderite Supergroup: Pharmacosiderite Group</p> <p>$\bar{4}3m$ Cubic Non-centrosymmetric</p>	<p>KFe₄³⁺(AsO₄)₃(OH)₄ • 6–7H₂O</p>
<p>Nickel-Strunz: 8.DK.10 - PHOSPHATES, ARSENATES, VANADATES - Phosphates, with additional anions, with H₂O, with large and medium-sized cations, [OH : XO₄ > 1 : 1 and < 2 : 1].</p> <p>- Piezoelectric -</p> <p>An oxidation product of arsenic-bearing sulfides.</p>		
<p>PICKERINGITE Halotrichite Group 2 Monoclinic Polar and Chiral</p>	<p>MgAl₂(SO₄)₄ • 22H₂O</p>
<p>Nickel-Strunz: 7.CB.85 - SULFATES (selenates, tellurates, chromates, molybdates and wolframates) - Sulfates (and selenates) without additional anions, with H₂O, with only medium-sized cations.</p> <p>- Pyroelectric, Piezoelectric -</p> <p>Formed by the alteration of pyrite in aluminous rocks and coal seams, and in fumaroles.</p>		
<p>PINNOITE $4/m$ Tetragonal Centrosymmetric</p>	<p>Mg[B₂O(OH)₆]</p>
<p>Nickel-Strunz: 6.BB.05 - BORATES - Diborates - Neso-diborates with double tetrahedra B₂O(OH)₆.</p> <p>- Pyroelectric, Piezoelectric -</p> <p>Found in marine salt deposits and around salt springs and lakes.</p>		

TABLE 4. Continued

PIRSSONITE **mm2** Orthorhombic

Polar

Nickel-Strunz: 5.CB.30 - CARBONATES (NITRATES) - Carbonates without additional anions, with H_2O , with large cations (alkali and alkali-earth carbonates).

- Pyroelectric, Piezoelectric -

Found in saline lake-bed sediments and oil shales.

PLUMBOJAROSITE

Alunite Supergroup: Jarosite Subgroup

3m Trigonal

Centrosymmetric

Nickel-Strunz: 7.BC.10 - SULFATES (selenates, tellurates, chromates, molybdates and wolframates) - Sulfates (and selenates) with additional anions, without H_2O , with medium-sized and large cations.

- Pyroelectric, Piezoelectric -

Formed by a reaction between galena and lead, especially in arid regions.

POVONDRITE

Tourmaline Supergroup: Alkali Group

3m Trigonal

Polar

Nickel-Strunz: 9.CK.05 - SILICATES (Germanates) - Cyclosilicates - $[\text{Si}_6\text{O}_{18}]_{12}$ six-membered single rings, with insular complex anions.

- Pyroelectric, Piezoelectric -

Found in fractures and lining cavities in schist metamorphosed from sedimentary rocks.

PREHNITE **mm2** Orthorhombic

Polar

Nickel-Strunz: 9.DP.20 - SILICATES (Germanates) - Inosilicates - Transitional ino-phyllosilicate structures.

- Pyroelectric, Piezoelectric -

Formed from low-grade metamorphism, and as a secondary or hydrothermal mineral in mafic volcanic rocks, as well as in granitic gneiss and syenite.

TABLE 4. Continued

PROUSTITE

Proustite Group

3m Trigonal

Centrosymmetric

Transition Temperature: 210 K

3m Trigonal

Polar

Transition Temperature: ≈ 55 K***m*** Monoclinic

Polar

Transition Temperature: 28.7 K

1 Triclinic

Polar and Chiral

Below approximately 55 K *PROUSTITE* undergoes a phase transition to a ferroelectric form.

Nickel-Strunz: 2.GA.05 - SULFIDES and SULFOSALTS (sulfides, selenides, tellurides; arsenides, antimonides, bismuthides; sulfarsenites, sulfantimonites and sulfbismuthites) - Sulfarsenites, sulfantimonites, sulfbismuthites - Neso-sulfarsenites, without additional sulfur.

- Paraelectric, Pyroelectric, Piezoelectric -

Associated with other silver minerals and sulfides in hydrothermal deposits, in the oxidized and enriched zone.

PYRARGYRITE

Proustite Group

3m Trigonal

Polar

Paraelectric

Transition Temperature: 75 K

(*m*) Monoclinic

Polar

Transition Temperature: 4.8 K

1 Triclinic

Polar and Chiral

Symmetry group ***m*** is an estimate.

Nickel-Strunz: 2.GA.05 - SULFIDES and SULFOSALTS (sulfides, selenides, tellurides; arsenides, antimonides, bismuthides; sulfarsenites, sulfantimonites and sulfbismuthites) - Sulfarsenites, sulfantimonites, sulfbismuthites - Neso-sulfarsenites, without additional sulfur.

- Paraelectric, Pyroelectric, Piezoelectric -

Formed in hydrothermal veins as a primary late-stage, low-temperature mineral; also formed by secondary processes.

TABLE 4. Continued

PYRITE

Pyrite Group

Cattierite – Pyrite Series

Pyrite – Vaesite Series

 $m\bar{3}$ Cubic

Centrosymmetric

PYRITE is paramagnetic and is an electrical semiconductor.

Nickel-Strunz: 2.EB.05a - SULFIDES and SULFOSALTS (sulfides, selenides, tellurides; arsenides, antimonides, bismuthides; sulfarsenites, sulfantimonites and sulfbismuthites) - Metal Sulfides, [Metal : Sulfur = 1 : 2] with Fe, Co, Ni and platinum group elements.

Formed under a wide variety of conditions, including in hydrothermal veins as very large bodies, as magmatic segregations, as an accessory mineral in igneous rocks, in pegmatites, in contact metamorphic deposits, also in metamorphic rocks, and as a diagenetic replacement in sedimentary rocks.

PYRITE VARIETY: BRAVOITE

Pyrite Group

Pyrite – Vaesite Series

 $m\bar{3}$ Cubic

Centrosymmetric

BRAVOITE is paramagnetic to antiferromagnetic, depending on composition. It is an electrical semiconductor.

Nickel-Strunz: 2.EB.05a - SULFIDES and SULFOSALTS (sulfides, selenides, tellurides; arsenides, antimonides, bismuthides; sulfarsenites, sulfantimonites and sulfbismuthites) - Metal Sulfides, [Metal : Sulfur = 1 : 2] with Fe, Co, Ni and platinum group elements.

Found in some sulfide ore localities.

PYROCHROITE

Brucite Group

 $\bar{3}m$ Trigonal

Centrosymmetric

Nickel-Strunz: 4.FE.05 - OXIDES (Hydroxides, V[5,6] vanadates, arsenites, antimonites, bismuthites, sulfites, selenites, tellurites and iodates) - Hydroxides (without vanadium or uranium) - Hydroxides with OH, without H₂O, with sheets of edge-sharing octahedra.**- Pyroelectric, Piezoelectric -**

Formed as a primary mineral in sulfide deposits and as a hydration mineral in manganese-rich metamorphic rock.

PYROLUSITE

Rutile Group

 $4/mmm$ Tetragonal

Centrosymmetric

Nickel-Strunz: 4.DB.05 - OXIDES (Hydroxides, V[5,6] vanadates, arsenites, antimonites, bismuthites, sulfites, selenites, tellurites and iodates) - [Metal : Oxygen = 1 : 2] with medium-sized cations, with chains of edge-sharing octahedra.

- Ferroelectric, Pyroelectric, Piezoelectric -

Commonly an alteration product of manganite, or formed under highly oxidizing conditions in manganese-bearing hydrothermal deposits and rocks, or in bogs, lakes, or shallow marine conditions.

TABLE 4. Continued

PYROMORPHITE

Apatite Supergroup: Pyromorphite Subgroup

6/m Hexagonal

Centrosymmetric

Nickel-Strunz: 8.BN.05 - PHOSPHATES, ARSENATES, VANADATES - Phosphates, with additional anions, without H_2O , with only large cations, $[\text{OH} : \text{XO}_4 = 0.33 : 1]$.

- Pyroelectric, Piezoelectric -

A secondary mineral found in the oxidized zone of lead deposits; rarely a volcanic sublimate.

PYROPHANITE

Ilmenite Group

3 Trigonal

Centrosymmetric

PYROPHANITE is paramagnetic.

Nickel-Strunz: 4.CB.05 - OXIDES (Hydroxides, V[5,6] vanadates, arsenites, antimonites, bismuthites, sulfites, selenites, tellurites and iodates) - $[\text{Metal} : \text{Oxygen} = 2 : 3 \text{ and } 3 : 5]$ with medium-sized cations.

Found principally in metamorphosed manganese deposits, and less commonly as an accessory mineral in granite, amphibolite, serpentinite, and also as a very rare component in chondritic meteorites.

PYRRHOTITE

Pyrrhotite Group

Transition Temperature: 578 K

m Monoclinic

Polar

There are monoclinic and hexagonal pyrrhotite polytypes reported:

PYRRHOTITE-4M Fe_7S_8 Monoclinic

PYRRHOTITE-5H Fe_9S_{10} Hexagonal

PYRRHOTITE-6M $\text{Fe}_{11}\text{S}_{12}$ Monoclinic

PYRRHOTITE-7H Fe_9S_{10} Monoclinic

PYRRHOTITE-11H $\text{Fe}_{10}\text{S}_{11}$ Hexagonal.

PYRRHOTITE is ferrimagnetic with varying magnetic powers, depending on the number of Fe vacancies in the crystal structure. A related species with no vacancies (and therefore non-magnetic), is called *TROILITE*. The temperature dependent magnetic spin direction is as follows: the angle with respect to the **c** axis = 73° at 0 K and 180° at 300 K. *PYRRHOTITE* is a metallic electrical conductor.

Nickel-Strunz: 2.CC.10 - SULFIDES and SULFOSALTS (sulfides, selenides, tellurides; arsenides, antimonides, bismuthides; sulfarsenites, sulfantimonites and sulfbismuthites) - Metal Sulfides, $[\text{Metal} : \text{Sulfur} = 1 : 1]$ with Ni, Fe, Co and platinum group elements.

- Pyroelectric (Hexagonal), Piezoelectric (Hexagonal) -

Found mainly in mafic igneous rocks, typically as magmatic segregations, also in pegmatites, and in high-temperature hydrothermal and replacement veins, and in sedimentary and metamorphic rocks, as well as in iron meteorites.

TABLE 4. Continued

QUARTZ

622 Hexagonal
Chiral

Transition Temperature: 846 K

32 Trigonal
Chiral

The low temperature phase is α -QUARTZ. The high temperature phase is β -QUARTZ.

Nickel-Strunz: 4.DA.05 - OXIDES (Hydroxides, V[5,6] vanadates, arsenites, antimonites, bismuthites, sulfites, selenites, tellurites and iodates) - [Metal : Oxygen = 1 : 2] with small cations - Silica family.

- Piezoelectric -

Found in hydrothermal veins, epithermal to alpine; characteristic of granites and granite pegmatites; in sandstones and quartzites, less abundant in other rock types; in hydrothermal metal deposits; common in carbonate rocks; a residual mineral in soils and sediments.

QUENSELITE

2/m Monoclinic
Centrosymmetric

Nickel-Strunz: 4.FE.30 - OXIDES (Hydroxides, V[5,6] vanadates, arsenites, antimonites, bismuthites, sulfites, selenites, tellurites and iodates) - Hydroxides (without vanadium or uranium) - Hydroxides with OH, without H₂O, with sheets of edge-sharing octahedra.

- Pyroelectric, Piezoelectric -

Found in metamorphosed iron-manganese ore bodies.

RETGERSITE

422 Tetragonal
Chiral

Nickel-Strunz: 7.CB.30 - SULFATES (selenates, tellurates, chromates, molybdates and wolframates) - Sulfates (and selenates) without additional anions, with H₂O, with only medium-sized cations.

- Piezoelectric -

A low-temperature secondary hydrothermal mineral found in nickel-rich deposits.

RHODIZITE

Rhodizite Group
Londonite – Rhodizite Series

43m Cubic
Non-centrosymmetric

Nickel-Strunz: 6.GC.05 - BORATES - Heptaborates and other megaborates - Tecto-dodecaborates.

- Piezoelectric -

A late-stage accessory mineral found in alkali-rich granite pegmatites.

RÖNTGENITE-Ce

3 Trigonal
Polar and Chiral

Along with *BASTNÄSITE-Ce*, synchesite-Ce and parisite-Ce, this mineral is composed of CeF layers that alternate with carbonate layers. Their geometries are still undetermined for all but *BASTNÄSITE-Ce*.

Nickel-Strunz: 5.BD.20d - CARBONATES (NITRATES) - Carbonates with additional anions, without H₂O, with rare earth elements.

- Pyroelectric, Piezoelectric -

Found in granite and alkalic pegmatites, as a late-stage hydrothermal mineral.

TABLE 4. Continued

ROQUESITE Chalcopyrite Group 42m Tetragonal Non-centrosymmetric	CuInS ₂
Nickel-Strunz: 2.CB.10a - SULFIDES and SULFOSALTS (sulfides, selenides, tellurides; arsenides, antimonides, bismuthides; sulfarsenites, sulfantimonites and sulfbismuthites) - Metal Sulfides, [Metal : Sulfur = 1 : 1] with Zn, Fe, Cu and Ag. - Piezoelectric - Found in association with copper sulfides in high-temperature Sn–W–Bi–Mo hydrothermal veins in highly metamorphosed rocks; a late-stage mineral in a skarn Fe–W ore pipe; in magnetite-bearing massive chalcopyrite ore.		
RUSSELLITE Koechlinite Group	Bi ₂ WO ₆
	Melting Temperature: 1313 K	(Not Known)
m Monoclinic Polar	Transition Temperature: 1023 K	
Orthorhombic	Transition Temperature: 973 K	
mm2 Orthorhombic Polar
The high-temperature phase of <i>RUSSELLITE</i> is paraelectric. Nickel-Strunz: 4.DE.15 - OXIDES (Hydroxides, V[5,6] vanadates, arsenites, antimonites, bismuthites, sulfites, selenites, tellurites and iodates) - [Metal : Oxygen = 1 : 2] with medium-sized cations, with various polyhedra. - Ferroelectric, Pyroelectric, Piezoelectric - An alteration product of earlier bismuth minerals in Sn–W-bearing high-temperature hydrothermal mineral deposits, greisen, or granite pegmatites.		
RUTILE Rutile Group 4/mmm Tetragonal Centrosymmetric	TiO ₂
<i>RUTILE</i> is one of five polymorphs of TiO ₂ found in nature, the others being brookite, anatase, akaogiite, and an α -PbO ₂ type high-pressure form (TiO ₂ II), not yet approved by the IMA. Nickel-Strunz: 4.DB.05 - OXIDES (Hydroxides, V[5,6] vanadates, arsenites, antimonites, bismuthites, sulfites, selenites, tellurites and iodates) - [Metal : Oxygen = 1 : 2] with medium-sized cations, with chains of edge-sharing octahedra. A common high-temperature, high-pressure accessory mineral in igneous rocks, anorthosite, and granite pegmatite, also found in hydrothermally-altered rocks, in gneiss, schist, contact metamorphosed limestone, and in clays and shales.		

TABLE 4. Continued

SAL AMMONIAC

Sal Ammoniac Group

m*3*m Cubic

Centrosymmetric

Nickel-Strunz: 3.AA.25 - HALIDES - Simple halides, without H_2O - [Metal : Halide = 1 : 1, 2 : 3 and 3 : 5].

- Piezoelectric -

Found in fumarolic deposits (from sublimation), as a combustion product in coal seams and waste piles, and in guano deposits.

SARCOLITE ***4/m*** Tetragonal

Centrosymmetric

Nickel-Strunz: 9.EH.15 - SILICATES (Germanates) - Phyllosilicates - Transitional structures between phyllosilicate and other silicate units.

- Pyroelectric, Piezoelectric -

Found in limestone-bearing volcanic ejecta subjected to contact metamorphism.

SCHORL

Tourmaline Supergroup: Alkali Group

3m Trigonal

Polar

Nickel-Strunz: 9.CK.05 - SILICATES (Germanates) - Cyclosilicates - $[\text{Si}_6\text{O}_{18}]_{12}$ six-membered single rings, with insular complex anions.

- Pyroelectric, Piezoelectric -

Found in granites and granite pegmatites, high-temperature hydrothermal veins, and some metamorphic rocks; also detrital.

SCOLECITE

Zeolite Group

m Monoclinic

Polar

Nickel-Strunz: 9.GA.05 - SILICATES (Germanates) - Tectosilicates with zeolitic H_2O , zeolite family - Zeolites with X_5O_{10} units, the fibrous zeolites.

- Pyroelectric, Piezoelectric -

Found primarily in cavities in basalts; in gneisses and amphibolites, and in laccoliths and dikes derived from syenitic and gabbroic magmas.

SCHULTENITE

Monoclinic

(Not Known)

Transition Temperature: 313.7 K

m Monoclinic

Polar

Above 313.7 K *SCHULTENITE* undergoes a phase transition to a paraelectric form.

Nickel-Strunz: 8.AD.30 - PHOSPHATES, ARSENATES, VANADATES - Phosphates, without additional anions, without H_2O , with only large cations.

- Ferroelectric, Pyroelectric, Piezoelectric -

A rare secondary mineral in the oxidized zone of some Pb–As-rich hydrothermal deposits.

TABLE 4. Continued

SEARLESITE

2 Monoclinic

Polar and Chiral

Nickel-Strunz: 9.EF.15 - SILICATES (Germanates) - Phyllosilicates - Single nets with six-membered rings, connected by metal [4] coordination, and metal [8] coordination.

- **Pyroelectric, Piezoelectric** -

Commonly interbedded with oil shales or marls; in boron-bearing evaporite deposits; rarely in vugs in phonolite.

SELENIUM

Selenium Group

32 Trigonal

Chiral

Nickel-Strunz: 1.CC.10 - ELEMENTS (Metals and intermetallic alloys; metalloids and nonmetals; carbides, silicides, nitrides and phosphides) - Metalloids and Nonmetals - Sulfur-selenium-iodine.

- **Piezoelectric** -

From the sublimation of fumarolic vapors, as well as from the oxidation of selenium-rich organic compounds in sandstone deposits with uranium and vanadium, and from the combustion of coal or pyrite ores.

SELIGMANNITE

Bournonite Group

mmm Orthorhombic

Centrosymmetric

Nickel-Strunz: 2.GA.50 - SULFIDES and SULFOSALTS (sulfides, selenides, tellurides; arsenides, antimonides, bismuthides; sulfarsenites, sulfantimonites and sulfbismuthites) - Sulfarsenites, sulfantimonites and sulfbismuthites - Neso-sulfarsenites, without additional sulfur.

- **Pyroelectric, Piezoelectric** -

Found in cavities in dolostone.

SHORTITE *mm2* Orthorhombic

Polar

Nickel-Strunz: 5.AC.25 - CARBONATES (NITRATES) - Carbonates without additional anions, without H_2O - Alkali and alkali-earth carbonates.

- **Pyroelectric, Piezoelectric** -

Found in saline dolomitic marl; in kimberlite dikes; in carbonatite; in differentiated alkalic massifs; and associated with intrusive alkalic gabbro-syenite complexes.

TABLE 4. Continued

SIDERITE Calcite Group $\bar{3}m$ Trigonal Centrosymmetric	FeCO_3 Transition Temperature: 20 to 60 K
(Not Known)		(Not Known)
<p><i>SIDERITE</i> is paramagnetic.</p> <p>Nickel-Strunz: 5.AB.05 - CARBONATES (NITRATES) - Carbonates without additional anions, without H_2O - Alkali-earth (and other metal²⁺) carbonates.</p> <p>Found as a common component of bedded sedimentary iron ores and metamorphic iron formations, as well as in hydrothermal metallic veins, and rarely in granite and nepheline syenite pegmatites, in carbonatites, and also as an authigenic mineral and in concretions.</p>		
SIEGENITE Linnaeite Group: Thiospinel Group $m\bar{3}m$ Cubic Centrosymmetric	$\text{CoNi}_2\text{S}_4 - \text{NiCo}_2\text{S}_4$
<p><i>SIEGENITE</i> is paramagnetic and is a metallic electrical conductor.</p> <p>Nickel-Strunz: 2.DA.05 - SULFIDES and SULFOSALTS (sulfides, selenides, tellurides; arsenides, antimonides, bismuthides; sulfarsenites, sulfantimonites and sulfbismuthites) - Metal Sulfides, [Metal : Sulfur = 3 : 4].</p> <p>- Thermoelectric -</p> <p>Found in hydrothermal veins with other Cu–Ni–Fe sulfides.</p>		
SILLÉNITE 23 Cubic Chiral	$\text{Bi}_{12}\text{SiO}_{20}$
(Not Known)	Transition Temperature: 92 K	(Not Known)
<p>Nickel-Strunz: 4.CB.70 - OXIDES (Hydroxides, V[5,6] vanadates, arsenites, antimonites, bismuthites, sulfites, selenites, tellurites and iodates) - [Metal : Oxygen = 2 : 3 and 3 : 5] with medium-sized cations.</p> <p>- Ferroelectric, Pyroelectric, Piezoelectric -</p> <p>A secondary mineral formed by the oxidation of bismuth-bearing minerals; also found in hydrothermal veins in skarns.</p>		
SINOITE $mm2$ Orthorhombic Polar	$\text{Si}_2\text{N}_2\text{O}$
<p>Nickel-Strunz: 1.DB.10 - ELEMENTS (Metals and intermetallic alloys; metalloids and nonmetals; carbides, silicides, nitrides and phosphides) - Nonmetallic Carbides and Nitrides - Nonmetallic nitrides.</p> <p>- Pyroelectric, Piezoelectric -</p> <p>Found embedded in enstatite in chondritic meteorites.</p>		

TABLE 4. Continued

SODALITE

Sodalite Group

 $\bar{4}3m$ Cubic

Non-centrosymmetric

Nickel-Strunz: 9.FB.10 - SILICATES (Germanates) - Tectosilicates without zeolitic H_2O - Tectosilicates with additional anions.

- Piezoelectric -

Found in nepheline syenites, phonolites and related rocks, in cavities in volcanic ejecta, and in metasomatized calcareous rocks.

SPANGOLITE **$3m$** Trigonal

Polar

Nickel-Strunz: 7.DD.15 - SULFATES (selenates, tellurates, chromates, molybdates and wolframates) - Sulfates (and selenates) with additional anions, with H_2O , with only medium-sized cations, with sheets of edge-sharing octahedra.

- Pyroelectric, Piezoelectric -

A secondary mineral found in the oxidization zone of hydrothermal copper deposits.

SPHALERITE

Sphalerite Group

 $\bar{4}3m$ Cubic

Non-centrosymmetric

Nickel-Strunz: 2.CB.05a - SULFIDES and SULFOSALTS (sulfides, selenides, tellurides; arsenides, antimonides, bismuthides; sulfarsenites, sulfantimonites and sulfbismuthites) - Metal Sulfides, [Metal : Sulfur = 1 : 1] with Zn, Fe, Cu and Ag.

- Piezoelectric -

Formed under a wide range of low- to high-temperature hydrothermal conditions; in coal, limestone, and other sedimentary deposits.

SPINEL

Spinel Group

 $m\bar{3}m$ Cubic

Centrosymmetric

Nickel-Strunz: 4.BB.05 - OXIDES (Hydroxides, V[5,6] vanadates, arsenites, antimonites, bismuthites, sulfites, selenites, tellurites and iodates) - [Metal : Oxygen = 3 : 4] with only medium-sized cations.

A common mineral, formed at high-temperatures as an accessory in igneous rocks, principally basalts, kimberlites, peridotites, and in xenoliths, also, in regionally metamorphosed aluminum-rich schists, and in regionally and contact metamorphosed limestones.

TABLE 4. Continued

SREBRODOLSKITE

Brownmillerite Group

Brownmillerite-Srebrodolskite Series

(Not Known)

Transition Temperature: 725 K

(Not Known)

mmm Orthorhombic

Centrosymmetric

SREBRODOLSKITE is (incompletely) antiferromagnetic.

Nickel-Strunz: 4.AC.10 - OXIDES (Hydroxides, V[5,6] vanadates, arsenites, antimonites, bismuthites, sulfites, selenites, tellurites and iodates) - [Metal : Oxygen = 1 : 1 and up to 1 : 1.25] with large cations ($\pm$ smaller ones).

Found in some skarns, as well as in some coal deposits as a combustion product, and as a hardpan formation component from mining waste.

STEPHANITE

Stephanite Group

mm2 Orthorhombic

Polar

Nickel-Strunz: 2.GB.10 - SULFIDES and SULFOSALTS (sulfides, selenides, tellurides; arsenides, antimonides, bismuthides; sulfarsenites, sulfantimonites and sulfbismuthites) - Sulfarsenites, sulfantimonites and sulfbismuthites - Neso-sulfarsenites, with additional sulfur.

- Pyroelectric, Piezoelectric -

A late-stage mineral in hydrothermal silver deposits.

STIBIOCOLUMBITE

Cervantite Group

Stibiocolumbite – Stibiotantalite Series

mm2 Orthorhombic

Polar

Nickel-Strunz: 4.DE.30 - OXIDES (Hydroxides, V[5,6] vanadates, arsenites, antimonites, bismuthites, sulfites, selenites, tellurites and iodates) - [Metal : Oxygen = 1 : 2] with medium-sized cations, with various polyhedra.

- Pyroelectric, Piezoelectric -

A rare accessory mineral in complex granite pegmatites.

STIBIOTANTALITE

Cervantite Group

Stibiocolumbite – Stibiotantalite Series

(Not Known)

Transition Temperature: 695 K

(Not Known)

mm2 Orthorhombic

Polar

Ferroelectric

Above 695 K *STIBIOTANTALITE* undergoes a phase transition to a paraelectric form.

Nickel-Strunz: 4.DE.30 - OXIDES (Hydroxides, V[5,6] vanadates, arsenites, antimonites, bismuthites, sulfites, selenites, tellurites and iodates) - [Metal : Oxygen = 1 : 2] with medium-sized cations, with various polyhedra.

- Ferroelectric, Pyroelectric, Piezoelectric -

An uncommon accessory mineral in complex granite pegmatites.

TABLE 4. Continued

STIBNITE Stibnite Group <i>mmm</i> Orthorhombic Centrosymmetric	Sb_2S_3
<hr/> <i>mm2</i> Orthorhombic Polar	Transition Temperature: 420 K	
<hr/> (Not Known)	Transition Temperature: 292 K	(Not Known)
Nickel-Strunz: 2.DB.05 - SULFIDES and SULFOSALTS (sulfides, selenides, tellurides; arsenides, antimonides, bismuthides; sulfarsenites, sulfantimonites and sulfbismuthites) - Metal Sulfides, [Metal : Sulfur = 2 : 3]. - Ferroelectric, Pyroelectric, Piezoelectric - Of hydrothermal origin, formed in veins through a wide range of temperatures.		
STILLEITE Sphalerite Group <i>43m</i> Cubic Non-centrosymmetric	ZnSe
Nickel-Strunz: 2.CB.05a - SULFIDES and SULFOSALTS (sulfides, selenides, tellurides; arsenides, antimonides, bismuthides; sulfarsenites, sulfantimonites and sulfbismuthites) - Metal Sulfides, [Metal : Sulfur = 1 : 1] with Zn, Fe, Cu and Ag. - Piezoelectric - Found with other selenides, or as an inclusion in linnaeite.		
STRUVITE Struvite Group <i>mm2</i> Orthorhombic Polar	$(\text{NH}_4)\text{Mg}(\text{PO}_4) \cdot 6\text{H}_2\text{O}$
Nickel-Strunz: 8.CH.40 - PHOSPHATES, ARSENATES, VANADATES - Phosphates without additional anions, with H_2O , with large and medium-sized cations, $[\text{XO}_4 : \text{H}_2\text{O} < 1 : 1]$. - Pyroelectric, Piezoelectric - Found in peaty earth intermixed with cattle dung; also formed in bird or bat guano in caves and surface deposits.		
SUOLUNITE <i>mm2</i> Orthorhombic Polar	$\text{Ca}_2(\text{H}_2\text{Si}_2\text{O}_7) \cdot \text{H}_2\text{O}$
Nickel-Strunz: 9.BE.10 - SILICATES (Germanates) - Sorosilicates - Si_2O_7 groups, with additional anions, with cations in octahedral [6] and greater coordination. - Pyroelectric, Piezoelectric - Found in veins cutting harzburgites in ultramafic intrusives; as a precipitate from alkaline springs in fault zones in basalts overlying ultramafic intrusives.		

TABLE 4. Continued

SWEDENBORGITE **6mm** Hexagonal

Polar

Nickel-Strunz: 4.AC.05 - OXIDES (Hydroxides, V[5,6] vanadates, arsenites, antimonites, bismuthites, sulfites, selenites, tellurites, iodates) - [Metal : Oxygen = 1 : 1 and up to 1 : 1.25] with large cations ($\pm$ smaller ones).

- Pyroelectric, Piezoelectric -

Found in skarn deposits with iron-manganese ores.

SYNGENITE

Syngenite Group

2/m Monoclinic

Centrosymmetric

Nickel-Strunz: 7.CD.35 - SULFATES (selenates, tellurates, chromates, molybdates and wolframates) - Sulfates (and selenates) without additional anions, with H_2O , with only large cations.

- Pyroelectric, Piezoelectric -

Formed from diagenesis in marine salt deposits, and from volcanic vent processes, as well as from bat guano.

TAUSONITE

Perovskite Group

m3m Cubic

Centrosymmetric

Paraelectric

Melting Temperature: 2353 K

Transition Temperature: 105 K

4/mmm Tetragonal

Centrosymmetric

Transition Temperature: 40 K

(Not Known)

Transition Temperature: 0.1 to 0.6 K

(Not Known)

(Not Known)

(Not Known)

Below 40 K *TAUSONITE* undergoes a phase transition to a ferroelectric form. *TAUSONITE* can exhibit a ferroelectric phase at low temperatures with stress along [100] and [110]. Variation in the lowest transition temperature is due to charge-carrier concentration differences. *TAUSONITE* is an electrical semiconductor. Below 0.1 to 0.6 K, *TAUSONITE* is an electrical superconductor.

Nickel-Strunz: 4.CC.35 - OXIDES (Hydroxides, V[5,6] vanadates, arsenites, antimonites, bismuthites, sulfites, selenites, tellurites and iodates) - [Metal : Oxygen = 2 : 3 and 3 : 5] with large and medium-sized cations.

