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Symmetry-based electricity in minerals and rocks: A review with examples of centrosymmetric minerals that exhibit pyro- and piezoelectricity

Review

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ABSTRACT

The Earth's core, mantle and crust are composed of rocks and minerals, and exhibit electrical and magnetic phenomena. Electrical data in particular are extremely sparse for Earth materials; fewer than one hundred minerals have piezoelectric data associated with them, for example. This type of data helps to constrain Earth processes and structures, such as core and mantle composition, geomagnetic anomalies, seismic electric signals, and others. In this review, two hundred seventeen 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. Some thermoelectric and magnetic data are also presented for minerals, and an overview of rock electricity is included. Recommendations for further study are given, as well, such as determining the dielectric behavior of rocks and minerals at depth, and testing minerals for alternative energy applications.

Keywords: mineral physics; piezoelectricity; pyroelectricity; ferroelectricity; dielectric; centrosymmetric.

INTRODUCTION

This review paper started as an exploration to see whether minerals might be useful in generating electricity, and whether that generation would 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 quantitative electrical and magnetic data for minerals (listed later in Tables 10 through 27) 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.

In this review paper, 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 (Downs, 2006; RRUFF Project, 2013).

Another current source is the Landolt-Börnstein Database, which was recently renamed SpringerMaterials (Springer, 2012), and many of the data in the tables in the article were taken from this resource. The Landolt-Börnstein Database (LBD) currently lists hundreds of thousands of substances and their properties (Poerschke, 2002; Madelung and Poerschke, 2008), 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 Cady (1946), Mason (1950), Nye (1957), 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 (1967, 1971) and Parkhomenko and Bondarenko (1972) are classic texts that deal with rocks and minerals in geologic settings.

LISTS OF MINERALS

Altogether, these sources list 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 1 lists 44 ferroelectric minerals, Table 2 lists 131 pyroelectric (but not ferroelectric) minerals and Table 3 lists 42 piezoelectric (but not ferro- or pyroelectric) minerals.

Table 1. Ferroelectric, Antiferroelectric and Paraelectric Minerals.

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

Notes: Underlined minerals have data associated with them. References are listed in Table 29.

Table 2. Pyroelectric Minerals.

Afwillite
Alunite
Amesite
Ammoniojarosite
Ardealite
Argentojarosite
Arsenogoyazite
Artinite
Batisite
Benstonite
Berthierine
Bertrandite
Beryl
Bournonite
Breithauptite
Bromellite
Brucite
Brushite
Buergerite
Bultfonteinite
Burbankite
Cadmoselite
Caledonite
Cancrinite
Childrenite
Chromium-dravite
Clinohedrite
Colemanite
Coquimbite
Crandallite
Creedite
Cronstedtite
Dawsonite
Diaboleite
Dravite
Dyscrasite
Elbaite
Elpidite
Enargite
Eosphorite
Epistilbite
Epistolite
Feruvite
Finnemanite
Flagstaffite
Fluor-dravite
Fluor-liddicoatite
Fluor-schorl
Foitite
Fresnoite
Georgbarsanovite
Goyazite
Greenockite
Halloysite-7Å
Halloysite-10Å
Halotrichite
Harmotome
Hartite
Hemimorphite
Heulandite-Ca

Table 2. Continued...

Hilgardite
Hydrocalumite
Innelite
Iodargyrite
Jarosite
Junitoite
Kaliborite
Krennerite
Larsenite
Liebigite
Marialite
Meionite
Melanovanadite
Meliphanite
Mesolite
Millerite
Minyulite
Moissanite
Mordenite
Murmanite
Muthmannite
Nacrite
Natroalunite
Natrojarosite
Natrolite
Nepheline
Neptunite
Nickeline
Nolanite
Olenite
Oxy-schorl
Parkerite
Pharmacolite
Pickeringite
Pinnoite
Pirssonite
Plumbojarosite
Povondraite
Prehnite
Pyrochroite
Pyromorphite
Pyrrhotite
Quenselite
Röntgenite-Ce
Sarcolite
Schorl
Scolecite
Searlesite
Seligmannite
Shortite
Sinoite
Spangolite
Stephanite
Stibiocolumbite
Struvite
Suolunite
Swedenborgite
Syngenite
Thaumasite
Thomsonite-Ca
Tilasite
Tourmaline
Tyrolite
Uranophane
Ussingite
Uvite
Vermiculite
Weloganite
Whitlockite
Wulfenite
Wurtzite
Yugawaralite
Zinkenite

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 30.

Table 3. Piezoelectric Minerals.

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

Notes: Underlined minerals have data associated with them. References are listed in Table 31.

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 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 4, 5 and 6 relist the minerals in Tables 1, 2 and 3 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). Thornasite 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 4, 5 and 6 signifies that the mineral has been listed in a reference as having the electrical property in question. Tables 29, 30 and 31 list these references.

Table 4. Ferroelectric Mineral Groups: Known Ferroelectric, Antiferroelectric or Paraelectric Minerals in Bold.

Alum Group	Alum-K, **Alum-Na**, Lanmuchangite, Tschermigite
Biphosphammite Group	**Archerite**, **Biphosphammite**
Boracite Group	**Boracite**, **Chambersite**, Congolite, **Ericaite**, Trembathite
Brownmillerite Group	Brownmillerite, **Srebrodolskite**
	Shulamitite is an intermediate mineral between Perovskite and the Brownmillerite-Srebrodolskite series.
Cervantite Group	Bismutocolumbite, Bismutotantalite, **Cervantite**, **Clinocervantite**, **Stibiocolumbite**, **Stibiotantalite**
Chalcocite-Digenite Group	**Chalcocite**, Digenite, Djurleite, Roxbyite
Chalcostibite Group	**Chalcostibite**, Emplectite
Changbaiite Group	**Changbaiite**
Chrysoberyl Group	Chrysoberyl, **Mariinskite**
Demicheleite Group	**Demicheleite-Br**, **Demicheleite-Cl**, **Demicheleite-I**
Diomignite Group	**Diomignite**
Galena Group	Alabandite, **Altaite**, Clausthalite, Galena, Niningerite, Oldhamite
Gwihabaite Group	**Gwihabaite**
Ice Group	**Ice**
Koechlinite Group	**Koechlinite**, **Russellite**, Tungstibite
Niter Group	**Niter**
Nitratine Group	**Nitratine**
Perovsksite Group	**Barioperovskite**, Isolueshite, **Lakargiite**, **Lueshite**, **Macedonite**, Megawite, **Perovskite**, **Tausonite**
Proustite Group	**Proustite**, **Pyrargyrite**, Pyrostilpnite, Xanthoconite
Pyrochlore Supergroup: Betafite Group	Oxycalciobetafite, Oxyuranobetafite
Pyrochlore Supergroup: Elsmoreite Group	Hydrokenoelsmoreite
Pyrochlore Supergroup: Microlite Group	Fluorcalciomicrolite, Fluornatromicrolite, Hydrokenomicrolite, Hydromicrolite, Hydroxycalciomicrolite, Hydroxykenomicrolite, Kenoplumbomicrolite, Oxycalciomicrolite, Oxystannomicrolite, Oxystibiomicrolite
Pyrochlore Supergroup: Pyrochlore Group	Fluorcalciopyrochlore, Fluorkenopyrochlore, Fluornatropyrochlore, Fluorstrontiopyrochlore, Hydropyrochlore, Hydroxycalciopyrochlore, Hydroxymanganopyrochlore, Kenoplumbopyrochlore, **Oxycalciopyrochlore**, Oxynatropyrochlore, **Oxyplumbopyrochlore**, Oxyyttropyrochlore-(Y)
Pyrochlore Supergroup: Roméite Group	Cuproroméite, Fluorcalcioroméite, Fluornatroroméite, **Hydroxycalcioroméite**, Oxycalcioroméite, Oxyplumboroméite
Rutile Group	Argutite, **Cassiterite**, **Paratellurite**, Plattnerite, **Pyrolusite**, Rutile, Stishovite, Tripuhyite
Schultenite Group	**Schultenite**
Sillénite Group	**Sillénite**
Stibnite Group	Antimonselite, **Bismuthinite**, Guanajuatite, Metastibnite, **Stibnite**, Pääkkönenite
Wolframite Group	Ferberite, **Heftetjernite**, Huanzalaite, Hübnerite, Sanmartinite
Xenotime Group	Chernovite-Y, Dreyerite, Pretulite, Wakefieldite-Ce, Wakefieldite-La, **Wakefieldite-Nd**, Wakefieldite-Y, Xenotime-Y, Xenotime-Yb

Notes: References are listed in Table 29.

Table 5. Pyroelectric Mineral Groups: Known Pyroelectric Minerals in Bold.

