Nitrates

Borates

Sulfates

Tungstates, Molybdates and Chromates

Phosphates, Arsenates and Vanadates

Nitrates

Nitratite (Soda Niter) **Crystal structure: Hexagonal**
$NaNO_3$

Structure and Composition

Nitratite is isostructural with calcite; and take the place of Ca^{2+} and CO_3^{2-}, respectively. It is always nearly pure, forming very limited solid solution with niter (saltpeter).

Occurrence and Associations

Because nitratite is highly soluble in water, it is only found in arid regions where it may be associated with other evaporite minerals.

Related Minerals

The only other common nitrate is niter (saltpeter).

Nitrates

Niter (Saltpeter) **Crystal structure: Orthorhombic**
KNO_3

Structure and Composition

Niter is isostructural with aragonite. It forms minor solid solutions with nitratite.

Occurrence and Associations

Niter is found in arid-region soils and unconsolidated sediments in caves.

Related Minerals

Soda niter (sodium nitrate), Ammonia niter (ammonium nitrate), and Strontium nitrate.

Eight or nine nitrate minerals are known, but all except niter and nitratite are extremely rare.

Borates

Anhydrous Borate Group
Boracite $Mg_3ClB_7O_{13}$
Sinhalite $MgAlBO_4$

Hydrous Borate Group

Borax $Na_2B_4O_5(OH)_4.8H_2O$
Kernite $Na_2B_4O_6(OH)_2 .3H_2O$
Ulexite $NaCaB_5O_6(OH)_6\ 5H_2O$
Colemanite $CaB_3O_4(OH).3H_2O$
Dumortierite $Al_{(6.5\text{-}7)}BSi_3O_{15}(O,OH)_3$

Although multiple borate minerals exist, most (especially the anhydrous borates) are very rare. Borate minerals have complex structures and chemistries, due in large part to the small size and trivalent nature of ionic boron. They have structural similarity to carbonates and nitrates because boron combines with oxygen to form anionic groups: $(BO_3)^{3-}$ or $(BO_4)^{5-}$

Borates

Borax
$Na_2B_4O_5(OH)_4.8H2O$

Crystal structure:
Monoclinic

Composition

Although the Na:B ratio is fixed, the amounts of $(OH)^-$ and (H_2O) in borax are variable.

Occurrence and Associations

Borax, associated with evaporite deposits in volcanic terranes, is the most common of the hydrous borate minerals. It is found in thick beds, similar to other salts, and as crusts and surface coatings. Common associated minerals are halite, NaCl; colemanite, $CaB_3O_4(OH)_3.H_2O$; ulexite, $NaCaB_5O_6.(OH)_6.5H_2O$; and gypsum, $CaSO_4.2H_2O$.

Related Minerals

Borax dehydrates easily to tincalconite, $Na_2B_4O_5(OH)_4.3H_2O$

Sulfates

Anhydrous Sulfate Group

Anhydrite CaSO4
Barite BaSO4
Celestite SrSO4
Anglesite PbSO4

Hydrous Sulfate Group

Gypsum $CaSO_4.2H_2O$
Chalcanthite $CuSO_4.5H_2O$
Epsomite $MgSO_4.7H_2O$
Antlerite $Cu_3SO_4(OH)_4$
Alunite $KAl_3(SO_4)_2(OH)_6$

Sulfate minerals are divided into two groups: the anhydrous sulfates and the hydrous sulfates. Chemistries and structures of the anhydrous sulfates are related to the carbonates, with SO_4 replacing the CO_3.

More than 100 sulfate minerals are known, and most are rare. Gypsum and anhydrite are the only rock-forming sulfates.

Sulfates

Anhydrite
$CaSO_4$

Crystal structure:
Orthorhombic

Composition

Anhydrite is generally close to $CaSO_4$ in composition but may be partially hydrated (tending toward gypsum).

Occurrence and Associations

Anhydrite is typically an evaporite mineral associated with gypsum, sulfur, halite, calcite, or dolomite. Thick anhydrite beds are well known. It is also found in amygdules or cracks in basalt, as a gangue mineral in hydrothermal ore deposits, as a component of soils, or as a hot spring deposit.

Related Minerals

Anhydrite is chemically related to other anhydrous sulfates, including barite ($BaSO_4$); celestite ($SrSO_4$); and anglesite ($PbSO_4$) , but has a different structure.

A polymorph of anhydrite, γ-$CaSO_4$, forms when gypsum ($CaSO_4.2H_2O$) is dehydrated.

Sulfates

Barite
$BaSO_4$

Crystal structure:
Orthorhombic

Occurrence and Associations

Barite is a common gangue mineral in hydrothermal veins, associated with fluorite, galena, quartz, calcite, or dolomite. It is also found in veins in limestone, and as residual masses in clays.

Related Minerals

Barite is chemically and structurally similar to celestite ($SrSO_4$); and anglesite ($PbSO_4$), although solid solutions between the three are limited in nature.