- Paraelectric, Pyroelectric, Piezoelectric -

Found in some alkalic massifs and in some carbonatite complexes within fenite dikes.

TABLE 4. Continued

TELLURIUM

Te

Selenium Group

32 Trigonal

Chiral

Nickel-Strunz: 1.CC.10 - ELEMENTS (Metals and intermetallic alloys; metalloids and nonmetals; carbides, silicides, nitrides and phosphides) - Metalloids and Nonmetals - Sulfur-selenium-iodine.

- Piezoelectric -

Found in hydrothermal veins, as a primary or secondary mineral, and from sublimation of vapor in fumaroles.

THAUMASITE $\text{Ca}_3(\text{SO}_4)[\text{Si}(\text{OH})_6](\text{CO}_3) \cdot 12\text{H}_2\text{O}$

Ettringite Group

6/m Hexagonal

Centrosymmetric

Nickel-Strunz: 7.DG.15 - SULFATES (selenates, tellurates, chromates, molybdates and wolframates) -

Sulfates (and selenates) with additional anions, with H_2O : With large and medium-sized cations, with NO_3 , CO_3 , $\text{B}(\text{OH})_4$, SiO_4 and IO_3 .

- Pyroelectric, Piezoelectric -

Found in sulfide ore deposits as a late-stage mineral, and in contact metamorphic zones where basalt or tuff have reacted with seawater or geothermal waters.

THOMSONITE-CA $\text{NaCa}_2\text{Al}_5\text{Si}_5\text{O}_{20} \cdot 7\text{H}_2\text{O}$

Zeolite Group

mmm Orthorhombic

Centrosymmetric

Nickel-Strunz: 9.GA.10 - SILICATES (Germanates) - Tectosilicates with zeolitic H_2O , zeolite family - Zeolites with X_5O_{10} units, the fibrous zeolites.

- Pyroelectric, Piezoelectric -

Found in amygdules and fractures in mafic igneous rocks, typically basalts; in some alkalic igneous rocks, contact metamorphic zones, and hypabyssal rocks; and as an authigenic cement in some sandstones.

THORNASITE $(\text{Na},\text{K})_{12}\text{Th}_3(\text{Si}_8\text{O}_{19})_4 \cdot 18\text{H}_2\text{O}$

Zeolite Group

3m Trigonal

Centrosymmetric

Nickel-Strunz (10th edition): 9.GF.50 - SILICATES (Germanates) - Tectosilicates with zeolitic H_2O , zeolite family - Other rare zeolites.

- Piezoelectric -

Found in intrusive alkalic gabbro-syenite complexes, and in cavities in nepheline syenite sills.

TABLE 4. Continued

TIEMANNITE

Sphalerite Group

43m Cubic

Non-centrosymmetric

Nickel-Strunz: 2.CB.05a - SULFIDES and SULFOSALTS (sulfides, selenides, tellurides; arsenides, antimonides, bismuthides; sulfarsenites, sulfantimonites and sulfbismuthites) - Metal Sulfides, [Metal : Sulfur = 1 : 1] with Zn, Fe, Cu and Ag.

- Piezoelectric -

Found in hydrothermal veins with other selenides and calcite.

TILASITE

Tilasite Group

m Monoclinic

Polar

Nickel-Strunz: 8.BH.10 - PHOSPHATES, ARSENATES, VANADATES - Phosphates, with additional anions, without H_2O , with medium-sized and large cations, $[\text{OH} : \text{XO}_4 = 1 : 1]$.

- Pyroelectric, Piezoelectric -

Found in metamorphosed manganese or zinc deposits containing arsenic.

TISTARITE

Hematite Group

3m Trigonal

Centrosymmetric

TISTARITE is paramagnetic.

Nickel-Strunz: 4.CB.05 - OXIDES (Hydroxides, V[5,6] vanadates, arsenites, antimonites, bismuthites, sulfites, selenites, tellurites and iodates) - [Metal : Oxygen = 2 : 3 and 3 : 5] with medium-sized cations.

Found in the Pueblito de Allende meteorite.

TOPAZ **mmm** Orthorhombic

Centrosymmetric

Nickel-Strunz: 9.AF.35 - SILICATES (Germanates) - Nesosilicates with additional anions, with cations in [4], [5] and/or only [6] coordination.

- Piezoelectric -

Found in veins and cavities in granite, granite pegmatite, rhyolite, and in greisen, formed from high-temperature, volatile-rich pneumatolytic hydrothermal fluids; from high-grade metamorphism of aluminous, quartz-rich, and fluorine-bearing sediments; as a heavy detrital mineral.

TOURMALINE SUPERGROUP **3m** Trigonal

Polar

Nickel-Strunz: 9.CK.05 - SILICATES (Germanates) - Cyclosilicates - $[\text{Si}_6\text{O}_{18}]_{12}$ six-membered single rings, with insular complex anions.

- Pyroelectric, Piezoelectric -

Tourmaline is a supergroup of minerals in solid solution, found in a variety of igneous and metamorphic settings.

TABLE 4. Continued

TREVORITE Spinel Group (Not Known)	NiFe_2O_4 Transition Temperature: 860 K	(Not Known)
<hr/> $m\bar{3}m$ Cubic Centrosymmetric Nickel-Strunz: 4.BB.05 - OXIDES (Hydroxides, V[5,6] vanadates, arsenites, antimonites, bismuthites, sulfites, selenites, tellurites and iodates) - [Metal : Oxygen = 3 : 4] with only medium-sized cations. - Thermoelectric - Found in nickeliferous serpentinite, from contact metamorphism between quartzite and an ultramafic intrusion, as well in gabbro intruding peridotites.		
TUGTUPITE Sodalite Group 4 Tetragonal Non-centrosymmetric Nickel-Strunz: 9.FB.10 - SILICATES (Germanates) - Tectosilicates without zeolitic H_2O - Tectosilicates with additional anions. - Piezoelectric - Replaces chkalovite in hydrothermal veins cutting sodalite syenite and syenite; an alteration product in pegmatites in differentiated alkalic massifs.	$\text{Na}_4\text{AlBeSi}_4\text{O}_{12}\text{Cl}$
TYROLITE mmm Orthorhombic Centrosymmetric Nickel-Strunz: 8.DM.10 - PHOSPHATES, ARSENATES, VANADATES - Phosphates, with additional anions, with H_2O , with large and medium-sized cations, [$\text{OH} : \text{XO}_4 > 2 : 1$]. - Pyroelectric, Piezoelectric - Found as a secondary mineral in oxidized hydrothermal copper deposits.	$\text{Ca}_2\text{Cu}_9(\text{AsO}_4)_4(\text{CO}_3)(\text{OH})_8 \cdot 11\text{H}_2\text{O}$
URANINITE Uraninite Group Thorianite-Uraninite Series $m\bar{3}m$ Cubic Centrosymmetric (Not Known)	UO_2 Transition Temperature: 30 K	(Not Known)
<hr/> URANINITE is paramagnetic. Nickel-Strunz: 4.DL.05 - OXIDES (Hydroxides, V[5,6] vanadates, arsenites, antimonites, bismuthites, sulfites, selenites, tellurites and iodates) - [Metal : Oxygen = 1 : 2] with large ($\pm$ medium-sized) cations; fluorite-type structures. Found in granite and syenite pegmatites, in hydrothermal high-temperature tin and moderate-temperature Co–Ni–Bi–Ag–As and other sulfide veins, in Colorado Plateau-type sandstone-hosted U–V deposits, and in uraniferous conglomerates.		

TABLE 4. Continued

URANOPHANE

Uranophane Group

2 Monoclinic

Polar and Chiral

Nickel-Strunz: 9.AK.15 - SILICATES (Germanates) - Nesosilicates - Uranyl neso- and polysilicates.

- Pyroelectric, Piezoelectric -

Found in uranium deposits as an alteration product of uraninite.

USSINGITE

1 Triclinic

Centrosymmetric

Nickel-Strunz: 9.EH.20 - SILICATES (Germanates) - Phyllosilicates - Transitional structures between phyllosilicate and other silicate units.

- Pyroelectric, Piezoelectric -

Found in alkalic pegmatites and in sodalite xenoliths.

UVITE

Tourmaline Supergroup: Calcic Group

3m Trigonal

Polar

Nickel-Strunz: 9.CK.05 - SILICATES (Germanates) - Cyclosilicates - $[\text{Si}_6\text{O}_{18}]_{12}$ six-membered single rings, with insular complex anions.**- Pyroelectric, Piezoelectric -**

Typically found in calcium-rich rocks subjected to contact metamorphism and metasomatic processes that have added boron.

VAESITE

Pyrite Group

Cattierite – Vaesite Series

Pyrite – Vaesite Series

m3 Cubic

Centrosymmetric

(Not Known)

Transition Temperature: 37 to 160 K

(Not Known)

(Not Known)

Transition Temperature: 30 K

(Not Known)

VAESITE is paramagnetic and is an electrical semiconductor. Below a phase transition at 37 to 160 K,*VAESITE* is antiferromagnetic; below 30 K it is (incompletely) antiferromagnetic.

Nickel-Strunz: 2.EB.05a - SULFIDES and SULFOSALTS (sulfides, selenides, tellurides; arsenides, antimonides, bismuthides; sulfarsenites, sulfantimonites and sulfbismuthites) - Metal Sulfides, [Metal : Sulfur = 1 : 2] with Fe, Co, Ni and platinum group elements.

Found in some dolostone, and as an alteration product of some hydrothermal vein minerals.

TABLE 4. Continued

VERMICULITE Montmorillonite-Vermiculite Group 2/m Monoclinic Centrosymmetric	(Mg,Fe,Al) ₃ [(Al,Si) ₄ O ₁₀](OH) ₂ • 4H ₂ O
Nickel-Strunz: 9.EC.50 - SILICATES (Germanates) - Phyllosilicates with mica sheets, composed of tetrahedral and octahedral nets. - Pyroelectric, Piezoelectric - Formed as an alteration product of biotite or phlogopite, and found in the contact between felsic and mafic rocks, as well as in carbonatites, metamorphosed limestones and soils.		
WAKEFIELDITE-ND Xenotime Group 4/mmm Tetragonal Centrosymmetric	NdVO ₄
Transition Temperature: 293 K		(Not Known)
Below 293 K <i>WAKEFIELDITE-ND</i> undergoes a phase transition to a ferroelectric form. Nickel-Strunz: 8.AD.35 - PHOSPHATES, ARSENATES, VANADATES - Phosphates, without additional anions, without H ₂ O, with only large cations. - Paraelectric, Pyroelectric, Piezoelectric - A product of metamorphism, in manganese-bearing deposits.		
WELOGANITE Donnayite Group 1 Triclinic Polar and Chiral	Na ₂ Sr ₃ Zr(CO ₃) ₆ • 3H ₂ O
Nickel-Strunz: 5.CC.05 - CARBONATES (NITRATES) - Carbonates without additional anions, with H ₂ O - With rare earth elements. - Pyroelectric, Piezoelectric - In alkalic sills or associated with intrusive alkalic gabbro-syenite complexes.		
WHITLOCKITE Whitlockite Group 3m Trigonal Polar	Ca ₉ (Mg,Fe ²⁺)(PO ₄) ₆ [PO ₃ (OH)]
Nickel-Strunz: 8.AC.45 - PHOSPHATES, ARSENATES, VANADATES - Phosphates, without additional anions, without H ₂ O, with medium-sized and large cations. - Pyroelectric, Piezoelectric - A secondary mineral in complex, zoned granite pegmatites; in phosphate rock deposits, or formed in caves from leached guano.		

TABLE 4. Continued

WULFENITE

Scheelite Group

Stolzite – Wulfenite Series

4/m Tetragonal

Centrosymmetric

Nickel-Strunz: 7.GA.05 - SULFATES (selenates, tellurates, chromates, molybdates and wolframates) - Molybdates, wolframates and niobates without additional anions or H_2O .

- Pyroelectric, Piezoelectric -

A secondary mineral formed in the oxidized zone of hydrothermal lead deposits, the molybdenum commonly introduced externally.

WURTZITE

Wurtzite Group

6mm Hexagonal

Polar

Nickel-Strunz: 2.CB.45 - SULFIDES and SULFOSALTS (sulfides, selenides, tellurides; arsenides, antimonides, bismuthides; sulfarsenites, sulfantimonites and sulfbismuthites) - Metal Sulfides, [Metal : Sulfur = 1 : 1] with Zn, Fe, Cu and Ag.

- Pyroelectric, Piezoelectric -

Of hydrothermal origin in veins with other sulfides; also along shrinkage fractures in clay-ironstone concretions, of low-temperature origin.

WÜSTITE

Periclase Group

m3m Cubic

Centrosymmetric

(Not Known)

Transition Temperature: 198 K

(Not Known)

WÜSTITE is paramagnetic.

Nickel-Strunz: 4.AB.25 - OXIDES (Hydroxides, V[5,6] vanadates, arsenites, antimonites, bismuthites, sulfites, selenites, tellurites and iodates) - [Metal : Oxygen = 1 : 1 and up to 1 : 1.25] with small to medium-sized cations only.

Formed as an alteration product of other iron-bearing minerals at high temperatures in a highly reducing environment, in highly-reduced iron-bearing basalts, as inclusions in diamonds in kimberlites, in precipitates from deep-sea hot brines and in Fe–Mn nodules, in microspherules of likely extraterrestrial origin found in a variety of geological environments, and in some meteorites.

XIEITE **mmm** Orthorhombic

Centrosymmetric

(Not Known)

Transition Temperature: 50 to 90 K

(Not Known)

XIEITE is paramagnetic; below 50 to 90 K, it is ferrimagnetic. *XIEITE* is a high-pressure polymorph of chromite. The *P-T* conditions for the phase transformation to *XIEITE* from chromite are estimated at 20–23 GPa and 1800°C to 2000°C, respectively.

Nickel-Strunz: 4.BB.25 - OXIDES (Hydroxides, V[5,6] vanadates, arsenites, antimonites, bismuthites, sulfites, selenites, tellurites and iodates) - [Metal : Oxygen = 3 : 4] with only medium-sized cations.

Found in a chondrite meteorite.

TABLE 4. Continued

YUGAWARALITE

Zeolite Group

m Monoclinic

Polar

Nickel-Strunz: 9.GB.15 - SILICATES (Germanates) - Tectosilicates with zeolitic H_2O , zeolite family - Chains of singly connected four-membered rings.

- Pyroelectric, Piezoelectric -

As crystals lining cavities, and veinlets, typically deposited in active geothermal areas.

ZINCITE

Zincite Group

6mm Hexagonal

Polar

Nickel-Strunz: 4.AB.20 - OXIDES (Hydroxides, V[5,6] vanadates, arsenites, antimonites, bismuthites, sulfites, selenites, tellurites and iodates) - [Metal : Oxygen = 1 : 1 and up to 1 : 1.25] with small to medium-sized cations only.

- Piezoelectric -

Found both as a primary mineral in layered metamorphic zinc ore and as a secondary mineral in oxidized zinc-rich deposits; also volcanic.

ZINCOCHROMITE

Spinel Group

m3m Cubic

Centrosymmetric

Transition Temperature: 17 K

(Not Known)

ZINCOCHROMITE is paramagnetic.

Nickel-Strunz: 4.BB.05 - OXIDES (Hydroxides, V[5,6] vanadates, arsenites, antimonites, bismuthites, sulfites, selenites, tellurites and iodates) - [Metal : Oxygen = 3 : 4] with only medium-sized cations.

Replacing chromian aegirine (itself an alkalic igneous and metamorphic mineral) in some micaceous metasomatites.

(Not Known)

ZINKENITE

Zinkenite-Scainiite Group

6 Hexagonal

Polar and Chiral

Nickel-Strunz: 2.JB.35a - SULFIDES and SULFOSALTS (sulfides, selenides, tellurides; arsenides, antimonides, bismuthides; sulfarsenites, sulfantimonites and sulfbismuthites) - Sulfosalts of PbS structure - Galena derivatives, with Pb.

- Pyroelectric, Piezoelectric -

Found in hydrothermal veins associated with base metals, tin sulfides and sulfosalts.

ZUNYITE *43m* Cubic

Non-centrosymmetric

Nickel-Strunz: 9.BJ.55 - SILICATES (Germanates) - Sorosilicates with Si_3O_{10} , Si_4O_{11} and similar anions, cations in octahedral [6] and greater coordination.

- Piezoelectric -

Found in highly aluminous shales and hydrothermally altered volcanic rocks.

TABLE 4. Continued

Notes: All of the minerals are listed under IMA approved names, except for tourmaline, which is a supergroup, rather than a single mineral, and is included for interest. For minerals of the tourmaline supergroup, formulas are given as $X(Y)_3Z_6(BO_3)_3Si_6O_{18}(V)_3W$ with the extra parentheses to aid the reader. Also note that a similar convention of having the empirical formula denote structural data has been followed for other minerals in this table, including those for batisite, fresnoite, londonite, magnetite, rhodizite, and whitlockite.

Small figures representing crystal lattice unit cells for each of the 32 crystal classes are shown by each mineral, and these are taken from webmineral.com (Barthelmy, 2012), originally drawn using software called FACES by Georges Favreau, no longer accessible. Reproduced with permission.

Transition temperatures are given at ambient pressures unless otherwise specified.

The Nickel-Strunz categories are from the 10th edition, available at mindat.org (Ralph and Chau, 2012).

The crystal system notation in the table above has one modification to it: Macron-bearing numbers are represented here as underlined numbers, so that the rhombohedral crystal class is written as 6, for example.

The descriptions under each mineral name are a combination of direct quotation and paraphrase from the Mineralogical Society of America's (MSA) *Handbook of Mineralogy* (Anthony et al., 2012), reproduced with permission, except for the descriptions of barioperovskite, cadmoindite, demicheleite-Br, demicheleite-Cl, demicheleite-I, fluor-dravite, mariinskite, oxycalciopyrochlore, oxyplumbopyrochlore, oxy-schorl, srebrodolskite, tistarite, and xieite, which are a combination of direct quotation, paraphrase and inference (based on geographical location of specimens) from mindat.org (Ralph and Chau, 2012), reproduced with permission, and halloysite-7Å, which is paraphrased from webmineral.com (Barthelmy, D., 2012), while the description of the pyrite variety bravoite is paraphrased from El Baz and Amstutz (1963), and clinocervantite, where the description is summarized from Basso et al. (1999), as well as cuprorhodsite, from Martin and Blackburn (2001), and lakargiite, from Guskin et al. (2008), plus wakefieldite-Nd from Moriyama et al. (2011).

References for the structural data in this table are given in Table 11 in Appendix G, p. 224.

APPENDIX B

ELECTRIC AND MAGNETIC MINERAL DATA

TABLE 22. Spontaneous Polarization (q) Data in Ferroelectric Minerals

Mineral	q : 10^{-3} C m^{-2}	T : $^{\circ}\text{C}$	Notes [T: $^{\circ}\text{C}$] [P: GPa]
Archerite	48	-183	PeakT [-183 to -150]
Barioperovskite*	200	≤ 135	
Boracite	8.0	267	PeakT [-173 to 327]
Demicheleite-Br	85	RT	
Demicheleite-I	85	RT	
Gwihabaite	7	120	PeakT [140 to 60, cooling]
	8	118	PeakT [60 to 140, heating]
Heftetjernite	≈ 0	5	
	500	-35	PeakT [-45 to 5]
Lueshite	120	RT	
Macedonite	400 to 800	500 to 0	Cooling
	120	210 to 225	Heating
Niter	80	118	PeakT [115.0 to 130.0]
Nitratine	0.6	RT	PeakP [4.7 to 5.8] $P = 5.8 \text{ GPa}$
Pyrolusite	0.12	50	PeakT [-60 to 110]
Stibiotantalite	130	300	PeakT [250 to 550]
Wakefieldite-Nd	30	0	

Notes: The spontaneous polarization (q) is the charge density per area caused by a change in temperature or pressure. P signifies pressure. T signifies temperature. RT signifies (ambient) room temperature. At 135°C Barioperovskite* undergoes a paraelectric phase transition. There is no ferroelectric spontaneous polarization exhibited above this temperature. References are listed in Table 27 in Appendix G, p. 228.

TABLE 23. Electrocaloric Effect, Ferroelectric Minerals

Mineral	ΔT : $^{\circ}\text{C}$	E: 10^3 V m^{-1}	T : $^{\circ}\text{C}$	Notes [E: 10^3 V m^{-1}] [T: $^{\circ}\text{C}$]
Archerite	$\Delta 1.0^{\circ}$	1250	RT	PeakE [0 to 1250]
Barioperovskite	$\Delta 0.43^{\circ}$	750	120	
Tausonite	$\Delta 0.11^{\circ}$	1000	-255	PeakE
	$\Delta 0.3^{\circ}$	199	-261	PeakT [-263 to -243]

Notes: The electrocaloric effect is a change in temperature due to the application of an electric field (E). T signifies temperature. RT signifies (ambient) room temperature. References are listed in Table 27 in Appendix G, p. 228.

TABLE 24. Other Electric Data, Ferroelectric Minerals

Mineral	Magnitude	T : °C	Notes [T: °C]
<u>Activation Energy for DC Conductivity</u>			
Tausonite	1.037 eV	RT	
<u>Pyroelectric Potential</u>			
Barioperovskite	50 V	109	Peak T
<u>Pyroelectric Current</u>			
Chalcostibite	2×10^{-10} A	93	Peak T [-15 to 135]
<u>Remanent Field</u>			
Oxyplumbopyrochlore	1.5×10^5 V m ⁻¹	RT	Peak T
<u>Coercive Field</u>			
Heftetjernite	4×10^3 V m ⁻¹	5	
	2×10^4 V m ⁻¹	-35	Peak T [-45 to 5]
Pyrolusite	1×10^4 V m ⁻¹	-60	Peak T [-60 to 110]
Stibiotantalite	10 V m ⁻¹	350	Peak T [250 to 550]

Notes: T signifies temperature. RT signifies (ambient) room temperature. The Activation Energy for DC Conductivity is the strength of the electric signal necessary to initiate the flow of electric charge. The Pyroelectric Potential is the magnitude of an electric potential caused by changes in temperature. The Pyroelectric Current is the magnitude of an electric current caused by changes in temperature. The Remanent Field is the strength of electric field remaining when no applied field is present. The Coercive Field is the strength of electric field needed to reverse the polarity of a ferroelectric material. References are listed in Table 27 in Appendix G, p. 228.

TABLE 25. Pyroelectric Polarization (p) Data for Minerals

Mineral	p : $10^{-6} \text{ C m}^{-2} \text{ K}^{-1}$	T : $^{\circ}\text{C}$	Notes [T: $^{\circ}\text{C}$]
Boracite	7.5	267	Peak T
	-2.4	RT	
Cadmoselite	3.7	RT	
Chambersite	850	135	Peak T [40 to 160]
Diomignite	-30	25	
	-120	-150	
Fresnoite	10	RT	
Greenockite	4.0	RT	Primary: $3.0 \times 10^{-6} \text{ C m}^{-2} \text{ K}^{-1}$
Macedonite	250	100	
Proustite	8.0	RT	
Tourmaline*	4.0	RT	Primary: $0.8 \times 10^{-6} \text{ C m}^{-2} \text{ K}^{-1}$
		110	$p = 4.791 - 0.103 \times (\text{wt\% FeO})$
		23	$p = 3.949 - 0.094 \times (\text{wt\% FeO})$
		-80	$p = 2.594 - 0.077 \times (\text{wt\% FeO})$
Wurtzite	0.43	RT	Primary: $0.34 \times 10^{-6} \text{ C m}^{-2} \text{ K}^{-1}$

Notes: The pyroelectric polarization (p) is electric polarization due to the pyroelectric effect. “Primary” is the amount of charge expressed via the primary pyroelectric effect. The secondary effect (due to piezoelectricity from lattice expansion during heating) has been calculated from a model of the crystal lattice. This value is then subtracted from the observed value to obtain the primary effect. Pyroelectric phenomena in Tourmaline* are correlated to Fe^{2+} occupancy of the Y site of the tourmaline crystal lattice, in an inverse linear relationship: more Fe^{2+} results in a weaker pyroelectric effect. Tourmaline is a mineral supergroup, described by the formula $\text{X}(\text{Y})_3\text{Z}_6(\text{BO}_3)_3\text{Si}_6\text{O}_{18}(\text{V})_3\text{W}$. The letters V, W, X, Y and Z signify lattice sites where a variety of atoms may be present. The formulas and observations for the pyroelectric polarization in tourmaline are from Hawkins et al. (1995). T signifies temperature. RT signifies (ambient) room temperature. Complete references are listed in Table 28 in Appendix G, p. 228.

TABLE 26. Thermoelectric Potential (*t*) Data for Minerals

Mineral	<i>t</i> : 10 ⁻⁶ V K ⁻¹	<i>T</i> : °C	Notes [T: °C]
Cadmoindite	-400	<i>RT</i>	Endmember CuCo ₂ S ₄
Carrollite	12.7	<i>RT</i>	
Coulsonite	340	<i>RT</i>	
Cuprokalinitite	16.0	<i>RT</i>	Endmember CuRh ₂ S ₄
Cuprorhodsite	25	<i>RT</i>	
Cuprospinel	-164	27	
Daubréelite	483	<i>RT</i>	Peak <i>T</i> [-235 to 265]
	475	-35	
Indite	360	<i>RT</i>	
Jacobsite	-450	25 to 375	Peak <i>T</i>
Kalinitite	222	<i>RT</i>	
Linnaeite	4.8	<i>RT</i>	
Lueshite	2.5	260	
Macedonite	200	350 to 700	
Magnesiocoulsonite	450	<i>RT</i>	
Magnetite	-85 to -120	600 to 1500	Endmember NiCo ₂ S ₄
	-50	-100 to -35	
Siegenite	-17.7	<i>RT</i>	
Trevorite	-110	125 to 725	

Notes: The thermoelectric potential (*t*) is an electric potential from the thermoelectric effect.

“Endmember” signifies that the value has only been measured for the end member indicated for a mineral that forms a solid solution. *T* signifies temperature. *RT* signifies (ambient) room temperature. References are listed in Table 29 in Appendix G, p. 229.

TABLE 30. Piezoelectric (Electric Charge) Strain Rates (d) for Minerals

Mineral	d : 10^{-12} C N $^{-1}$			T : °C	Notes	$[T$: °C]
Analcime	(31) 0.2 to 0.5			RT		
Archerite	(36) 16.8			100		
	(36) 25.4			0		
Barioperovskite	(31) -520	(33) 1,000		130	Peak T	[15 to 130]
	(15) 392	(31) -34.5	(33) 85.6	25		
	(15) 700			15	Peak T	[15 to 130]
Berlinite	(11) -3.0	(14) 1.3		RT		
	(11) -5.56	(14) 1.19		25		
Biphosphammite	(36) 43.2			100		
	(36) 51.7			0		
Boracite*	(14) 13.5	(33) 3.9		265	Peak T	
	(14) 8.5			264.5	Near Transition T	
	(33) 1.4			150		
	(14) 4.5			25		
	(33) 0.6			RT		
	(14) -2.0	(25) -2.4	(36) 3.60	RT		
Bromellite	(31) 0.1	(33) 0.2		RT		
Cadmoselite	(15) -10.52	(31) -3.92	(33) 7.85	RT		
Cancrinite	(15) -9.0	(31) -0.6	(33) 4.3	RT		
	(15) 9.01	(31) 0.7	(33) 4.3	RT		
Changbaiite	(33) 81			RT		
Cinnabar	(11) -0.6	(14) $\approx$ 1.7		RT		
Diomignite	(31) 0.92	(33) 7.2		RT		
Epsomite	(14) -2.0	(25) -2.4	(36) -3.6	RT		
	(14) -2.06	(25) -2.72	(36) -3.8	20		
Eulytine	(14) 1.6			RT		
Fresnoite	(31) 2.7	(33) 7.8	(h) 12.7	RT		
	(15) 18	(31) 2.7	(33) 3.8	RT		
	(15) 9.3	(31) 3.1	(33) 4.0	20		
Goslarite	(14) -1.9	(25) -3.5	(36) -3.07	20		
Greenockite*	(15) -13.98	(31) -5.18	(33) 10.32	25		
	(15) -7.55	(31) -4.36	(33) 6.49	(h) <0.05	RT	
	(15) -14	(31) -3.7	(33) 11	RT		
	(15) -11.91	(31) -5.09	(33) 9.71	20	In the Dark	
	(15) -11.4	(31) -4.8	(33) 9.5	-269		
Ice	(33) 2			0		
Macedonite	(15) 6.5	(31) -2.5	(33) 11.7	RT		
Magnetite	(11) $\approx$ 0.16	(12) $\approx$ 0.63	(13) $\approx$ 0.19	(31) $\geq$ 0.11 -269.0	(32) $\geq$ 0.06	(33) $\geq$ 0.25
Morenosite	(14) 1.99	(25) -2.95	(36) -3.21	RT		
Nepheline	(33) 0.5 to 1.3			RT		
Paratellurite	(14) 8.13			20		
Proustite	(15) -20	(22) 12.1	(31) -13.8	(33) 30		20
Pyrargyrite	(15) 31.6	(22) 16.2	(31) -19.5	(33) 62.2		27
	(22) 13.8	(31) -23	(33) 35	20		
Pyrolusite	(?) 800 to 930			RT	β -Pyrolusite	

TABLE 30. Continued

Mineral	$d: 10^{-12} \text{ C N}^{-1}$			$T: ^\circ\text{C}$	Notes	$[T: ^\circ\text{C}]$
Quartz*	(14) -1.82			626	β -Quartz	
	(14) -1.86			612	β -Quartz	
	(14) -1.89			585	β -Quartz	
	(11) 1.27	(14) -1.87		570		
	(11) 2.05			100		
	(11) 2.16			100		
	(11) 2.18			100	Synthetic	
	(11) 2.3	(14) -0.67		RT		
	(11) 2.22			RT		
	(11) 2.20 to 2.30			RT		
	(11) -2.232			RT	Brazilian	
	(11) 2.31	(14) -0.670		RT		
	(11) -2.252			RT	Synthetic	
	(11) 2.27			20 to 22	Brazilian	
	(11) 2.31	(14) -0.72		20		
	(11) 2.31			< -196		
	(11) 2.13			< -196	Synthetic	
	(11) 2.32			-269 and -271.7		
	(111) 5.0	$\times 10^{-20} \text{ C}^2 \text{ N}^{-2}$		RT	Brazilian	
	(111) 3.6	$\times 10^{-20} \text{ C}^2 \text{ N}^{-2}$		RT	Synthetic	
	(112) 7.1	$\times 10^{-20} \text{ C}^2 \text{ N}^{-2}$		RT		
	(112) 14.2	$\times 10^{-20} \text{ C}^2 \text{ N}^{-2}$		RT	Brazilian	
	(1112) -9.6	$\times 10^{-26} \text{ C}^3 \text{ N}^{-3}$		RT		
	(1112) -57	$\times 10^{-26} \text{ C}^3 \text{ N}^{-3}$		RT	Brazilian	
Retgersite	(14) 6.0			RT		
Russellite	(11) 40	(13) -8.7	(12) 14	RT		
Sal Ammoniac	(14) 0.112			RT		
Schorl*	(33) 1.6	(h) 2.2		-192 to 16		
Selenium	(11) 30 to 200			RT		
Sillénite	(14) 40.5			-196 to 227		
	(14) 37.8			RT		
Sodalite	(14) 1.3			RT		
Sphalerite	(14) 3.18			25		
	(31) -1.13	(33) 1.92	(15) -2.52	20	10% Wurtzite	
	(14) 3.46			-196		
Stibiotantalite	(33) 150			380		
	(33) 370			RT		
	(33) 117			RT		
Stilleite	(14) 1.1			RT		
Tausonite	(33) 150			RT	Peak T	
	Tausonite: with an applied electric field of $5 \times 10^5 \text{ V m}^{-1}$ along [001]					
Tellurium	(11) 3,000			RT		
Tourmaline	(22) -0.3	(31) -0.34	(33) -1.8	(15) -3.625	(h) 4.00	RT
	(15) 3.64	(22) -0.3	(31) 0.3	(33) 1.8		RT
Wurtzite*	(31) -1.1	(33) 3.2	(15) -2.8	RT		
	(31) 2.0	(33) 3.9	(15) 5.1	20	0.30:0.70::Mg:Zn	
	(31) -2.14	(33) 3.66	(15) -4.37	20	0.10:0.90::Mg:Zn	
	(31) 0.95	(33) 3.3	(15) 2.6	-273		
Zincite	(15) -10	(31) -4.6	(33) 12	RT		

TABLE 30. Continued

Notes: The piezoelectric strain rate (d) is electric charge per unit force due to the piezoelectric effect. Parentheses signify the lattice directions in Voigt notation. The location of electricity is shown by the first number, and strain by the second. (See Chapter 3, p. 18 and 19.) The entries $d(h)$ present the strain rate under hydrostatic pressure, according to $d(i1) + d(i2) + d(i3)$, where i is the polar axis. "Brazilian" is a natural quartz specimen from Brazil. Boracite* undergoes a ferroelectric to paraelectric phase transition near $T = 265^\circ\text{C}$. Greenockite* exhibits changes in piezoelectric rates with light intensity, as per Ogawa and Kojima (1966). For Quartz*, $d(11)$ is reported to have a flat maximum near $T = RT$, decreasing as T rises, and zero at $T = 573^\circ\text{C}$, which is the transition temperature to β -quartz structure. Also note the units of the higher order piezoelectric strain rates for quartz. With Schorl*, also see the tourmaline entry for more numerical data listings. The colons by two of the Wurtzite* entries signify percent ratios. Complete references are listed in Table 37 in Appendix G, p. 229.