Afwillite Group	**Afwillite**
Alunite Supergroup: Alunite Subgroup	**Alunite**, Ammonioalunite, Beaverite-Zn, **Natroalunite**
Alunite Supergroup: Beudantite Subgroup	Beudantite, Corkite, Gallobeudantite, Hidalgoite, Hinsdalite, Kemmlitzite, Schlossmacherite, Svanbergite, Woodhouseite
Alunite Supergroup: Crandallite Subgroup	Arsenocrandallite, Arsenogorceixite, **Arsenogoyazite**, **Crandallite**, Dussertite, Gorceixite, **Goyazite**, Kintoreite, Philipsbornite, Plumbogummite, Segnitite, Springcreekite
Alunite Supergroup: Jarosite Subgroup	**Ammoniojarosite**, **Argentojarosite**, Hydroniumjarosite, **Jarosite**, **Natrojarosite**, **Plumbojarosite**
Ardealite Group	**Ardealite**
Artinite Group	**Artinite**, Chlorartinite
Batisite Group	**Batisite**, Noonkanbahite, Shcherbakovite, **Benstonite**
Bertrandite Group	**Bertrandite**
Beryl Group	Bazzite, **Beryl**, Pezzottaite, Stoppaniite
Bournonite Group	**Bournonite**, **Seligmannite**, Součekite
Brucite Group	**Brucite**, Portlandite, **Pyrochroite**
Brushite Group	**Brushite**
Burbankite Group (Varieties)	**Burbankite**, Calcioburbankite, Strontioburbankite
Caledonite Group	**Caledonite**
Cancrinite Group	Afghanite, Alloriite, Biachellaite, Bystrite, **Cancrinite**, Cancrisilite, Davyne, Depmeierite, Franzinite, Giuseppettite, Hydroxycancrinite, Kircherite, Kyanoxalite, Liottite, Marinellite, Microsommite, Pitiglianoite, Quadridavyne, Sacrofanite, Tounkite, Vishnevite
Childrenite - Eosphorite Series	**Childrenite**, **Eosphorite**
Clinohedrite Group	**Clinohedrite**
Colemanite Group	**Colemanite**
Coquimbite Group	**Coquimbite**, Aluminocoquimbite, Paracoquimbite
Creedite Group	**Creedite**
Dawsonite Group	**Dawsonite**
Diaboleite Group	**Diaboleite**
Donnayite Group	Donnayite-Y, **Weloganite**
Dyscrasite Group	**Dyscrasite**
Elpidite Group	**Elpidite**
Enargite Group	**Enargite**, Petrukite
Ettringite Group	Bentorite, Buryatite, Carraraite, Charlesite, Ettringite, Hielscherite, Jouravskite, Kottenheimite, Micheelsenite, Sturmanite, **Thaumasite**
Eudialyte Group	Alluaivite, Andrianovite, Aqualite, Carbokentbrooksite, Davinciite, Dualite, Eudialyte, Feklichevite, Fengchengite, Ferrokentbrooksite, **Georgbarsanovite**, Golyshevite, Ikranite, Johnsenite-Ce, Kentbrooksite, Khomyakovite, Labyrinthite, Manganoeudialyte, Manganokhomyakovite, Mogovidite, Oneillite, Raslakite, Rastsvetaevite, Taseqite, UM1998-21-SiO:CaCeClHMnNaZr, Voronkovite, Zirsilite-Ce
Finnemanite Group	**Finnemanite**
Flagstaffite Group	**Flagstaffite**

Table 5. Continued...

Fresnoite Group	**Fresnoite**
Halotrichite Group	Apjohnite, Bilinite, Dietrichite, **Halotrichite**, **Pickeringite**, Wupatkiite
Hartite Group	**Hartite**
Hemimorphite Group	**Hemimorphite**
Hilgardite Group	**Hilgardite**, Kurgantaite, Leucostaurite, Tyretskite
Hydrocalumite Group	**Hydrocalumite**
Innelite Group	**Innelite**
Iodargyrite Group	**Iodargyrite**
Junitoite Group	**Junitoite**
Kaliborite Group	**Kaliborite**
Krennerite Polymorphs	Calaverite, **Krennerite**
Larsenite Group	**Larsenite**
Leucophanite Group	**Leucophanite**
Liebigite Group	**Liebigite**
Melanovanadite Group	**Melanovanadite**
Meliphanite Group	**Meliphanite**
Mesolite Group	**Mesolite**
Millerite Group	**Millerite**, Mäkinenite
Minyulite Group	**Minyulite**
Moissanite Group	**Moissanite (-6H)**, Moissanite-3C, Moissanite-2H, Moissanite-4H, Moissanite-5H, Moissanite-15R, Moissanite-33R
Montmorillonite-Vermiculite Group	Montmorillonite, **Vermiculite**
Murmanite Group	**Epistolite**, **Murmanite**, Vuonnemite
Muthmannite Group	**Muthmannite**
Nepheline Group	**Nepheline**
Neptunite Group	**Neptunite**
Nickeline Group	Achavalite, **Breithauptite**, Freboldite, Langisite, **Nickeline**
Nolanite Group	**Nolanite**, Rinmanite, Kamiokite
Parkerite Group	**Parkerite**
Pharmacolite Group	**Pharmacolite**
Pinnoite Group	**Pinnoite**
Pirssonite Group	**Pirssonite**
Prehnite Group	**Prehnite**
Quenselite Group	**Quenselite**
Röntgenite-Ce Group	**Röntgenite-Ce**
Sarcolite Group	**Sarcolite**
Scapolite Group	**Marialite**, **Meionite**, Silvialite

Table 5. Continued...

Scheelite Group	Fergusonite-Ce, Fergusonite-Nd, Fergusonite-Y, Powellite, Scheelite, Stolzite, **Wulfenite**
Searlesite Group	**Searlesite**
Serpentine Group	**Amesite**, Antigorite, **Berthierine**, **Brindleyite**, Caryopilite, Chrysotile, **Cronstedtite**, Dickite, Fraipontite, Greenalite, **Halloysite-7Å**, Halloysite-10Å, Kaolinite, Kellyite, Lizardite, Manandonite, **Nacrite**, Népouite, Odinite, Pecoraite
Shortite Group	**Shortite**
Sinoite Group	**Sinoite**
Spangolite Group	**Spangolite**
Stephanite Group	Selenostephanite, **Stephanite**
Struvite Group	Hazenite, **Struvite**, Struvite-K
Suolunite Group	**Suolunite**
Swedenborgite Group	**Swedenborgite**
Syngenite Group	**Syngenite**, Koktaite
Tilasite Group	Durangite, Isokite, Maxwellite, Panasqueiraite, **Tilasite**
Tourmaline Supergroup: Alkali Group	**Buergerite**, **Chromium-dravite**, Chromo-alumino-povondraite, **Dravite**, **Elbaite**, **Fluor-dravite**, Fluor-elbaite, **Fluor-schorl**, K-Tourmaline, Luinaite-OH, **Olenite**, Oxy-dravite, Oxy-schorl, Pb-dominant Tourmaline, **Povondraite**, **Schorl**, Tsilaisite, Vanadium-dravite
Tourmaline Supergroup: Calcic Group	**Feruvite**, Fluor-feruvite, **Fluor-liddicoatite**, Liddicoatite, **Uvite**
Tourmaline Supergroup: X-Vacant Group	**Foitite**, Magnesiofoitite, Oxy-rossmanite, Rossmanite
Tyrolite Group	**Tyrolite**
Uranophane Group	Boltwoodite, Natroboltwoodite, **Uranophane**, β-Uranophane
Ussingite Group	**Ussingite**
Whitlockite Group	Bobdownsite, Ferromerrillite, Merrillite, Strontiowhitlockite, **Whitlockite**
Wurtzite Group	Buseckite, **Cadmoselite**, **Greenockite**, Rambergite, **Wurtzite**
Zeolite Group	Amicite, Ammonioleucite, Analcime, Barrerite, Bellbergite, Bikitaite, Boggsite, Brewsterite-Ba, Brewsterite-Sr, Chabazite-Ca, Chabazite-K, Chabazite-Mg, Chabazite-Na, Chabazite-Sr, Chiavennite, Clinoptilolite-Ca, Clinoptilolite-K, Clinoptilolite-Na, Cowlesite, Dachiardite-Ca, Dachiardite-Na, Direnzoite, Edingtonite, **Epistilbite**, Erionite-Ca, Erionite-K, Erionite-Na, Faujasite-Ca, Faujasite-Mg, Faujasite-Na, Ferrierite-K, Ferrierite-Mg, Ferrierite-Na, Flörkeite, Garronite, Gaultite, Gismondine-Ba, Gismondine-Ca, Gmelinite-Ca, Gmelinite-K, Gmelinite-Na, Gobbinsite, Gonnardite, Goosecreekite, Gottardiite, **Harmotome**, Heulandite-Ba, **Heulandite-Ca**, Heulandite-K, Heulandite-Na, Heulandite-Sr, Hsianghualite, Laumontite, Leucite, Lévyne-Ca, Lévyne-Na, Lovdarite, Maricopaite, Mazzite-Mg, Mazzite-Na, Merlinoite, **Mesolite**, Montesommaite, **Mordenite**, Mutinaite, **Natrolite**, Offretite, Pahasapaite, Paranatrolite, Parthéite, Paulingite-Ca, Paulingite-K, Paulingite-Na, Perlialite, Phillipsite-Ca, Phillipsite-K, Phillipsite-Na, Pollucite, Roggianite, Scolecite, Stellerite, Stilbite-Ca, Stilbite-Na, Terranovaite, **Thomsonite-Ca**, Thomsonite-Sr, Thornasite, Tschernichite, Tschörtnerite, Wairakite, Weinebeneite, Wenkite, Willhendersonite, **Yugawaralite**
Zincite Group	**Bromellite**, **Zincite**
Zinkenite-Scainiite Group	**Zinkenite**, Scainiite, Pillaite, Pellouzite, Chovanite, Tazieffite