Sulfates

Anglesite
$PbSO_4$

Crystal structure:
Orthorhombic

Occurrence and Associations

Anglesite, a common alteration product of galena, PbS, is found in oxidized portions of Pb deposits. Associated minerals include wulfenite, $PbMoO_4$; smithsonite, $ZnCO_3$; hemimorphite, $Zn_4(Si_2O_7)(OH)2.H2O$; and pyromorphite, $Pb_5(PO_4)_3Cl$
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Related Minerals

Anglesite is isostructural with barite, $BaSO_4$, and celestite, $SrSO_4$, and is one of only a few common Pb minerals.

Sulfates

Gypsum
$CaSO_4.2H_2O$

Crystal structure:
Monoclinic

Composition near pure end-member, rarely containing significant impurities.

Occurrence and Associations

Gypsum, the most common sulfate mineral, is a rock-forming mineral of many evaporite deposits where it may be associated with other bedded salts. It is also found interlayered with limestones or shales and may be found in fractures or cracks in a variety of sedimentary rocks. It is a gangue mineral or alteration product in some ore deposits and is occasionally found around fumaroles.

Related Minerals

Other hydrous sulfates include chalcanthite, $CuSO4.5H_2O$; epsomite, $MgSO_4.7H_2O$; antlerite, $Cu_3SO_4(OH)_4$; and alunite, $KAl_3(SO_4)_2(OH)_6$. Gypsum forms from, or alters to, anhydrite, $CaSO_4$.

TUNGSTATES, MOLYBDATES, AND CHROMATES

Tungstate Group

Wolframite series
Huebnerite $MnWO_4$
Ferberite $FeWO_4$
Scheelite $CaWO_4$

Molybdate Group
Wulfenite $PbMoO_4$

Chromate Group
Crocoite $PbCrO_4$

Tungstates, molybdates, and chromates are chemically and structurally related to the anhydrous sulfates. Generally rare minerals, they may be locally concentrated in ore deposits.

Tungstate

Wolframite
$(Fe,Mn)WO_4$

Crystal structure:
Monoclinic

A complete solid solution exists between ferberite $FeWO_4$ and huebnerite $MnWO_4$, the two principal wolframite end members. The basic structure consists of layers of distorted tetrahedra joined by octahedral Fe or Mn.

Occurrence and Associations

Wolframite is usually found in high-temperature quartz veins associated with granitic igneous rocks, it is, however, the most important tungsten ore mineral. It is also found in sulfide-rich veins, associated with scheelite, cassiterite, pyrite, or galena. It may contain minor amounts of Ca, Mg, or rare earth elements.

Related Minerals

Similar minerals include the rare tungstates sanmartinite, $(Zn,Fe)WO_4$,and raspite, $Pb(WO_4)$.

Tungstate

Scheelite
$CaWO_4$

Crystal structure:
Tetragonal

Scheelite is usually close to end member composition, but a limited solid solution exists with powellite, CaMoO4 . It may also incorporate small amounts of Cu or Mn. In the structure, isolated tetrahedra $(WO_4)^{2-}$ are linked by 8-coordinated Ca.

Occurrence and Associations

Scheelite is a high-temperature mineral found in metamorphic aureoles, in granites and pegmatites, and in some hydrothermal veins. It may be found with cassiterite, SnO_2; topaz, $Al_2SiO_4(F,OH)_2$; fluorite, CaF_2 ; apatite, $Ca_5(PO_4)_3(OH,F,Cl)$**; and with other tungstates or molybdates.**

Related Minerals

Scheelite is isostructural with wulfenite, $PbMoO_4$

Molybdate

Wulfenite
$PbMoO_4$

Crystal structure:
Tetragonal

Scheelite is usually close to end member composition, but a limited solid solution exists with powellite, CaMoO4 . It may also incorporate small amounts of Cu or Mn. In the structure, isolated tetrahedra $(WO_4)^{2-}$ are linked by 8-coordinated Ca.

Occurrence and Associations

Wulfenite is a rare secondary mineral found in the oxidized portions of Pb deposits. It may be associated with galena, PbS; cerussite, $PbCO_3$; vanadinite, $Pb5(VO_4)_3Cl$
; or pyromorphite, $Pb_5Cl(PO_4)_3$**.**

Related Minerals

Wulfenite is isostructural with scheelite, with which it forms limited solid solutions. It also forms limited solid solutions with powellite, $CaMoO_4$, and raspite, $Pb(WO_4)$.

Chromate

Crocoite
$PbCrO_4$

Crystal structure:
Monoclinic

Crocoite is isostructural with monazite, $(Ce,La,Th,Y)PO_4$.

Occurrence and Associations

Crocoite is a rare secondary Pb mineral associated with veined lead deposits. It may be found with cerussite, PbCO3; pyromorphite, $Pb(PO_4)_3Cl$; or wulfenite, $PbMoO_4$.

Related Minerals

Crocoite is isostructural with monazite, $(Ce,La,Th,Y)PO_4$, and with several other rare earth silicates and phosphates. It is closely related to xenotime, $Y(PO_4)$, and pucherite, $Bi(VO_4)$.