TABLE 31. Piezoelectric (Electric Charge) Stress Rates (e) for Minerals

Mineral	e : C m ⁻²		T : °C	Notes
Archerite*	(36) 0.097		100	
	(36) 0.158		0	
	(345) 0.07		<i>RT</i>	
Berlinite	(11) -0.192	(14) 0.143	<i>RT</i>	
Biphosphammite	(36) 0.254		100	
	(36) 0.318		0	
Bournonite	(33) 0.85		<i>RT</i>	
Cancrinite	(14) 0.12	(15) -0.28	16	
Cinnabar	(11) 0.315		<i>RT</i>	
Diomignite	(15) 0.472	(31) 0.290	(33) 0.928	<i>RT</i>
Eulytine	(14) 0.083		<i>RT</i>	
Greenockite	(15) -0.210	(31) -0.244	(33) 0.440	25
	(15) -0.21	(31) -0.24	(33) 0.434	<i>RT</i>
	(15) -0.183	(31) -0.262	(33) 0.385	20
Langbeinite	(14) 0.021		<i>RT</i>	
Paratellurite	(14) 0.216		20	
Proustite	(15) -0.18	(22) 0.32	(31) -0.29	(33) 0.27 20
Pyrargyrite	(15) 0.38	(22) 0.44	(31) 0.20	(33) 1.12 27
Quartz	(11) 0.062		568	
	(11) 0.138		494	
	(11) 0.170		118	
	(11) 0.17	(14) 0.04	<i>RT</i>	
	(11) 0.171	(14) -0.0406	20	
	(11) 0.170		18	
Sphalerite	(14) 0.147		25	
	(14) 0.162		-196	
10% Wurtzite	(15) -0.072	(31) -0.137	(33) 0.165	20
Tourmaline	(15) 0.246	(22) -0.017	(31) -0.103	(33) 0.320 <i>RT</i>
	(15) 0.25	(22) -0.018	(31) 0.103	(33) 0.32 <i>RT</i>
Wurtzite	(15) 0.07	(33) 0.14	<i>RT</i>	
	(15) -0.08	(31) -0.09	(33) 0.34	<i>RT</i>
	(15) 0.13	(33) 0.34	<i>RT</i>	.30:.70::Mg:Zn
	(15) -0.118	(31) -0.238	(33) 0.265	20 .10:.90::Mg:Zn

Notes: The piezoelectric stress rate (e) is the product of electric charge per unit force and pressure, caused by the piezoelectric effect. Parentheses signify the directions in Voigt notation. The location of electricity is shown by the first number, and stress by the second. The third-order value for Archerite* shows electricity at the first number, and stress at the second and third. (See Chapter 3, p. 18 and 19.) T signifies temperature. *RT* signifies (ambient) room temperature. References are listed in Table 37 in Appendix G, p. 229.

TABLE 32. Piezoelectric (Electric Field) Strain Rates (g) for Minerals

Mineral	g : 10^{-3} V m N $^{-1}$	T : °C	Notes
Archerite	(36) 110	100	
	(36) 119	0	
Barioperovskite	(15) 15.3 (31) -23.1 (33) 57.6	25	
Biphosphammite	(36) 354	100	
	(36) 360	0	
Boracite*	(14) 90	265	
	(14) 83	264.5	Near Transition T
	(14) 60	25	
Fresnoite	(33) 88 (h) 110	RT	
	(33) 82 (h) 130	RT	
Paratellurite	(14) 40.1	20	
Quartz	(11) 57.8 (14) 18.2	20	
Sphalerite	(14) 41	RT	

Notes: The piezoelectric field strain rate (g) is the electric potential per unit force (per unit area) due to the piezoelectric effect. Parentheses signify the lattice directions in Voigt notation. The location of electricity is shown by the first number, and strain by the second. (See Chapter 3, p. 18 and 19.) The entries $g(h)$ present the strain rate under hydrostatic pressure, according to $g(i1) + g(i2) + g(i3)$, where i is the polar axis. Boracite* undergoes a ferroelectric to paraelectric phase transition near $T = 265^\circ\text{C}$. T signifies temperature. RT signifies (ambient) room temperature. References are listed in Table 37 in Appendix G, p. 229.

TABLE 33. Piezoelectric (Electric Field) Stress Rates (h) for Minerals

Mineral	h : 10^8 V m $^{-1}$	T : °C
Archerite	(36) 6.48	100
	(36) 7.50	0
Biphosphammite	(36) 22.4	100
	(36) 25.1	0
Eulytine	(14) 5.78	RT
Paratellurite	(14) 10.7	20
Pyrargyrite	(22) 25 (31) 11 (33) 61 (15) 21	27
Quartz	(11) 43.6 (14) -10.4	20

Notes: The piezoelectric field stress rate (h) is the product of the electric potential per unit force (per unit area) and pressure, caused by the piezoelectric effect. T signifies temperature. RT signifies (ambient) room temperature. References are listed in Table 37 in Appendix G, p. 229.

TABLE 34. Electromechanical Coupling Factors (k) for Minerals

Mineral	$k: 10^{-2}$				$T: ^\circ\text{C}$
Barioperovskite	(15) 0.570	(31) 0.315	(33) 0.560		25
Berlinite	(11) 0.162	(14) 0.240			<i>RT</i>
	(26) 0.232				<i>RT</i>
	(11) 0.111	(26) 0.175	(t) 0.11		<i>RT</i>
Bournonite	(33) 0.16				<i>RT</i>
Cancrinite	(14) 0.065	(15) 0.216	(31) 0.020	(33) 0.065	<i>RT</i>
Changbaiite	(t) 0.26				<i>RT</i>
Cinnabar	(11) 0.235				<i>RT</i>
Diomignite	(15) 0.21	(31) 0.093	(33) 0.42		<i>RT</i>
Eulytine	(14) 0.0305				<i>RT</i>
Fresnoite	(p) 0.14	(t) 0.225			<i>RT</i>
	(15) 0.28	(31) 0.10	(33) 0.11		<i>RT</i>
	(15) 0.34	(t) 0.23			20
Greenockite	(15) 0.1885	(31) -0.1191	(33) 0.262	(t) 0.154	25
	(15) 0.166	(31) 0.117	(33) 0.256	(t) 0.135	20
Langbeinite	(14) 0.015				<i>RT</i>
Macedonite	(15) 0.43	(31) 0.24	(33) 0.64	(p) 0.40	<i>RT</i>
Paratellurite	(14) -0.093				20
Proustite	(31) 0.18	(33) 0.29			20
Pyrargyrite	(15) 0.26	(22) 0.14	(31) 0.17	(33) 0.40	27
	(13) 0.363				20
	(33) 0.38				-173 to 117
	(33) 0.345				-183 to -128
Quartz	(11) 0.092	(26) 0.137	(t) 0.0084		<i>RT</i>
	(11) 0.10	(14) 0.03			20
Sillénite	(14) 0.31	(31) 0.28	(t) 0.20		<i>RT</i>
Sphalerite	(14) 0.0795				25
	(14) 0.089				-196
10% Wurtzite	(15) 0.049	(31) 0.039	(33) 0.075	(t) 0.051	20
Stephanite	(33) 0.21				<i>RT</i>
Tourmaline	(15) 0.131	(22) 0.02	(31) 0.0214		25
Wurtzite*	(15) 0.09	(31) 0.05	(33) 0.13	(t) 0.10	20 .30: .70::Mg:Zn
	(15) 0.084	(31) 0.072	(33) 0.14	(t) 0.080	20 .10: .90::Mg:Zn

Notes: The electromechanical coupling factor (k) is a calculated value from which any of the piezoelectric coefficients can be determined. Parentheses signify the directions in Voigt notation. The location of electricity is shown by the first number, and strain or stress by the second. (See Chapter 3, p. 18 and 19.) The poled electromechanical coupling factor $k(p)$ is taken from a thin disk of the crystal cut normal to the z axis with measurements taken under an externally applied electric field. The thickness compressional coupling factor $k(t)$ is taken from a thin disk cut normal to a symmetry axis or parallel to a symmetry plane, so that the compressional component is not coupled to the shear component. The colons by two of the Wurtzite* entries signify percent ratios. T signifies temperature. *RT* signifies (ambient) room temperature. The References are listed in Table 37 in Appendix G, p. 229.

TABLE 35. Ferroelectric Piezoelectric Strain and Stress Rates for Minerals

Mineral	Magnitude					T : °C
<u>Strain Rate</u>	$\frac{\text{m}^4 \text{C}^{-2}}{}$					
Sillénite	(11) 0.28 (12) 2160	(12) -0.125	(13) -0.025	(44) 0.18	(h) 0.12	RT -181
<u>Stress Rate</u>	$\frac{10^{-18} \text{m}^2 \text{V}^{-2}}{}$					
Sillénite	(11) 0.042	(12) -0.019	(13) -0.037	(44) 0.028		RT

Notes: These square values are used in calculations for ferroelectric materials. Parentheses signify the directions in Voigt notation. The location of electricity is shown by the first number, and strain or stress by the second. (See Chapter 3, p. 18 and 19.) T signifies temperature. RT signifies (ambient) room temperature. References are listed in Table 37 in Appendix G, p. 229.

TABLE 36. Piezoelectric Rates (d , e and k) During Temperature Variations for Minerals

Mineral	Magnitude				T : °C	Notes
<u>$\Delta(d)/d\Delta T$</u>	$\frac{10^{-4} \text{K}^{-1}}{}$					
Berlinite	(11) -3.2	(14) 8.7			25	
Boracite	(14) -10				320	
Epsomite	(14) ≈ 20	(25) < 2	(36) < 2		-10 to 30	
Proustite	(22) -18.5	(31) -5.6	(33) -50	(15) -4.2	-40 to 20	
Quartz	(14) -12.8				585 to 625	β -Quartz
	(11) -2.0	(14) 17.7			20 to 100	
	(11) -2.3	(14) 13.6			25 to 80	
	(11) -2.15	(14) 12.9			15 to 45	
	(11) 9.7				-60 to 0	
<u>$\Delta(e)/e\Delta T$</u>	$\frac{10^{-4} \text{K}^{-1}}{}$					
Berlinite	(11) -2.7	(14) -5.6			RT	
Fresnoite	(31) 25.81	(15) -1.28			RT	
Proustite	(22) -23	(31) -210	(33) -90	(15) -4.3	-40 to 20	
Quartz	(11) -1.6				15 to 45	
<u>$(\Delta k)^2/k^2\Delta T$</u>	$\frac{10^{-4} \text{K}^{-1}}{}$					
Pyrargyrite	(13) 55				-40 to 20	

Notes: The piezoelectric strain rate (d) is electric charge per unit force due to the piezoelectric effect. The piezoelectric stress rate (e) is the product of electric charge per unit force and pressure, caused by the piezoelectric effect. The electromechanical coupling factor (k) is a calculated value from which any of the piezoelectric coefficients can be determined. T signifies temperature. RT signifies (ambient) room temperature. Parentheses signify the directions in Voigt notation. The location of electricity is shown by the first number, and strain or stress by the second. (See Chapter 3, p. 18 and 19.) References are listed in Table 37 in Appendix G, p. 229.

TABLE 38. Relative Dielectric Strength (K) of Minerals

Mineral	K_1	K_2	K_3	T : °C	f: kHz	Notes [T : °C][f: kHz]
Archerite	80		50,000	-150	0.8	Peak T [-225 to 25]
Barioperovskite	1,783.00		130	RT		
	10,000		10,000	120		Peak T [-90 to 120]
	168.0			25		
	7,000		300	-5		Peak T [-90 to 120]
	4,000		200	-90		Peak T [-90 to 120]
Berlinite	6.47		200	RT	1	
	6.40		200	RT	1000	
	6.05			25		
	4.73		4.62	RT	1	
			6.32	20	1	
			6.32	20	1000	
			6.15	-175	1	
			6.22	-175	1000	
Biphosphammite	57.6		14.0	18.5	10	
	100		35	-125		Peak T [-180 to 0]
	54			-220		Peak P = 3.0 GPa
Boracite	K_{110} = 16.5			265	100	Peak T [0 to 350]
	8.0			40	100	Constant Stress
			8.1	20	50	Constant Stress
	5.4	5.23	5.79	RT		
Bournonite	40			27	1.5×10^4	Constant Stress
Cadmoselite	9.7		10.65	RT		
Cancrinite	9.5		11.2	RT		Constant Stress
Cervantite	1,400			565		Peak T [100 to 700]
Chambersite			16	410	1000	Peak T [0 to 500]
	28			135		Peak T [40 to 160]
Changbaiite*	24,000	24,000		560		Peak T
		260		27	$1 \text{ to } 10^4$	
Cinnabar	15.0		25.5	RT		Constant Stress
	14.0		25.5	RT		Constant Strain
Clinocervantite	1,400			565		Peak T [100 to 700]
Colemanite	≈ 20			-20 to 20		
		50		RT		
Cuprospinel	K = 8.65			RT		
Diomignite*	25			505	0.1	Peak T [25 to 505]
			1,800	195	0.1	Peak T [25 to 325]
	8.90		8.07	RT		Constant Strain
Epsomite	5.40	5.23	5.79	RT		
	5.26	6.05	8.28	RT		
Ericaite*	K_{111} = 43			340	300	Peak T [150 to 450]
Eulytine	16.2			RT		
Franklinite	70,000			RT	10	Peak f [10 to 10^7]
Fresnoite			11.0	RT	1	Constant Stress
	15		11	RT		Constant Stress
	9			RT	1	Constant Stress
	12.5		8.55	20	1×10^4	
Greenockite*	8.7		9.25	27		Constant Strain
	9.02		9.53	25		Constant Strain
	10.55		7.80	25	0.05	
	9.74		7.48	25	1	
	9.35		10.33	25	10	Constant Stress

TABLE 38. Continued

Mineral	K_1	K_2	K_3	T : °C	f: kHz	Notes [T : °C][f: kHz]
Greenockite, cont'd*	9.43		7.77	25	10	
	9.25		7.68	25	100	
	8.82		7.96	25	1000	
	7.96		7.67	25	4×10^4	
			10.33	RT		Constant Stress
in the dark	8.94		9.96	RT		Constant Stress
in the dark	8.88		9.93	RT		Constant Strain
in the dark	8.92		10.20	20		Constant Stress
in the dark	8.67		9.53	20		Constant Strain
	9.33		6.76	-65	0.05	
	8.76		7.02	-65	1	
	9.17		6.97	-65	10	
	9.63		6.95	-65	100	
	8.02		6.60	-65	300	
	8.48		9.48	-196	10	Constant Stress
	8.45		9.12	-248		
	8.37		9.00	-265		Constant Strain
Heftetjernite		7,500		5	1	Peak T [-75 to 25]
Koechlinite	$K = 105$			570		Peak T [0 to 700]
	102			RT	1.2×10^4	Unpoled Crystal
Lakargiite	$K = 24.6$			RT	1000	Endmember CaZrO_3
Langbeinite	6.9			RT		
Lecontite			14.7	-161	10	Constant Stress
			9.3	-161	10^7 to 10^{10}	Constant Stress
Lueshite*	$K = 1,600$			350	1	Peak T [100 to 460]
	$K = 1,500$			350		Peak T
Macedonite	$K = 9,500$			490		Peak T
	$K = 3,200$			232		Peak T [200 to 265]
	210		126	RT		Constant Stress
	115		51	RT		Constant Strain
Magnesioferrite	$K = 30,000$			RT	0.020	Peak f [0.020 to 900]
	$K = 8.53$			RT		
Natrolite			6.0	RT	1	
Nitratine	$K = 110$			RT	$p = 4.3$ GPa	Peak P [0 to 5.5]
Oxycalciopyrochlore			120	580		Peak T [0 to 580]
		170	500	RT		Peak T [0 to 500]
	180			450		Peak T [0 to 600]
Oxyplumbopyrochlore	$K = 300$			-260	1	Peak T [-270 to 25]
Paratellurite	21.4		24.9	RT		
	22.7			RT		Constant Strain
	22.9		24.7	20	100	Constant Stress
Perovskite	$K = 186$			RT	1	
Proustite	22		22	RT		Constant Strain
	44.5		21.4	RT		Static Measurement
	20		20	RT	2×10^4	
	20.2		20.2	20		Constant Strain
	21.5		22.0	20	1×10^3	Constant Stress
	22			-243.2		
	250		12	-244.5		Monoclinic (m)
Pyrargyrite	21.7		24.7	20	≈ 1	Constant Stress

TABLE 38. Continued

Mineral	K_1	K_2	K_3	T : °C	f: kHz	Notes [T : °C][f: kHz]
Quartz	4.5208		4.6368	27	1	Constant Stress
	4.5208		4.6368	27	10	Constant Stress
			4.435	27		Constant Strain
	4.51		4.60	20	1	
	4.520		4.640	20		Constant Stress
	4.435		4.640	20		Constant Strain
	4.51		4.63	20	9×10^3	Constant Strain
			4.430	-193		Constant Strain
Retgersite	6.2		6.8	RT		
Russellite	3,100		400	920		Peak T [0 to 1000]
Rutile	86		170	RT	100	
Schorl*			6.4	30	100	
Schultenite	42			35		Peak T
Sillénite	50.0			30		Constant Stress
	47			RT		Constant Stress
	42			RT		Constant Strain
	56			RT		Constant Stress
	41			RT		Constant Strain
Sphalerite	10.49			25	0.1	Constant Stress
	9.41			25	1	Constant Stress
	8.37			25	10	Constant Stress
	8.32			25	10	Constant Strain
	8.12			25	100	
	7.29			25	1×10^3	
	7.12			25	1.6×10^4	
	7.92			25	4×10^7	Constant Strain
	8.14			-196		Constant Stress
	8.08			-196		Constant Strain
10% Wurtzite	8.60		8.57	20		Constant Stress
10% Wurtzite	8.58		8.52	20		Constant Strain
Spinel	$K = 8.5$			500		Peak T [0 to 500]
	$K = 8.64$			RT	0.1 to 10	
Stephanite			20	RT	9.2×10^6	Constant Strain
Stibiotantalite			16,000	420		Peak T
	$K = 22$			400		Peak T [250 to 550]
			300 to 450	20		
Stibnite			150	44	10^3	
			108	44	$1 \text{ to } 4.2 \times 10^6$	
Stilleite	$K = 9.1$			RT		
Tausonite	$K = 0.1$			25		
	$K = 700$			RT	2.5×10^9	Peak P [(1 to 7) $\times 10^9$]
	$K = 17,000$			-263		
	$K = 22,000$			-263	100	Peak T [-263 to -168]
Tourmaline			6.4	30	100	Schorl
	6.3		7.1	RT		
	8.2		7.5	RT	1	Constant Stress
Trevorite	$K = 19$			RT		
Wakefieldite-Nd	$K = 100$			22	1	Peak T [2 to 42]

TABLE 38. Continued

Mineral	K_1	K_2	K_3	T : °C	f: kHz	Notes [T : °C][f: kHz]
Wurtzite*	8.64		8.393	25	0.05	
	8.54		8.170	25	1	
	8.58		8.001	25	10	Constant Stress
	8.48		7.877	25	100	
	8.58		8.037	25	300	
0.103:0.897::Mg:Zn	8.25		8.59	20		Constant Strain
0.103:0.897::Mg:Zn	8.31		8.76	20		Constant Stress
	8.92		8.224	-65	0.05	
	8.65		7.912	-65	1	
	8.49		7.877	-65	10	
	8.50		7.895	-65	100	
	8.81		8.090	-65	300	
Zincite	$K = 8.2$			RT		

Notes: K signifies relative dielectric strength, with the subscript representing the x , y , or z axis. T signifies temperature. RT signifies (ambient) room temperature. The frequency f is of the alternating current used to test the crystal. “Constant Strain” signifies measurements taken under constant strain conditions.

“Constant Stress” signifies measurements taken under constant stress conditions. The hysteresis loop in Changbaiite* is not saturated by $6.0 \times 10^6 \text{ V m}^{-1}$ at RT , signifying that the actual value is higher than what is written. Measurements in Diomignite* displayed a critical point at 445°C where the dielectric strength started to rise quickly. Measurements for Ericaite* were taken under a biased electric field of $5 \times 10^3 \text{ V m}^{-1}$. Greenockite* exhibits changes in piezoelectric rates (and therefore also dielectric behavior) with light intensity, as per Ogawa and Kojima (1966). Measurements for Lueshite* were taken under an electric field of $+5 \times 10^3 \text{ V m}^{-1}$. For Schorl*, also see the Tourmaline entry for more numerical data listings. The colons by two of the Wurtzite* entries signify percent ratios. References are listed in Table 40 in Appendix G, p. 230.

TABLE 39. Relative Dielectric Strength (K) of Minerals During Temperature Variation

Mineral	$\Delta K_1/K_1\Delta T$	$\Delta K_3/K_3\Delta T$	T : °C	Notes
Fresnoite	0.05	3.29	RT	Constant Strain
Greenockite	1.92	2.12	-93 to 27	
Proustite*	3.0	5.8	-40 to 20	Constant Stress
	5.3	3.2	-40 to 20	Constant Strain
Pyrargyrite	16.7	8.44	-40 to 20	Constant Stress
Quartz	0.025	0.16	300 to 380	
	-0.029	0.056	140 to 240	
	0.28	0.39	25 to 100	
Sillénite*	$K_1 = 58.26 - (12.48 \times 10^{-2} T) + (3.04 \times 10^{-4} T^2)$		$T > 200$	
	$K_1 = 45.57 + (6.14 \times 10^{-4} T)$		$T = 130$ to 200	
	6		30 to 150	
Sphalerite	3.8	2.2	RT	10% Wurtzite
Wurtzite	1.7	1.8	RT	.10:.90::Mg:Zn

Notes: K signifies relative dielectric strength, with the subscript representing the x , y , or z axis. T signifies temperature. RT signifies (ambient) room temperature. “Constant Strain” signifies measurements taken under constant strain conditions. “Constant Stress” signifies measurements taken under constant stress conditions. Proustite* values ($i=1$ and $i=3$) seem suspect: They appear to have been transposed for stress and strain for one set of measurements. The formulas for Sillénite* take T values in °C. References are listed in Table 40 in Appendix G, p. 230.

TABLE 41. Magnetic Susceptibility (χ) Data for Minerals

Mineral	χ : 10^{-3}	T : °C	Notes [T : °C]
Breithauptite	0.104	<i>RT</i>	
Carrollite	0.07	<i>RT</i>	
Chambersite	0.002	-155	Peak T [-155 to 375]
Clinoferrosilite	31	<i>RT</i>	Peak T
Cuprorhodsite	0.0554	<i>RT</i>	
Demicheleite-Br	-0.0268	-195 to 75	
Demicheleite-Cl	-0.0242	-195 to 75	
Demicheleite-I	-0.0283	-195 to 75	
Ericaite	20	-195	Peak T [-195 to 725]
Eskolaite	1.6	30	Peak T [-200 to 400]
Fayalite	14	-250	Peak T [-269 to -95]
Ferberite	0.00377	20	Peak T [20 to 260]
Franklinite	3	-185	Peak T [-185 to 525]
Hauerite	1.95	20	
	2.51	-225	Néel temperature
Hematite	1.3	<i>RT</i>	
Ilmenite	40	-217	Néel temperature
Kalininite	20	-26 3	Peak T [-269 to 510]
Kamiokite	1.392	<i>RT</i>	
	94.5	-214	Peak T
Karelianite	400	-98	Peak T [-263 to 65]
Krut'aite	0.02	<i>RT</i>	
Löllingite	-0.0064	<i>RT</i>	
Magnesiocoulsonite	0.9	-20	Peak T [-20 to 20]
Magnesioferrite	0.365	425	Peak T [425 to 1075]
Mattagamite	0.313	20	
Nickeline	0.024	> 25	
Nisbite	-0.10	<i>RT</i>	
Penroseite	0.087	25	Endmember NiSe ₂
Pyrite	0.020	<i>RT</i>	
Pyrite Variety: Bravoite	0.095 to 0.55	25	
	0.15 to 0.927	-269	
Pyrophanite	45	-173	Peak T
Siderite	4.7	20	
Srebrodolskite	0.71	450	Peak T
Tistarite	0.076	340	Peak T [-180 to 340]
Uraninite	3.2	-227	Peak T [-253 to -227]
Wüstite	8.4	<i>RT</i>	
Zincochromite	32 to 17	-263 to 27	

Notes: The magnetic susceptibility (χ) of a material is its ability to strengthen (or weaken) an applied magnetic field. T signifies temperature. *RT* signifies (ambient) room temperature. The Néel temperature is a magnetic transition to a paramagnetic state. Data were taken from Landolt-Börnstein New Series volumes (Hellwege and Hellwege, 1970a, 1970b, 1978, 1980; Wijn, 1988, 1991a, 1991b, 1994, 1995, 1996a, 1996b, 2005). Units were converted using the chart in Goldfarb and Fickett (1985). To convert mass and molar magnetic susceptibilities into volume magnetic susceptibilities, density and molecular weight data for minerals were taken from webmineral (Barthelmy, 2012), mindat.org (Ralph and Chau, 2012), as well as from Demartin et al. (2009) for demicheleite-Cl. Cost was prohibitive for obtaining much of the extant, relevant magnetic data available online (e.g., Springer, 2012). Only a small selection is included here.

TABLE 42. Spontaneous Magnetization (M_0) Data for Minerals

Mineral	M_0 : A m ⁻¹	T : °C
Pyrrhotite	6.1	RT
Vaesite	4,400	-269
Xieite	5,000	-183 to 27
	96,000	-273 to -233

Notes: Spontaneous magnetization (M_0) is a measure of magnetic field strength without an externally applied magnetic field. T signifies temperature. RT signifies (ambient) room temperature. References are listed in the notes of Table 41, p. 172. Cost was prohibitive for obtaining much of the extant, relevant magnetic data available online (e.g., Springer, 2012). Only a small selection is included here.

TABLE 43. Saturation Magnetization (M_S) Data for Ferromagnetic Minerals

Mineral	M_S : A m ⁻¹	T : °C	Notes [T : °C]
Coulsonite	179,000	RT	Peak T [75 to 525]
Cuprokalinitite	400,000	525	
Cuprospinel	148,400	RT	
Hematite	≈ 2,000	RT	
Maghemite	370,000	RT	
Magnetite	485,000	11.32	
	492,000	-16.62	
	496,000	-40.41	
	500,000	-64.65	
	504,000	-89.23	
	506,000	-113.44	
	508,000	-141.98	
	509,000	-163.12	
	510,000	-183.26	
	511,000	-211.31	
	511,000	-243.38	
	512,000	-268.94	
Trevorite	245,900	RT	

Notes: Saturation magnetization (M_S) is the field strength needed to reverse the magnetic polarity of a ferromagnetic material. T signifies temperature. RT signifies (ambient) room temperature. References are listed in the notes of Table 41, p. 172. Cost was prohibitive for obtaining much of the extant, relevant magnetic data available online (e.g., Springer, 2012). Only a small selection is included here.