Notes: References are listed in Table 30.

Table 6. Piezoelectric Mineral Groups: Known Piezoelectric Minerals in Bold.

Aminoffite Group	**Aminoffite**
Apatite Supergroup: Apatite Subgroup	Carbonate-rich Fluorapatite, Carbonate-rich Hydroxylapatite, Chlorapatite, Fluorapatite, Fluorstrophite, Hydroxylapatite
Apatite Supergroup: Pyromorphite Subgroup	**Mimetite**, **Pyromorphite**, Vanadinite
Apatite Supergroup: Svabite Subgroup	Fluorphosphohedyphane, Hedyphane, Phosphohedyphane, Svabite
Baryte Group	Celestite, Baryte, Anglesite, **Olsacherite**
Bastnäsite Group	**Bastnäsite-Ce**, Bastnäsite-La, Bastnäsite-Y, Hydroxylbastnäsite-Ce
Bavenite–Bohseite Series	**Bavenite**, Bohseite
Berlinite Group	Alarsite, **Berlinite**, Rodolicoite
Chalcopyrite Group	Chalcopyrite, Eskebornite, **Gallite**, Laforêtite, Lenaite, **Roquesite**
Cinnabar Polymorphs	**Cinnabar**, Hypercinnabar, Metacinnabar
Dioptase Group	**Dioptase**
Edingtonite Group	**Edingtonite**
Epsomite Group	**Epsomite**, **Goslarite**, **Morenosite**
Eulytine Group	**Eulytine**
Helvine Group	Danalite, Genthelvine, **Helvine**
Jeremejevite Group	**Jeremejevite**
Langbeinite Group	**Langbeinite**, Manganolangbeinite, Efremovite
Leucophanite Group	**Leucophanite**
Melilite Group	Åkermanite, Alumoåkermanite, Gehlenite, **Gugiaite**, Hardystonite, Okayamalite
Nitrobarite Group	**Nitrobarite**
Pharmacosiderite Supergroup: Ivanyukite Group	Ivanyukite-Cu, Ivanyukite-K, Ivanyukite-Na-C
Pharmacosiderite Supergroup: Pharmacoalumite Group	Bariopharmacoalumite, Natropharmacoalumite, Pharmacoalumite
Pharmacosiderite Supergroup: Pharmacosiderite Group	Bariopharmacosiderite, Hydroniumpharmacosiderite, Natropharmacosiderite, **Pharmacosiderite**, Strontiopharmacosiderite
Quartz Polymorphs	Coesite, Cristobalite, Mogánite, **α-Quartz**, **β-Quartz**, Seifertite, Stishovite, Tridymite
Retgersite Polymorphs	Nickelhexahydrite, **Retgersite**
Rhodizite Group	**Londonite**, **Rhodizite**
Sal Ammoniac Group	**Sal Ammoniac**, Lafossaite
Selenium Group	**Selenium**, **Tellurium**
Sodalite Group	Haüyne, Lazurite, Nosean, **Sodalite**, Tsaregorodtsevite, **Tugtupite**, Vladimirivanovite
Sphalerite Group	Coloradoite, Hawleyite, Metacinnabar, **Sphalerite**, **Stilleite**, **Tiemannite**
Topaz Group	**Topaz**

Table 6. Continued...

Zeolite Group	Amicite, Ammonioleucite, **Analcime**, Barrerite, Bellbergite, Bikitaite, Boggsite, Brewsterite-Ba, Brewsterite-Sr, Chabazite-Ca, Chabazite-K, Chabazite-Mg, Chabazite-Na, Chabazite-Sr, Chiavennite, Clinoptilolite-Ca, Clinoptilolite-K, Clinoptilolite-Na, Cowlesite, Dachiardite-Ca, Dachiardite-Na, Direnzoite, **Edingtonite**, Epistilbite, Erionite-Ca, Erionite-K, Erionite-Na, Faujasite-Ca, Faujasite-Mg, Faujasite-Na, Ferrierite-K, Ferrierite-Mg, Ferrierite-Na, Flörkeite, Garronite, Gaultite, Gismondine-Ba, **Gismondine-Ca**, Gmelinite-Ca, Gmelinite-K, **Gmelinite-Na**, Gobbinsite, Gonnardite, Goosecreekite, Gottardiite, Harmotome, Heulandite-Ba, Heulandite-Ca, Heulandite-K, Heulandite-Na, Heulandite-Sr, Hsianghualite, Laumontite, Leucite, Lévyne-Ca, Lévyne-Na, Lovdarite, Maricopaite, Mazzite-Mg, Mazzite-Na, Merlinoite, Mesolite, Montesommaite, Mordenite, Mutinaite, Natrolite, Offretite, Pahasapaite, Paranatrolite, Parthéite, Paulingite-Ca, Paulingite-K, Paulingite-Na, Perlialite, Phillipsite-Ca, Phillipsite-K, Phillipsite-Na, Pollucite, Roggianite, Scolecite, Stellerite, Stilbite-Ca, Stilbite-Na, Terranovaite, Thomsonite-Ca, Thomsonite-Sr, **Thornasite**, Tschernichite, Tschörtnerite, Wairakite, Weinebeneite, Wenkite, Willhendersonite, Yugawaralite
Zunyite Group	**Zunyite**

Notes: References are listed in Table 31.

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 7 lists these symmetry-based electrical minerals by crystal system, crystal class, and symmetry. Excerpted from these in Table 8 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 structure is symmetric (Blinc, 2011). The minerals that are not ferroelectric, antiferroelectric or paraelectric have been underlined in Table 8. For these minerals that are centrosymmetric and exhibit symmetry-based electrical phenomena (but are not ferroelectric, antiferroelectric or paraelectric) a reference has been provided to confirm the structure, and to provide a possible explanation for further ordering, which in general reduces the symmetry of the mineral. The author suggests that the reduction in symmetry allows for the electrical phenomena. The minerals are arranged alphabetically.

Table 7. Minerals Exhibiting Ferro-, Pyro- or Piezoelectricity, by Crystal Class.

System	Class	Symmetry	Minerals
Triclinic	**1**	Polar, Chiral	Amesite, Epistilbite, Hartite, Hilgardite, Weloganite
Triclinic	**$\bar{1}$**	Centrosymmetric	Bultfonteinite, Epistolite, Innelite, Melanovanadite, Murmanite, Ussingite
Monoclinic	**2**	Polar, Chiral	Colemanite, Epistilbite, Halotrichite, Hydrocalumite, Oxycalciopyrochlore, Oxyplumbopyrochlore, Pickeringite, Searlesite, Uranophane
Monoclinic	***m***	Polar	Afwillite, Berthierine, Brushite, Clinohedrite, Halloysite-7Å, Halloysite-10Å, Nacrite, Neptunite, Pharmacolite, Scolecite, Schultenite, Tilasite, Yugawaralite
Monoclinic	**2/*m***	Centrosymmetric	Artinite, Chalcocite, Creedite, Gismondine-Ca, Harmotome, Heftetjernite, Heulandite-Ca, Innelite, Kaliborite, Muthmannite, Parkerite, Quenselite, Syngenite, Vermiculite
Orthorhombic	**222**	Polar, Chiral	Edingtonite, Epsomite, Goslarite, Leucophanite, Morenosite, Olsacherite
Orthorhombic	***mm*2**	Polar	Batisite, Bertrandite, Boracite, Bournonite, Caledonite, Chambersite, Changbaiite, Childrenite, Dyscrasite, Enargite, Flagstaffite, Hemimorphite, Junitoite, Koechlinite, Krennerite, Larsenite, Liebigite, Mesolite, Minyulite, Mordenite, Natrolite, Pirssonite, Prehnite, Russellite, Shortite, Sinoite, Stephanite, Stibiocolumbite, Stibiotantalite, Stibnite, Struvite, Suolunite

Table 7. Continued...

