Geological Thermometers

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Common Ore Minerals

List of the Common Ore Minerals

Metal	Ore Mineral	Composition	Percent Metal	Primary	Supergene
Gold	Native gold	Au	100	X	X
	Calaverite	$AuTe_2$	39	X	
	Sylvanite	$(Au,Ag)Te_2$	..	X	
Silver	Native silver	Ag	100	X	X
	Argentite	Ag_2S	87	X	X
	Cerargyrite	AgCl	75		X
Iron	Magnetite	$FeO \cdot Fe_2O_3$	72	X	
	Hematite	Fe_2O_3	70	X	X
	"Limonite"	$Fe_2O_3 \cdot H_2O$	60		X
	Siderite	$FeCO_3$	48	X	X
Copper	Native copper	Cu	100	X	X
	Bornite	Cu_5FeS_4	63	X	X
	Brochantite	$CuSO_4 \cdot 3Cu(OH)_2$	62		X
	Chalcocite	Cu_2S	80	X	X
	Chalcopyrite	$CuFeS_2$	34	X	X
	Covellite	CuS	66	X	X
	Cuprite	Cu_2O	89		X
	Enargite	$3Cu_2S \cdot As_2S_5$	48	X	
	Malachite	$CuCO_3 \cdot Cu(OH)_2$	57		X
	Azurite	$2CuCO_3 \cdot Cu(OH)_2$	55		X
	Chrysocolla	$CuSiO_3 \cdot 2H_2O$	36		X
Lead	Galena	PbS	86	X	
	Cerussite	$PbCO_3$	77		X
	Anglesite	$PbSO_4$	68		X
Zinc	Sphalerite	ZnS	67	X	
	Smithsonite	$ZnCO_3$	52		X
	Hemimorphite	H_2ZnSiO_5	54		X
	Zincite	ZnO	80	X	
Tin	Cassiterite	SnO_2	78	X	?
	Stannite	$Cu_2S \cdot FeS \cdot SnS_2$	27	X	?
Nickel	Pentlandite	(Fe,Ni)S	22	X	
	Garnierite	$H_2(Ni,Mg)SiO_3 \cdot H_2O$	..		X
Chromium	Chromite	$FeO \cdot Cr_2O_3$	68	X	
Manganese	Pyrolusite	MnO_2	63		X
	Psilomelane	$Mn_2O_3 \cdot xH_2O$	45		X
	Braunite	$3Mn_2O_3 \cdot MnSiO_3$	69	?	X
	Manganite	$Mn_2O_3 \cdot H_2O$	62		X
Aluminum	Bauxite	$Al_2O_3 \cdot 2H_2O$	39		X
Antimony	Stibnite	Sb_2S_3	71	X	
Bismuth	Bismuthinite	Bi_2S_3	81	X	X
Cobalt	Smaltite	$CoAs_2$	28	X	
	Cobaltite	CoAsS	35	X	
Mercury	Cinnabar	HgS	86	X	
Molybdenum	Molybdenite	MoS_2	60	X	
	Wulfenite	$PbMoO_4$	39		X
Tungsten	Wolframite	$(Fe,Mn)WO_4$	76	X	
	Huebnerite	$MnWO_4$	76	X	
	Scheelite	$CaWO_4$	80	X	

Common Gangue Minerals

List of Common Gangue Minerals

Class	Name	Composition	Primary	Supergene
Oxides	Quartz	SiO_2	X	X
	Other silica	SiO_2	X	X
	Bauxite, etc.	$Al_2O_3 \cdot 2H_2O$		X
	Limonite	$Fe_2O_3 \cdot H_2O$		X
Carbonates	Calcite	$CaCO_3$	X	X
	Dolomite	$(Ca,Mg)CO_3$	X	X
	Siderite	$FeCO_3$	X	X
	Rhodochrosite	$MnCO_3$	X	
Sulphates	Barite	$BaSO_4$	X	
	Gypsum	$CaSO_4 + 2H_2O$		X
Silicates	Feldspar	....	X	
	Garnet	....	X	
	Rhodonite	$MnSiO_3$	X	
	Chlorite	....	X	
	Clay minerals	....	X	X
Miscellaneous	Rock matter		X	
	Fluorite	CaF_2	X	
	Apatite	$(CaF)Ca_4(PO_4)_3$	X	
	Pyrite	FeS_2	X	X
	Marcasite	FeS_2	X	X
	Pyrrhotite	$Fe_{1-x}S$	X	
	Arsenopyrite	FeAsS	X	