TABLE 44. Magnetostriction Data for Minerals

Mineral	H: A m ⁻¹	Strain
Hematite	625,000	9×10^{-7} Expansive
	-625,000	7×10^{-7} Expansive
	0 to -150,000	2×10^{-7} Contractive

Notes: H is the strength of an applied magnetic field. *T* signifies temperature. Values were obtained at ambient room temperature. References are listed in the notes of Table 41, p. 172. Cost was prohibitive for obtaining much of the extant, relevant magnetic data available online (e.g., Springer, 2012). Only a small selection is included here.

APPENDIX C

MINERALS ARRANGED BY MINERAL GROUP AND CHEMISTRY

TABLE 12. Ferroelectric Mineral Groups, with Known Ferroelectric, Antiferroelectric or Paraelectric Minerals in Bold Type

- <i>Alum Group</i> - Alum-K	Alum-Na	Lanmuchangite	Tschermigite
- <i>Biphosphammite Group</i> - Archerite	Biphosphammite		
- <i>Boracite Group</i> - Boracite Chambersite	Congolite	Ericaite	Trembathite
- <i>Brownmillerite Group</i> - Brownmillerite	Srebrodolskite		
- <i>Cervantite Group</i> - Bismutocolumbite Bismutotantalite	Cervantite Clinocervantite	Stibiocolumbite	Stibiotantalite
- <i>Chalcocite-Digenite Group</i> - Chalcocite	Digenite	Djurleite	Roxbyite
- <i>Chalcostibite Group</i> - Chalcostibite	Emplectite		
- <i>Changbaiite</i> -			
- <i>Chrysoberyl Group</i> - Chrysoberyl	Mariinskite		
- <i>Demicheleite Group</i> - Demicheleite-Br	Demicheleite-Cl	Demicheleite-I	
- <i>Diomignite</i> -			
- <i>Galena Group</i> - Alabandite Altaite	Clausthalite Galena	Ninningerite	Oldhamite
- <i>Gwihabaite</i> -			
- <i>Ice</i> -			
- <i>Koechlinite Group</i> - Koechlinite	Russellite	Tungstibite	
- <i>Niter</i> -			
- <i>Nitratine</i> -			

TABLE 12. Continued

- <i>Perovskite Group</i> - Barioperovskite Isolueshite	Lakargiite Lueshite	Macedonite Megawite	Perovskite Tausonite
Shulamitite is an intermediate mineral between Perovskite and the Brownmillerite – Shrebrodolkite series.			
- <i>Proustite Group</i> - Proustite	Pyrargyrite	Pyrostilpnite	Xanthoconite
- <i>Pyrochlore Supergroup</i> - - <i>Betafite Group</i> - Oxycalciobetafite - <i>Elsmoreite Group</i> - Hydrokenoelsmoreite - <i>Microlite Group</i> - Fluorcalciomicrolite Fluornatromicrolite Hydrokenomicrolite - <i>Pyrochlore Group</i> - Fluorcalciopyrochlore Fluorkenopyrochlore Fluornatropyrochlore - <i>Roméite Group</i> - Cuproroméite Fluorcalcioroméite	Oxyuranobetafite Hydromicrolite Hydroxycalciomicrolite Hydroxykenomicrolite Fluorstrontiopyrochlore Hydropyrochlore Hydroxycalciopyrochlore Fluornatrroméite Hydroxycalcioroméite	Kenoplumbomicrolite Oxycalciomicrolite Hydroxymanganopyrochlore Kenoplumbopyrochlore Oxycalciopyrochlore Oxycalcioroméite	Oxystannomicrolite Oxystibiomicrolite Oxynatropyrochlore Oxyplumbopyrochlore Oxyttropyrochlore-(Y) Oxyplumboroméite
- <i>Rutile Group</i> - Argutite Cassiterite	Paratellurite Plattnerite	Pyrolusite Rutile	Stishovite Tripuhyite
- <i>Schultenite</i> -			
- <i>Sillénite</i> -			
- <i>Stibnite Group</i> - Antimonselite Bismuthinite	Guanajuatite Metastibnite	Stibnite	Pääkkönenite
- <i>Wolframite Group</i> - Ferberite Heftetjernite	Huanzalaite	Hübnerite	Sanmartinite
- <i>Xenotime Group</i> - Chernovite-Y Dreyerite Pretulite	Wakefieldite-Ce Wakefieldite-La	Wakefieldite-Nd Wakefieldite-Y	Xenotime-Y Xenotime-Yb

Notes: Individual italicized mineral names are from "groups" that have only a single member, and thus bear no group name. Minerals in bold type are listed in the references indicated in Table 15 in Appendix G, p. 226.

TABLE 13. Pyroelectric Mineral Groups, with Known Pyroelectric Minerals in Bold Type

- Afwillite -**- Alunite Supergroup -****- Alunite Subgroup -****Alunite**

Ammonioalunite

Beaverite-Zn

Natroalunite**- Beudantite Subgroup -**

Beudantite

Hidalgoite

Kemmlitzite

Svanbergite

Corkite

Hinsdalite

Schlossmacherite

Woodhouseite

Gallobaudantite

- Crandallite Subgroup -

Arsenocrandallite

Crandallite**Goyazite**

Plumbogummite

Arsenogorceixite

Dussertite

Kintoreite

Segnitite

Arsenogoyazite

Gorceixite

Philipsbornite

Springcreekite

- Jarosite Subgroup -**Ammoniojarosite**

Hydroniumjarosite

Natrojarosite**Plumbojarosite****Argentojarosite****Jarosite****- Ardealite -****- Artinite Group -****Artinite**

Chlorartinite

- Batisite Group -**Batisite****Benstonite**

Noonkanbahite

Shcherbakovite

- Bertrandite -**- Beryl Group -**

Bazzite

Beryl

Pezzottaite

Stoppaniite

- Bournonite Group -**Bournonite****Seligmannite**

Součekite

- Brucite Group -**Brucite**

Portlandite

Pyrochroite**- Brushite -****- Burbankite Varieties -****Burbankite**

Calcioburbankite

Strontioburbankite

- Caledonite -**- Cancrinite Group -**

Afghanite

Davyne

Kircherite

Pitiglianoite

Alloriite

Depmeierite

Kyanoxalite

Quadridavyne

Biachellaite

Franzinite

Liottite

Sacrofanite

Bystrite

Giuseppettite

Marinellite

Toukrite

Cancrinite

Hydroxycancrinite

Microsommite

Vishnevite

Cancrisilite

- Childrenite—Eosphorite Series -

TABLE 13. Continued

- Clinohedrite -**- Colemanite -**

- *Coquimbite Group* -
Aluminocoquimbite

Coquimbite

Paracoquimbite

- Creedite -**- Dawsonite -****- Diaboleite -**

- *Donnayite Group* -
Donnayite-Y

Weloganite**- Dyscrasite -****- Elpidite -**

- *Enargite Group* -
Enargite

Petrukite

- *Ettringite Group* -
Bentorite
Buryatite
Carraraite

Charlesite
Ettringite
Hielscherite

Jouravskite
Kottenheimite
Micheelsenite

Sturmanite
Thaumasite

- *Eudialyte Group*
Alluaivite
Andrianovite
Aqualite
Carbokentbrooksit
Davinciite
Dualite
Eudialyte

Feklichevite
Fengchengite
Ferrokentbrooksit
Georgbarsanovite
Golyshevite
Ikranite
Johnsenite-Ce

Kentbrooksit
Khomyakovite
Labyrinthite
Manganoeudialyte
Manganokhomyakovite
Mogovidite
Oneillite

Raslakite
Rastsvetaevite
Taseqite
UM1998-21-SiO:
CaCeClHMnNaZr
Voronkovite
Zirsilite-Ce

- Finnemanite -**- Flagstaffite -****- Fresnoite -**

- *Halotrichite Group* -
Apjohnite
Bilinite

Dietrichite
Halotrichite

Pickeringite

Wupatkiite

- Hartite -

- *Hilgardite Group* -
Hilgardite

Kurgantaite

Leucostaurite

Tyretskite

- Hemimorphite -

TABLE 13. Continued

- Hydrocalumite -**- Innelite -****- Iodargyrite -****- Junitoite -****- Kaliborite -****- Krennerite Polymorphs -**
Calaverite**Krennerite****- Larsenite -****- Leucophanite -****- Liebigite -****- Melanovanadite -****- Meliphanite -****- Mesolite -****- Millerite Group -**
Mäkinenite**Millerite****- Minyulite -****- Moissanite Group -****Moissanite (-6H)**

Moissanite-2H

Moissanite-5H

Moissanite-33R

Moissanite-3C

Moissanite-4H

Moissanite-15R

- Montmorillonite-Vermiculite Group -

Montmorillonite

Vermiculite**- Murmanite Group -****Epistolite****Murmanite**

Vuonnemite

- Muthmannite -**- Nepheline -****- Neptunite -****- Nickeline Group -**

Achavalite

Freboldite

Nickeline**Breithauptite**

Langisite

- Nolanite Group -**Nolanite**

Rinmanite

Kamiokite

- Parkerite -

TABLE 13. Continued

*- Pharmacolite -**- Pinnoite -**- Pirssonite -**- Prehnite -**- Quenselite -**- Röntgenite-Ce -**- Sarcolite -**- Scapolite Group -***Marialite****Meionite**

Silvialite

- Scheelite Group -

Fergusonite-Ce

Fergusonite-Y

Scheelite

Wulfenite

Fergusonite-Nd

Powellite

Stolzite

*- Searlesite -**- Serpentine Group -***Amesite**

Chrysotile

Halloysite-7Å

Manandonite

Antigorite

Cronstedtite**Halloysite-10Å****Nacrite****Berthierine**

Dickite

Kaolinite

Népouite

Brindleyite

Fraipontite

Kellyite

Odinite

Caryopilite

Greenalite

Lizardite

Pecoraite

*- Shortite -**- Sinoite -**- Spangolite -**- Stephanite Group -*

Selenostephanite

Stephanite*- Struvite Group -*

Hazenite

Struvite

Struvite-K

*- Suolunite -**- Swedenborgite -**- Syngenite Group -*

Koktaite

Syngenite*- Tilasite Group -*

Durangite

Maxwellite

Panasqueiraite

Tilasite

Isokite

TABLE 13. Continued

<i>- Tourmaline Supergroup -</i>			
<i>- Alkali Group -</i>			
Buergerite	Elbaite	Luinaite-OH	Povondraite
Chromium-dravite	Fluor-dravite	Olenite	Schorl
Chromo-alumino-	Fluor-elbaite	Oxy-dravite	Tsilaisite
povondraite	Fluor-schorl	Oxy-schorl	Vanadium-dravite
Dravite	K-Tourmaline	Pb-dominant Tourmaline	
<i>- Calcic Group -</i>			
Feruvite	Fluor-liddicoatite	Uvite	
Fluor-feruvite	Liddicoatite		
<i>- X-Vacant Group -</i>			
Foite	Magnesiofoite	Oxy-rossmanite	Rossmannite
<i>- Tyrolite -</i>			
<i>- Uranophane Group -</i>			
Boltwoodite	Natroboltwoodite	Uranophane	β -Uranophane
<i>- Ussingite -</i>			
<i>- Whitlockite Group -</i>			
Bobdownsite	Merrillite	Whitlockite	
Ferromerrillite	Strontiowhitlockite		
<i>- Wurtzite Group -</i>			
Buseckite	Greenockite	Rambergite	Wurtzite
Cadmoselite			
<i>- Zeolite Group -</i>			
Amicite	Erionite-Ca	Heulandite-K	Paulingite-K
Ammonioleucite	Erionite-K	Heulandite-Na	Paulingite-Na
Analcime	Erionite-Na	Heulandite-Sr	Perliaite
Barrerite	Faujasite-Ca	Hsianghualite	Phillipsite-Ca
Bellbergite	Faujasite-Mg	Laumontite	Phillipsite-K
Bikitaite	Faujasite-Na	Leucite	Phillipsite-Na
Boggsite	Ferrierite-K	Lévyne-Ca	Pollucite
Brewsterite-Ba	Ferrierite-Mg	Lévyne-Na	Roggianite
Brewsterite-Sr	Ferrierite-Na	Lovdarite	Scolecite
Chabazite-Ca	Flörkeite	Maricopaite	Stellerite
Chabazite-K	Garronite	Mazzite-Mg	Stilbite-Ca
Chabazite-Mg	Gaultite	Mazzite-Na	Stilbite-Na
Chabazite-Na	Gismondine-Ba	Merlinoite	Terranovaite
Chabazite-Sr	Gismondine-Ca	Mesolite	Thomsonite-Ca
Chiavennite	Gmelinite-Ca	Montesommaite	Thomsonite-Sr
Clinoptilolite-Ca	Gmelinite-K	Mordenite	Thornasite
Clinoptilolite-K	Gmelinite-Na	Mutinaite	Tschernichite
Clinoptilolite-Na	Gobbsite	Natrolite	Tschörtnerite
Cowlesite	Gonnardite	Offretite	Wairakite
Dachiardite-Ca	Goosecreekite	Pahasapaite	Weinebeneite
Dachiardite-Na	Gottardiite	Paranatrolite	Wenkite
Direnzoite	Harmotome	Parthéite	Willhendersonite
Edingtonite	Heulandite-Ba	Paulingite-Ca	Yugawaralite
Epistilbite	Heulandite-Ca		

TABLE 13. Continued

<i>- Zincite Group -</i>			
Bromellite	Zincite		
<i>- Zinkenite-Scainiite Group -</i>			
Chovanite	Pillaite	Tazieffite	Zinkenite
Pellouzite	Scainiite		

Notes: Individual italicized mineral names are from "groups" that have only a single member, and thus bear no group name. Minerals in bold type are listed in the references indicated in Table 16 in Appendix G, p. 227.

TABLE 14. Piezoelectric Mineral Groups, with Known Piezoelectric Minerals in Bold Type

- Aminoffite -**- Apatite Supergroup -****- Apatite Subgroup -**

Carbonate-rich Fluorapatite

Chlorapatite

Fluorstrophite

Carbonate-rich Hydroxylapatite

Fluorapatite

Hydroxylapatite

- Pyromorphite Subgroup -**Mimetite****Pyromorphite**

Vanadinite

- Svabite Subgroup -

Fluorophosphohedyphane

Hedyphane

Phosphohedyphane

Svabite

- Baryte Group -

Anglesite

Baryte

Celestite

Olsacherite**- Bastnäsite Group -****Bastnäsite-Ce**

Bastnäsite-Y

Hydroxylbastnäsite-Ce

Bastnäsite-La

- Bavenite–Bohseite Series -**- Berlinite Group -**

Alarsite

Berlinite

Rodolicoite

- Chalcopyrite Group -

Chalcopyrite

Gallite

Lenaite

Roquesite

Eskebornite

Laforêtite

- Cinnabar Polymorphs -**Cinnabar**

Hypercinnabar

Metacinnabar

- Diopside -**- Edingtonite -****- Epsomite Group -****Epsomite****Goslarite****Morenosite****- Eulytine -****- Helvine Group -**

Danalite

Genthelvine

Helvine**- Jeremejevite -****- Langbeinite Group -**

Efremovite

Langbeinite

Manganolangbeinite

- Leucophanite -**- Melilite Group -**

Åkermanite

Gehlenite

Hardystonite

Okayamalite

Alumoåkermanite

Gugiaite

TABLE 14. Continued

- Nitrobarite -**- Pharmacosiderite Supergroup -****- Ivanyukite Group -**

Ivanyukite-Cu	Ivanyukite-K	Ivanyukite-Na-C
- Pharmacocoalumite Group -		
Bariopharmacocoalumite	Natropharmacocoalumite	Pharmacocoalumite
- Pharmacosiderite Group -		
Bariopharmacosiderite	Natropharmacosiderite	Strontiopharmacosiderite
Hydroniumpharmacosiderite	Pharmacosiderite	

- Quartz Polymorphs -

Coesite	Mogánite	β-Quartz	Stishovite
Cristobalite	α-Quartz	Seifertite	Tridymite

- Retgersite Polymorphs -

Nickelhexahydrite	Retgersite
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- Rhodizite Group -

Londonite	Rhodizite
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- Sal Ammoniac Group -

Lafossaite	Sal Ammoniac
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- Selenium Group -

Selenium	Tellurium
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- Sodalite Group -

Haüyne	Nosean	Tsaregorodtsevite	Vladimirivanovite
Lazurite	Sodalite	Tugtupite	

- Sphalerite Group -

Coloradoite	Metacinnabar	Stilleite	
Hawleyite	Sphalerite	Tiemannite	

- Topaz -**- Zeolite Group -**

Amicite	Clinoptilolite-K	Ferrierite-Na	Heulandite-K
Ammonioleucite	Clinoptilolite-Na	Flörkeite	Heulandite-Na
Analcime	Cowlesite	Garronite	Heulandite-Sr
Barrerite	Dachiardite-Ca	Gaultite	Hsianghualite
Bellbergite	Dachiardite-Na	Gismondine-Ba	Laumontite
Bikitaite	Direnzoite	Gismondine-Ca	Leucite
Boggsite	Edingtonite	Gmelinite-Ca	Lévyne-Ca
Brewsterite-Ba	Epistilbite	Gmelinite-K	Lévyne-Na
Brewsterite-Sr	Erionite-Ca	Gmelinite-Na	Lovdarite
Chabazite-Ca	Erionite-K	Gobbsite	Maricopaite
Chabazite-K	Erionite-Na	Gonnardite	Mazzite-Mg
Chabazite-Mg	Faujasite-Ca	Goosecreekite	Mazzite-Na
Chabazite-Na	Faujasite-Mg	Gottardiite	Merlinoite
Chabazite-Sr	Faujasite-Na	Harmotome	Mesolite
Chiavennite	Ferrierite-K	Heulandite-Ba	Montesommaite
Clinoptilolite-Ca	Ferrierite-Mg	Heulandite-Ca	Mordenite

TABLE 14. Continued

- Zeolite Group, continued -

Mutinaite	Paulingite-Na	Stellerite	Tschörtnerite
Natrolite	Perliaite	Stilbite-Ca	Wairakite
Offretite	Phillipsite-Ca	Stilbite-Na	Weinebeneite
Pahasapaite	Phillipsite-K	Terranovaite	Wenkite
Paranatrolite	Phillipsite-Na	Thomsonite-Ca	Willhendersonite
Parthéite	Pollucite	Thomsonite-Sr	Yugawaralite
Paulingite-Ca	Roggianite	Thornasite	
Paulingite-K	Scolecite	Tschernichite	

- Zunyite -

Notes: Individual italicized mineral names are from "groups" that have only a single member, and thus bear no group name. Minerals in bold type are listed in the references indicated in Table 17 in Appendix G, p. 228.

TABLE 18. The 10th Edition Nickel-Strunz Classification of Minerals, with Ferroelectric, Pyroelectric or Piezoelectric Minerals in Bold Type and Thermoelectric Minerals in *Italic*

1.A - ELEMENTS: METALS AND INTERMETALLIC ALLOYS

Copper-Cupralite Family	Indium-Tin Family	1.AD.20a	Platinum Group Elements (PGE)	1.AG.45
1.AA.05	1.AC.05	1.AD.20b		1.AG.50
1.AA.10a	1.AC.10	1.AD.25	1.AF.05	1.AG.55
1.AA.10.b	1.AC.15	1.AD.30	1.AF.10	1.AG.60
1.AA.15				1.AG.65
1.AA.20		Iron-Chromium Family	PGE-Metal Alloys	1.AG.70
1.AA.25	Mercury-Amalgam Family	1.AE.05	1.AG.05	
	1.AD.05	1.AE.10	1.AG.10	Miscellaneous Elements, Alloys
Zinc-Brass Family	1.AD.10	1.AE.15	1.AG.15	
1.AB.05	1.AD.15a	1.AE.20	1.AG.20	1.AH
1.AB.10	1.AD.15b	1.AE.25	1.AG.25	
1.AB.10a	1.AD.15c	1.AE.30	1.AG.30	
1.AB.10b	1.AD.15d		1.AG.35	
			1.AG.40	

1.B - ELEMENTS: METALLIC CARBIDES, SILICIDES, NITRIDES AND PHOSPHIDES

Carbides	1.BA.30	1.BB.15	Nitrides	Phosphides
1.BA.05		1.BB.20	1.BC.	1.BD.05
1.BA.10	Silicides	1.BB.25	1.BC.05	1.BD.10
1.BA.15	1.BB.	1.BB.30	1.BC.10	1.BD.15
1.BA.20	1.BB.05	1.BB.35	1.BC.15	1.BD.20
1.BA.25	1.BB.10	1.BB.40	1.BC.20	

1.C - ELEMENTS: METALLOIDS AND NONMETALS

Arsenic Group Elements	Carbon-Silicon Family	1.CB.10a	Sulfur-Selenium-Iodine	Se
1.CA.05	1.CB.05a	1.CB.10b	1.CC.05	Tellurium
1.CA.10	1.CB.05b	1.CB.15	<u>1.CC.10</u>	Te
1.CA.15	1.CB.05c		Selenium	

1.D - ELEMENTS: NONMETALLIC CARBIDES AND NITRIDES

Nonmetallic Carbides	Moissanite	Nonmetallic Nitrides	<u>1.DB.10</u>
<u>1.DA.</u>	SiC	1.DB.05	Sinoite
			Si₂N₂O

2.A - SULFIDES AND SULFOSALTS: ALLOYS

Alloys of Metalloids with Copper, Silver or Gold	2.AA.30	2.AB.15	2.AC.10c	2.AC.25e
	<u>2.AA.35</u>		2.AC.15a	2.AC.25f
	Dyscrasite	Alloys of Metalloids with Platinum Group Elements	2.AC.15b	2.AC.30
	Ag₃Sb		2.AC.20a	2.AC.35a
2.AA.10a	2.AA.40		2.AC.20b	2.AC.35b
2.AA.10b	2.AA.45		2.AC.20c	2.AC.40
2.AA.10d			2.AC.25a	2.AC.45a
2.AA.15	Nickel-Metalloid	2.AC.05a	2.AC.25b	2.AC.45b
2.AA.20	Alloys	2.AC.05b	2.AC.25c	2.AC.45c
2.AA.25	2.AB.10	2.AC.10a	2.AC.25d	
		2.AC.10b		

TABLE 18. Continued

2.B - SULFIDES AND SULFOSALTS: METAL SULFIDES, METAL:SULFUR > 1:1 (MAINLY 2:1)

With Copper,	2.BA.55	Palladium,	2.BC.60	2.BD.50
Silver and Gold	2.BA.60	Platinum and	2.BC.65	2.BD.55
<u>2.BA.05</u>	2.BA.65	Similar		
Chalcocite	2.BA.70	2.BC.	With Mercury and	With Lead
Cu₂S	2.BA.75	2.BC.05	Thallium	and Bismuth
2.BA.10	2.BA.80	2.BC.10	2.BD.	2.BE.05
2.BA.15		2.BC.15	2.BD.05	2.BE.10
2.BA.20	With Nickel	2.BC.20	2.BD.10	2.BE.15
2.BA.25	2.BB.	2.BC.25	2.BD.15	<u>2.BE.20</u>
2.BA.30	2.BB.05	2.BC.30	2.BD.20	Parkerite
2.BA.35	2.BB.10	2.BC.35	2.BD.25	Ni₃Bi₂S₂
2.BA.40	2.BB.15	2.BC.40	2.BD.30	2.BE.25
2.BA.40d		2.BC.45	2.BD.35	2.BE.30
2.BA.45	With	2.BC.50	2.BD.40	
2.BA.50	Rhodium,	2.BC.55	2.BD.45	

2.C - SULFIDES AND SULFOSALTS: METAL SULFIDES, METAL:SULFUR = 1:1 AND SIMILAR

With Copper	Tiemannite	<u>2.CB.45</u>	With Nickel,	2.CC.25
2.CA.05a	HgSe	Cadmoselite	Iron, Cobalt,	2.CC.30
2.CA.05b	2.CB.05b	CdSe	Platinum Group	2.CC.35a
2.CA.05c	2.CB.05c	Greenockite	Elements and	2.CC.35b
2.CA.05d	<u>2.CB.10a</u>	CdS	Similar	
2.CA.10	Gallite	Wurtzite	2.CC.	With Tin,
2.CA.15	CuGaS₂	(Zn,Fe)S	<u>2.CC.05</u>	Lead,
	Roquesite	2.CB.55a	Breithauptite	Mercury and
With Zinc,	CuInS₂	2.CB.55b	NiSb	Similar
Iron, Copper,	2.CB.10b	2.CB.60	Nickeline	2.CD.05
Silver and	2.CB.15a	2.CB.65	NiAs	<u>2.CD.10</u>
Similar	2.CB.15b	2.CB.70	<u>2.CC.10</u>	Altaite
2.CB.05	2.CB.15c	2.CB.75	Pyrrhotite	PbTe
<u>2.CB.05a</u>	2.CB.20	2.CB.80	Fe_{1-(0 to 0.17)S}	<u>2.CD.15a</u>
Sphalerite	2.CB.30	<u>2.CB.85</u>	2.CC.15	Cinnabar
ZnS	2.CB.35a	Muthmannite	<u>2.CC.20</u>	HgS
Stilleite	2.CB.35b	AuAgTe₂	Millerite	2.CD.15b
ZnSe	2.CB.40		NiS	

2.D - SULFIDES AND SULFOSALTS: METAL:SULFUR = 3:4 AND 2:3

Metal:Sulfur = 3:4	<i>(Cu,Fe)Rh₂S₄</i>	<i>Siegenite</i>	<u>2.DB.05</u>	2.DB.30
<u>2.DA.05</u>	<i>Daubréelite</i>	<i>CoNi₂S₄</i> –	Bismuthinite	2.DB.35
<i>Cadmoindite</i>	<i>FeCr₂S₄</i>	<i>NiCo₂S₄</i>	Bi₂S₃	
<i>CdIn₂S₄</i>	<i>Indite</i>	2.DA.10	Stibnite	Variable
<i>Carrollite</i>	<i>FeIn₂S₄</i>	2.DA.15	Sb₂S₃	Metal:Sulfur
<i>Cu(Co,Ni)₂S₄</i>	<i>Kalininite</i>	2.DA.20	2.DB.10	Ratio
<i>Cuprokalininite</i>	<i>ZnCr₂S₄</i>	2.DA.25	2.DB.15	2.DC.05
<i>CuCr₂S₄</i>	<i>Linnaeite</i>		2.DB.20	
<i>Cuprorhodsite</i>	<i>Co₃S₄</i>	Metal:Sulfur = 2:3	2.DB.25	

TABLE 18. Continued

2.E - SULFIDES AND SULFOSALTS: METAL SULFIDES, METAL:SULFUR $\leq$ 1:2

Metal:Sulfur =	2.EA.20	Elements and	2.EB.10e	2.EB.35
1:2 with Copper,	2.EA.25	Similar	2.EB.10f	
Silver and Gold	2.EA.30	2.EB.05a	2.EB.15a	Metal:Sulfur
2.EA.05		2.EB.05b	2.EB.15b	= 1:(>2)
2.EA.10	Metal:Sulfur =	2.EB.10a	2.EB.15c	2.EC.05
<u>2.EA.15</u>	1:2 with Iron,	2.EB.10b	2.EB.20	2.EC.10
Krennerite	Cobalt, Nickel,	2.EB.10c	2.EB.25	
(Au,Ag)Te₂	Platinum Group	2.EB.10d	2.EB.30	

2.F - SULFIDES AND SULFOSALTS: SULFIDES OF ARSENIC, ALKALIES; SULFIDES WITH HALIDE, OXIDE, HYDROXIDE AND H₂O

With Arsenic,	2.FA.35	With Chlorine,	2.FC.20c	2.FD.05
Antimony and	2.FA.40	Bromine and	<u>2.FC.25</u>	2.FD.10
Sulfur		Iodine (Halide-	Demicheleite-Br	2.FD.20
2.FA.05	With Alkalies,	Sulfides)	BiSBr	2.FD.25
2.FA.10	Without Chlorine	2.FC.05	Demicheleite-Cl	2.FD.30
2.FA.15a	and Similar	2.FC.10	BiSCl	2.FD.35
2.FA.15b	Halides	2.FC.15a	Demicheleite-I	2.FD.40
2.FA.15c	2.FB.05	2.FC.15b	BiSI	2.FD.45
2.FA.15d	2.FB.10	2.FC.15c		2.FD.50
2.FA.20	2.FB.15	2.FC.15d	With Oxygen,	
2.FA.25	2.FB.20	2.FC.20a	OH and H ₂ O	
2.FA.30	2.FB.25	2.FC.20b	2.FD.	