Orthorhombic	***mmm***	Centrosymmetric	Analcime, Bavenite, Bismuthinite, Cervantite, Chalcostibite, Clinocervantite, Dawsonite, Demicheleite-Br, Demicheleite-Cl, Demicheleite-I, Elpidite, Eosphorite, Gwihabaite, Lakargiite, Lueshite, Mariinskite, Niter, Perovskite, Seligmannite, Srebrodolskite, Stibnite, Thomsonite-Ca, Topaz, Tyrolite
Tetragonal	**4**	Polar, Chiral	(No Listings)
Tetragonal	$\bar{4}$	Non-centrosymmetric	Meliphanite, Tugtupite
Tetragonal	**4/*m***	Centrosymmetric	Aminoffite, Analcime, Marialite, Meionite, Pinnoite, Sarcolite, Wakefieldite-Nd, Wulfenite
Tetragonal	**422**	Chiral	Paratellurite, Retgersite
Tetragonal	**4*mm***	Polar	Barioperovskite, Diaboleite, Diomignite, Fresnoite, Macedonite
Tetragonal	$\bar{4}2m$	Non-centrosymmetric	Archerite, Biphosphammite, Edingtonite, Gallite, Gugiaite, Roquesite
Tetragonal	**4/*mmm***	Centrosymmetric	Cassiterite, Pyrolusite
Trigonal	**3**	Polar, Chiral	Jarosite, Röntgenite-Ce
Trigonal	$\bar{3}$	Centrosymmetric	Analcime, Benstonite, Dioptase
Trigonal	**32**	Chiral	Berlinite, Cinnabar, α-Quartz, Selenium, Tellurium
Trigonal	**3*m***	Polar	Alunite, Ammoniojarosite, Argentojarosite, Buergerite, Cronstedtite, Dravite, Ericaite, Elbaite, Feruvite, Fluor-dravite, Fluor-liddicoatite, Fluor-schorl, Foitite, Georgbarsanovite, Millerite, Natroalunite, Natrojarosite, Olenite, Oxy-schorl, Povondraite, Pyrargyrite, Schorl, Spangolite, Uvite, Whitlockite
Trigonal	$\bar{3}m$	Centrosymmetric	Arsenogoyazite, Brucite, Coquimbite, Crandallite, Goyazite, Nitratine, Plumbojarosite, Proustite, Pyrochroite, Thornasite
Hexagonal	**6**	Polar, Chiral	Cancrinite, Nepheline, Zinkenite
Hexagonal	$\bar{6}$	Non-centrosymmetric	(No Listings)
Hexagonal	**6/*m***	Centrosymmetric	Jeremejevite, Mimetite, Pyromorphite, Thaumasite
Hexagonal	**622**	Chiral	β-Quartz
Hexagonal	**6*mm***	Polar	Bromellite, Burbankite, Cadmoselite, Greenockite, Iodargyrite, Moissanite, Nolanite, Swedenborgite, Wurtzite, Zincite
Hexagonal	$\bar{6}m2$	Non-centrosymmetric	Bastnäsite-Ce
Hexagonal	**6/*mmm***	Centrosymmetric	Beryl, Breithauptite, Chalcocite, Finnemanite, Gmelinite-Na, Ice, Nickeline
Cubic	**23**	Chiral	Langbeinite, Sillénite
Cubic	$\bar{4}3m$	Non-centrosymmetric	Eulytine, Helvine, Londonite, Pharmacosiderite, Rhodizite, Sodalite, Sphalerite, Stilleite, Tiemannite, Zunyite
Cubic	$m\bar{3}$	Centrosymmetric	Alum-Na, Nitrobarite
Cubic	**432**	Chiral	(No Listings)
Cubic	$m\bar{3}m$	Centrosymmetric	Altaite, Analcime, Hydroxycalcioroméite, Sal Ammoniac, Tausonite

Notes: The crystal structures of oxyplumbopyrochlore and batisite are very poorly constrained. References are listed in Table 32.

Table 8. Centrosymmetric Minerals that Exhibit Symmetry-Based Electricity.

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

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.

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. The zeolite group's symmetries can be found in Armbruster and Gunter (2001). Zeolite minerals often exist in several forms. 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).

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.

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 mathematics 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. 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, Breitinger et al. (2006) demonstrate with Raman spectroscopy that the sites occupied by $[PO_4]^{3-}$ and $[HPO_4]^{2-}$ 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.

Dioptase

For more information on the crystal structure of the cyclosilicate dioptase, 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 dioptase.

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 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 $[AsO_3]^{3-}$ 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 $[HPO_4]^{2-}$ ions in goyazite are essentially randomly distributed with the $[PO_4]^{3-}$ 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, $\bar{\mathbf{1}}$ monoclinic $\mathbf{2}/\boldsymbol{m}$) 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 $\mathbf{6}/\boldsymbol{m}$ structure was to model an absence of OH^- groups, and assume fluorine occupancy of their sites. The presence of F^- and 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 $B(O,OH)_4$ tetrahedra and three $B(O,OH)_3$ triangles (what they call the fundamental building block) 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 atoms 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 Na^+ and 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 ($\boldsymbol{m}$, polar) and hexagonal ($\mathbf{6}/\boldsymbol{m}$, 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.

Nirobarite

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 $\boldsymbol{m\bar{3}}$ symmetry during a neutron diffraction study, and though Nowotny and Heger dismissed that assignation on the basis of the decent fit of an $\boldsymbol{m\bar{3}}$ 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 $\boldsymbol{m\bar{3}}$. 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 $[B_2O(OH)_6]^{2-}$ ions, though the $[BO_2]_n^{n-}$ 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 $Fe(OH)_4O_2$ 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 managanese-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 OH^-, and the F^-, OH^- and H_2O are in a relationship with the site of CO_3 or SO_4 occupancy, such that a sulfate ion causes a double vacancy of F^-, OH^-, or H_2O and a carbonate ion causes a single vacancy there. Absent carbonate or sulfate, two units of F^-, 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 $Cu\text{-}S_4$ 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 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 $Ca_3[Si(OH)_6 \bullet 12H_2O]^{3+}$ 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 likely due to ordering of the fluorine and hydroxide, which is well-established, as described in Akizuki et al. (1979). Topaz is geometrically centrosymmetric, but (F,OH) lattice ordering reduces its symmetry, and allows for anomalous 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 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 a 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 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 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.

(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 a crystal, and allow for piezoelectricity. Evidence suggests that dioptase and sal ammoniac belong to this class.

The above findings are summarized in Table 9. 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 9. Explanations for Pyro- and Piezoelectricity in Centrosymmetric Minerals.

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

MINERAL DATA

Mineral data are organized according to physical phenomena:

(1) Ferroelectricity, pyroelectricity and thermoelectricity data are presented in Tables 10 through 14. 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 33, 34 and 35.)

(2) Piezoelectricity data are provided in Tables 15 through 21. These relate closely to pressure and physical displacement. (Data references: see Table 36.)

(3) Capacitance data are presented in Tables 22 and 23. Capacitance, measured as dielectric coefficients, relates to the electrical environment near minerals. (Data references: see Table 37.)

(4) A selection of magnetic data are provided in Tables 24 through 27. These relate to the magnetic environment near minerals.

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 13) under the Tourmaline entry, The chemical formula for tourmaline is $X(Y)_3Z_6(BO_3)_3Si_6O_{18}(V)_3W$. 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.

Additional minerals have not yet been tested. As an aside: icosahedrite ($Al_{63}Cu_{24}Fe_{13}$), the first discovered 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 dimenstions. 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.

Table 10. Spontaneous Polarization (*q*) Data in Ferroelectric Minerals.

Mineral	***q*: 10^{-3} C m^{-2}**	***T*: °C**	**Notes [*T*: °C] [*P*: GPa]**
Archerite	48	-183	Peak*T* [-183 to -150]
Barioperovskite*	200	≤ 135	
Boracite	8	267	Peak*T* [-173 to 327]
Demicheleite-Br	85	*RT*	
Demicheleite-I	85	*RT*	
Gwihabaite	7	120	Peak*T* [140 to 60, cooling]
	8	118	Peak*T* [60 to 140, heating]
Heftetjernite	≈ 0	5	
	500	-35	Peak*T* [-45 to 5]
Lueshite	120	*RT*	
Macedonite	400 to 800	500 to 0	Cooling
	120	210 to 225	Heating
Niter	80	118	Peak*T* [115.0 to 130.0]
Nitratine	0.6	*RT*	Peak*P* [4.7 to 5.8]; *P* = 5.8 GPa
Pyrolusite	0.12	50	Peak*T* [-60 to 110]
Stibiotantalite	130	300	Peak*T* [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 33.