Common Gangue Minerals

DATA ON METALS AND THEIR ORES

Metal	Unit of Measure	Tenor		Common Associates	Commercial Unit	Price Ranges,	
		Low	Average			1925–40	1941–49
Gold	oz/ton	0.15	0.2–0.3	Ag	oz Troy	20.67–35.00	35.00
Silver	oz/ton	10	12–30	Au, Pb	oz Troy	0.25–0.70	0.35–0.90
Platinum	oz/ton	0 1	0 3	Pt group	oz Troy	31.00–67.65	36.00–93.00
Iron	% Fe	30	40–60	Mn	ton iron	15 00–24.00	20.00–34 00
Copper	% Cu	0.7	1–5	Au, Ag	lb Cu	0.05–0.21	0.12–0 235
Lead	% Pb	3	5–10	Zn, Ag	lb Pb	0.03–0.09	0.06–0 215
Zinc	% Zn	3	10–30	Pb	lb Zn	0.03–0.08	0.075–0.175
Tin	% Sn	0.5	1–5	W	lb Sn	0.22–0.65	0.52–1.03
Nickel	% Ni	1 5	1.5–3	Cu, Pb	lb Ni	0.35–0.39	0.31–0.35
Aluminum	% Al_2O_3	30	55–65	.....	lb Al	0.17–0.24	0.15–0.17
Antimony	% Sb	20	40–60	Ag	lb Sb	0.05–0 17	0 14–0.417
Bismuth	% Bi	BP*	40–60	W	lb Bi	0.85–1.30	1.25–2.00
Beryllium	% BeO	8	10–12	. ....	unit BeO	30.00–35 00	26.00–47.00
Arsenic	% As_2O_3	BP	.....	.....	lb As_2O_3	0.01–0.03	0.04–0.06
Cobalt	% Co	5	8–10	Ag, Cu	lb Co	1.10–3.00	1.50–1.80
Chromium	% Cr_2O_3	32	35–50	.... ..	ton Cr_2O_3	17.00–47.00	34.00–48.00
Cadmium	% Cd	BP	. ....	Zn	lb Cd	0.55–1.42	0.75–2.00
Manganese	% Mn	35	45–55	Fe	units/ton	0.18–0.55	0.70–0.73
Mercury	% Hg	0.5	1–3	. .. ..	flask–76 lb	58.00–202.00	76.00–196.00
Molybdenum	% MoS_2	0.4	1–3	. .. .	lb MoS_2	0.34–0.45	0.45–0.54
Titanium	% TiO_2	3	4–40	Fe	lb TiO_2	..... .	5.00–6.00
Tungsten	% Wo_3	....	60–70	..... .	unit WO_3	9.20–20.61	24.00–28.50
Vanadium	% V_2O_5	2	3–8	.....	lb V_2O_5	0.20–1 05	0.27–0.275

* BP = by-product.

Modes of Formation

- Crystallization from Magma
- Sublimation
- Distillation
- Evaporation & Super Saturation
- Biogenic Precipitation
- Reaction of liquids with liquid/solid
- Reaction of gasses with other solid/liquid/gasses

Geological Thermometers

- Four Groups:
  - Fairly accurate
  - Upper or Lower end of formation or not formation
  - Range of Temperature
  - Rough indication

Geological Thermometers

- Direct Measurement
- Melting Point
- Dissociation
- Inversion Point
- Exsolution
- Recrystallization
- Liquid inclusion
- Changes in physical properties
- Associated Minerals

Geological Thermometers

- Direct Measurement:
  - Lava/Magma
  - Fumaroles
  - Hot Springs
- Melting Point:

Table 1.1. Melting temperatures of some common minerals

	Minerals	*Melting temperatures*
1.	Olivine (Forsterite)	1890°C
2.	Anorthite	1550°C
3.	Diopside	1391°C
4.	Albite	1120°C
5.	Antimony	630°C
6.	Stibnite	546°C
7.	Bismuth	271°C
8.	Sulphur	119°C

Geological Thermometers

- Inversion Point:

Table 1.2. Inversion temperatures of some common minerals

Minerals	*Inversion temperatures*
1. Tridymite inverts to Cristobalite	1470°C
2. Sphalerite to Wurtzite	1020°C
3. Kyanite to Mullite	1000°C
4. High Quartz (β-Quartz) to Tridymite	870°C
5. Low Quartz (α-Quartz) to High Quartz (β-Quartz)	573°C

- Dissociation Temperature:

Table 1.3. Dissociation temperatures of some minerals

Minerals	*Dissociation temperatures*
1. Tremolite yields diopside	900°C
2. Calcite (at 1 atm) dissociates	900°C
3. Pyrite into Pyrrhotite and sulphur vapour (1 atm)	685°C

Geological Thermometers

- Exsolution temprature:

Table 1.4. Ex-solution temperatures of some minerals

Minerals	*Exsolution temperatures*
1. Magnetite	800°C
2. Magnetite-Ilmenite	700°C
3. Chalcopyrite-Pyrrhotite	600°C
4. Stannite-Chalcopyrite	500°C
5. Bornite-Tetrahedrite	275°C

- Recrystallization

Table 1.5. Recrystallisation temperatures of a few native minerals

Minerals	*Recrystallisation temperatures*
1. Copper	450°C
2. Gold	360°C
3. Silver	200°C