2.G - SULFIDES AND SULFOSALTS: SULFARSENITES, SULFANTIMONITES AND SULFBISMUTHITES

Neso-Sulfarsenites	2.GA.15	Seligmannite	2.GB.15	2.GC.35
and Similar	2.GA.20	PbCuAsS₃	2.GB.20	2.GC.40a
Without	2.GA.25			2.GC.40b
Additional Sulfur	2.GA.30	Neso-Sulfarsenites	Poly-Sulfarsenites	2.GC.40c
<u>2.GA.05</u>	2.GA.35	and Similar with	2.GC.05	2.GC.40d
Proustite	2.GA.40	Additional Sulfur	2.GC.10	2.GC.40e
Ag₃AsS₃	2.GA.45	2.GB.05	2.GC.15	2.GC.45
Pyrargyrite	<u>2.GA.50</u>	<u>2.GB.10</u>	2.GC.20	2.GC.50
Ag₃SbS₃	Bournonite	Stephanite	2.GC.25	
2.GA.10	CuPbSbS₃	Ag₃SbS₄	2.GC.30	

2.H - SULFIDES AND SULFOSALTS: SULFOSALTS OF SNS ARCHETYPE

With Copper,	With Copper,	2.HB.20a	2.HC.05e	2.HC.35
Silver and Iron,	Silver, Iron, Tin	2.HB.20b	2.HC.05f	2.HC.40
Without Lead	and Lead	2.HB.20c	2.HC.05g	
<u>2.HA.05</u>	2.HB.05	2.HB.20d	2.HC.10a	With
Chalcostibite	2.HB.05a	2.HB.20e	2.HC.10b	Thallium
CuSbS₂	2.HB.05b		2.HC.10c	2.HD.05
2.HA.10	2.HB.05c	With Only Lead	2.HC.10d	2.HD.15
2.HA.20	2.HB.10a	2.HC.05a	2.HC.15	2.HD.20
2.HA.25	2.HB.10b	2.HC.05b	2.HC.20	2.HD.25
	2.HB.10c	2.HC.05c	2.HC.25	2.HD.30
	2.HB.15	2.HC.05d	2.HC.30	2.HD.35

TABLE 18. Continued

2.H - SULFIDES AND SULFOSALTS: SULFOSALTS OF SNS ARCHETYPE, CONTINUED

With Thallium	2.HD.50	With Alkalies	With SnS and	2.HF.25a
(Continued)	2.HD.55	and H ₂ O	PbS Archetype	2.HF.25b
2.HD.40	2.HD.60	2.HE.05	Structure Units	2.HF.30
2.HD.45		2.HE.10	2.HF.20	

2.J - SULFIDES AND SULFOSALTS: SULFOSALTS OF PBS ARCHETYPE

Galena	2.JA.10a	2.JB.15	2.JB.30c	2.JB.55
Derivatives with	2.JA.10b	2.JB.20	<u>2.JB.35a</u>	2.JB.60
Little or No Lead	2.JA.10c	2.JB.25a	Zinkenite	2.JB.65
2.JA.05	2.JA.10d	2.JB.25b	Pb₉Sb₂₂S₄₂	
2.JA.05a	2.JA.10e	2.JB.25c	2.JB.35b	Galena
2.JA.05b	2.JA.15	2.JB.25d	2.JB.35d	Derivatives
2.JA.05c	2.JA.20	2.JB.25f	2.JB.35e	with Thallium
2.JA.05d		2.JB.25g	2.JB.40	2.JC.05
2.JA.05e	Galena	2.JB.25h	2.JB.40a	2.JC.10
2.JA.05f	Derivatives with	2.JB.25i	2.JB.40b	2.JC.25e
2.JA.05g	Lead	2.JB.25j	2.JB.40c	2.JC.40a
2.JA.05h	2.JB.05	2.JB.30a	2.JB.40d	
2.JA.05i	2.JB.10	2.JB.30b	2.JB.40e	

2.K - SULFIDES AND SULFOSALTS: SULFARSENATES AND SULFANTIMONATES

Sulfarsenates with	<u>2.KA.05</u>	2.KA.10	Sulfarsenates with
(As,Sb)S ₄	Enargite	2.KA.15	Additional Sulfur
Tetrahedra	Cu₃AsS₄		2.KB.05

2.L - SULFIDES AND SULFOSALTS: UNCLASSIFIED SULFOSALTS

Without Essential	2.LA.25	2.LA.50	With Essential	2.LB.40
Lead	2.LA.30	2.LA.55	Lead	2.LB.45
2.LA.10	2.LA.35	2.LA.60	2.LB.05	
2.LA.15	2.LA.40	2.LA.65	2.LB.30	
2.LA.20	2.LA.45		2.LB.35	

2.M - SULFIDES AND SULFOSALTS: OXYSULFOSALTS

Oxysulfosalts	2.MA.05	2.MA.10
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3.A - HALIDES: SIMPLE HALIDES WITHOUT H₂O

Metal:Halogen =	3.AA.20	3.AA.45	3.AB.05	Metal:Halo-
1:1, 2:3, 3:5 and	<u>3.AA.25</u>	3.AA.50	3.AB.10	gen = 1:3
Similar	Sal	3.AA.55	3.AB.15	3.AC.05
3.AA.05	Ammoniac	3.AA.60	3.AB.20	3.AC.10
<u>3.AA.10</u>	NH₄Cl		3.AB.25	3.AC.15
Iodargyrite	3.AA.30	Metal:Halogen =	3.AB.30	3.AC.20
AgI	3.AA.35	1:2	3.AB.35	
3.AA.15	3.AA.40	3.AB.		

TABLE 18. Continued

3.B - HALIDES: SIMPLE HALIDES WITH H₂O

Metal:Halogen = 1:1 and 2:3	Metal:Halogen = 1:2	3.BB.25	3.BC.05	3.BD.10
3.BA.05	3.BB.05	3.BB.30		3.BD.15
3.BA.10	3.BB.10	3.BB.35	Simple Halides with H ₂ O and	3.BD.20
	3.BB.15	Metal:Halogen =	Additional OH	3.BD.25
	3.BB.20	1:3	3.BD.05	

3.C - HALIDES: COMPLEX HALIDES

Borofluorides	Soro- Aluminofluorides	Tecto- Aluminofluorides	Ca₃SO₄Al₂ F₈(OH)₂ •2H₂O	Manganese and Copper; X = Halogen
3.CA.05	3.CC.05	3.CF.05	3.CG.20	3.CJ.05
3.CA.10	3.CC.10	3.CF.10	3.CG.25	3.CJ.10
Neso- Aluminofluorides	3.CC.15	3.CF.15		3.CJ.15
3.CB.05	3.CC.20		Silicofluorides	3.CJ.20
3.CB.15	Ino- Aluminofluorides	Alumino- fluorides with	3.CH.05	3.CJ.25
3.CB.20	3.CD.05	CO ₃ , SO ₄ and	3.CH.10	3.CJ.30
3.CB.25	3.CD.10	PO ₄	3.CH.15	
3.CB.30		3.CG.05	3.CH.20	Halides of
3.CB.35		3.CG.10	3.CH.25	Bismuth and
3.CB.40	Phyllo- Aluminofluorides	<u>3.CG.15</u>		Similar
3.CB.45	3.CE.05	Creedite	With MX ₆ Complexes; M = Iron,	3.CK.05
3.CB.50				

3.D - HALIDES: OXYHALIDES, HYDROXYHALIDES AND RELATED DOUBLE HALIDES

With Copper and Similar, Without Lead	3.DA.60	3.DB.45	3.DC.45	3.DD.25
3.DA.05	With Lead, Copper and Similar	3.DB.50	3.DC.50	3.DD.30
3.DA.10a	3.DB.	With Lead, Arsenic,	3.DC.55	3.DD.35
3.DA.10b	<u>3.DB.05</u>	Antimony and	3.DC.60	3.DD.40
3.DA.10c	Diaboleite	Bismuth, Without	3.DC.65	3.DD.45
3.DA.10d	Pb₂CuCl₂	Copper	3.DC.70	3.DD.50
3.DA.15	(OH)₄	3.DC.05	3.DC.75	3.DD.55
3.DA.20	3.DB.10	3.DC.10	3.DC.80	3.DD.60
3.DA.25	3.DB.15	3.DC.15	3.DC.85	3.DD.65
3.DA.30	3.DB.20	3.DC.20	3.DC.90	
3.DA.35	3.DB.25	3.DC.25	3.DC.95	With Rare Earth
3.DA.40	3.DB.30	3.DC.30	With Mercury	Elements
3.DA.45	3.DB.35	3.DC.35	3.DD.05	3.DE.05
3.DA.50	3.DB.40	3.DC.37	3.DD.10	
3.DA.55		3.DC.40	3.DD.15	
			3.DD.20	

TABLE 18. Continued

4.A - OXIDES: METAL:OXYGEN = 2:1 AND 1:1

Cation:Anion (Metal:Oxygen) = 2:1 (and 1.8:1) <u>4.AA.05</u> Ice H₂O 4.AA.10 4.AA.15	Metal:Oxygen = 1:1 (and up to 1:1.25) with Small to Medium-Sized Cations Only 4.AB.05 4.AB.10 4.AB.15	<u>4.AB.20</u> Bromellite BeO Zincite (Zn,Mn,Fe)O 4.AB.25 4.AB.30	Metal:Oxygen = 1:1 (and up to 1:1.25) with Large Cations (± Smaller Ones) <u>4.AC.05</u>	Swedenborg- ite NaBe₄SbO₇ 4.AC.10 4.AC.15 4.AC.20 4.AC.25
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4.B - OXIDES: METAL:OXYGEN = 3:4 AND SIMILAR

With Small and Medium-Sized Cations <u>4.BA.05</u> Mariinskite BeCr₂O₄ 4.BA.05	With Only Medium-Sized Cations <u>4.BB.05</u> <i>Coulsonite</i> <i>FeV₂O₄</i> <i>Cuprospinel</i> <i>CuFe₂O₄</i>	<i>Jacobsite</i> <i>MnFe₂O₄</i> <i>Magnesiocoulsonite</i> <i>MgV₂O₄</i> <i>Trevorite</i> <i>NiFe₂O₄</i> 4.BB.10 4.BB.15	4.BB.20 4.BB.25 With Medium- Sized and Large Cations 4.BC.05 4.BC.10	With Only Large Cations 4.BD.05
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4.C - OXIDES: METAL:OXYGEN = 2:3, 3:5 AND SIMILAR

With Small Cations 4.CA	4.CB.35 <u>4.CB.40</u> Nolanite (V,Fe,Fe,T)₁₀ O₁₄(OH)₂ 4.CB.45 4.CB.50 4.CB.55 4.CB.60 4.CB.65 <u>4.CB.70</u> Sillénite	Bi₁₂SiO₂₀ 4.CB.75 4.CB.80 With Large and Medium-Sized Cations 4.CC.05 4.CC.10 4.CC.15 4.CC.20 4.CC.25	<u>4.CC.30</u> Barioperov- skite BaTiO₃ Lakargiite Ca(Zr,Sn,Ti)O₃ Lueshite NaNbO₃ Perovskite CaTiO₃ <u>4.CC.35</u> Macedonite	PbTiO₃ Tausonite SrTiO₃ 4.CC.40 4.CC.45 4.CC.50 4.CC.55 4.CC.60
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4.D - OXIDES: METAL:OXYGEN = 1:2 AND SIMILAR

With Small Cations, Silica Family <u>4.DA.05</u> Quartz SiO₂ 4.DA.10 4.DA.15 4.DA.20 4.DA.25 4.DA.30 4.DA.35 4.DA.40 4.DA.45	4.DA.50 With Medium- Sized Cations and Chains of Edge- Sharing Octahedra <u>4.DB.05</u> Cassiterite SnO₂ Pyrolusite MnO₂ 4.DB.10 4.DB.15a 4.DB.15b	4.DB.15c 4.DB.20 4.DB.25 <u>4.DB.30</u> Heftetjernite ScTaO₄ 4.DB.35 4.DB.40 4.DB.45 4.DB.50 4.DB.55 4.DB.60	With Medium- Sized Cations and Sheets of Edge- Sharing Octahedra 4.DC.05 4.DC.10 With Medium- Sized Cations and Frameworks of Edge-Sharing Octahedra 4.DD.05 4.DD.10	With Medium- Sized Cations, with Various Polyhedra 4.DE.05 4.DE.10 <u>4.DE.15</u> Koechlinite Bi₂MoO₆ Russellite Bi₂WO₆ 4.DE.20
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TABLE 18. Continued

4.D - OXIDES: METAL:OXYGEN = 1:2 AND SIMILAR, CONTINUED

With Medium-Sized Cations, with Various Polyhedra (Continued)	Cations and Dimers and Trimers of Edge-Sharing Octahedra	With Large ($\pm$) Medium-Sized) Cations and Sheets of Edge-Sharing Octahedra	4.DH.25 4.DH.30 4.DH.35 4.DH.40 4.DH.45	4.DK.10
<u>4.DE.25</u>	<u>4.DF.05</u>			
Paratellurite	<u>4.DF.10</u>			
TeO₂	Changbaiite			
<u>4.DE.30</u>	PbNb₂O₆	4.DH.05	With Large ($\pm$) Medium-Sized)	With Large ($\pm$) Medium-Sized)
Cervantite	4.DF.15	4.DH.10	Cations and Polyhedral Frameworks	Cations and Fluorite-Type Structures
Sb₂O₄		<u>4.DH.15</u>		4.DL.05 4.DL.10
Clinocervantite	With Large ($\pm$) Medium-Sized)	Oxycalcipyrochlore		
Sb₂O₄		Ca₂Nb₂O₇	4.DJ.05	With Large ($\pm$) Medium-Sized)
Stibiocolumbite	Cations and Chains of Edge-Sharing Octahedra	Oxyplumbopyrochlore		Cations, Unclassified
Sb(Nb,Ta)O₄		Pb₂Nb₂O₇	With Large ($\pm$) Medium-Sized)	4.DM.05
Stibiotantalite	4.DG.05	<u>4.DH.20</u>	Cations and Tunnel Structures	4.DM.15
Sb(Ta,Nb)O₄	4.DG.10	Hydroxycalcioroméite	4.DK.05	4.DM.20
4.DE.35	4.DG.15	(Ca,Sb)₂(Sb,Fe,Ti)₂O₆(OH)	4.DK.05a 4.DK.05b	4.DM.25
With Large ($\pm$) Medium-Sized)	4.DG.20			

4.E - OXIDES: METAL:OXYGEN $\leq$ 1:2

Metal:Oxygen $\leq$ 1:2	4.EA
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4.F - OXIDES: HYDROXIDES WITHOUT VANADIUM OR URANIUM

Hydroxides with OH, Without H ₂ O, with Corner-Sharing Tetrahedra	4.FC.15 4.FC.20 4.FC.25	Brucite Mg(OH)₂ Pyrochroite Mn(OH)₂	Hydroxides with OH, Without H ₂ O, Unclassified	Hydroxides with H ₂ O $\pm$ OH, with Chains of Edge-Sharing Octahedra
4.FA.05a	Hydroxides with OH, Without H ₂ O, with Chains of Edge-Sharing Octahedra	4.FE.10	4.FG.05	4.FK.05
4.FA.05b		4.FE.15	4.FG.10	
4.FA.10		4.FE.20	4.FG.15	
		4.FE.25		
Hydroxides with OH, Without H ₂ O, with Insular Octahedra	4.FD.05	<u>4.FE.30</u>	Hydroxides with H ₂ O $\pm$ OH, with Insular Octahedra	Hydroxides with H ₂ O $\pm$ OH, with Sheets of Edge-Sharing Octahedra
4.FB.	4.FD.10	Quenselite PbMnO₂(OH)	4.FH.05	4.FL.
4.FB.05	4.FD.15	4.FE.35		4.FL.05
4.FB.10	4.FD.20	4.FE.40	Hydroxides with H ₂ O $\pm$ OH, with Corner-Sharing Octahedra	<u>4.FL.10</u>
		4.FE.45		Hydrocalumite
Hydroxides with OH, Without H ₂ O, with Corner-Sharing Octahedra	Hydroxides with OH, Without H ₂ O, with Sheets of Edge-Sharing Octahedra	Hydroxides with OH, Without H ₂ O, with Various Polyhedra	4.FJ.05 4.FJ.10 4.FJ.15 4.FJ.20	Ca₂Al(OH)₇•2H₂O
4.FC.05		4.FF.05		4.FL.15
4.FC.10	<u>4.FE.05</u>			4.FL.20

TABLE 18. Continued

4.F - OXIDES: HYDROXIDES WITHOUT VANADIUM OR URANIUM, CONTINEUD

Hydroxides with	4.FL.35	4.FL.80	4.FM.25	of Corner
H ₂ O ± OH, with	4.FL.40	4.FL.85	4.FM.30	and/or Face-
Sheets of Edge-	4.FL.45		4.FM.35	Sharing
Sharing	4.FL.55	Hydroxides		Octahedra
Octahedra	4.FL.60	with H ₂ O ±	Hydroxides	4.FN.05
(Continued)	4.FL.65	OH,	with H ₂ O ±	
4.FL.25	4.FL.70	Unclassified	OH, with	
4.FL.30	4.FL.75	4.FM.15	Frameworks	

4.G - OXIDES: URANYL HYDROXIDES

Without	(Potassium,	4.GB.15	4.GB.60	Hexagonal
Additional	Calcium, Barium,	4.GB.20	4.GB.65	Polyhedra
Cations	Lead and Similar)	4.GB.25	4.GB.70	4.GC.05
4.GA.05	with Mainly	4.GB.30		4.GC.10
4.GA.10	UO ₂ (O,OH) ₅	4.GB.35	With	4.GC.15
4.GA.15	Pentagonal	4.GB.40	Additional	
	Polyhedra	4.GB.45	Cations with	
With Additional	4.GB.05	4.GB.50	Mainly	
Cations	4.GB.10	4.GB.55	UO ₂ (O,OH) ₆	

4.H - OXIDES: V [5,6] VANADATES

V [> 4] Neso-	4.HB.40	4.HD.20	4.HE.30	4.HG.15
Vanadates		4.HD.25	4.HE.35	4.HG.20
4.HA	V [6] Soro-	4.HD.30	4.HE.40	4.HG.25
	Vanadates			4.HG.30
Uranyl Soro-	4.HC.05	Phyllo-	Tecto-	4.HG.35
Vanadates	4.HC.10	Vanadates	Vanadates	4.HG.40
4.HB.05	4.HC.15	<u>4.HE.05</u>	4.HF.05	4.HG.45
4.HB.10		Melanovanadite		4.HG.50
4.HB.15	Ino-	CaV₄O₁₀•5H₂O	Unclassified	4.HG.55
4.HB.20	Vanadates	4.HE.10	Vanadium	4.HG.60
4.HB.25	4.HD.05	4.HE.15	Oxides	4.HG.65
4.HB.30	4.HD.10	4.HE.20	4.HG.05	
4.HB.35	4.HD.15	4.HE.25	4.HG.10	

4.J - OXIDES: ARSENITES, ANTIMONITES, BISMUTHITES, SULFITES, SELENITES, TELLURITES AND IODATES

Arsenites,	4.JA.25	Bismuthites with	4.JB.40	Arsenites,
Antimonites,	4.JA.30	Additional	<u>4.JB.45</u>	Antimonites,
Bismuthites	4.JA.35	Anions, Without	Finnemanite	Bismuthites
Without	4.JA.40	H ₂ O	Pb₅(AsO₃)₅Cl	Without
Additional	4.JA.45	4.JB.05	4.JB.50	Additional
Anions, Without	4.JA.50	4.JB.10	4.JB.55	Anions, with
H ₂ O	4.JA.55	4.JB.15	4.JB.60	H ₂ O
4.JA.05	4.JA.60	4.JB.20	4.JB.65	4.JC.05
4.JA.10		4.JB.25	4.JB.70	4.JC.10
4.JA.15	Arsenites,	4.JB.30	4.JB.75	4.JC.15
4.JA.20	Antimonites,	4.JB.35		4.JC.20

TABLE 18. Continued

4.J - OXIDES: ARSENITES, ANTIMONITES, BISMUTHITES, SULFITES, SELENITES, TELLURITES AND IODATES, CONTINUED

Arsenites,	Selenites with	Selenites with	4.JK.45	Additional
Antimonites,	Additional	Additional	4.JK.50	Anions, with
Bismuthites	Anions, Without	Anions, with H ₂ O	4.JK.55	H ₂ O
with Additional	H ₂ O	4.JJ.05	4.JK.60	4.JM.05
Anions, with	4.JG.	4.JJ.10	4.JK.65	4.JM.10
H ₂ O	4.JG.05	4.JJ.15	4.JK.70	4.JM.15
4.JD.05	4.JG.10	4.JJ.20	4.JK.75	4.JM.20
4.JD.10	4.JG.15	4.JJ.25		
4.JD.15	4.JG.20		Tellurites with	Tellurites
	4.JG.25	Tellurites Without	Additional	with
Sulfites	4.JG.30	Additional	Anions, Without	Additional
4.JE.05	4.JG.35	Anions, Without	H ₂ O	Anions, with
4.JE.10	4.JG.40	H ₂ O	4.JL.05	H ₂ O
4.JE.15		4.JK.05	4.JL.10	4.JN.05
4.JE.20	Selenites Without	4.JK.10	4.JL.15	4.JN.10
	Additional	4.JK.15	4.JL.20	4.JN.15
Selenites	Anions, with H ₂ O	4.JK.20	4.JL.25	4.JN.20
Without	4.JH.05	4.JK.25	4.JL.30	4.JN.25
Additional	4.JH.10	4.JK.30		4.JN.30
Anions, Without	4.JH.15	4.JK.35	Tellurites	
H ₂ O	4.JH.20	4.JK.40	Without	
4.JF.05	4.JH.25			

4.K - OXIDES: IODATES, TRIGONAL (IO₃) PYRAMIDS (MOSTLY)

Iodates Without	Iodates with	4.KB.15	4.KC.10	4.KD.05
Additional	Additional			4.KD.10
Anions, Without	Anions, Without	Iodates Without	Iodates with	
H ₂ O	H ₂ O	Additional	Additional	
4.KA.05	4.KB.05	Anions, with H ₂ O	Anions, with	
	4.KB.10	4.KC.05	H ₂ O	

5.A - CARBONATES (NITRATES): CARBONATES WITHOUT ADDITIONAL ANIONS, WITHOUT H₂O

Alkali Carbonates	5.AB.05	Benstonite	5.AC.20	With Rare
5.AA.05	5.AB.10	(Ba,Sr)₆(Ca,Mn)₆	<u>5.AC.25</u>	Earth
5.AA.10	5.AB.15	Mg(CO₃)₁₃	Shortite	Elements
5.AA.15	5.AB.20	5.AB.60	Na₂Ca₂(CO₃)₃	5.AD.05
5.AA.20	5.AB.25		<u>5.AC.30</u>	5.AD.15
5.AA.25	5.AB.30	Alkali and	Burbankite	5.AD.20
5.AA.30	5.AB.35	Alkali-Earth	(Na,Ca)₃(Sr,	
	5.AB.40	Carbonates	Ba,Ce)₃(CO₃)₅	
Alkali-Earth (and	5.AB.45	5.AC.05		
Other Metal ²⁺)	5.AB.50	5.AC.10		
Carbonates	<u>5.AB.55</u>	5.AC.15		

TABLE 18. Continued

5.B - CARBONATES (NITRATES): CARBONATES WITH ADDITIONAL ANIONS, WITHOUT H₂O

With Copper, Cobalt, Nickel, Zinc, Magnesium and Manganese	<u>5.BB.10</u> Dawsonite NaAlCO₃(OH)₂	5.BD.05 5.BD.10 5.BD.15 5.BD.18 <u>5.BD.20a</u> Bastnäsité-Ce (Ce,La)(CO₃)F	5.BD.35 With Lead and Bismuth 5.BE.05 5.BE.10 5.BE.15 5.BE.20 5.BE.25 5.BE.30 5.BE.35	SO ₄ , PO ₄ and TeO ₃ 5.BF.05 5.BF.10 5.BF.15 5.BF.20 5.BF.25 5.BF.30 5.BF.35 5.BF.40
5.BA.05 5.BA.10 5.BA.15 5.BA.20 5.BA.25 5.BA.30	5.BB.15 5.BB.20 With Alkali-Earth Cations 5.BC.05 5.BC.10 5.BC.15	5.BD.20b 5.BD.20c <u>5.BD.20d</u> Röntgenite-Ce Ca₂(Ce,La)₃ (CO₃)₅F₃		
With Alkalies and Similar 5.BB.05	With Rare Earth Elements	5.BD.25	With Chlorine,	

5.C - CARBONATES (NITRATES): CARBONATES WITHOUT ADDITIONAL ANIONS, WITH H₂O

With Medium- Sized Cations 5.CA.05 5.CA.10 5.CA.15 5.CA.20	With Large Cations (Alkali and Alkali-Earth Carbonates) 5.CB.05 5.CB.10 5.CB.15 5.CB.20	5.CB.25 <u>5.CB.30</u> Pirssonite Na₂Ca(CO₃)₂ •2H₂O 5.CB.35 5.CB.40 5.CB.45	5.CB.50 With Rare Earth Elements <u>5.CC.05</u> Weloganite Na₂Sr₃Zr(CO₃)₆ •3H₂O	5.CC.10 5.CC.15 5.CC.20 5.CC.25 5.CC.30 5.CC.35 5.CC.40
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5.D - CARBONATES (NITRATES): CARBONATES WITH ADDITIONAL ANIONS, WITH H₂O

With Medium- Sized Cations 5.DA.05 <u>5.DA.10</u> Artinite Mg₂(CO₃)(OH)₂ •3H₂O 5.DA.15	5.DA.20 5.DA.25 5.DA.30 5.DA.35 5.DA.40 5.DA.45 5.DA.50 5.DA.55	With Large and Medium-Sized Cations 5.DB.05 5.DB.10 5.DB.15 5.DB.20	5.DB.25 5.DB.30 With Large Cations 5.DC.05 5.DC.10 5.DC.15	5.DC.20 5.DC.25 5.DC.30 5.DC.35
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5.E - CARBONATES (NITRATES): URANYL CARBONATES

UO ₂ :CO ₃ > 1:1 5.EA.05 5.EA.10 5.EA.15 5.EA.20 5.EA.25 5.EA.30 5.EA.35	UO ₂ :CO ₃ = 1:1 5.EB.05 5.EB.10 5.EB.15 5.EB.20 UO ₂ :CO ₃ < 1:1 to 1:2 5.EC.05 5.EC.10	UO ₂ :CO ₃ = 1:3 5.ED.05 5.ED.10 5.ED.15 <u>5.ED.20</u> Liebigite Ca₂(UO₂)(CO₃)₃ •11H₂O 5.ED.25	5.ED.30 5.ED.35 5.ED.40 5.ED.45 5.ED.50 UO ₂ :CO ₃ = 1:4 5.EE.05 5.EE.10	UO ₂ :CO ₃ = 1:5 5.EF.05 With SO ₄ or SiO ₄ 5.EG.05 5.EG.10
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TABLE 18. Continued

5.N - CARBONATES (NITRATES): NITRATES

Without OH or H ₂ O	Ba(NO₃)₂	(NH₄,K)NO₃	With H ₂ O	H ₂ O
<u>5.NA.05</u>	<u>5.NA.10</u>	5.NA.20	5.NC.05	5.ND.05
Nitratine	Niter		5.NC.10	5.ND.10
NaNO₃	KNO₃	With OH		5.ND.15
Nitrobarite	<u>5.NA.15</u>	5.NB.05	With OH (and Similar) and	5.ND.20
	Gwihabaite			

6.A - BORATES: MONOBORATES

BO ₃ Without Additional	Single Triangles	6.AB.40	B(O,OH) ₄	6.AC.30
Anions, with	plus OH and	6.AB.45	Without and with	6.AC.35
Single Triangles	Similar	6.AB.50	Additional	6.AC.40
6.AA.05	6.AB.05	6.AB.55	Anions; with	6.AC.45
6.AA.15	6.AB.10	6.AB.60	Single Tetrahedra	6.AC.50
6.AA.35	<u>6.AB.15</u>	6.AB.65	plus OH and	6.AC.55
6.AA.40	Jeremejevite	6.AB.70	Similar	6.AC.60
	Al₆(BO₃)₅(F,OH)₃	6.AB.75	6.AC.05	6.AC.65
	6.AB.20	6.AB.80	6.AC.10	6.AC.70
BO ₃ with	6.AB.25	6.AB.85	6.AC.15	
Additional	6.AB.30		6.AC.20	
Anions, with	6.AB.35		6.AC.25	

6.B - BORATES: DIBORATES

Neso-Diborates with Double Triangles	6.BA.10	Tetrahedra	Ino-Diborates	Tecto-
B ₂ (O,OH) ₅ and	6.BA.15	B ₂ O(OH) ₆	with Triangles	Diborates
Similar	6.BA.20	<u>6.BB.05</u>	and/or Tetrahedra	with
6.BA.05	Neso-Diborates	Pinnoite	6.BC.10	Tetrahedra
	with Double	Mg[B₂O(OH)₆]	6.BC.15	6.BD.05
		6.BB.10	6.BC.20	

6.C - BORATES: TRIBORATES

Neso-	6.CA.25	6.CA.50	Colemanite	6.CB.25
Triborates	6.CA.30	6.CA.55	Ca[B₃O₄(O)₃]	
6.CA.10	6.CA.35	Ino-	•H₂O	Phyllo-
6.CA.15	6.CA.40	Triborates	6.CB.15	Triborates
6.CA.20	6.CA.45	<u>6.CB.10</u>	6.CB.20	6.CC.05

6.D - BORATES: TETRABORATES

Neso-Tetraborates	6.DA.30	Ino-	Phyllo-	Tecto-
6.DA.10	6.DA.35	Tetraborates	Tetraborates	Tetraborates
6.DA.15	6.DA.40	6.DB.05	6.DC	<u>6.DD.05</u>
6.DA.20	6.DA.60			Diomignite
6.DA.25				Li₂B₄O₇

TABLE 18. Continued

6.E - BORATES: PENTABORATES

Neso-Pentaborates	Ino-Pentaborates	Phyllo-	6.EC.25	<u>6.ED.05</u>
6.EA.05	6.EB.05	Pentaborates	6.EC.30	Hilgardite
6.EA.10	6.EB.10	6.EC.05	6.EC.35	Ca₂B₅O₉Cl
6.EA.15	6.EB.15	6.EC.10		•H₂O
6.EA.25	6.EB.20	6.EC.15	Tecto-	
	6.EB.25	6.EC.20	Pentaborates	

6.F - BORATES: HEXABORATES

Neso-	6.FA.20	6.FB.05	Phyllo-	6.FC.20
Hexaborates	6.FA.25	<u>6.FB.10</u>	Hexaborates	
6.FA.05		Kaliborite	6.FC.05	
6.FA.10	Ino-	KMg₂H[B₆O₈	6.FC.10	
6.FA.15	Hexaborates	(OH)₅]₂(H₂O)₄	6.FC.15	

6.G - BORATES: HEPTABORATES AND OTHER MEGABORATES

Tecto-	Fe₃B₇O₁₃Cl	6.GB.10	(Cs,K,Rb)Al₄	6.GD.05
Heptaborates	6.GA.10	6.GB.15	Be₄(B,Be)₁₂O₂₈	6.GD.10
<u>6.GA.05</u>	6.GA.30	6.GB.20	Rhodizite	
Boracite			(K,Cs)Al₄Be₄	
Mg₃B₇O₁₃Cl	Phyllo-	Tecto-	(B,Be)₁₂O₂₈	
Chambersite	Nonaborates and	Dodecaborates		
Mn₃B₇O₁₃Cl	Similar	<u>6.GC.05</u>	Mega-	
Ericaite	6.GB.05	Londonite	Tectoborates	

6.H - BORATES: UNCLASSIFIED BORATES

Unclassified Borates	6.HA
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7.A - SULFATES (SELENATES, TELLURATES, CHROMATES, MOLYBDATES AND WOLFRAMATES): SULFATES (SELENATES AND SIMILAR) WITHOUT ADDITIONAL ANIONS, WITHOUT H₂O