Table 11. Electrocaloric Effect, Ferroelectric Minerals.

Mineral	**Δ*T* : °C**	**E: 10^3 V m^{-1}**	***T*: °C**	**Notes [E: 10^3 V m^{-1}] [*T*: °C]**
Archerite	Δ 1.0°	1250	*RT*	PeakE [0 to 1250]
Barioperovskite	Δ 0.43°	750	120	
Tausonite	Δ 0.11°	1000	-255	PeakE
	Δ 0.3°	199	-261	Peak*T* [-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 33.

Table 12. Other Electrical Data, Ferroelectric Minerals.

Property | Mineral	**Magnitude**	***T*: °C**	**Notes [*T*: °C]**
Activation Energy for DC Conductivity			
Tausonite	1.037 eV	*RT*	
Pyroelectric Potential			
Barioperovskite	50 V	109	Peak*T*
Pyroelectric Current			
Chalcostibite	2×10^{-10} A	93	Peak*T* [-15 to 135]
Remanent Field			
Oxyplumbopyrochlore	1.5×10^5 Vm^{-1}	*RT*	Peak*T*

Table 12. Continued...

Coercive Field			
Heftetjernite	$4x10^3$ Vm^{-1}	5	
	$2x10^4$ Vm^{-1}	-35	Peak*T* [-45 to 5]
Pyrolusite	$1x10^4$ Vm^{-1}	-60	Peak*T* [-60 to 110]
Stibiotantalite	10 Vm^{-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 electic potential caused by changes in temperature. The Pyroelectric Current is the magnitude of an electic 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 33.

Table 13. Pyroelectric Polarization (*p*) Data for Minerals.

Mineral	***p*: 10^{-6} C m^{-2} K^{-1}**	***T*: °C**	**Notes [*T*: °C] [*p*: 10^{-6} C m^{-2} K^{-1}]**
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
Macedonite	250	100	
Proustite	8.0	*RT*	
Tourmaline*	4.0	*RT*	Primary=0.8
		110	p=4.791 – 0.103 x (wt% FeO)
		23	p=3.949 – 0.094 x (wt% FeO)
		-80	p=2.594 – 0.077 x (wt% FeO)
Wurtzite	0.43	*RT*	Primary=0.34

Notes: The pyroelectric polarization (*p*) is electrical 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 $X(Y)_3Z_6(BO_3)_3Si_6O_{18}(V)_3W$. 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. References are listed in Table 34.

Table 14. Thermoelectric Potential (*t*) Data for Minerals.

Mineral	***t*: 10^{-6} V K^{-1}**	***T*: °C**	**Notes [*T*: °C]**
Cadmoindite	-400	*RT*	
Carrollite	12.7	*RT*	Endmember $CuCo_2S_4$
Coulsonite	340	*RT*	
Cuprokalininite	16	*RT*	
Cuprorhodsite	25	*RT*	Endmember $CuRh_2S_4$

Table 14. Continued...

Cuprospinel	-164	27	
Daubréelite	483	*RT*	
	475	-35	Peak*T* [-235 to 265]
Indite	360	*RT*	
Jacobsite	-450	25 to 375	
Kalininite	222	*RT*	
Linnaeite	4.8	*RT*	
Lueshite	2.5	260	Peak*T*
Macedonite	200	350 to 700	
Magnesiocoulsonite	450	*RT*	
Magnetite	-85 to -120	600 to 1500	
	-50	-100 to -35	
Siegenite	-17.7	*RT*	Endmember $NiCo_2S_4$
Trevorite	-110	125 to 725	

Notes: The thermoelectric potential (*t*) is an electrical 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 35.

Table 15. 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) 1000	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) ≈ |1.7|	*RT*	
Diomignite	(31) 0.92 (33) 7.2	*RT*	

Table 15. Continued...

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) ≈ 0.16 (12) ≈ 0.63 (13) ≈ 0.19 (31) ≥ 0.11 (32) ≥ 0.06 (33) ≥ 0.25	-269.0	
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
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) $5.0\text{x}10^{-20}$ C^2 N^{-2}	*RT*	Brazilian
	(111) $3.6\text{x}10^{-20}$ C^2 N^{-2}	*RT*	Synthetic
	(112) $7.1\text{x}10^{-20}$ C^2 N^{-2}	*RT*	

Table 15. Continued...

	(112) $14.2\mathrm{x}10^{-20}$ C^2 N^{-2}	*RT*	Brazilian
	(1112) $-9.6\mathrm{x}10^{-26}$ C^3 N^{-3}	*RT*	
	(1112) $-57\mathrm{x}10^{-26}$ C^3 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 x 10^5 V m^{-1} along [001]		
Tellurium	(11) 3000	*RT*	
Tourmaline	(22) -0.3 (31) -0.34 (33) -1.8 (15) -3.6	25	
	(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*	

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. 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 ºC. 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 ºC, 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. References are listed in Table 36.

Table 16. 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	*RT*	

Table 16. Continued...

Berlinite	(11) -0.192 (14) 0.143	*RT*	
Biphosphammite	(36) 0.254	100	
	(36) 0.318	0	
Bournonite	(33) 0.85	*RT*	
Cancrinite	(14) 0.12 (15) -0.28	16	
Cinnabar	(11) 0.315	*RT*	
Diomignite	(15) 0.472 (31) 0.290 (33) 0.928	*RT*	
Eulytine	(14) 0.083	*RT*	
Greenockite	(15) -0.210 (31) -0.244 (33) 0.440	25	
	(15) -0.21 (31) -0.24 (33) 0.434	*RT*	
	(15) -0.183 (31) -0.262 (33) 0.385	20	
Langbeinite	(14) 0.021	*RT*	
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	*RT*	
	(11) 0.171 (14) -0.0406	20	
	(11) 0.170	18	
Sphalerite	(14) 0.147	25	
	(15) -0.072 (31) -0.137 (33) 0.165	20	10% Wurtzite
	(14) 0.162	-196	
Tourmaline	(15) 0.246 (22) -0.017 (31) -0.103 (33) 0.320	*RT*	
	(15) 0.25 (22) -0.018 (31) 0.103 (33) 0.32	*RT*	
Wurtzite	(15) 0.07 (33) 0.14	*RT*	
	(15) -0.08 (31) -0.09 (33) 0.34	*RT*	
	(15) 0.13 (33) 0.34	*RT*	0.30:0.70=Mg:Zn
	(15) -0.118 (31) -0.238 (33) 0.265	20	0.10:0.90=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, except for Archerite* where electricity is at the first number, and stress at the second and third. *T* signifies temperature. *RT* signifies (ambient) room temperature. References are listed in Table 36.

Table 17. 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	

Table 17. Continued...

	(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. 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 ºC. *T* signifies temperature. *RT* signifies (ambient) room temperature. References are listed in Table 36.

Table 18. 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 36.

Table 19. Electromechanical Coupling Factors (*k*) for Minerals.

Mineral	***k*: 10^{-2}**	***T*: °C**	**Notes**
Barioperovskite	(15) 0.570 (31) 0.315 (33) 0.560	25	
Berlinite	(11) 0.162 (14) 0.240	*RT*	
	(26) 0.232	*RT*	
	(11) 0.111 (26) 0.175 (t) 0.11	*RT*	
Bournonite	(33) 0.16	*RT*	
Cancrinite	(14) 0.065 (15) 0.216 (31) 0.020 (33) 0.065	*RT*	
Changbaiite	(t) 0.26	*RT*	
Cinnabar	(11) 0.235	*RT*	
Diomignite	(15) 0.21 (31) 0.093 (33) 0.42	*RT*	
Eulytine	(14) 0.0305	*RT*	
Fresnoite	(p) 0.14 (t) 0.225	*RT*	
	(15) 0.28 (31) 0.10 (33) 0.11	*RT*	
	(15) 0.34 (t) 0.23	20	

Table 19. Continued...