PHOSPHATES, ARSENATES, AND VANADATES

<u>Phosphate Group Minerals</u>

Monazite	**$(Ce,La,Th,Y)PO_4$**
Triphylite	**$Li(Fe,Mn)PO_4$**
Apatite	**$Ca_5(PO_4)_3(OH,F,Cl)$**
Pyromorphite	**$Pb_5(PO_4)_3Cl$**
Amblygonite	**$LiAl(PO_4)F$**
Lazulite	**$(Mg,Fe)Al_2(PO_4)_2(OH)_2$**
Wavellite	**$Al_3(PO_4)_2(OH)_3 .5H_2O$**
Turquoise	**$CuAl_6(PO_4)_4(OH)_8.4H2O$**
Autunite	**$Ca(UO_2)_2(PO_4)_2.10H_2O$**

<u>Vanadate Group Minerals</u>

Vanadinite	**$Pb_5(VO_4)_3Cl$**
Carnotite	**$K_2(UO_2)_2(VO_4)_2.3H2O$**

<u>Arsenate Group Minerals</u>

Erythrite	**$Co_3(AsO_4)_2.8H_2O$**

Phosphate

Monazite
$(Ce,La,Th,Y)PO_4$

Crystal structure:
Monoclinic

Monazite is isostructural with crocoite.

All the rare earths may be present, but Ce, La, and Th are usually the dominant large cations. Small amounts of Si may substitute for P in the tetrahedral sites.

Occurrence and Associations

Monazite is a rare secondary mineral is silicic igneous rocks. It is also found in unconsolidated beach or stream sediments, where it is associated with other heavy minerals such as magnetite and ilmenite.

Related Minerals

Monazite is isostructural with crocoite, $PbCrO_4$, and forms solid solutions with huttonite, $ThSiO_4$.
It is chemically related to xenotime, $Y(PO_4)$, with which it forms a minor solid solution.

Phosphate

Apatite
$Ca_5(PO_4)_3(OH,F,Cl)$

Crystal structure:
Hexagonal

Complete solid solution exists between hydroxyapatite (OH end member), fluorapatite (F end member), and chlorapatite (Cl end member).

In addition, transition metals or Sr may replace Ca; and $(CO3)^{2-}$, $(OH)^-$, $(SO_4)^{2-}$ or may replace some $(PO_4)^{2-}$.

In the apatite structure, chains run parallel to the c-axis. is located around channels occupied by (F,Cl,OH).

Occurrence and Associations

Apatite is a common accessory mineral but only rarely a major rock former. It is common in all igneous rocks, including pegmatites and hydrothermal veins, in metamorphic rocks, and in marine sediments.

Related Minerals

A large number of phosphates, sulfates, arsenates, vanadanates, and silicates are isostructural with apatite, but none are common.

Phosphate

Pyromorphite
$Pb_5(PO_4)_3Cl$

Crystal structure:
Hexagonal

Pyromorphite is isostructural with apatite. Some Ca may substitute for Pb.

P may be replaced by As.

Occurrence and Associations

Pyromorphite is a secondary mineral, found with other oxidized Pb or Zn minerals, in oxidized zones associated with Pb deposits.

Related Minerals

It is isostructural with apatite and with mimetite, $Pb(AsO_4)_3Cl$, with which it forms a complete solid solution.

Phosphate

Turquoise
$CuAl_6(PO_4)_4(OH)_8.4H2O$

Crystal structure:
Triclinic

Fe^{3+} may substitute for Al^{3+}.

Occurrence and Associations

Turquoise occurs as a secondary mineral associated with Al-rich volcanic rocks. It forms in small seams, veins, stringers, and crusts. Associated minerals include kaolinite, $Al_2Si_2O_5(OH)_4$; limonite, Fe(O,OH)n ; and chalcedony, SiO_2.

Blue-green varieties of turquoise are called faustite.

Related Minerals

Complete solid solution exists between turquoise and chalcosiderite, $CuFe_6(PO_4)_4\ (OH)_8.4H_2O$.

Arsenates

Erythrite
$Co_3(AsO_4)_2 .8H_2O$

Crystal structure:
Monoclinic

Ni may substitute for Al.

Occurrence and Associations

Erythrite may form as a pink powdery coating, called cobalt bloom, on other cobalt minerals such as cobaltite, (Co,Fe)AsS, or skutterudite, (Co, Ni)As_3 .

Related Minerals

Annabergite, $Ni_3(AsO_4)_2 .8H_2O$, also called nickel bloom, is isostructural with erythrite, but has an apple-green color.

A complete solid solution exists between erythrite and annabergite.

Vanadates

Vanadinite
$Pb_5(VO_4)_3Cl$

Crystal structure:
Hexagonal

Vanadinite is isostructural with apatite. P or As may substitute for V in small amounts. Minor amounts of Ca, Zn, and Cu may also be present.

Occurrence and Associations

Vanadinite is a rare mineral found in the oxidized portions of Pb deposits where it is often associated with galena, cerussite, or limonite.

Related Minerals

Vanadinite is isostructural with apatite, $Ca5(PO_4)_3(OH,F,Cl)$, and with a number of other arsenates, vanadates, and phosphates.

It forms solid solutions with mimetite, $Pb_5(AsO_4)_3Cl$, and intermediate compositions are called Endlichite.