With Small Cations	7.AB.10	Langbeinite	With Only Large Cations	7.AD.30
7.AA	With Medium- Sized and Large Cations	K₂Mg₂(SO₄)₃		<u>7.AD.35</u>
		7.AC.15	7.AD.05	Olsacherite
		7.AC.20	7.AD.10	Pb₂(SeO₄)
With Medium- Sized Cations	7.AC.05	7.AC.25	7.AD.15	(SO₄)
	7.AC.08	7.AC.30	7.AD.20	7.AD.40
7.AB.05	<u>7.AC.10</u>	7.AC.35	7.AD.25	

7.B - SULFATES (SELENATES, TELLURATES, CHROMATES, MOLYBDATES AND WOLFRAMATES): SULFATES (SELENATES AND SIMILAR) WITH ADDITIONAL ANIONS, WITHOUT H₂O

With Small Cations	7.BB.05	7.BB.35	With Medium- Sized and Large Cations	Alunite
7.BA	7.BB.10	7.BB.40		KAl₃(SO₄)₂
	7.BB.15	7.BB.45		(OH)₆
	7.BB.20	7.BB.50		
With Medium- Sized Cations	7.BB.25	7.BB.55	7.BC.05	
	7.BB.30	7.BB.60	<u>7.BC.10</u>	

TABLE 18. Continued

7.B - SULFATES (SELENATES, TELLURATES, CHROMATES, MOLYBDATES AND WOLFRAMATES): SULFATES (SELENATES AND SIMILAR) WITH ADDITIONAL ANIONS, WITHOUT H₂O, CONTINUED

With Medium-Sized and Large Cations (Continued)	KFe₃(SO₄)₂(OH)₆	7.BC.25	7.BC.65	7.BD.25
	Natroalunite	7.BC.30	7.BC.70	7.BD.30
	(Na,K)Al₃(SO₄)₂(OH)₆	7.BC.35	7.BC.75	7.BD.35
		7.BC.40	7.BC.80	7.BD.40
Ammoniojarosite	Natrojarosite	7.BC.45		7.BD.45
	(NH₄)Fe₃(SO₄)₂(OH)₆	<u>7.BC.50</u>	With Only Large Cations	7.BD.50
	Plumbojarosite	Caledonite		7.BD.55
Argentojarosite	Pb_{0.5}Fe₃(SO₄)₂(OH)₆	Pb₅Cu₂(SO₄)₃(CO₃)(OH)₆	7.BD.05	7.BD.60
			7.BD.10	7.BD.65
			7.BD.15	7.BD.70
Jarosite		7.BC.60	7.BD.20	

7.C - SULFATES (SELENATES, TELLURATES, CHROMATES, MOLYBDATES AND WOLFRAMATES): SULFATES (SELENATES AND SIMILAR) WITHOUT ADDITIONAL ANIONS, WITH H₂O

With Small Cations	Epsomite	Halotrichite	7.CC.25	7.CD.15
7.CA	MgSO₄•7H₂O	FeAl₂(SO₄)₄•22H₂O	7.CC.30	7.CD.20
	Goslarite		7.CC.35	7.CD.25
	ZnSO₄•7H₂O	Pickeringite	7.CC.40	7.CD.30
With Only Medium-Sized Cations	Morenosite	MgAl₂(SO₄)₄•22H₂O	7.CC.45	<u>7.CD.35</u>
	NiSO₄•7H₂O		7.CC.50	Syngenite
7.CB.05	7.CB.45	7.CB.90	7.CC.55	K₂Ca(SO₄)₂•H₂O
7.CB.07	7.CB.50		7.CC.60	
7.CB.10	<u>7.CB.55</u>	With Medium-Sized and Large Cations	7.CC.65	7.CD.40
7.CB.15	Coquimbite		7.CC.70	7.CD.45
7.CB.20	Fe_{1.5}Al_{0.5}(SO₄)₃•9H₂O		7.CC.75	7.CD.50
7.CB.25	7.CB.60		7.CC.80	7.CD.55
<u>7.CB.30</u>	7.CB.65		7.CC.85	7.CD.60
				7.CD.65
Retgersite	7.CB.70	<u>7.CC.20</u>	With Only Large Cations	
NiSO₄•6H₂O	7.CB.75	Alum-Na		
7.CB.35	7.CB.80	NaAl(SO₄)₂•12H₂O	7.CD.05	
<u>7.CB.40</u>	<u>7.CB.85</u>		7.CD.10	

7.D - SULFATES (SELENATES, TELLURATES, CHROMATES, MOLYBDATES AND WOLFRAMATES): SULFATES (SELENATES AND SIMILAR) WITH ADDITIONAL ANIONS, WITH H₂O

With Small Cations	7.DB.25	7.DC.20	Cu₆Al(SO₄)Cl(OH)₁₂•3H₂O	7.DD.75
7.DA	7.DB.30	7.DC.25		7.DD.80
	7.DB.35	7.DC.30	7.DD.20	7.DD.85
			7.DD.25	
With Only Medium-Sized Cations, with Insular Octahedra and Finite Units	With Only Medium-Sized Cations, with Chains of Edge-Sharing Octahedra	With Only Medium-Sized Cations, with Sheets of Edge-Sharing Octahedra	7.DD.30	With Only Medium-Sized Cations, Unclassified
7.DB.05	7.DC.05	7.DD.05	7.DD.35	7.DD.40
7.DB.10	7.DC.10	7.DD.10	7.DD.45	7.DD.50
7.DB.15		<u>7.DD.15</u>	7.DD.55	7.DD.60
7.DB.20	7.DC.15	Spangolite	7.DD.65	7.DD.70
				7.DD.75

TABLE 18. Continued

7.D - SULFATES (SELENATES, TELLURATES, CHROMATES, MOLYBDATES AND WOLFRAMATES): SULFATES (SELENATES AND SIMILAR) WITH ADDITIONAL ANIONS, WITH H₂O, CONTINUED

With Only	7.DE.62	7.DF.25	7.DF.85	Ca₃(SO₄)
Medium-Sized	7.DE.65	7.DF.30		[Si(OH)₆]
Cations,	7.DE.70	7.DF.35	With Large and	(CO₃)
Unclassified	7.DE.75	7.DF.40	Medium-Sized	•12H₂O
(Continued)		7.DF.45	Cations, with	7.DG.20
7.DE.25	With Large and	7.DF.50	NO ₃ , CO ₃ ,	7.DG.25
7.DE.35	Medium-Sized	7.DF.55	B(OH) ₄ , SiO ₄ and	7.DG.30
7.DE.40	Cations	7.DF.60	IO ₃	7.DG.35
7.DE.45	7.DF.05	7.DF.65	7.DG.05	7.DG.40
7.DE.50	7.DF.10	7.DF.70	7.DG.10	7.DG.45
7.DE.55	7.DF.15	7.DF.75	<u>7.DG.15</u>	
7.DE.60	7.DF.20	7.DF.80	Thaumasite	

7.E - SULFATES (SELENATES, TELLURATES, CHROMATES, MOLYBDATES AND WOLFRAMATES): URANYL SULFATES

Without	With Medium-	With Medium-	7.EC.10
Cations	Sized Cations	Sized and Large	7.EC.15
7.EA.05	7.EB.05	Cations	7.EC.20
7.EA.10	7.EB.10	7.EC.05	

7.F - SULFATES (SELENATES, TELLURATES, CHROMATES, MOLYBDATES AND WOLFRAMATES): CHROMATES

With Additional	With Additional	7.FB.15	7.FC.05	Dichromates
Anions	Oxygen,	7.FB.20	7.FC.10	7.FD.05
7.FA.05	Vanadium, Sulfur	7.FB.25	7.FC.15	
7.FA.10	and Chlorine		7.FC.20	
7.FA.15	7.FB.05	With PO ₄ , AsO ₄		
7.FA.20	7.FB.10	and SiO ₄		

7.G - SULFATES (SELENATES, TELLURATES, CHROMATES, MOLYBDATES AND WOLFRAMATES): MOLYBDATES, WOLFRAMATES AND NIOBATES

Without	PbMoO₄	With Additional	7.GB.15	7.GB.40
Additional Anions	7.GA.10	Anions and/or	7.GB.20	7.GB.45
or H ₂ O	7.GA.15	H ₂ O	7.GB.25	7.GB.50
<u>7.GA.05</u>		7.GB.05	7.GB.30	
Wulfenite		7.GB.10	7.GB.35	

7.H - SULFATES (SELENATES, TELLURATES, CHROMATES, MOLYBDATES AND WOLFRAMATES): URANIUM AND URANYL MOLYBDATES AND WOLFRAMATES

With	7.HA.10	With	7.HB.20
Uranium ⁴⁺	7.HA.15	Uranium ⁶⁺	7.HB.25
7.HA.05		7.HB.15	

7.J - SULFATES (SELENATES, TELLURATES, CHROMATES, MOLYBDATES AND WOLFRAMATES): THIOSULFATES

Thiosulfates of Pb	7.JA.05	7.JA.10
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TABLE 18. Continued

8.A - PHOSPHATES, ARSENATES AND VANADATES: PHOSPHATES AND SIMILAR WITHOUT ADDITIONAL ANIONS, WITHOUT H₂O

With Small	8.AB.05	8.AC.18	8.AC.75	<u>8.AD.30</u>
Cations (Some	8.AB.10	8.AC.20	8.AC.80	Schultenite
Also with Larger	8.AB.15	8.AC.25	8.AC.85	Pb(HAsO₄)
Ones)	8.AB.20	8.AC.30		<u>8.AD.35</u>
<u>8.AA.05</u>	8.AB.25	8.AC.35	With Only	Wakefieldite
Berlinite	8.AB.30	8.AC.40	Large Cations	-Nd
AlPO₄	8.AB.35	<u>8.AC.45</u>	8.AD.05	NdVO₄
8.AA.10	8.AB.40	Whitlockite	8.AD.10	8.AD.40
8.AA.15		Ca₉(Mg,Fe)(PO₄)₆	<u>8.AD.15</u>	8.AD.45
8.AA.20	With Medium-	[PO₃(OH)]	Archerite	8.AD.50
8.AA.25	Sized and Large	8.AC.50	K(H₂PO₄)	8.AD.55
8.AA.30	Cations	8.AC.55	Biphosphammite	8.AD.60
	8.AC.05	8.AC.60	NH₄(H₂PO₄)	8.AD.65
With Medium-	8.AC.10	8.AC.65	8.AD.20	
Sized Cations	8.AC.15	8.AC.70	8.AD.25	

8.B - PHOSPHATES, ARSENATES AND VANADATES: PHOSPHATES AND SIMILAR WITH ADDITIONAL ANIONS, WITHOUT H₂O

With Small and	8.BB.80	Cations, (OH and	Similar):XO ₄	8.BH.05
Medium-Sized	8.BB.85	Similar):XO ₄ >	< 0.5:1	<u>8.BH.10</u>
Cations	8.BB.90	2:1	8.BF.05	Tilasite
8.BA.05		8.BE.05	8.BF.10	CaMg
8.BA.10	With Only	8.BE.10	8.BF.15	(AsO₄)F
8.BA.15	Medium-Sized	8.BE.15	8.BF.20	8.BH.15
	Cations, (OH and	8.BE.20		8.BH.20
With Only	Similar):XO ₄ >	8.BE.25	With	8.BH.25
Medium-Sized	1:1 and < 2:1	8.BE.30	Medium-	8.BH.30
Cations, (OH and	8.BC.05	8.BE.35	Sized and	8.BH.35
Similar):XO ₄	8.BC.10	8.BE.40	Large	8.BH.40
about 1:1	8.BC.15	8.BE.45	Cations, (OH	8.BH.45
8.BB.05		8.BE.50	and	8.BH.50
8.BB.10	With Only	8.BE.55	Similar):XO ₄	8.BH.55
8.BB.15	Medium-Sized	8.BE.60	= 0.5:1	8.BH.60
8.BB.20	Cations, (OH and	8.BE.65	8.BG.05	8.BH.65
8.BB.25	Similar):XO ₄ =	8.BE.70	8.BG.10	
8.BB.30	2:1	8.BE.75	8.BG.15	With
8.BB.35	8.BD.05	8.BE.80		Medium-
8.BB.40	8.BD.10	8.BE.85	With	Sized and
8.BB.45	8.BD.15		Medium-	Large
8.BB.50	8.BD.20	With	Sized and	Cations, (OH
8.BB.55	8.BD.25	Medium-	Large	and
8.BB.60	8.BD.30	Sized and	Cations, (OH	Similar):XO ₄
8.BB.65		Large	and	= 1.5:1
8.BB.70	With Only	Cations, (OH	Similar):XO ₄	8.BJ
8.BB.75	Medium-Sized	and	= 1:1	

TABLE 18. Continued

8.B - PHOSPHATES, ARSENATES AND VANADATES: PHOSPHATES AND SIMILAR WITH ADDITIONAL ANIONS, WITHOUT H₂O, CONTINUED

With Medium-Sized and Large Cations, (OH and Similar):XO ₄ = 2:1 and 2.5:1	Similar):XO ₄ = 3:1	8.BL.15	Cations, (OH and Similar):XO ₄ = 0.33:1	and Similar):XO ₄ about 1:1
8.BK.05	8.BL.05	8.BL.25		8.BO.05
8.BK.10	<u>8.BL.10</u>	With Medium-Sized and Large Cations, (OH and Similar):XO ₄ = 4:1	<u>8.BN.05</u>	8.BO.10
8.BK.15	Arsenogoyazite		Mimetite	8.BO.15
8.BK.20	SrAl₃(AsO₄)₂(OH)₅•H₂O	8.BM.05	Pb₅(AsO₄)₃Cl	8.BO.20
8.BK.25	Crandallite	8.BM.10	Pyromorphite	8.BO.25
	CaAl₃(PO₄)₂•H₂O	8.BM.15	Pb₅(PO₄)₃Cl	8.BO.30
	Goyazite		8.BN.10	8.BO.35
With Medium-Sized and Large Cations, (OH and	SrAl₃(PO₄)₂(OH)₅•H₂O	With Only Large	With Only Large Cations, (OH	8.BO.40
	8.BL.13			8.BO.45

8.C - PHOSPHATES, ARSENATES AND VANADATES: PHOSPHATES AND SIMILAR WITHOUT ADDITIONAL ANIONS, WITH H₂O

With Small and Large/Medium Cations	8.CB.40	8.CE.05	8.CG.05	8.CJ.05
8.CA.05	8.CB.45	8.CE.10	8.CG.10	8.CJ.10
8.CA.10	8.CB.50	8.CE.15	8.CG.15	8.CJ.15
8.CA.15	8.CB.55	8.CE.20	8.CG.20	8.CJ.20
8.CA.20	8.CB.60	8.CE.25	8.CG.25	8.CJ.25
8.CA.25		8.CE.30	8.CG.35	8.CJ.30
8.CA.30	With Only	8.CE.35		8.CJ.35
8.CA.35	Medium-Sized	8.CE.40	With Large and Medium-Sized Cations,	8.CJ.40
8.CA.40	Cations, XO ₄ :H ₂ O = 1:1.5	8.CE.45	XO ₄ :H ₂ O < 1:1	8.CJ.45
8.CA.45	8.CC.05	8.CE.50		<u>8.CJ.50</u>
8.CA.50	8.CC.10	8.CE.55		Ardealite
8.CA.55	8.CC.15	8.CE.60	8.CH.05	Ca₂(HPO₄)(SO₄)•4H₂O
8.CA.60	With Only	8.CE.65	8.CH.10	Brushite
8.CA.65	Medium-Sized	8.CE.70	8.CH.15	Ca(HPO₄)•2H₂O
8.CA.70	Cations, XO ₄ :H ₂ O = 1:2	8.CE.75	8.CH.20	Pharmacolite
	8.CD.05	8.CE.80	8.CH.25	Ca(HAsO₄)•2H₂O
With Only Medium-Sized Cations, XO ₄ :H ₂ O = 1:1	8.CD.10	8.CE.85	8.CH.30	
8.CB.05	8.CD.15	With Large and Medium-Sized Cations, XO ₄ :H ₂ O > 1:1	8.CH.35	<u>8.CH.40</u>
8.CB.10	8.CD.20		8.CH.45	Struvite
8.CB.15	8.CD.25		8.CH.50	(NH₄)Mg(P O₄)•6H₂O
8.CB.20	8.CD.30	8.CF.05	8.CH.55	8.CJ.55
8.CB.25	With Only	8.CF.10	8.CH.60	8.CJ.60
8.CB.30	Medium-Sized	With Large and Medium-Sized Cations, XO ₄ :H ₂ O = 1:1		8.CJ.65
8.CB.35	Cations, XO ₄ :H ₂ O about 1:2.5		With Only Large Cations	8.CJ.70

With Small (and Occasionally Larger) Cations	8.DC.15 8.DC.17 8.DC.20 8.DA.05 8.DA.10 8.DA.15 8.DA.20 8.DA.25 8.DA.30 8.DA.35 8.DA.40 8.DA.45 8.DA.50	8.DE.25 8.DE.35 8.DE.40 8.DE.45	8.DH.40 8.DH.45 8.DH.50 8.DH.55 8.DH.60	8.DL.05 8.DL.10 8.DL.15 8.DL.20 8.DL.25
With Only Medium-Sized Cations, (OH and Similar):XO ₄ < 1:1	8.DC.27 8.DC.30 8.DC.32 8.DC.35 8.DC.37 8.DC.40 8.DC.45 8.DC.47 8.DC.50 8.DC.52 8.DC.55 8.DC.57 8.DC.60	With Only Medium-Sized Cations, (OH and Similar):XO ₄ > 3:1 8.DF.05 8.DF.10 8.DF.15 8.DF.20 8.DF.25 8.DF.30 8.DF.35 8.DF.40	With Large and Medium-Sized Cations, (OH and Similar):XO ₄ = 1:1 8.DJ.05 8.DJ.10 8.DJ.15 8.DJ.20 8.DJ.25 8.DJ.30 8.DJ.35 8.DJ.40 8.DJ.45	With Large and Medium-Sized Cations, (OH and Similar):XO ₄ > 2:1 8.DM.05 <u>8.DM.10</u> Tyrolite Ca₂Cu₉(AsO₄)₄(CO₃)(OH)₈•11H₂O 8.DM.15 8.DM.20 8.DM.25 8.DM.30 8.DM.35 8.DM.40
With Only Medium-Sized Cations, (OH and Similar):XO ₄ = 2:1	8.DD.05 8.DD.10 8.DD.15 <u>8.DD.20</u>	With Large and Medium-Sized Cations, (OH and Similar):XO ₄ < 0.5:1 8.DG.05	With Large and Medium-Sized Cations, (OH and Similar):XO ₄ > 1:1 and < 2:1 8.DK. <u>8.DK.10</u> Pharmacosiderite KFe₄(AsO₄)₃(OH)₄•6-7H₂O 8.DK.12 8.DK.15 8.DK.20 8.DK.25 8.DK.30 8.DK.35	8.DM.15 8.DM.20 8.DM.25 8.DM.30 8.DM.35 8.DM.40
8.DB.05 8.DB.10 8.DB.15 8.DB.20 8.DB.25 8.DB.30 8.DB.35 8.DB.40 8.DB.45 8.DB.50 8.DB.55 8.DB.60 8.DB.65 8.DB.70 8.DB.75	With Only Medium-Sized Cations, (OH and Similar):XO ₄ = 3:1 8.DC.52 8.DC.55 8.DC.57 8.DC.60 Childrenite (Fe,Mn)Al(PO₄)(OH)₂•H₂O Eosphorite (Mn,Fe)Al(PO₄)(OH)₂•H₂O	With Large and Medium-Sized Cations, (OH and Similar):XO ₄ < 1:1 <u>8.DH.05</u> Minyulite KAl₂(PO₄)₂(OH,F)•4H₂O 8.DH.10 8.DH.15 8.DH.20 8.DH.25 8.DH.30 8.DH.35	8.DK.12 8.DK.15 8.DK.20 8.DK.25 8.DK.30 8.DK.35	8.DN.05 8.DN.10 8.DN.15 8.DN.20
With Only Medium-Sized Cations, (OH and Similar):XO ₄ = 1:1 and < 2:1	8.DC.05 8.DC.07 8.DC.10 8.DC.12	8.DH.05 8.DH.10 8.DH.15 8.DH.20 8.DH.25 8.DH.30 8.DH.35	With Large and Medium-Sized Cations, (OH and Similar):XO ₄ ::2:1	With CO ₃ , SO ₄ and SiO ₄ 8.DO.05 8.DO.10 8.DO.15 8.DO.20 8.DO.25 8.DO.30 8.DO.40 8.DO.45

UO ₂ :XO ₄ =	8.EA.10	UO ₂ :XO ₄ =	8.EB.10	8.EB.25
1:2	8.EA.15	1:1	8.EB.15	8.EB.30
8.EA.05	8.EA.20	8.EB.05	8.EB.20	8.EB.35

TABLE 18. Continued

8.E - PHOSPHATES, ARSENATES AND VANADATES: URANYL PHOSPHATES AND ARSENATES, CONTINUED

UO ₂ :XO ₄ =	8.EB.50	8.EC.05	8.EC.30	Unclassified
1:1	8.EB.55	8.EC.10	8.EC.35	8.ED.05
(Continued)		8.EC.15	8.EC.40	8.ED.10
8.EB.40	UO ₂ :XO ₄ =	8.EC.20		8.ED.15
8.EB.45	3:2	8.EC.25		

8.F - PHOSPHATES, ARSENATES AND VANADATES: POLYPHOSPHATES, POLYARSENATES AND [4]-POLYVANADATES

Polyphosphates and Similar, Without OH and H ₂ O, with Dimers of Corner-Sharing XO ₄ Tetrahedra	8.FA.15 8.FA.20 8.FA.25	Polyphosphates and Similar, with H ₂ O Only	8.FC.30	Ino-[4]-Vanadates
8.FA.05	Polyphosphates and Similar, with OH Only	8.FC.05	Polyphosphates and Similar, with OH and H ₂ O	8.FE.05
8.FA.10	8.FB.05	8.FC.10 8.FC.15 8.FC.20 8.FC.25	8.FD.05	

9.A - SILICATES (GERMANATES): NESOSILICATES

Nesosilicates Without Additional Anions, with Cations in Tetrahedral [4] Coordination	Octahedral [6] Coordination 9.AC.05 9.AC.10 9.AC.15 9.AC.20	H ₂ O), with Cations in Tetrahedral [4] Coordination	9.AF.25 9.AF.30 <u>9.AF.35</u> Topaz Al₂SiO₄(F,OH)₂	9.AG.40a 9.AG.40b 9.AG.45 9.AG.50 9.AG.55 9.AG.60 9.AG.65 9.AG.70
9.AA.05	Nesosilicates Without Additional Anions, with Cations in [6] and/or Greater Coordination	9.AE.05 9.AE.10 9.AE.15 9.AE.20 9.AE.25 <u>9.AE.30</u> Clinohedrite CaZnSiO₄•H₂O	9.AF.40 9.AF.45 9.AF.50 9.AF.55 9.AF.60 9.AF.65 9.AF.70 9.AF.75 9.AF.80 9.AF.85 9.AF.90	<u>9.AG.75</u> Afwillite Ca₃(HSiO₄)₂•2H₂O <u>9.AG.80</u> Bultfonteinite Ca₂(HSiO₄)F•H₂O
9.AB.05	9.AD.05	9.AE.35 9.AE.40 9.AE.45 9.AE.50		
<u>9.AB.10</u> Larsenite PbZnSiO₄	9.AD.10 9.AD.15 9.AD.20 9.AD.25 9.AD.30 9.AD.35 <u>9.AD.40</u> Eulytine Bi₄(SiO₄)₃	Nesosilicates with Additional Anions, with Cations in [4], [5] and/or [6] (Single) Coordination	Nesosilicates with Additional Anions, with Cations in [6] ± [6] Coordination	9.AG.85 9.AG.90 Nesosilicates with CO ₃ , SO ₄ , PO ₄ and Similar
9.AB.15		9.AF.05 9.AF.10 9.AF.15 9.AF.20 9.AF.23	9.AG.05 9.AG.10 9.AG.15 9.AG.20 9.AG.25 9.AG.30 9.AG.35	9.AH.05 9.AH.10 9.AH.15 9.AH.20 9.AH.25
9.AB.20	Nesosilicates with Additional Anions (Oxygen, OH, Fluorine and			

TABLE 18. Continued

9.A - SILICATES (GERMANATES): NESOSILICATES, CONTINUED

Nesosilicates with	9.AJ.05	9.AJ.40	<u>9.AK.15</u>	9.AK.30
BO ₃ Triangles	9.AJ.10		Uranophane	9.AK.35
and/or Boron[4],	9.AJ.15	Uranyl Neso-	Ca(UO₂)₂	9.AK.40
Beryllium[4]	9.AJ.20	and	(HSiO₄)₂	
Tetrahedra,	9.AJ.25	Polysilicates	•5H₂O	
Cornersharing	9.AJ.30	9.AK.05	9.AK.20	
with SiO ₄	9.AJ.35	9.AK.10	9.AK.25	

9.B - SILICATES (GERMANATES): SOROSILICATES

Si ₂ O ₇ Groups	Anions, with	9.BE.23	Tetrahedral [4]	Aminoffite
Without Non-	Cations in	9.BE.25	and Greater	Ca₃Be(OH)₂
Tetrahedral	Tetrahedral [4]	<u>9.BE.27</u>	Coordination	Si₃O₁₀
Anions, with	and Greater	Murmanite	9.BF.05	9.BH.10
Cations in	Coordination	Na₂Ti₂(Si₂O₇)O₂	9.BF.10	9.BH.15
Tetrahedral [4]	<u>9.BD.05</u>	•2H₂O	9.BF.15	9.BH.20
Coordination	Bertrandite	<u>9.BE.30</u>	9.BF.20	
9.BA	Be₄Si₂O₇(OH)₂	Epistolite		Sorosilicates
	<u>9.BD.10</u>	Na₂(Nb,Ti)₂	Sorosilicates	with Si ₃ O ₁₀ ,
Si ₂ O ₇ Groups	Hemimorphite	(Si₂O₇)O₂•nH₂O	with mixed SiO ₄	Si ₄ O ₁₁ and
Without Non-	Zn₄Si₂O₇	9.BE.32	and Si ₂ O ₇	Similar
Tetrahedral	(OH)₂•H₂O	9.BE.35	Groups, with	Groups, with
Anions, with	<u>9.BD.15</u>	9.BE.37	Cations in	Cations in
Cations in	Junitoite	<u>9.BE.40</u>	Octahedral [6]	Octahedral
Tetrahedral [4]	CaZn₂Si₂O₇	Innelite	and Greater	[6] and
and Greater	•H₂O	Na₂CaBa₄Ti₃	Coordination	Greater
Coordination	9.BD.20	(Si₂O₇)₂(SO₄)₂O₄	9.BG.05	Coordination
<u>9.BB.10</u>	9.BD.25	9.BE.42	9.BG.05a	9.BJ.05
Gugiaite	9.BD.30	9.BE.45	9.BG.05b	9.BJ.10
Ca₂BeSi₂O₇	9.BD.35	9.BE.47	9.BG.10	9.BJ.15
9.BB.15		9.BE.50	9.BG.15	9.BJ.20
9.BB.20	Si ₂ O ₇ Groups with	9.BE.55	9.BG.20	9.BJ.25
	Additional Anions,	9.BE.60	9.BG.25	9.BJ.30
Si ₂ O ₇ Groups	with Cations in	9.BE.65	9.BG.30	9.BJ.35
Without Non-	Octahedral [6] and	9.BE.67	9.BG.35	9.BJ.40
Tetrahedral	Greater	9.BE.70	9.BG.40	9.BJ.45
Anions, with	Coordination	9.BE.72	9.BG.45	9.BJ.50
Cations in	9.BE.02	9.BE.75	9.BG.50	<u>9.BJ.55</u>
Octahedral [6]	9.BE.05	9.BE.77	9.BG.55	Zunyite
and Greater	9.BE.07	9.BE.80		Al₁₃Si₅O₂₀Cl
Coordination	<u>9.BE.10</u>	9.BE.82	Sorosilicates	(OH,F)₁₈
9.BC.05	Suolunite	9.BE.85	with Si ₃ O ₁₀ ,	9.BJ.60
9.BC.10	Ca₂(H₂Si₂O₇)	9.BE.87	Si ₄ O ₁₁ and	9.BJ.65
9.BC.15	•H₂O	9.BE.90	Similar	
9.BC.20	9.BE.12	9.BE.92	Groups, with	Unclassified
9.BC.25	<u>9.BE.15</u>	9.BE.95	Cations in	Sorosilicates
9.BC.30	Fresnoite		Tetrahedral	9.BK
9.BC.35	Ba₂Ti(Si₂O₇)O	Sorosilicates with	[4] and	
	9.BE.17	mixed SiO ₄ and	Greater	
Si ₂ O ₇ Groups with	9.BE.20	Si ₂ O ₇ Groups,	Coordination	
Additional	9.BE.22	with Cations in	<u>9.BH.05</u>	