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	*RT*	
Macedonite	(15) 0.43 (31) 0.24 (33) 0.64 (p) 0.40	*RT*	
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	*RT*	
	(11) 0.10 (14) 0.03	20	
Sillénite	(14) 0.31 (31) 0.28 (t) 0.20	*RT*	
Sphalerite	(14) 0.0795	25	
	(14) 0.089	-196	
	(15) 0.049 (31) 0.039 (33) 0.075 (t) 0.051	20	10% Wurtzite
Stephanite	(33) 0.21	*RT*	
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	0.30:0.70=Mg:Zn
	(15) 0.084 (31) 0.072 (33) 0.14 (t) 0.080	20	0.10:0.90=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. The poled electromechanical coupling factor *k*(p) is taken from a thin disk of the crystal cut normal to the **z** axis while 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. *T* signifies temperature. *RT* signifies (ambient) room temperature. The References are listed in Table 36.

Table 20. Ferroelectric Piezoelectric Strain and Stress Rates for Minerals.

Mineral	**Magnitude**	***T*: °C**
Strain Rate	m^4 C^{-2}	
Sillénite	(11) 0.28 (12) -0.125 (13) -0.025 (44) 0.18 (h) 0.12	*RT*
	(12) 2160	-181
Stress Rate	10^{-18} m^2 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 by the second. *T* signifies temperature. *RT* signifies (ambient) room temperature. References are listed in Table 36.

Table 21. Piezoelectric Rates (*d*, *e* and *k*) During Temperature Variation.

Mineral	**Magnitude**	***T*: °C**	**Notes**
$\Delta(d)/d\Delta T$	10^{-4} K^{-1}		
Berlinite	(11) -3.2 (14) 8.7	25	
Boracite	(14) -10	320	

Table 21. Continued...

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	

$\Delta(e)/e\Delta T$	10^{-4} 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

$(\Delta k)^2/k^2\Delta T$	10^{-4} 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. References are listed in Table 36.

Table 22. Relative Dielectric Strength (*K*) of Minerals.

Mineral	K_1	K_2	K_3	***T*: °C**	**f: kHz**	**Notes [*T*: °C][f: kHz]**
Archerite	80		50000	-150	0.8	Peak*T* [-225 to 25]
Barioperovskite	1783.00		130	*RT*		
	10000		10000	120		Peak*T* [-90 to 120]
	168.0			25		
	7000		300	-5		Peak*T* [-90 to 120]
	4000		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

Table 22. Continued...

	5.4	5.23	5.79	*RT*		
Bournonite	40			27	1.5x10^{4}	Constant Stress
Cadmoselite	9.7		10.65	*RT*		
Cancrinite	9.5		11.2	*RT*		Constant Stress
Cervantite	1400			565		Peak*T* [100 to 700]
Chambersite			16	410	1000	Peak*T* [0 to 500]
	28			135		Peak*T* [40 to 160]
Changbaiite*	24000	24000		560		Peak*T*
		260		27	1 to 10^{4}	
Cinnabar	15.0		25.5	*RT*		Constant Stress
	14.0		25.5	*RT*		Constant Strain
Clinocervantite	1400			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]
			1800	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	70000			*RT*	10	Peakf [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	1x10^{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
	9.43		7.77	25	10	
	9.25		7.68	25	100	
	8.82		7.96	25	1000	
	7.96		7.67	25	4x10^{4}	
			10.33	*RT*		Constant Stress
	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; In the Dark
	9.33		6.76	-65	0.05	
	8.76		7.02	-65	1	
	9.17		6.97	-65	10	

Table 22. Continued...

	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		7500		5	1	Peak*T* [-75 to 25]
Koechlinite	*K*=105			570		Peak*T* [0 to 700]
	102			*RT*	1.2x10^4	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*=1600			350	1	Peak*T* [100 to 460]
	K=1500			350		Peak*T*
Macedonite	*K*=9500			490		Peak*T*
	K=3200			232		Peak*T* [200 to 265]
	210		126	*RT*		Constant Stress
	115		51	*RT*		Constant Strain
Magnesioferrite	*K*=30000			*RT*	0.02	Peakf [0.020 to 900]
	K=8.53			*RT*		
Natrolite			6.0	*RT*	1	
Nitratine	*K*=110			*RT*		Peak*P* [0 to 5.5]; *P*=4.3 GPa
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*	2x10^4	
	20.2		20.2	20		Constant Strain
	21.5		22.0	20	1x10^3	Constant Stress
	22			-243.2		
	250		12	-244.5		Monoclinic (***m***)
Pyrargyrite	21.7		24.7	20	≈1	Constant Stress
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	
	4.52		4.640	20		Constant Stress
	4.435		4.640	20		Constant Strain

Table 22. Continued...

	4.51	4.63	20	9x10^{3}	Constant Strain
		4.430	-193		Constant Strain
Retgersite	6.2	6.8	*RT*		
Russellite	3100	400	920		Peak*T* [0 to 1000]
Rutile	86	170	*RT*	100	
Schorl*		6.4	30	100	
Schultenite	42		35		
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	1x10^{3}	
	7.12		25	1.6x10^{4}	
	7.92		25	4x10^{7}	Constant Strain
	8.14		-196		Constant Stress
	8.08		-196		Constant Strain
	8.60	8.57	20		Constant Stress; 10% Wurtzite
	8.58	8.52	20		Constant Strain; 10% Wurtzite
Spinel	*K*=8.5		500		Peak*T* [0 to 500]
	K=8.64		*RT*	0.1 to 10	
Stephanite		20	*RT*	9.2x10^{6}	Constant Strain
Stibiotantalite		16000	420		Peak*T*
	K=22		400		Peak*T* [250 to 550]
		300 to 450	20		
Stibnite		150	44	10^{3}	
		108	44	1 to 4.2x10^{6}	
Stilleite	*K*=9.1		*RT*		
Tausonite	*K*=0.1		25		
	K=700		*RT*	2.5x10^{9}	Peak*P* [1-7 x 10^{9}]
	K=17000		-263		
	K=22000		-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]
Wurtzite	8.64	8.393	25	0.05	
	8.54	8.170	25	1	

Table 22. Continued...

	8.58	8.001	25	10	Constant Stress
	8.48	7.877	25	100	
	8.58	8.037	25	300	
	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	
	8.25	8.59	20		Constant Strain; 0.103:0.897=Mg:Zn
	8.31	8.76	20		Constant Stress; 0.103:0.897=Mg:Zn
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 6.0×10^{6} 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 starts to rise quickly. Measurements for Ericaite* were taken under a biased electrical field of 5×10^{3} 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 $+5 \times 10^{3}$ V m^{-1}. For Schorl*, also see the Tourmaline entry for more numerical data listings. References are listed in Table 37.

Table 23. Relative Dielectric Strength (*K*) 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*			>200	$K_1 = 58.26 - (12.48 \times 10^{-2} T) + (3.04 \times 10^{-4} T^2)$
			130 to 200	$K_1 = 45.57 + (6.14 \times 10^{-4} T)$
	6		30 to 150	
Sphalerite	3.8	2.2	*RT*	10% Wurtzite
Wurtzite	1.7	1.8	*RT*	0.10:0.90=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 37.

Table 24. Magnetic Susceptibility (χ) Data for Minerals.

Mineral	**χ: 10^{-3}**	***T*: °C**	**Notes [*T*: °C]**
Breithauptite	0.104	*RT*	
Carrollite	0.07	*RT*	
Chambersite	0.002	-155	Peak*T* [-155 to 375]

Table 24. Continued...

Clinoferrosilite	31	*RT*	Peak*T*
Cuprorhodsite	0.0554	*RT*	
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	*RT*	
Ilmenite	40	-217	Néel temperature
Kalininite	20	-263	Peak*T* [-269 to 510]
Kamiokite	1.392	*RT*	
	94.5	-214	Peak*T*
Karelianite	400	-98	Peak*T* [-263 to 65]
Krut'aite	0.02	*RT*	
Löllingite	-0.0064	*RT*	
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	*RT*	
Penroseite	0.087	25	Endmember $NiSe_2$
Pyrite	0.020	*RT*	
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	*RT*	
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 25. Spontaneous Magnetization (M_0) Data for Minerals.

Mineral	**M_0: A m^{-1}**	***T*: °C**
Pyrrhotite	6.1	*RT*
Vaesite	4400	-269
Xieite	5000	-183 to 27
	96000	-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 24. 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 26. Saturation Magnetization (M_S) Data for Ferromagnetic Minerals.

Mineral	**M_S: A m^{-1}**	***T*: °C**	**Notes [*T*: °C]**
Coulsonite	179000	*RT*	
Cuprokalininite	400000	525	Peak*T* [75 to 525]
Cuprospinel	148400	*RT*	
Hematite	≈ 2000	*RT*	
Maghemite	370000	*RT*	
Magnetite	485000	11.32	
	492000	-16.62	
	496000	-40.41	
	500000	-64.65	
	504000	-89.23	
	506000	-113.44	
	508000	-141.98	
	509000	-163.12	
	510000	-183.26	
	511000	-211.31	
	511000	-243.38	
	512000	-268.94	
Trevorite	245900	*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 24. 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 27. Magnetostriction Data for Minerals.