Geological Thermometers

- Liquid Inclusion
- Physical Changes

Table 1.6. Physical changes in some minerals at certain temperatures

	Minerals	*Physical changes*	*Temperatures*
1.	Limestone	Pigment expelled	605°C
2.	Mica	Pleochroic haloes destroyed	480°C
3.	Smoky quartz	Colour disappears	300°C
4.	Amethyst	Loses colour	240°-260°C
5.	Fluorite	Loses colour	Around 175°C

Geological Thermometers

- Associated Minerals

Table 1.7 : Comparative temperatures of formations of some minerals

High temperature	*Intermediate temperature*	*Low temperature*
Magnetite	Chalcopyrite	Marcasite
Pyrrhotite	Arsenopyrite	Adularia
Cassiterite	Galena	Chalcedony
Garnet	Sphalerite	Rhodochrosite
Pyroxene	Tetrahedrite	Siderite

List of Geologic Thermometers

Temperature (°C)	Mineral	Nature	Remarks	Authority
1890	Olivine (forsterite)	Melting point		Bowen
1713	Cristobalite	Melting point		Wright-Larsen
1550	Anorthite	Melting point		Bowen
1470	Tridymite to cristobalite	Inversion point		Wright-Larsen
1391	Diopside	Melting point		Bowen
1248	Nepheline to carnegite	Inversion point		Bowen
1185	Basalt lava at Kilauea	Measured		Day-Shepherd
1157–1187	Pyrrhotite	Melting point		Bowen
1150±20	Orthoclase	Melts incongruently	Yields leucite	Morey-Bowen
1125±	Wollastonite to pseudowollastonite	Inversion point	$CaMg(SiO_3)_2$ in solution raises to 1300°	Osborn-Schairer
1120	Galena melts	Melting point		Jaeger-Van Klooster
1120	Albite melts	Melting point		Bowen
1045	PbS-ZnS eutectic melts	Melting point	PbS = 94%	Ramdohr
1020	Sphalerite to wurtzite	Inversion point	If 17% Fe T is 880°	Allen-Crenshaw-Merwin
1000	Sillimanite, kyanite, andalusite		Yields mullite	Posnjak-Bowen
955–1140	Orthorhombic pyroxene to monoclinic pyroxene	Inversion point	Upper limit of orth. pyr.	Bowen-Schairer
990	Aegirine	Melts	Incongruently	Bowen
900	Tremolite	Dissociation	Yields diopside	Posnjak-Bowen

870	High-quartz to tridymite	Inversion point	Sluggish	Sosman
842	Argentite	Melting point		Edwards
830–900	Cobaltite inverts	Inversion point		Ramdohr
800	Garnet loses birefringence			Lindgren
800	Magnetite-spinel	Exsolution		Ramdohr
600–700	Carbon driven out of limestone		800° at 40 atm	Lindgren
700	Magnetite-ilmenite unmixing	Exsolution	Doubtful — too high	Ramdohr
685	Pyrite to pyrrhotite-sulphur (1 atm)	Dissociation		Bowen
675	Hematite-ilmenite unmixing	Exsolution	Doubtful — too high	Ramdohr
630	Galena-argentite eutectic melts	Melting point		Bowen
630	Antimony	Melting point		Edwards
609	Jamesonite melts	Melting point	Incongruently	Jaeger, Van Klooster
605	Pigment of limestone expelled			Erdmannsdörffer
603	α-Leucite to β-leucite	Inversion		Schairer
600	Chalcopyrite-pyrrhotite	Exsolution		Hewitt-Schwartz
580	Cinnabar	Sublimes		Edwards
573	Low quartz to high quartz	Inversion point	Enantiotropic	Wright-Larsen
550?	Sphalerite and chalcopyrite unmix	Exsolution?		Borchert
550	Maghemite-hematite	Recrystallization		Ramdohr
546	Stibnite melts	Melting point		Jaeger, Van Klooster

175	Fluorite — color disappears			Lindgren
175–225	Bornite-chalcocite unmix	Exsolution	Slow	Schwartz
168	Carnallite	Melts incongruently		Van't Hoff-Meyerhoffer
150	Ag_2Te			Ramdohr
149	Hessite	Inversion point		
144–139	Pyrrhotite	Inversion point	Low hex. to high ortho.	Roberts
135	Sphalerite of Tri-State	Vacuoles		Newhouse
133	Ag_2S_2			Ramdohr
130	Goethite — unstable above —			Posnjak-Merwin
119	Sulphur melts	Melting point		Wigand
100	Stromeyerite inversion	Inversion point		Ramdohr
100±	Zeolites — max. limit of formation		Low pressure	Bowen
100+	Adularia		Lower limit	
93–105	Chalcocite, ortho. to hexagonal	Inversion point	Prompt	Zies et al.
75	Bismuth inversion	Inversion point		Ramdohr
70–75	Chalcocite-covellite unmix	Exsolution		Bateman
70	Bismuth, α to β	Inversion point		Edwards
−43	Aragonite to calcite	Inversion point	Monotropic	Bäckström

Any Questions??

Thank You !!!