TABLE 18. Continued

9.C - SILICATES (GERMANATES): CYCLOSILICATES

[Si ₃ O ₉] ₆ Three-Membered Single Rings (Dreier-Einfachringe), Without Insular Complex Ions	9.CE.25 9.CE.30a 9.CE.30b 9.CE.30c 9.CE.30d 9.CE.30e 9.CE.30f 9.CE.30g 9.CE.30h 9.CE.45	Be₃Al₂(Si₆O₁₈) 9.CJ.10 9.CJ.15a 9.CJ.15b 9.CJ.15c 9.CJ.25 <u>9.CJ.30</u> Diopside CuSiO₃•H₂O 9.CJ.35 9.CJ.40 9.CJ.45 9.CJ.50 9.CJ.55 9.CJ.60	(OH) ₄ Fluor-dravite NaMg₃Al₆(BO₃)₃Si₆O₁₈(OH)₃F Fluor-liddicoatite Ca(Li₂Al)Al₆(BO₃)₃Si₆O₁₈(OH)₃F Fluor-schorl NaFe₃Al₆(BO₃)₃Si₆O₁₈(OH)₃F Foite ([Li,Na)Fe₂Al₇(BO₃)₃Si₆O₁₈(OH)₄ Olenite NaAl₉(BO₃)₃(Si₆O₁₈)O₃(OH) Oxy-schorl Na(Fe,Al)₃Al₆(BO₃)₃Si₆O₁₈(OH)₃O Povondraite NaMg₂Fe₇(BO₃)₃Si₆O₁₈(OH)₃O Schorl NaFe₃Al₆(BO₃)₃Si₆O₁₈(OH)₄ Uvite CaMg₄Al₅(BO₃)₃Si₆O₁₈(OH)₄ 9.CK.10 9.CK.15 9.CK.20	[Si ₆ O ₁₈] ₁₂ Branched Six-Membered Single Rings 9.CL.05 [Si ₆ O ₁₈] ₁₂ Six-Membered Double Rings (Sechser-Doppelringe) 9.CM.05 [Si ₈ O ₂₄] ₁₆ Eight-Membered Rings 9.CN.05 [Si ₉ O ₂₇] ₁₈ Nine-Membered Rings <u>9.CO.10</u> Georgbarnovite Na₁₂(Mn,Sr,REE)₃Ca₆Fe₃Zr₃NbSi₂₅O₇₆Cl₂•H₂O Twelve-Membered and Larger Rings 9.CP.05 9.CP.10
[Si ₃ O ₉] ₆ Three-Membered Single Rings, with Insular Complex Ions	9.CF.05 9.CF.10 9.CF.15 9.CF.20 9.CF.25	[Si ₆ O ₁₈] ₁₂ Six-Membered Single Rings, with Insular Complex Ions 9.CK. <u>9.CK.05</u> Buergerite Na(Fe₃)Al₆(BO₃)₃Si₆O₁₈O₃F Chromium-dravite NaMg₃Cr₆(BO₃)₃Si₆O₁₈(OH)₄ Dravite NaMg₃Al₆(BO₃)₃Si₆O₁₈(OH)₄ Elbaite Na(Li_{1.5}Al_{1.5})Al₆(BO₃)₃Si₆O₁₈(OH)₄ Feruvite CaFe₃MgAl₅(BO₃)₃Si₆O₁₈		
[Si ₃ O ₉] ₆ Branched Three-Membered Single Rings	[Si ₄ O ₁₂] ₈ Branched Four-Membered Single Rings 9.CG.05			
[Si ₃ O ₉] ₆ Three-Membered Double Rings	[Si ₄ O ₁₂] ₈ Four-Membered Double Rings 9.CH.05 9.CH.10			
[Si ₄ O ₁₂] ₈ Four-Membered Single Rings (Vierer-Einfachringe), Without Insular Complex Ions	[Si ₆ O ₁₈] ₁₂ Six-Membered Single Rings (Sechser-Einfachringe), Without Insular Complex Ions <u>9.CJ.05</u> Beryl			

9.D - SILICATES (GERMANATES): INOSILICATES

Inosilicates with Two-Periodic Single Chains, Si ₂ O ₆ : Pyroxene Family	9.DA.10 9.DA.15 9.DA.20 9.DA.25 9.DA.30	Inosilicates with Two-Periodic Single Chains, Si ₂ O ₆ : Pyroxene-Related Minerals	9.DB.10 9.DB.15 9.DB.17 9.DB.20 9.DB.25 9.DB.30	9.DB.35 9.DB.40 9.DB.45 9.DB.50
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TABLE 18. Continued

9.D - SILICATES (GERMANATES): INOSILICATES, CONTINUED

Inosilicates with Branched Two-Periodic Single Chains, Si ₂ O ₆ plus 2SiO ₃ and Si ₄ O ₁₂	9.DF.30	Single Chains, Si ₄ O ₁₂	Inosilicates with Five-Periodic Single Chains	Inosilicates with Seven-, Eight-, Ten-, Twelve-, and Fourteen-Periodic Chains
9.DC.05	Inosilicates with Three-Periodic Single and Multiple Chains	<u>9.DH.05</u> Leucophanite NaCaBeSi₂O₆F	9.DK.05	9.DO.05
	9.DG.05	9.DH.10	9.DK.10	9.DO.10
	9.DG.07	9.DH.15	9.DK.15	9.DO.15
Inosilicates with Two-Periodic Double Chains, Si ₄ O ₁₁ :	9.DG.08	<u>9.DH.20</u> Batisite BaNa₂Ti₂(Si₄O₁₂)O₂	9.DK.20	9.DO.20
Orthoamphiboles	9.DG.10		Inosilicates with Five-Periodic Double Chains, Si ₁₀ O ₂₈	9.DO.25
9.DD.05	9.DG.15	9.DH.25	9.DL.05	Transitional Ino-Phyllosilicate Structures
	9.DG.20	9.DH.30	9.DL.10	<u>9.DP.05</u>
	9.DG.25	9.DH.35		Meliphanite (Ca,Na)₂(Be,Al)[Si₂O₆(OH,F)]
	9.DG.30	9.DH.40	Inosilicates with Six-Periodic Single Chains	9.DP.15
Inosilicates with Two-Periodic Double Chains, Si ₄ O ₁₁ :	9.DG.35	9.DH.45	9.DM.05	<u>9.DP.20</u>
Clinoamphiboles	9.DG.40	9.DH.50	9.DM.10	Prehnite Ca₂Al₂Si₃O₁₀(OH)₂
9.DE.05	9.DG.45	9.DH.55	9.DM.15	9.DP.25
9.DE.10	9.DG.50	9.DH.60	9.DM.20	9.DP.30
9.DE.15	9.DG.55	9.DH.65	9.DM.25	9.DP.35
9.DE.20	<u>9.DG.65</u> Elpidite Na₂ZrSi₆O₁₅•3H₂O	9.DH.70	9.DM.30	9.DP.40
9.DE.25	9.DG.60	9.DH.75	9.DM.35	Modular Inosilicate-Sorosilicate Structures
	9.DG.70	Inosilicates with Four-Periodic Double and Triple Chains	9.DM.40	9.DQ.05
	9.DG.75	9.DJ.05	Inosilicates with Six-Periodic Double Chains	
Inosilicates with Two-Periodic Multiple Chains	9.DG.80	9.DJ.10	9.DN.05	
9.DF.05	9.DG.85	9.DJ.15	9.DN.10	
9.DF.15	9.DG.90	9.DJ.20	9.DN.15	
9.DF.20	9.DG.92	9.DJ.25		
<u>9.DF.25</u> Bavenite Ca₄Be₂Al₂Si₉O₂₆(OH)₂	9.DG.97	9.DJ.30		
	Inosilicates with Four-Periodic			

9.E - SILICATES (GERMANATES): PHYLLOSILICATES

Single Nets of Tetrahedra with Four-, Five-, Six- and Eight-Membered Rings	9.EA.40	Double Nets with Four- and Six-Membered Rings	Tetrahedral and Octahedral Nets	Vermiculite (Mg,Fe,Al)₃[(Al,Si)₄O₁₀](OH)₂•4H₂O
9.EA.05	9.EA.45	9.EB.05	9.EC.05	9.EC.55
9.EA.10	9.EA.50	9.EB.10	9.EC.10	9.EC.60
9.EA.15	9.EA.55	9.EB.15	9.EC.15	9.EC.65
9.EA.20	9.EA.60	9.EB.20	9.EC.20	9.EC.70
9.EA.25	9.EA.65		9.EC.25	9.EC.75
9.EA.30	9.EA.70	Phyllosilicates with Mica Sheets, Composed of	9.EC.30	9.EC.80
9.EA.35	9.EA.75		9.EC.35	
	9.EA.80		9.EC.40	
	9.EA.85		9.EC.45	
			<u>9.EC.50</u>	

TABLE 18. Continued

9.E - SILICATES (GERMANATES): PHYLLOSILICATES, CONTINUED

Phyllosilicates with Kaolinite Layers	(Fe,Al,Mg) ₂₋₃ [(Si,Al) ₂ O ₅](OH) ₄	9.EE.65 9.EE.70 9.EE.75 9.EE.80 9.EE.85	Membered and Larger Rings	9.EH.05 Neptunite Na₂KLi (Fe,Mn)₂Ti₂ (Si₈O₂₄)
Composed of Tetrahedral and Octahedral Nets	Single		9.EG.05 9.EG.10 9.EG.15	9.EH.10
<u>9.ED.05</u> Nacrite Al₂(Si₂O₅)(OH)₄	Tetrahedral Nets of Six-Membered Rings Connected by Octahedral Nets or Octahedral Bands	Single Nets with Six-Membered Rings, Connected by Metal[4], Metal[8], and Similar	9.EG.20 9.EG.25 9.EG.30 9.EG.35 9.EG.40 9.EG.45 9.EG.50 9.EG.55	<u>9.EH.15</u> Sarcosite Na₂Ca₁₂ (Ca,K,Fe,Sr,Mg)₂Al₈Si₁₂ (P,Si)O₅₂F₂
<u>9.ED.10</u> Halloysite-7Å Al₂(Si₂O₅)(OH)₄			9.EG.60 9.EG.65 9.EG.70 9.EG.75	<u>9.EH.20</u> Ussingite Na₂AlSi₃O₈ OH
Halloysite-10Å Al₂(Si₂O₅)(OH)₄•2H₂O		<u>9.EF.15</u> Searlesite Na(H₂BSi₂O₇)		9.EH.25 9.EH.30
<u>9.ED.15</u> Cronstedtite Fe₃[(SiFe)₂O₅](OH)₄		9.EF.20 9.EF.25 9.EF.30	Transitional Structures Between Phyllosilicate and Other Silicate Units	Unclassified Phyllosilicates
Amesite Mg₂Al(AlSiO₅) Berthierine	9.EE.30 9.EE.35 9.EE.40 9.EE.45 9.EE.50 9.EE.55 9.EE.60			9.EJ.05 9.EJ.10

9.F - SILICATES (GERMANATES): TECTOSILICATES WITHOUT ZEOLITIC H₂O

Tectosilicates Without Additional Non-Tetrahedral Anions	9.FA.25 9.FA.30 9.FA.35 9.FA.40 9.FA.45 9.FA.50 9.FA.55 9.FA.60 9.FA.65 9.FA.70	9.FA.75 Tectosilicates with Additional Anions <u>9.FB.05</u> Cancrinite Na_xCa_y(AlSiO₄)₆(CO₃)•nH₂O <u>9.FB.10</u> Helvine	Mn₄ (Be₃Si₃O₁₂)S Sodalite Na₈(Al₆Si₆O₂₄)Cl₂ Tugtupite Na₄AlBeSi₄O₁₂Cl <u>9.FB.15</u> Marialite	Na₄ (Al₃Si₉O₂₄)Cl Meionite Ca₄Al₆Si₆O₂₄CO₃
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9.G - SILICATES (GERMANATES): TECTOSILICATES WITH ZEOLITIC H₂O: ZEOLITE FAMILY

Zeolites with X ₅ O ₁₀ Units: The Fibrous Zeolites	Na₂Al₂Si₃O₁₀•2H₂O Scolecite CaAl₂Si₃O₁₀•3H₂O <u>9.GA.10</u> Thomsonite-Ca NaCa₂Al₅Si₅O₂₀	•7H₂O <u>9.GA.15</u> Edingtonite BaAl₂Si₃O₁₀•4H₂O	Membered Rings <u>9.GB.05</u> Analcime Na₈(Al₈Si₁₆O₄₈)•8H₂O	Yugawaralite CaAl₂Si₆O₁₆•4H₂O
<u>9.GA.05</u> Mesolite Na₂Ca₂Al₆Si₉O₃₀•8H₂O Natrolite		Chains of Singly Connected Four-	9.GB.10 <u>9.GB.15</u>	9.GB.20 9.GB.25 9.GB.30 9.GB.35

TABLE 18. Continued

9.G - SILICATES (GERMANATES): TECTOSILICATES WITH ZEOLITIC H₂O: ZEOLITE FAMILY, CONTINUED

Chains of	9.GC.25	9.GD.30	<u>9.GE.05</u>	9.GF.25
Doubly-	9.GC.30	<u>9.GD.35</u>	Heulandite-Ca	9.GF.30
Connected Four-	9.GC.35	Mordenite	(Ca,Na)₂₋₃A₁₃	9.GF.35
Membered Rings		(Na₂,Ca,K₂)	(Al,Si)₂Si₁₃O₃₆	9.GF.40
<u>9.GC.05</u>	Chains of Six-	Al₂Si₁₀O₂₄•7H₂O	•12H₂O	<u>9.GF.50</u>
Gismondine-Ca	Membered Rings:	9.GD.40	9.GE.10	Thornasite
CaAl₂Si₂O₈	Tabular Zeolites	<u>9.GD.45</u>	9.GE.15	(Na,K)₁₂Th₃
•4H₂O	<u>9.GD.05</u>	Epistilbite	9.GE.20	(Si₈O₁₉)₄
<u>9.GC.10</u>	Gmelinite-Na	CaAl₂Si₆O₁₆		•18H₂O
Harmotome	(Na₂,Ca)Al₂	•5H₂O	Other Rare	9.GF.55
(Ba_{0.5},Ca_{0.5},K,	Si₄O₁₂•6H₂O	9.GD.50	Zeolites	
Na)₅(Al₅Si₁₁O₃₂)	9.GD.10	9.GD.55	9.GF.05	Unclassified
•12H₂O	9.GD.15		9.GF.10	Zeolites
9.GC.15	9.GD.20	Chains of X ₁₀ O ₂₀	9.GF.15	9.GG.05
9.GC.20	9.GD.25	Tetrahedra	9.GF.20	9.GG.10

9.H - SILICATES (GERMANATES): UNCLASSIFIED SILICATES

With Alkali and	9.HA.65	With Manganese	9.HE.10	9.HG.20
Alkali-Earth	9.HA.70	and Iron		
Elements	9.HA.75	9.HC.05	With Niobium,	With Lead
9.HA.05	9.HA.80	9.HC.10	Tantalum and	9.HH.05
9.HA.10	9.HA.85		Zirconium	9.HH.10
9.HA.20	9.HA.90	With Cobalt and	9.HF.05	9.HH.15
9.HA.25		Nickel	9.HF.10	9.HH.20
9.HA.30	With Titanium,	9.HD		9.HH.25
9.HA.40	Vanadium and		With Rare Earth	
9.HA.50	Chromium	With Copper	Elements and	
9.HA.55	9.HB.05	and Zinc	Thorium	
9.HA.60	9.HB.10	9.HE.05	9.HG.15	

9.J - SILICATES (GERMANATES): GERMANATES

Germanates	9.JA
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10.A - ORGANIC COMPOUNDS: SALTS OF ORGANIC ACIDS

Formates,	10.AA.30	10.AB.20	10.AB.55	Benzene Salts
Acetates and	10.AA.35	10.AB.25	10.AB.60	10.AC.05
Similar		10.AB.30	10.AB.65	10.AC.10
10.AA.05	Oxalates	10.AB.35	10.AB.70	10.AC.15
10.AA.10	10.AB.05	10.AB.40	10.AB.75	Cyanates
10.AA.20	10.AB.10	10.AB.45	10.AB.80	10.AD.05
10.AA.25	10.AB.15	10.AB.50		10.AD.10

10.B - ORGANIC COMPOUNDS: HYDROCARBONS

Hydrocarbons	Hartite	10.BA.20	10.BA.35	10.BA.50
10.BA.05	C₂₀H₃₄	10.BA.25	10.BA.40	
<u>10.BA.10</u>	10.BA.15	10.BA.30	10.BA.45	

TABLE 18. Continued

10.C - ORGANIC COMPOUNDS: MISCELLANEOUS ORGANIC MINERALS

Miscellaneous	10.CA.05	C₁₀H₂₂O₃	10.CA.25
Organic	<u>10.CA.10</u>	10.CA.15	10.CA.30
Minerals	Flagstaffite	10.CA.20	10.CA.35
10.CA.40			

Notes: The categories and numerical codes are from mindat.org (Ralph and Chau, 2012). The electrical activity of minerals in underlined codes can be found in references listed in Tables 15, 16 and 17 in Appendix G, p. 226 through 228.

APPENDIX D
MINERALS ARRANGED BY SYMMETRY

TABLE 19. Minerals Exhibiting Ferro-, Antiferro-, Para-, Pyro- or Piezoelectricity Arranged by Crystal System, Crystal Class and Overall Symmetry

System	Class	Symmetry		
<u>Triclinic</u>	1	<i>Polar, Chiral</i>		
Amesite	Epistilbite	Hartite	Hilgardite	Weloganite
<u>Triclinic</u>	1	<i>Centrosymmetric</i>		
Bultfonteinite	Innelite	Melanovanadite	Murmanite	Ussingite
Epistolite				
<u>Monoclinic</u>	2	<i>Polar, Chiral</i>		
Colemanite	Halotrichite	Oxycalcio-pyrochlore	Oxyplumbo-pyrochlore*	Pickeringite
Epistilbite	Hydrocalumite			Searlesite
<u>Monoclinic</u>	m	<i>Polar</i>		
Afwillite	Clinohedrite	Nacrite	Schultenite	Yugawaralite
Berthierine	Halloysite-7Å	Neptunite	Scolecite	
Brushite	Halloysite-10Å	Pharmacolite	Tilasite	
<u>Monoclinic</u>	2/m	<i>Centrosymmetric</i>		
Artinite	Gismondine-Ca	Heulandite-Ca	Muthmannite	Syngenite
Chalcocite	Harmotome	Innelite	Parkerite	Vermiculite
Creedite	Heftetjernite	Kaliborite	Quenselite	
<u>Orthorhombic</u>	222	<i>Polar, Chiral</i>		
Edingtonite	Goslarite	Leucophanite	Morenosite	Olsacherite
Epsomite				
<u>Orthorhombic</u>	mm2	<i>Polar</i>		
Batisite*	Childrenite	Krennerite	Pirssonite	Stibiotantalite
Bertrandite	Dyscrasite	Larsenite	Prehnite	Stibnite
Boracite	Enargite	Liebigite	Russellite	Struvite
Bournonite	Flagstaffite	Mesolite	Shortite	Suolunite
Caledonite	Hemimorphite	Minyulite	Sinoite	
Chambersite	Junitoite	Mordenite	Stephanite	
Changbaiite	Koehlinite	Natrolite	Stibiocolumbite	
<u>Orthorhombic</u>	mmm	<i>Centrosymmetric</i>		
Analcime	Clinocervantite	Elpidite	Mariinskite	Stibnite
Bavenite	Dawsonite	Eosphorite	Niter	Thomsonite-Ca
Bismuthinite	Demicheleite-Br	Gwihabaite	Perovskite	Topaz
Cervantite	Demicheleite-Cl	Lakargiite	Seligmannite	Tyrolite
Chalcostibite	Demicheleite-I	Lueshite	Srebrodolskite	
<u>Tetragonal</u>	4	<i>Polar, Chiral</i>		
(No Listings)				
<u>Tetragonal</u>	4	<i>Non-centrosymmetric</i>		
Meliphanite	Tugtupite			
<u>Tetragonal</u>	4/m	<i>Centrosymmetric</i>		
Aminoffite	Marialite	Pinnoite	Wakefieldite-Nd	Wulfenite
Analcime	Meionite	Sarcosite		

TABLE 19. Continued

System	Class	Symmetry			
<u>Tetragonal</u> Paratellurite	422 Retgersite	<i>Chiral</i>			
<u>Tetragonal</u> Barioperovskite	4mm Diaboleite	<i>Polar</i> Diomignite	Fresnoite	Macedonite	
<u>Tetragonal</u> Archerite Biphosphammite	42m Edingtonite	<i>Non-centrosymmetric</i> Gallite	Gugiaite	Roquesite	
<u>Tetragonal</u> Cassiterite	4/mmm Pyrolusite	<i>Centrosymmetric</i>			
<u>Trigonal</u> Jarosite	3 Röntgenite-Ce	<i>Polar, Chiral</i>			
<u>Trigonal</u> Analcime	3 Benstonite	<i>Centrosymmetric</i> Diopase			
<u>Trigonal</u> Berlinite	32 Cinnabar	<i>Chiral</i> α -Quartz	Selenium	Tellurium	
<u>Trigonal</u> Alunite Ammoniojarosite Argentojarosite Buergerite Cronstedtite	3m Dravite Elbaite Ericaite Feruvite Fluor-dravite	<i>Polar</i> Fluor-liddicoatite Fluor-schorl Foitite Georgbarsanovite Millerite	Natroalunite Natrojarosite Olenite Oxy-schorl Povondraite	Pyrargyrite Schorl Spangolite Uvite Whitlockite	
<u>Trigonal</u> Arsenogoyazite Brucite	3m Coquimbite Crandallite	<i>Centrosymmetric</i> Goyazite Nitratine	Plumbojarosite Proustite	Pyrochroite Thornasite	
<u>Hexagonal</u> Cancrinite	6 Nepheline	<i>Polar, Chiral</i> Zinkenite			
<u>Hexagonal</u> (No Listings)	6	<i>Non-centrosymmetric</i>			
<u>Hexagonal</u> Jeremejevite	6/m Mimetite	<i>Centrosymmetric</i> Pyromorphite	Thaumasite		
<u>Hexagonal</u> β -Quartz	622	<i>Chiral</i>			
<u>Hexagonal</u> Bromellite Burbankite	6mm Cadmoselite Greenockite	<i>Polar</i> Iodargyrite Moissanite	Nolanite Swedenborgite	Wurtzite Zincite	
<u>Hexagonal</u> Bastnäs-Ce	6m2	<i>Non-centrosymmetric</i>			

TABLE 19. Continued

System	Class	Symmetry		
<u>Hexagonal</u>	6/mmm	<i>Centrosymmetric</i>		
Beryl	Chalcocite	Gmelinite-Na	Ice	Nickeline
Breithauptite	Finnemanite			
<u>Cubic</u>	23	<i>Chiral</i>		
Langbeinite	Sillénite			
<u>Cubic</u>	43m	<i>Non-centrosymmetric</i>		
Eulytine	Londonite	Rhodizite	Sphalerite	Tiemannite
Helvine	Pharmacosiderite	Sodalite	Stilleite	Zunyite
<u>Cubic</u>	m3	<i>Centrosymmetric</i>		
Alum-Na	Nitrobarite			
<u>Cubic</u>	432	<i>Chiral</i>		
(No Listings)				
<u>Cubic</u>	m3m	<i>Centrosymmetric</i>		
Altaite	Analcime	Hydroxycalcio- roméite	Sal Ammoniac	Tausonite

Notes: The asterisk* denotes minerals whose crystal structure is poorly constrained. References are listed in Table 11 in Appendix G, p. 224.

APPENDIX E

MINERALS ARRANGED BY PETROLOGIC SETTING

TABLE 45. Minerals Listed by Petrologic Setting

METEORITES: PRIMARY MINERALS

Daubréelite, Eskolaite, Moissanite, Pyrophanite, Pyrrhotite, Sinoite, Tistarite, Wüstite

INCLUSION MINERALS

Barioperovskite, Diomignite, Macedonite, Moissanite, Perovskite, Stilleite, Wüstite

ULTRAMAFIC MINERALS: IGNEOUS INTRUSIVE ROCK

Fayalite, Ilmenite, Magnesioferrite, Moissanite, Nickeline, Perovskite, Shortite, Spinel

ULTRAMAFIC MINERALS: IGNEOUS EXTRUSIVE ROCK

Fayalite

ULTRAMAFIC ROCK: SECONDARY MINERALS

Maghemite, Suolunite

KIMBERLITE MINERALS

Bultfonteinite, Moissanite

MAFIC MINERALS: IGNEOUS INTRUSIVE ROCK

Burbankite, Cadmoindite, Coulsonite, Cuprorhodite, Ilmenite, Magnetite, Natrolite, Nickeline, Pyrite, Pyrrhotite, Rutile, Scolecite, Spinel

MAFIC MINERALS: PEGMATITES

Batisite, Coulsonite, Feruvite, Gmelinite, Ilmenite, Innelite, Löllingite, Magnetite, Pyrite, Pyrrhotite

MAFIC MINERALS: IGNEOUS EXTRUSIVE ROCK

Analcime, Bismuthinite, Coquimbite, Coulsonite, Edingtonite, Epistilbite, Gismondine, Gmelinite, Greenockite, Magnesioferrite, Magnetite, Mesolite, Pyrite, Scolecite, Selenium, Spinel, Tellurium, Trevorite, Wüstite, Zincite

MAFIC ROCK: SECONDARY MINERALS

Analcime, Coquimbite, Demicheleite-Br, Demicheleite-Cl, Demicheleite-I, Fayalite, Greenockite, Harmotome, Heulandite, Jarosite, Maghemite, Marialite, Meionite, Mordenite, Natroalunite, Nisbite, Prehnite, Tellurium, Thomsonite-Ca, Vermiculite, Yugawaralite

INTERMEDIATE MINERALS: IGNEOUS INTRUSIVE ROCK

Pyrite

INTERMEDIATE MINERALS: IGNEOUS EXTRUSIVE ROCK

Analcime, Bismuthinite, Cadmoindite, Coulsonite, Halotrichite, Magnetite, Mattagamite, Mesolite, Pickeringite, Pyrite, Sal Ammoniac, Selenium

INTERMEDIATE ROCK: SECONDARY MINERALS

Heulandite, Jarosite, Mordenite, Natrojarosite, Vermiculite

FELSIC MINERALS: IGNEOUS INTRUSIVE ROCK

Bastnäsite, Beryl, Cassiterite, Elbaite, Elpidite, Fluor-schorl, Helvine, Hematite, Ilmenite, Magnetite, Mariinskite, Pickeringite, Pyrite, Pyrophanite, Quartz, Rutile, Schorl, Topaz

FELSIC MINERALS: GRANITIC PEGMATITES

Bastnäsite-Ce, Bavenite, Beryl, Cassiterite, Childrenite, Coulsonite, Crandallite, Diomignite, Elbaite, Eosphorite, Fayalite, Ferberite, Fluor-dravite, Fluor-liddicoatite, Fluor-schorl, Foitite, Goyazite, Heftetjernite, Helvine, Jeremejevite, Kamiokite, Londonite, Magnetite, Mariinskite, Olenite, Oxycalcipyrochlore, Oxyplumbopyrochlore, Oxy-schorl, Pyrite, Quartz, Rhodizite, Röntgenite-Ce, Rutile, Schorl, Siderite, Stibiocolumbite, Stibiotantalite, Uraninite, Whitlockite

FELSIC MINERALS: IGNEOUS EXTRUSIVE ROCK

Bertrandite, Bismuthinite, Buergerite, Cadmoindite, Cassiterite, Halotrichite, Hematite, Londonite, Magnetite, Mattagamite, Moissanite, Pyrite, Quartz, Sal Ammoniac, Selenium, Tellurium, Topaz

FELSIC ROCK: SECONDARY MINERALS

Beryl, Changbaite, Clinoferrosilite, Eosphorite, Jarosite, Mariinskite, Mordenite, Natroalunite, Natrojarosite, Quartz, Russellite, Tellurium, Vermiculite

ALKALIC (SI-POOR) MINERALS: IGNEOUS INTRUSIVE ROCK

Bastnäsite-Ce, Beryl, Burbankite, Cancrinite, Coulsonite, Elpidite, Lueshite, Magnesioferrite, Magnetite, Mariinskite, Meliphanite, Murmanite, Nepheline, Pyrite, Rutile, Scolecite, Shortite, Sodalite, Tausonite, Thornasite, Ussingite, Weloganite

TABLE 45. Continued

ALKALIC (SI-POOR) MINERALS: PEGMATITES

Bastnäsite-Ce, Bromellite, Coulsonite, Elpidite, Epistolite, Georgbarsanovite, Leucophanite, Macedonite, Magnetite, Murmanite, Nepheline, Oxycalciopyrochlore, Oxylumbopyrochlore, Perovskite, Pyrite, Röntgenite-Ce, Siderite, Sodalite, Tugtupite, Uraninite, Ussingite

ALKALIC (SI-POOR) MINERALS: IGNEOUS EXTRUSIVE ROCK

Bromellite, Cadmoindite, Coulsonite, Edingtonite, Gismondine, Magnetite, Natrolite, Nepheline, Pyrite, Selenium, Tellurium

ALKALIC (SI-POOR) ROCK: SECONDARY MINERALS

Analcime, Cancrinite, Dawsonite, Demicheleite, Harmotome, Jarosite, Murmanite, Natroalunite, Natrojarosite, Nepheline, Prehnite, Searlesite, Sodalite, Tellurium, Thomsonite-Ca, Tugtupite

CARBONATITE MINERALS

Bastnäsite-Ce, Benstonite, Burbankite, Crandallite, Goyazite, Ilmenite, Magnesioferrite, Oxycalciopyrochlore, Oxylumbopyrochlore, Perovskite, Shortite, Siderite, Tausonite

METAMORPHIC (AND HYDROTHERMAL) ORE MINERALS

Altaite, Argentojarosite, Arsenogoyazite, Bastnäsite-Ce, Bismuthinite, Bournonite, Breithauptite, Carrollite, Chalcocite, Chalcostibite, Cinnabar, Clinohedrite, Coulsonite, Cronstedtite, Cuprokalininite, Cuprospinel, Dyscrasite, Enargite, Epistolite, Eskolaite, Eulytine, Ferberite, Finnemanite, Franklinite, Gallite, Harmotome, Hauerite, Hematite, Hydroxycalcioroméite, Ilmenite, Indite, Jacobsite, Kalininite, Kamiokite, Karelianite, Krennerite, Krut'aite, Linnaeite, Löllingite, Maghemite, Magnesiocoulsonite, Magnetite, Morenosite, Nickeline, Nisbite, Nolanite, Paratellurite, Parkerite, Penroseite, Proustite, Pyrargyrite, Pyrite, Pyrite (variety: Bravoite), Pyrochroite, Pyrolusite, Pyrophanite, Pyrrhotite, Quartz, Quenselite, Retgersite, Roquesite, Selenium, Siderite, Siegenite, Sphalerite, Stephanite, Stibnite, Stilleite, Tellurium, Thaumasite, Tiemannite, Tilasite, Trevorite, Uraninite, Wakefieldite-Nd, Wurtzite, Zincite, Zinkenite

HYDROTHERMAL: LOW-TEMPERATURE MINERALS

Artinite, Benstonite, Beryl, Bismuthinite, Brucite, Chalcocite, Chalcostibite, Childrenite, Cinnabar, Clinohedrite, Cronstedtite, Goyazite, Halloysite-7Å, Halloysite-10Å, Hauerite, Jarosite, Mariinskite, Millerite, Minyulite, Morenosite, Muthmannite, Nacrite, Pyrargyrite, Retgersite, Sphalerite, Stibnite, Wurtzite