Mineral	**H: A m^{-1}**	**Strain**
Hematite	625000	9×10^{-7} Expansive
	-625000	7×10^{-7} Expansive
	0 to -150000	2×10^{-7} Contractive

Notes: H is the strength of an applied magnetic field. Values were obtained at ambient room temperature. References are listed in the notes of Table 24. 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.

Electrical and magnetic mineral data in petrologic setting

Table 28 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).

Table 28. Minerals in this Article 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, Cuprorhodsite, 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, Oxycalciopyrochlore, 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, Changbaiite, 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 28. Continued...

Alkalic (Si-Poor) Minerals: Pegmatites	Bastnäsite-Ce, Bromellite, Coulsonite, Elpidite, Epistolite, Georgbarsanovite, Leucophanite, Macedonite, Magnetite, Murmanite, Nepheline, Oxycalciopyrochlore, Oxyplumbopyrochlore, 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, Oxyplumbopyrochlore, 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, Jeremejevite, 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, Dioptase, 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
Si-Rich Sourcerock: High-Grade Primary Metamorphic Minerals	Coulsonite, Crandallite, Cuprokalininite, Elbaite, Epistilbite, Ferberite, Fluor-schorl, Fresnoite, Harmotome, Helvine, Ilmenite, Maghemite, Magnetite, Natrolite, Pyrite, Quartz, Rutile, Schorl, Scolecite, Spinel, Topaz
Si-Rich Sourcerock: Contact and Low Grade Primary Metamorphic Minerals	Amesite, Cassiterite, Eskolaite, Prehnite, Pyrite, Thaumasite, Thomsonite-Ca
Si-Rich Sourcerock: Secondary Metamorphic Minerals	Alunite, Changbaiite, Halloysite-7Å, Halloysite-10Å, Jarosite, Natrojarosite, Pickeringite, Prehnite, Quartz, Vermiculite, Zunyite

Table 28. Continued...

Alkalic (Si-Poor) Sourcerock: Metamorphic Minerals	Coulsonite, Gugiaite, Lueshite, Magnetite, Natrolite, Nepheline, Pyrite, Thomsonite-Ca
Carbonate Regional Metamorphism: Minerals	Breithauptite, Brucite, Dravite, Franklinite, Kalininite, Löllingite, Magnesioferrite, Marialite, Meionite, Rutile
Skarn And Carbonate Contact Metamorphism: Minerals	Afwillite, Aminoffite, Bastnäsite-Ce, Bavenite, Benstonite, Bromellite, Brucite, Bultfonteinite, Coulsonite, Eskolaite, Gugiaite, Helvine, Hydrocalumite, Lakargiite, Leucophanite, Liebigite, Maghemite, Magnesioferrite, Magnetite, Marialite, Meionite, Perovskite, Roquesite, Sarcolite, Sillénite, Spinel, Srebrodolskite, Swedenborgite
Metasomatic Minerals	Alum-Na, Ammoniojarosite, Berlinite, Chromium-dravite, Dravite, Jarosite, Natrojarosite, Nepheline, Sodalite, Uvite
Sulfate-Water Processes: Secondary Minerals	Alum-Na, Alunite, Ammoniojarosite, Cadmoselite, Hauerite, Jarosite, Morenosite, Natroalunite, Natrojarosite, Retgersite, Thaumasite
Evaporite Minerals	Boracite, Chambersite, Colemanite, Epsomite, Ericaite, Hilgardite, Kaliborite, Langbeinite, Nitratine, Pinnoite, Searlesite, Syngenite
Authigenic Precipitate Processes: Minerals	Analcime, Boracite, Burbankite, Colemanite, Crandallite, Dawsonite, Dravite, Eskolaite, Greenockite, Hematite, Langbeinite, Magnetite, Mordenite, Natroalunite, Nitratine, Pirssonite, Pyrite, Pyrrhotite, Siderite, Sphalerite, Suolunite, Thomsonite-Ca, Wurtzite, Wüstite
Marl and Dolostone: Minerals	Magnesioferrite, Searlesite, Seligmannite, Shortite, Vaesite
Marine Reducing Sedimentary Environment: Minerals	Ammoniojarosite, Berthierine, Cadmoselite, Crandallite, Pyrolusite
Placer Deposit Minerals	Bastnäsite-Ce, Cassiterite, Cuprorhodsite, Elbaite, Eskolaite, Ferberite, Fluor-liddicoatite, Fluor-schorl, Goyazite, Ilmenite, Magnetite, Mariinskite, Moissanite, Oxy-schorl, Quartz, Rutile, Schorl, Spinel, Topaz, Uraninite
Glacial Deposits	Eskolaite, Hydroxycalcioroméite, Karelianite
Depleted Soil Minerals	Berthierine, Crandallite, Vermiculite
Plant-Matter Processes: Secondary Minerals	Alum-Na, Ammoniojarosite, Flagstaffite, Halotrichite, Hartite, Millerite, Niter, Pickeringite, Sal Ammoniac, Selenium, Sphalerite, Srebrodolskite
Guano Minerals	Archerite, Ardealite, Biphosphammite, Gwihabaite, Lecontite, Niter, Nitratine, Nitrobarite, Sal Ammoniac, Syngenite, Whitlockite
Minerals with a Microbial Component	Magnetite, Siderite

Notes: Underlined minerals are listed in the scientific literature as exhibiting symmetry-based electrical phenomena.

BULK ROCK ELECTRICAL PHENOMENA

For materials that are semiconductors, the band gap is the 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} 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 in two settings: first, from elementary particles with a combined net electric dipole moment of zero (i.e. in a neutral material), and 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 displacement of electrons.

(2) Ionic polarization is caused by the 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.

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 above.

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

The electrical conductivity values of water (plus solutes) can be 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 also 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).

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 10,000 Hz (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 (Tuck et al., 1977; Sasaoka et al., 1998). 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

The electrical conductivity of rocks may vary markedly with temperature and pressure. 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 materials 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 ºC 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 cause lattice defects in the material, and that will serve to increase capacitance.

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 modeled for the upper mantle (Shaocheng Ji et al., 1996), where olivine is thought to control the electrical conductivity. Both microanisotropy and macroanisotropy are involved. Thus, 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.

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).

DISCUSSION

The present review included, studies of Earth electricity and of electrification of minerals are useful; the need for mineral data is great. For example, the observed piezoelectric phenomena in centrosymmetric minerals follow any of ten mechanisms (see Table 9), and these exceptional materials open the possibility that there are many more minerals that may have interesting electrical properties, currently untested.

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 (Tables 4, 5 and 6). 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, metamorphism or other processes.

The Earth's upper mantle is known to be both seismically and electrically anisotropic (Backus, 1965; Wolfe and Silver, 1998). Seismic and electrical waves are reflected and transmitted preferrentially, 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 (Fouch et al., 2000; Yuancheng Gung et al., 2003), 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-but this would be possible only if the physical data for minerals were more complete.

Since heat drives plate tectonics, it is worthwhile to note which minerals are favored in petrologic 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. 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, e.g. regions of high heat may tend to produce minerals with high dielectric strength and low thermal conductivity. This trend, if it exists, might suggest a framework for determining which chemical reactions are favored in the solid state in various regions of the Earth. A framework of this type would be useful in determining the mineral compositions of rock at high temperatures and pressures, where data are scarce.

Relative dielectric strength data are given in Tables 22 and 23, and changes to the dielectric properties of minerals with temperature and pressure are presented where 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 under 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.

Several peak values are evident in Table 22, and these data were originally gathered to constrain the phase transitions. 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

$$\mathbf{E} \propto T^{\mathrm{D}}, \qquad (1)$$

where **E** is the electric field tensor, *T* is temperature, and D is the critical exponent. In this case, **E** is the physical quantity, *T* is the parameter, and D determines when criticality is reached. Equation 1 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, to constrain another parameter.

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 22 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.

Note that this sample size is small, and the trend might be attributed to natural variations in sample material or 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 22 in the entries for greenockite, lecontite, sphalerite, stibnite and wurtzite, with the entries for berlinite and quartz being equivocal. This is another open question.

Crowdsourcing well-defined tasks in research is a feasible mode for promoting science literacy and science outreach to children and adults. There are now more than 4,000 minerals approved by the IMA. Classroom projects might generate some of the data needed. If there were an online repository of these data, some of the projects described in this discussion would benefit, e.g. a search for minerals with a high thermoelectric effect.

Members of several of the mineral groups listed at the beginning of this discussion 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 geoscience, technology and science education. The outcomes are bound to help define the electrical environment of the Earth and lead to technological innovation. Even in advanced topics such as this, there is an immediate possibility for progress. It is hoped that this review was helpful.