HYDROTHERMAL: MEDIUM-TEMPERATURE MINERALS

Benstonite, Beryl, Bismuthinite, Bournonite, Cassiterite, Creedite, Enargite, Jeremejevitte, Löllingite, Mariinskite, Mesolite, Sphalerite, Stibnite, Uraninite

HYDROTHERMAL: HIGH-TEMPERATURE MINERALS

Aminoffite, Bastnäsite-Ce, Bavenite, Berlinite, Bertrandite, Beryl, Bismuthinite, Bromellite, Cassiterite, Coulsonite, Elbaite, Ferberite, Feruvite, Fluor-schorl, Greenockite, Hematite, Hydrocalumite, Magnetite, Mariinskite, Nickeline, Olenite, Povondraite, Pyrrhotite, Quartz, Rutile, Schorl, Sphalerite, Stibnite, Uraninite

SECONDARY ORE MINERALS

Argentojarosite, Arsenogoyazite, Caledonite, Cervantite, Chalcocite, Clinocervantite, Coquimbite, Cuprospinel, Diaboleite, Diopside, Dyscrasite, Goslarite, Greenockite, Halotrichite, Hematite, Hemimorphite, Hydroxycalcioroméite, Indite, Iodargyrite, Jacobsite, Jarosite, Junitoite, Koechlinite, Larsenite, Liebigite, Linnaeite, Melanovanadite, Millerite, Mimetite, Morenosite, Muthmannite, Natrojarosite, Nolanite, Olsacherite, Parkerite, Pharmacolite, Pharmacosiderite, Pickeringite, Plumbojarosite, Pyrargyrite, Pyrochroite, Pyrolusite, Pyromorphite, Quenselite, Retgersite, Russellite, Schultenite, Selenium, Sillénite, Spangolite, Tellurium, Tyrolite, Uranophane, Vaesite, Wulfenite, Wüstite, Zincite

MAFIC SOURCEROCK: PRIMARY METAMORPHIC MINERALS

Eskolaite, Fayalite, Ferberite, Hematite, Ilmenite, Kamiokite, Karelianite, Mariinskite, Neptunite, Pyrite, Pyrophanite, Thaumasite, Thomsonite-Ca, Trevorite, Zincite

MAFIC SOURCEROCK: SECONDARY METAMORPHIC MINERALS

Amesite, Artinite, Berthierine, Beryl, Brucite, Cronstedtite, Eskolaite, Halloysite-7Å, Halloysite-10Å, Hematite, Jarosite, Junitoite, Marialite, Meionite, Millerite, Nacrite, Natrojarosite, Neptunite, Nolanite, Prehnite, Pyrophanite, Trevorite, Vermiculite, Zincite

TABLE 45. Continued

<i>SI-RICH SOURCEROCK: HIGH-GRADE PRIMARY METAMORPHIC MINERALS</i>
Coulsonite, <u>Crandallite</u> , Cuprokalinitite, <u>Elbaite</u> , <u>Epistilbite</u> , Ferberite, <u>Fluor-schorl</u> , <u>Fresnoite</u> , <u>Harmotome</u> , <u>Helvine</u> , Ilmenite, Maghemite, Magnetite, <u>Natrolite</u> , Pyrite, <u>Quartz</u> , Rutile, <u>Schorl</u> , <u>Scolecite</u> , Spinel, <u>Topaz</u>
<i>SI-RICH SOURCEROCK: CONTACT AND LOW GRADE PRIMARY METAMORPHIC MINERALS</i>
<u>Amesite</u> , <u>Cassiterite</u> , Eskolaite, <u>Prehnite</u> , Pyrite, <u>Thaumasite</u> , <u>Thomsonite-Ca</u>
<i>SI-RICH SOURCEROCK: SECONDARY METAMORPHIC MINERALS</i>
<u>Alunite</u> , <u>Changbaiite</u> , <u>Halloysite-7Å</u> , <u>Halloysite-10Å</u> , <u>Jarosite</u> , <u>Natrojarosite</u> , <u>Pickeringite</u> , <u>Prehnite</u> , <u>Quartz</u> , <u>Vermiculite</u> , <u>Zunyite</u>
<i>ALKALIC (SI-POOR) SOURCEROCK: METAMORPHIC MINERALS</i>
Coulsonite, <u>Gugiaite</u> , <u>Lueshite</u> , Magnetite, Natrolite, <u>Nepheline</u> , Pyrite, <u>Thomsonite-Ca</u>
<i>CARBONATE REGIONAL METAMORPHISM: MINERALS</i>
<u>Breithauptite</u> , <u>Brucite</u> , <u>Dravite</u> , Franklinite, Kalinitite, Löllingite, Magnesioferrite, <u>Marialite</u> , <u>Meionite</u> , Rutile
<i>SKARN AND CARBONATE CONTACT METAMORPHISM: MINERALS</i>
<u>Afwillite</u> , <u>Aminoffite</u> , <u>Bastnäsite-Ce</u> , Bavenite, <u>Benstonite</u> , <u>Bromellite</u> , <u>Brucite</u> , <u>Bultfonteinite</u> , Coulsonite, Eskolaite, <u>Gugiaite</u> , <u>Helvine</u> , <u>Hydrocalumite</u> , <u>Lakargiite</u> , <u>Leucophanite</u> , <u>Liebigite</u> , Maghemite, Magnesioferrite, Magnetite, <u>Marialite</u> , <u>Meionite</u> , <u>Perovskite</u> , <u>Roquesite</u> , <u>Sarcolite</u> , <u>Sillénite</u> , Spinel, <u>Srebrodolskite</u> , <u>Swedenborgite</u>
<i>METASOMATIC MINERALS</i>
<u>Alum-Na</u> , <u>Ammoniojarosite</u> , <u>Berlinite</u> , <u>Chromium-dravite</u> , <u>Dravite</u> , <u>Jarosite</u> , <u>Natrojarosite</u> , <u>Nepheline</u> , <u>Sodalite</u> , <u>Uvite</u>
<i>SULFATE-WATER PROCESSES: SECONDARY MINERALS</i>
<u>Alum-Na</u> , <u>Alunite</u> , <u>Ammoniojarosite</u> , <u>Cadmoselite</u> , Hauerite, <u>Jarosite</u> , <u>Morenosite</u> , <u>Natroalunite</u> , <u>Natrojarosite</u> , <u>Retgersite</u> , <u>Thaumasite</u>
<i>EVAPORITE MINERALS</i>
<u>Boracite</u> , <u>Chambersite</u> , Colemanite, <u>Epsomite</u> , <u>Ericaite</u> , <u>Hilgardite</u> , <u>Kaliborite</u> , <u>Langbeinite</u> , <u>Nitratine</u> , <u>Pinnoite</u> , <u>Searlesite</u> , <u>Syngenite</u>
<i>AUTHIGENIC PRECIPITATE PROCESSES: MINERALS</i>
<u>Analcime</u> , Boracite, Burbankite, Colemanite, <u>Crandallite</u> , Dawsonite, <u>Dravite</u> , Eskolaite, <u>Greenockite</u> , Hematite, <u>Langbeinite</u> , Magnetite, <u>Mordenite</u> , <u>Natroalunite</u> , <u>Nitratine</u> , <u>Pirssonite</u> , Pyrite, <u>Pyrrhotite</u> , <u>Siderite</u> , <u>Sphalerite</u> , <u>Suolunite</u> , <u>Thomsonite-Ca</u> , <u>Wurtzite</u> , Wüstite
<i>MARL AND DOLOSTONE: MINERALS</i>
Magnesioferrite, <u>Searlesite</u> , <u>Seligmannite</u> , <u>Shortite</u> , Vaesite
<i>MARINE REDUCING SEDIMENTARY ENVIRONMENT: MINERALS</i>
<u>Ammoniojarosite</u> , <u>Berthierine</u> , <u>Cadmoselite</u> , <u>Crandallite</u> , <u>Pyrolusite</u>
<i>PLACER DEPOSIT MINERALS</i>
<u>Bastnäsite-Ce</u> , <u>Cassiterite</u> , Cuprorhodsite, <u>Elbaite</u> , Eskolaite, Ferberite, <u>Fluor-liddicoatite</u> , <u>Fluor-schorl</u> , <u>Goyazite</u> , Ilmenite, Magnetite, <u>Mariinskite</u> , <u>Moissanite</u> , <u>Oxy-schorl</u> , <u>Quartz</u> , Rutile, <u>Schorl</u> , Spinel, <u>Topaz</u> , Uraninite
<i>GLACIAL DEPOSITS</i>
Eskolaite, <u>Hydroxycalcioroméite</u> , Kareljanite
<i>DEPLETED SOIL MINERALS</i>
<u>Berthierine</u> , <u>Crandallite</u> , <u>Vermiculite</u>
<i>PLANT MATTER PROCESSES: SECONDARY MINERALS</i>
<u>Alum-Na</u> , <u>Ammoniojarosite</u> , <u>Flagstaffite</u> , <u>Halotrichite</u> , <u>Hartite</u> , <u>Millerite</u> , <u>Niter</u> , <u>Pickeringite</u> , <u>Sal Ammoniac</u> , <u>Selenium</u> , <u>Sphalerite</u> , <u>Srebrodolskite</u>
<i>GUANO MINERALS</i>
<u>Archerite</u> , <u>Ardealite</u> , <u>Biphosphammite</u> , <u>Gwihabaite</u> , Lecontite, <u>Niter</u> , <u>Nitratine</u> , <u>Nitrobarite</u> , <u>Sal Ammoniac</u> , <u>Syngenite</u> , <u>Whitlockite</u>
<i>MINERALS WITH A MICROBIAL COMPONENT</i>
Magnetite, Siderite

Note: Underlined minerals are listed in scientific literature as exhibiting symmetry-based electrical effects.

APPENDIX F

LIST AND SOURCES OF SUPPLIES FOR PREPARING SAMPLES

TABLE 5. List of Supplies for Preparing Samples and Retail Contact Information

Equipment	Make and Model	Cost	Retail Outlet
Alumina Suspension	0.05 Micron Product #AS0005-16 16 oz.	\$40	South Bay Technology
Colloidal Silica	Type SBT 16 oz.	\$25	South Bay Technology
Diamond Blade	Diameter: 7" Arbor: 5/8" Thickness: 0.025"	\$200	UKAM Industrial Superhard Tools
Diamond Suspension	3 Micron MicroDi Poly Product #DSP030-16 16 oz.	\$120	South Bay Technology
Digital Angle Gauge	Unbranded	\$12	Harbor Freight Tools
Digital Caliper	Cen Tech Digital Thickness Gauge Accuracy: 0.1 mm Item #66319	\$10	Harbor Freight Tools
Digital Caliper	Pittsburgh 4" Digital Caliper Accuracy: 0.0254 mm (0.001") Model #47256	\$18	Harbor Freight Tools
Electron Backscatter Diffraction (EBSD)	Oxford Instruments HKL	\$45/hr (Guest - UC Irvine)	Oxford Instruments
Heat Gun	Drill Master Model #96289	\$25	Harbor Freight Tools
Lapping and Polishing Machine	South Bay Technology Model #920	\$75 (Guest - UC Irvine)	South Bay Technology
Melamine-Coated Particle Board	Unbranded	\$8	Home Depot, Lowe's
Mini Cut-Off Saw	Drill Master Model #42307	\$25	Harbor Freight Tools
Polishing Cloth (for Lapper)	Rayon Diameter: 20 cm (8") Product #PRA08A-10	\$40	South Bay Technology
Scanning Electron Microscope (SEM)	FEI Quanta 3D FEG Dual Beam SEM with FIB	\$45/hr (Guest - UC Irvine)	FEI

TABLE 5. Continued

Equipment	Make and Model	Cost	Retail Outlet
Silicon Carbide Powder	50.0 Micron (240 Grit) 1 lb.	\$20	South Bay Technology
	600 Grit 1 lb.	\$12	Michael's Lapidary & Gift Shop
	1200 Grit 4 oz.	\$8	Michael's Lapidary & Gift Shop
Steel Plate	Length: 4 ½" Width: 4 ½" Thickness: ¼"	n/a	Scrap
Table Saw	Chicago Electric Power Tools 1.5 HP Bridge Tile Saw with Stand Model #97360	\$200	Harbor Freight Tools
Teflon [®] Rod	Unbranded	\$11	ebay
Teflon [®] Sheet	Unbranded	\$15	ebay
Thermocouple	K-Type	\$20	Omega Engineering
	Thermocouple Connector UTC-USB	\$75	Omega Engineering

Notes: Retail contact information is listed on this page in Table 6. Prices are rounded off (or approximate values) from 2012.

TABLE 6. Retail Contact Information for Supplies Listed in Table 5

ebay http://www.ebay.com/	Omega Engineering, Inc. One Omega Drive, Box 4047 Stamford, CT 06907-0047 (203) 359-1660 http://www.omega.com/
Harbor Freight Tools http://www.harborfreight.com/	South Bay Technology 1120 Via Callejon San Clemente, CA 92673 www.southbaytech.com
Home Depot http://www.homedepot.com/	UKAM Industrial Superhard Tools Valencia, CA http://www.ukam.com/
Lowe's http://www.lowes.com/	
Michael's Lapidary & Gift Shop 2406 North Glassell St. Orange, CA 92865 (714) 998-7209	

Notes: Web addresses are current as of 2012.

APPENDIX G
SOURCES OF MINERAL DATA FOR THE TABLES

TABLE 11. References for Crystal Structure Data in the List of Minerals in Table 4, Page 90

Reference	Minerals
Akizuki et al., 1979	Topaz
Armbruster and Gunter, 2001	Analcime, Edingtonite, Epistilbite, Gismondine-Ca, Gmelinite-Na, Goyazite, Harmotome, Heulandite-Ca, Mesolite, Mordenite, Scolecite, Thomsonite-Ca, Yugawaralite
Badreddine et al., 2002	Vermiculite
Bahfenne and Frost, 2010	Finnemanite
Baranov et al., 2001	Parkerite
Barnett et al., 2000	Thaumasite
Barthelmy, 2012	Minerals not otherwise listed
Bell et al., 2010	Cinnabar
Belokoneva et al., 2002	Diopside
Belovitskaya et al., 2000	Burbankite
Bindi and Cipriani, 2004	Muthmannite
Birnstock, 1967	Nitrobarite
Breitinger et al., 2006	Crandallite, Goyazite
Burns and Hawthorne, 1994	Kaliborite
Cámara et al., 2008	Murmanite
Capitani et al., 2007	Moissanite
Curry and Jones, 1971	Brushite
Frost and Bouzaid, 2007	Dawsonite
Frost et al., 2009	Artinite
Frost et al., 2013a	Arsenogoyazite
Frost et al., 2013b	Creedite
Gilberg, 1981	Sal Ammoniac
Goreaud and Raveau, 1980	Crandallite
Grice and Hawthorne, 1989	Leucophanite
Gritsenko and Spiridonov, 2005	Nickeline
Hashimoto and Matsumoto, 1998	Pyromorphite
Hawthorne et al., 2000	Alum-Na
Heller, 1970	Pinnoite
<u>Hellwege and Hellwege</u> , 1970a	Hematite, Siderite, Srebrodolskite, Wüstite
<u>Hellwege and Hellwege</u> , 1970b	Ferberite
<u>Hellwege and Hellwege</u> , 1978	Clinoferrosilite, Eskolaite, Fayalite, Franklinite, Kalininite, Kamiokite, Xieite, Zincochromite
Hewitt, 1948	Breithauptite
Hibbs et al., 2000	Wulfenite
Hoyos et al., 1993	Eosphorite
Huminicki and Hawthorne, 2002a	Amnoffite
Huminicki and Hawthorne, 2002b	Brushite
Johnson and Rossman, 2004	Ussingite
Kloprogge et al., 2002	Syngenite
Konnert and Evans, 1987	Melanovanadite
Krivovichev, et al., 2006	Tyrolite
Krogh-Moe, 1967	Pinnoite
Libowitzky and Beran, 2006	Beryl
Lussier and Hawthorne, 2011	Bavenite
Majzlan et al., 2010	Coquimbite
Malik and Jeffery, 1976	Afwillite
Manseau et al., 2002	Quenselite
Maras and Paris, 1987	Sarcolite
Matsumoto, 1998	Pyromorphite
McIver, 1963	Bultfonteinite

TABLE 11. Continued

Reference	Minerals
Nowotny and Heger, 1983	Nitrobarite
Parise et al., 1998	Pyrochroite
Pepinsky et al., 1956	Alum-Na
Peterson et al., 1979	Brucite
Pramana et al., 2008	Finnemanite
Ralph and Chau, 2012	Minerals not otherwise listed
Rastsvetaeva, 2009	Georgbarsanovite
Rodellas et al., 1983	Jeremejevite
Rodríguez-Blanco et al., 2007	Pharmacolite
Rouse, 1971	Quenselite
Ruiz-Salvador et al., 2000	Heulandite-Ca
Scheetz and White, 1977	Benstonite
Sherriff et al., 2000	Meionite
<u>Shiozaki et al., 2002a</u>	Barioprovskite, Lakargiite, Lueshite, Macedonite, Perovskite, Tausonite
<u>Shiozaki et al., 2002b</u>	Cervantite, Chambersite, Changbaiite, Clinocervantite, Diomignite, Ericaite, Heftetjernite, Mariinskite, Oxycalciopyrochlore, Oxyplumbopyrochlore, Russellite, Stibiotantalite, Uraninite, Wakefieldite-Nd
<u>Shiozaki et al., 2004</u>	Archerite, Biphosphammite, Demicheleite-Br, Demicheleite-I, Gwihabaite, Niter, Nitratine, Proustite, Pyrargyrite, Schultenite
<u>Shiozaki et al., 2005</u>	Stibnite
Sokolova and Hawthorne, 2004	Epistolite
Sokolova et al., 1996	Marialite
Sokolova et al., 2011	Innelite
Sowa et al., 2004	Millerite
Szymanski, J.T., 1985	Plumbojarosite
Takeuchi and Haga, 1969	Seligmannite
Tančić et al., 2010	Beryl
Uvarova et al., 2003	Batisite
Venetopoulos and Rentzeperis, 1976	Clinohedrite
<u>Wijn, 1988</u>	Cuprokalinitite, Cuprorhodsite, Daubréelite, Hauerite, Krut'aite, Linnaeite, Nickeline, Pyrrhotite, Vaesite
<u>Wijn, 1991a</u>	Cuprospinel, Jacobsite, Karelianite, Maghemite, Magnesioferrite, Magnetite, Trevorite
<u>Wijn, 1994</u>	Ilmenite
Wolfram Alpha*, 2012	Minerals not otherwise listed
Wu Ziuling et al., 1998	Röntgenite-Ce
Xiaodong Zhang et al., 2011	Nolanite
Yaping Li et al., 2000	Thornasite
Yongshan Dai et al., 1991	Mimetite
Yunxiang Ni et al., 1993	Röntgenite-Ce
Yuodvershis et al., 1969	Bismuthinite
Zubkova et al., 2011	Elpidite
Zuo et al., 1990	Magnetite

Notes: Data sources that are part of the Landolt-Börnstein Database in SpringerMaterials are underlined, for ease in distinguishing these (Springer, 2012). Wolframalpha.com* does a meta-search of five sites: webmineral.com, minerals.net, mineralatlas.com, mindat.org, and the United States Geological Survey (USGS) mineral resources on-line spatial data website.

TABLE 15. References for Ferroelectric, Antiferroelectric and Paraelectric Minerals Included in Table 7, Page 40, and Table 12, Page 176

Reference	Minerals
Bhide and Damle, 1960	Pyrolusite
Bieniulis et al., 1987	Chalcocite
Buch et al., 1998	Ice
Dengel et al., 1964	Ice
Deshpande and Bhide, 1961	Cassiterite
Grigas et al., 1976	Chalcostibite
<u>Hellwege and Hellwege</u> , 1970a	Srebrodolskite
Howe and Whitworth, 1989	Ice
Kuhs et al., 1987	Ice
Lines and Glass, 1977	Altaite
<u>Nelson</u> , 1993	Boracite, Pyrargyrite, Sillénite
Parkhomenko, 1971	Hydroxycalcioroméite
Pepinsky et al., 1956	Alum-Na
<u>Shiozaki et al.</u> , 2002a	Barioperovskite, Lakargiite, Lueshite, Macedonite, Perovskite, Tausonite
<u>Shiozaki et al.</u> , 2002b	Boracite, Cervantite, Chambersite, Changbaiite, Clinocervantite, Diomignite, Ericaite, Heftetjernite, Koechlinite, Mariinskite, Oxycalciopyrochlore, Oxyplumbopyrochlore, Russellite, Stibiotantalite, Wakefieldite-Nd
<u>Shiozaki et al.</u> , 2004	Archerite, Biphosphammite, Demicheleite-Br, Demicheleite-I, Gwihabaite, Niter, Nitratine, Proustite, Pyrargyrite, Schultenite
<u>Shiozaki et al.</u> , 2005	Stibnite
Yuodvershis et al. 1969	Bismuthinite

Notes: Data sources that are part of the Landolt-Börnstein Database in SpringerMaterials are underlined, for ease in distinguishing these (Springer, 2012).

TABLE 16. References for Pyroelectric Minerals Included in Table 8, Page 41 and Table 13, Page 178

Reference	Minerals
Bond, 1943	Iodargyrite
Hawkins et al., 1995	Tourmaline
Mirgorodsky et al., 1989	Sinoite
<u>Nelson</u> , 1993	Bournonite, Cancrinite, Fresnoite, Greenockite, Schorl, Stephanite, Tourmaline, Wurtzite
Parkhomenko, 1971	Amesite, Ammoniojarosite, Ardealite, Argentojarosite, Arsenogoyazite, Artinite, Benstonite, Berthierine, Beryl, Breithauptite, Brucite, Bultfonteinite, Cadmoselite, Childrenite, Colemanite, Coquimbite, Crandallite, Creedite, Cronstedtite, Dawsonite, Diaboleite, Dyscrasite, Elpidite, Enargite, Eosphorite, Epistolite, Finnemanite, Georgbarsanovite, Goyazite, Halloysite-7Å, Halloysite-10Å, Halotrichite, Harmotome, Hartite, Heulandite-Ca, Innelite, Kaliborite, Krennerite, Liebigite, Marialite, Meionite, Melanovanadite, Meliphanite, Millerite, Minyulite, Moissanite, Mordenite, Murmanite, Muthmannite, Nacrite, Natrojarosite, Natrolite, Nepheline, Nickeline, Nolanite, Parkerite, Pharmacolite, Pickeringite, Pinnoite, Plumbojarosite, Prehnite, Pyrochroite, Pyromorphite, Pyrrhotite (hexagonal), Quenselite, Röntgenite-Ce, Sarcosite, Seligmannite, Swedenborgite, Syngenite, Thaumassite, Thomsonite-Ca, Tyrolite, Uranophane, Ussingite, Vermiculite, Wulfenite, Zinkenite
Ralph and Chau, 2012	Chromium-dravite, Feruvite, Fluor-dravite, Fluor-liddicoatite, Fluor-schorl, Foitite, Natroalunite, Olenite, Oxy-schorl, Povondraite, Sinoite
Shannon, 2011	Afwillite, Alunite, Batisite, Bertrandite, Bromellite, Brushite, Buergerite, Burbankite, Caledonite, Clinohedrite, Dravite, Elbaite, Epistilbite, Flagstaffite, Hemimorphite, Hilgardite, Hydrocalumite, Innelite, Jarosite, Junitoite, Larsenite, Mesolite, Neptunite, Pirssonite, Schorl, Scolecite, Searlesite, Shortite, Spangolite, Stibiocolumbite, Struvite, Suolunite, Tilasite, Uvite, Weloganite, Whitlockite, Yugawaralite

Notes: Iodargyrite is listed in Bond (1943) as exhibiting piezoelectricity, but is pyroelectric as well, since it belongs to a polar crystal class. Data sources that are part of the Landolt-Börnstein Database in SpringerMaterials are underlined, for ease in distinguishing these (Springer, 2012).

TABLE 17. References for Piezoelectric Minerals Included in Table 9, Page 42 and Table 14, Page 184

Reference	Minerals
Barthelmy, 2012	Gallite
Bond, 1943	Tiemannite, Topaz, Zunyite
Cady, 1946	Topaz
<u>Nelson, 1993</u>	Analcime, Berlinite, Cinnabar, Epsomite, Eulytine, Goslarite, Langbeinite, Paratellurite, Quartz, Sphalerite
Parkhomenko, 1971	Morenosite, Retgersite, Sal Ammoniac, Selenium, Sodalite, Stilleite, Tellurium, Zincite
Ralph and Chau, 2012	Roquesite
Shannon, 2011	Aminoffite, Analcime, Bastnäs-Ce, Bavenite, Diopside, Edingtonite, Gismondine-Ca, Gmelinite-Na, Gugiaite, Helvine, Jeremejevite, Leucophanite, Londonite, Mimetite, Nitrobarite, Olsacherite, Pharmacosiderite, Quartz, Rhodizite, Thornasite, Tugtupite

Notes: Data sources that are part of the Landolt-Börnstein Database in SpringerMaterials are underlined, for ease in distinguishing these (Springer, 2012).

TABLE 27. References for Ferroelectric Data (from Minerals) Included in Tables 22 through 24, Pages 156 and 157

Reference	Minerals
Bhide and Damle, 1960	Pyrolusite
Grigas et al., 1976	Chalcostibite
<u>Nelson, 1993</u>	Boracite
<u>Shiozaki et al., 2002a</u>	Barioperovskite, Lueshite, Macedonite, Tausonite
<u>Shiozaki et al., 2002b</u>	Boracite, Heftetjernite, Oxyplumbopyrochlore, Stibiotantalite, Wakefieldite-Nd
<u>Shiozaki et al., 2004</u>	Archerite, Demicheleite-Br, Demicheleite-I, Gwihabaite, Niter, Nitratine

Notes: Data sources that are part of the Landolt-Börnstein Database in SpringerMaterials are underlined, for ease in distinguishing these (Springer, 2012).

TABLE 28. References for Pyroelectric Data (from Minerals) Included in Table 25, Page 158

Reference	Minerals
Hawkins et al., 1995	Tourmaline
<u>Nelson, 1993</u>	Boracite, Fresnoite, Greenockite, Tourmaline, Wurtzite
Parkhomenko, 1971	Cadmoselite
<u>Shiozaki et al., 2002a</u>	Macedonite
<u>Shiozaki et al., 2002b</u>	Boracite, Chambersite, Diomignite
<u>Shiozaki et al., 2004</u>	Proustite

Notes: Data sources that are part of the Landolt-Börnstein Database in SpringerMaterials are underlined, for ease in distinguishing these (Springer, 2012).

TABLE 29. References for Thermoelectric Data (from Minerals) Included in Table 26, Page 159

Reference	Minerals
<u>Hellwege and Hellwege</u> , 1970b	Cuprospinel, Magnetite
<u>Hellwege and Hellwege</u> , 1978	Kalininite
<u>Shiozaki et al.</u> , 2002a	Cadmoindite, Carrollite, Lueshite, Macedonite
<u>Wijn</u> , 1988	Cuprokalinitite, Cuprorhodsite, Daubréelite, Indite, Linnaeite, Siegenite
<u>Wijn</u> , 1991a	Coulsonite, Jacobsite, Magnesio-coulsonite, Trevorite

Notes: Data sources that are part of the Landolt-Börnstein Database in SpringerMaterials are underlined, for ease in distinguishing these (Springer, 2012).

TABLE 37. References for Piezoelectric Data (from Minerals) Included in Tables 30 through 36, Pages 160 through 166

Reference	Minerals
Bhide and Damle, 1960	Pyrolusite
<u>Hellwege et al.</u> , 1990	Barioperovskite
<u>Nelson</u> , 1993	Analcime, Berlinite, Boracite, Bournonite, Cancrinite, Cinnabar, Epsomite, Eulytine, Fresnoite, Greenockite, Langbeinite, Magnetite, Paratellurite, Proustite, Pyrargyrite, Quartz, Schorl, Sillénite, Sphalerite, Stibiotantalite, Tourmaline, Wurtzite
Parkhomenko, 1971	Bromellite, Cadmoselite, Ice, Morenosite, Nepheline, Retgersite, Sal Ammoniac, Selenium, Sodalite, Stilleite, Tellurium, Zincite
<u>Shiozaki et al.</u> , 2002a	Macedonite, Tausonite
<u>Shiozaki et al.</u> , 2002b	Changbaiite, Diomignite, Russellite
<u>Shiozaki et al.</u> , 2004	Archerite, Biphosphammite

Notes: Data sources that are part of the Landolt-Börnstein Database in SpringerMaterials are underlined, for ease in distinguishing these (Springer, 2012).

TABLE 40. References for Dielectric Data (from Minerals) Included in Table 38, Page 167, and Table 39, Page 171

Reference	Minerals
<u>Hellwege and Hellwege</u> , 1970b	Cuprospinel
<u>Hellwege and Hellwege</u> , 1978	Spinel
<u>Hellwege et al.</u> , 1990	Barioperovskite
<u>Nelson</u> , 1993	Berlinite, Boracite, Bournonite, Cancrinite, Cinnabar, Colemanite, Epsomite, Eulytine, Fresnoite, Greenockite, Koechlinite, Langbeinite, Lecontite, Natrolite, Paratellurite, Proustite, Pyrargyrite, Quartz, Schorl, Sillénite, Sphalerite, Stephanite, Stibiotantalite, Stibnite, Tourmaline, Wurtzite
Parkhomenko, 1971	Cadmoselite, Retgersite, Stilleite, Zincite
<u>Shiozaki et al.</u> , 2002a	Lakargiite, Lueshite, Macedonite, Perovskite, Tausonite
<u>Shiozaki et al.</u> , 2002b	Cervantite, Chambersite, Changbaiite, Clinocervantite, Diomignite, Ericaite, Heftetjernite, Koechlinite, Oxycalciopyrochlore, Oxyplumbopyrochlore, Russellite, Rutile, Stibiotantalite, Wakefieldite-Nd
<u>Shiozaki et al.</u> , 2004	Archerite, Biphosphammite, Nitratine, Schultenite
<u>Wijn</u> , 1991a	Franklinite, Magnesioferrite, Trevorite

Notes: Data sources that are part of the Landolt-Börnstein Database in SpringerMaterials are underlined, for ease in distinguishing these (Springer, 2012).

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