Table 29. Short references for Ferroelectric, Antiferroelectric and Paraelectric Minerals in Tables 1, 4 and 8.

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
Hellwege and Hellwege (1970a)	Srebrodolskite
Howe and Whitworth (1989)	Ice
Kuhs et al. (1987)	Ice
Lines and Glass (1977)	Altaite
Nelson (1993)	Boracite, Pyrargyrite, Sillénite
Parkhomenko (1971)	Hydroxycalcioroméite
Pepinsky et al. (1956)	Alum-Na
Shiozaki et al. (2002a)	Barioperovskite, Lakargiite, Lueshite, Macedonite, Perovskite, Tausonite
Shiozaki et al. (2002b)	Boracite, Cervantite, Chambersite, Changbaiite, Clinocervantite, Diomignite, Ericaite, Heftetjernite, Koechlinite, Mariinskite, Oxycalciopyrochlore, Oxyplumbopyrochlore, Russellite, Stibiotantalite, Wakefieldite-Nd
Shiozaki et al. (2004)	Archerite, Biphosphammite, Demicheleite-Br, Demicheleite-I, Gwihabaite, Niter, Nitratine, Proustite, Pyrargyrite, Schultenite
Shiozaki et al. (2005)	Stibnite
Yuodvershis et al. (1969)	Bismuthinite

Notes: Full references are at the end of the article. Data sources that are part of the Landolt-Börnstein Database in SpringerMaterials are underlined, for ease in distinguishing these (Springer, 2012).

Table 30. Short references for Pyroelectric Minerals in Tables 2, 5 and 8.

Reference	**Minerals**
Bond (1943)	Iodargyrite
Hawkins et al. (1995)	Tourmaline
Mirgorodsky et al. (1989)	Sinoite

Table 30. Continued...

Nelson (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, Sarcolite, Seligmannite, Swedenborgite, Syngenite, Thaumasite, 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: Full references are at the end of the article. 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 31. Short references for Piezoelectric Minerals in Tables 3, 6 and 8.

Reference	**Minerals**
Barthelmy (2012)	Gallite
Bond (1943)	Tiemannite, Topaz, Zunyite
Cady (1946)	Topaz
Nelson (1993)	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, Bastnäsite-Ce, Bavenite, Dioptase, Edingtonite, Gismondine-Ca, Gmelinite-Na, Gugiaite, Helvine, Jeremejevite, Leucophanite, Londonite, Mimetite, Nitrobarite, Olsacherite, Pharmacosiderite, Quartz, Rhodizite, Thornasite, Tugtupite

Notes: Full references are at the end of the article. Data sources that are part of the Landolt-Börnstein Database in SpringerMaterials are underlined, for ease in distinguishing these (Springer, 2012).

Table 32. Short references for Crystal Structure Data.

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)	Dioptase
Belovitskaya et al. (2000)	Burbankite
Bindi and Cipriani (2004)	Muthmannite
Birnstock (1967)	Nitrobarite
Breitinger et al. (2006)	Crandallite, Goyazite
Burns and Hawthore (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
Hellwege and Hellwege (1970a)	Hematite, Siderite, Srebrodolskite, Wüstite
Hellwege and Hellwege (1970b)	Ferberite
Hellwege and Hellwege (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

Table 32. Continued...

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
McIver (1963)	Bultfonteinite
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
Shiozaki et al. (2002a)	Barioperovskite, Lakargiite, Lueshite, Macedonite, Perovskite, Tausonite
Shiozaki et al. (2002b)	Cervantite, Chambersite, Changbaiite, Clinocervantite, Diomignite, Ericaite, Heftetjernite, Mariinskite, Oxycalciopyrochlore, Oxyplumbopyrochlore, Russellite, Stibiotantalite, Uraninite, Wakefieldite-Nd
Shiozaki et al. (2004)	Archerite, Biphosphammite, Demicheleite-Br, Demicheleite-I, Gwihabaite, Niter, Nitratine, Proustite, Pyrargyrite, Schultenite
Shiozaki et al. (2005)	Stibnite
Sokolova and Hawthorne (2004)	Epistolite
Sokolova et al. (1996)	Marialite
Sokolova et al. (2011)	Innelite
Sowa et al. (2004)	Millerite
Szymanski (1985)	Plumbojarosite
Takeuchi and Haga (1969)	Seligmannite
Tančić et al. (2010)	Beryl
Uvarova et al. (2003)	Batisite
Venetopoulos and Rentzeperis (1976)	Clinohedrite
Wijn (1988)	Cuprokalininite, Cuprorhodsite, Daubréelite, Hauerite, Krut'aite, Linnaeite, Nickeline, Pyrrhotite, Vaesite
Wijn (1991a)	Cuprospinel, Jacobsite, Karelianite, Maghemite, Magnesioferrite, Magnetite, Trevorite
Wijn (1994)	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

Table 32. Continued...

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: Full references are at the end of the article. 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 33. Short references for Ferroelectric Data (from Minerals) in Tables 10 to 12.

Reference	**Minerals**
Bhide and Damle (1960)	Pyrolusite
Grigas et al. (1976)	Chalcostibite
Nelson (1993)	Boracite
Shiozaki et al. (2002a)	Barioperovskite, Lueshite, Macedonite, Tausonite
Shiozaki et al. (2002b)	Boracite, Heftetjernite, Oxyplumbopyrochlore, Stibiotantalite, Wakefieldite-Nd
Shiozaki et al. (2004)	Archerite, Demicheleite-Br, Demicheleite-I, Gwihabaite, Niter, Nitratine

Notes: Full references are at the end of the article. Data sources that are part of the Landolt-Börnstein Database in SpringerMaterials are underlined, for ease in distinguishing these (Springer, 2012).

Table 34. Short references for Pyroelectric Data (from Minerals) in Table 13.

Reference	**Minerals**
Hawkins et al. (1995)	Tourmaline
Nelson (1993)	Boracite, Fresnoite, Greenockite, Tourmaline, Wurtzite
Parkhomenko (1971)	Cadmoselite
Shiozaki et al. (2002a)	Macedonite
Shiozaki et al. (2002b)	Boracite, Chambersite, Diomignite
Shiozaki et al. (2004)	Proustite

Notes: Full references are at the end of the article. Data sources that are part of the Landolt-Börnstein Database in SpringerMaterials are underlined, for ease in distinguishing these (Springer, 2012).

Table 35. Short references for Thermoelectric Data (from Minerals) in Table 14.

Reference	**Minerals**
Hellwege and Hellwege (1970b)	Cuprospinel, Magnetite
Hellwege and Hellwege (1978)	Kalininite
Shiozaki et al. (2002a)	Cadmoindite, Carrollite, Lueshite, Macedonite
Wijn (1988)	Cuprokalininite, Cuprorhodsite, Daubréelite, Indite, Linnaeite, Siegenite
Wijn (1991a)	Coulsonite, Jacobsite, Magnesiocoulsonite, Trevorite

Notes: Full references are at the end of the article. Data sources that are part of the Landolt-Börnstein Database in SpringerMaterials are underlined, for ease in distinguishing these (Springer, 2012).

Table 36. Short references for Piezoelectric Data (from Minerals) in Tables 15 to 21.

Reference	**Minerals**
Bhide and Damle (1960)	Pyrolusite
Hellwege et al. (1990)	Barioperovskite
Nelson (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
Shiozaki et al. (2002a)	Macedonite, Tausonite
Shiozaki et al. (2002b)	Changbaiite, Diomignite, Russellite
Shiozaki et al. (2004)	Archerite, Biphosphammite

Notes: Full references are at the end of the article. Data sources that are part of the Landolt-Börnstein Database in SpringerMaterials are underlined, for ease in distinguishing these (Springer, 2012).

Table 37. Short references for Dielectric Data (from Minerals) Included in Table 22 and Table 23.

Reference	**Minerals**
Hellwege and Hellwege (1970b)	Cuprospinel
Hellwege and Hellwege (1978)	Spinel
Hellwege et al. (1990)	Barioperovskite
Nelson (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
Shiozaki et al. (2002a)	Lakargiite, Lueshite, Macedonite, Perovskite, Tausonite
Shiozaki et al. (2002b)	Cervantite, Chambersite, Changbaiite, Clinocervantite, Diomignite, Ericaite, Heftetjernite, Koechlinite, Oxycalciopyrochlore, Oxyplumbopyrochlore, Russellite, Rutile, Stibiotantalite, Wakefieldite-Nd
Shiozaki et al. (2004)	Archerite, Biphosphammite, Nitratine, Schultenite
Wijn (1991a)	Franklinite, Magnesioferrite, Trevorite

Notes: Full references are at the end of the article. 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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